FINAL REPORT

Managing Loblolly Pine (*Pinus taeda*) Stands for the Restoration of Red-cockaded Woodpecker (*Picoides borealis*) Habitat

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Joan L. Walker
U.S. Forest Service

G. Geoff Wang
Clemson University

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14. ABSTRACT

Objectives Throughout the southeastern United States, upland sites that were once dominated by longleaf pine (Pinus palustris Mill.) have been widely converted to faster growing species such as loblolly pine (P. taeda L.). Consequently, existing populations of the federally endangered redcockaded woodpecker (RCW; Picoides borealis) are currently occupying mature loblolly pine stands. Reports of declining loblolly pine health in some locations raised concerns about the longevity of existing RCW habitat and underscored the need to convert upland forests back to longleaf pine. Forest managers needed protocols to restore longleaf pine on sites where canopy pines are retained. Further, because protocol suitability is likely to vary among site types based on productivity and the structure and composition of the canopy and ground layer vegetation protocol development on a range of site conditions was necessary. The need for such protocols were deemed critical at Fort Benning, Georgia, where as many as 70% of the active RCW cavities were found in loblolly pine trees. Because longleaf pine seedling growth tends to decrease as canopy cover increases, the conversion of loblolly pine stands to longleaf was expected to require a balance between canopy removal to increase the growth of planted longleaf pine seedlings and canopy retention for RCW habitat and other ecosystem services (e.g., fuel inputs from needlefall). Retaining the trees likely to live the longest would secure the most RCW habitat value through time; thus, a model for predicting tree longevity would be a valuable management tool. Additionally, an increased understanding of environmental factors associated with reduced loblolly pine health was needed to inform RCW management decisions at Fort Benning. The objective of the project was to address three main research questions: (1) develop stand level silvicultural protocols for restoring longleaf pine forests while retaining a canopy component on Fort Benning in the sandhills of Georgia and at Marine Corps Base Camp Lejeune on the coast of North Carolina; (2) model stand vulnerability to declining loblolly pine vigor on Fort Benning where loblolly pine health was a management concern; and (3) develop a model to forecast individual loblolly pine tree mortality in stands showing reduced canopy health of Fort Benning. Technical Approach The research was conducted at Fort Benning and Camp Lejeune, sites that differ in ecological characteristics including topography, soils, weather patterns, and native flora. Such differences may influence the success of restoration protocols, and thereby inform the development of management guidance across a range of site conditions. We installed a field experiment using a randomized split plot design replicated on eight blocks at each location. We planted longleaf pine seedlings in loblolly stands treated with seven canopy treatments (main plot treatments)

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LIST OF ACRONYMS

AIK	Akaike's Information Criteria
ANCOVA	analysis of covariance
ANOVA	analysis of variance
AREA60	section 3.9 variable: integrated area under the temperature curve above 60 °C
AREAAMB	section 3.9 variable: integrated area under the temperature curve above ambient temperature
AUC	area under the curve
BA	basal area
BURNED	section 3.9 variable: cover of area burned
CEC	cation exchange capacity
CPd	correctly predicted dead
CPl	correctly predicted alive
CVC	crown vigor class
CVC1	crown vigor class 1
CVC2	crown vigor class 2
CVC3	crown vigor class 3
D1HR	section 3.9 variable: difference of pre-post 1 hr fuel
D10HR	section 3.9 variable: difference of pre-post 10 hr fuel
D100HR	section 3.9 variable: difference of pre-post 100 hr fuel
DBARE	section 3.9 variable: difference of pre-post bare ground cover
DBH	diameter at breast height (1.4 m)
DC	dead class
DGR	section 3.9 variable: difference of pre-post bare ground cover
DIB	diameter inside bark
DLITT	section 3.9 variable: difference of pre-post litter depth
DoD	Department of Defense
DPNDL	section 3.9 variable: difference of pre-post pine needle cover
DUR60	section 3.9 variable: duration of temperature above 60 °C
DURAMB	section 3.9 variable: duration of temperature above ambient
DURMAX	section 3.9 variable: duration of temperature at maximum
FWD	fine woody debris
FWS	Fish and Wildlife Service
G	cultural treatment: native grass establishment
GIS	Geographic Information Systems
GLI	gap light index
GLM	general linear model
H	cultural treatment: herbicide application
H+F	cultural treatment: herbicide plus fertilizer application
IER	ion exchange resin
IV	importance value
LBP	loblolly pine
LG	group selection to create circular "large" gap (5027 m^2; radius = 40 m)

LLP	longleaf pine
LowBA	single tree selection to create uniform canopy with target basal area of 5 m^2/ha
LSD	least significant difference
MAXT	section 3.9 variable: maximum temperature
MCBCL	Marine Corps Base Camp Lejeune
MedBA	single tree selection to create uniform canopy with target basal area of 9 m^2/ha
MG	group selection to create circular “medium” gap (2827 m^2; radius = 30 m)
MRPP	multi-response permutation procedure
NMS	non-metric multidimensional scaling
NT	cultural treatment: no treatment applied
OAI	overstory abundance index
OM	organic matter
PAR	photosynthetically active radiation
PEd5	predicted dead within 5 years of actual year of death
PEd6-10	predicted dead within 6-10 years of actual year of death
PMS	plant moisture stress
PRE1HR	section 3.9 variable: pre-fire 1 hr fuel
PRE10HR	section 3.9 variable: pre-fire 10 hr fuel
PRE100HR	section 3.9 variable: pre-fire 100 hr fuel
PREBARE	section 3.9 variable: pre-fire bare ground cover
PREGR	section 3.9 variable: pre-fire graminoid cover
PRELITT	section 3.9 variable: pre-fire litter depth
PREPNDL	section 3.9 variable: pre-fire pine needle cover
RCW	red-cockaded woodpecker
RCD	root collar diameter
ROC	receiver operating characteristics
SCT	light transmittance through the subcanopy
SD	stem density
SDI	stand density index
SG	group selection to create circular “small” gap (1257 m^2; radius = 20 m)
SI	site index
SE	standard error
SERDP	Strategic Environmental Research and Development Program
SON	statement of need
TLT	total light transmittance to level of pine seedlings
TPH	trees per hectare
USAIC	United States Army Infantry Center
USDA	United Stated Department of Agriculture
USDI	United States Department of the Interior

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KEYWORDS

longleaf pine, *Pinus palustris*, loblolly pine, *Pinus taeda*, red-cockaded woodpecker, *Picoides borealis*, ecological restoration, stand conversion, ecological forestry, underplanting, variable retention harvest, thinning, gap-phase regeneration, fire management, herbicide release, foliar nutrients, gap light index, silviculture, soil moisture, xylem water potential, crown vigor class, tree mortality, basal area increment, xylem water potential, dendrochronology, tree mortality

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ABSTRACT

Objectives

Throughout the southeastern United States, upland sites that were once dominated by longleaf pine (*Pinus palustris* Mill.) have been widely converted to faster growing species such as loblolly pine (*P. taeda* L.). Consequently, existing populations of the federally endangered red-cockaded woodpecker (RCW; *Picoides borealis*) are currently occupying mature loblolly pine stands. Reports of declining loblolly pine health in some locations raised concerns about the longevity of existing RCW habitat and underscored the need to convert upland forests back to longleaf pine. Forest managers needed protocols to restore longleaf pine on sites where canopy pines are retained. Further, because protocol suitability is likely to vary among site types based on productivity and the structure and composition of the canopy and ground layer vegetation, protocol development on a range of site conditions was necessary. The need for such protocols were deemed critical at Fort Benning, Georgia, where as many as 70% of the active RCW cavities were found in loblolly pine trees.

Because longleaf pine seedling growth tends to decrease as canopy cover increases, the conversion of loblolly pine stands to longleaf was expected to require a balance between canopy removal to increase the growth of planted longleaf pine seedlings and canopy retention for RCW habitat and other ecosystem services (e.g., fuel inputs from needlefall). Retaining the trees likely to live the longest would secure the most RCW habitat value through time; thus, a model for predicting tree longevity would be a valuable management tool. Additionally, an increased understanding of environmental factors associated with reduced loblolly pine health was needed to inform RCW management decisions at Fort Benning.

The objective of the project was to address three main research questions: (1) develop stand level silvicultural protocols for restoring longleaf pine forests while retaining a canopy component on Fort Benning in the sandhills of Georgia and at Marine Corps Base Camp Lejeune on the coast of North Carolina; (2) model stand vulnerability to declining loblolly pine vigor on Fort Benning where loblolly pine health was a management concern; and (3) develop a model to forecast individual loblolly pine tree mortality in stands showing reduced canopy health of Fort Benning.

Technical Approach

The research was conducted at Fort Benning and Camp Lejeune, sites that differ in ecological characteristics including topography, soils, weather patterns, and native flora. Such differences may influence the success of restoration protocols, and thereby inform the development of management guidance across a range of site conditions. We installed a field experiment using a randomized split plot design replicated on eight blocks at each location. We planted longleaf pine seedlings in loblolly stands treated with seven canopy treatments (main plot treatments), including three different sized gaps, uniform thinning to three different residual basal areas (0, 4.5, and 9 m^2/ha), and an uncut check (basal area $\geq$ 14 m^2/ha). In each plot, additional split-plot treatments included chemical vegetation release, chemical release plus fertilizer, establishment of native grasses, and an untreated check. Response variables include the survival and growth of

seedlings and planted native grasses, light, soil nitrogen, soil moisture, foliar nutrients, and seedling water potential. We used results of our field experiment to project the development of suitable RCW habitat under experimental scenarios. We developed tree mortality and stand vulnerability models applicable to loblolly forests at Fort Benning. The models were based on existing inventory data and on data collected from a stratified sample of all upland loblolly stands at Benning. In ninety 90 plots in mature loblolly stands we measured site and stand characteristics, and evaluated tree health by assessing crown condition. We used standard ANOVA, regression, and non-parametric methods for most analyses, and dendrochronology methods plus logistic regression and time series analysis to forecast tree mortality.

Results

Overall, we found a low occurrence of trees in poor health (2.9%). Tree health was positively correlated with site productivity, whereas poor tree health was more common on coarse textured soils than on fine textured soils. Individual tree mortality could be predicted from the mean basal area increment from the past three years and the basal area growth relative to tree size using dendrochronological methods. Canopy removal increased light availability for longleaf pine seedlings and ground layer vegetation, and both responded with increased growth. Ground layer vegetation provided important competition for longleaf pine seedlings, especially at Camp Lejeune, where woody vegetation dominated the ground layer. At both installations, the continuity of prescribed fires applied after longleaf restoration treatments was reduced with canopy removal (reduced needle inputs from canopy pines), suggesting that attention must be given to reaching prescribed fire objectives in areas with canopy gaps or reduced canopy density. Determining appropriate silvicultural treatments for restoring longleaf pine to loblolly stands requires an understanding of the initial stand conditions relative to RCW habitat requirements and ground layer species and composition. To increase longleaf seedling growth, we recommend reducing canopy basal area to below 7 m^2/ha if allowable. In stands where canopy reduction is restricted, small canopy gaps (0.1 ha) can be used to create patches of suitable conditions for longleaf seedlings. We found that fertilizer had few benefits for longleaf pine restoration, but chemical control that targets woody vegetation will increase longleaf seedling growth and enhance the ground layer community in stands with encroachment of woody species.

Benefits

Results can be used to guide longleaf pine restoration in loblolly pine stands at Fort Benning and Camp Lejeune, and experimental plots remain to demonstrate the effects of management alternatives for longleaf restoration and the quality and production of RCW habitat. The results can be used in planning and landscape models to predict consequences of stand management choices. The combined results at two locations provide a framework for restoring longleaf pine on other DoD installations, though details may differ. Applying study results will improve the likelihood of southeastern installations fulfilling endangered species management and recovery goals, thereby minimizing potential conflicts with the training mission. Contributions to science include a better understanding of the gap regeneration processes and of individual tree mortality in the southern pine ecosystems.

1. Introduction

This project supported CSSON-06-02 (Restoration of Longleaf Pine for Red-cockaded Woodpecker Habitat) that identified the need for protocols to manage forested landscapes currently used by red-cockaded woodpeckers (RCWs) in a way that maintains suitability for the bird.

1.1. Problem statement

At the heart of the challenge to provide RCW habitat is a landscape level problem, that is, how to schedule forest regeneration in time and space. That task is central to forest management planning, and it must rely on forest growth models coupled with an understanding of RCW population processes at a landscape scale. However, forest models depend on a good understanding of stand level processes, specifically, the performance of regenerating forests under local conditions. The research addressed significant gaps in knowledge about longleaf pine growth and possible loblolly pine forest decline at the stand level. Results of a stand level study can be used to improve the predictability of forest growth models and ultimately refine landscape scale management strategies. Because there is widespread agreement on the structure of stands that benefit the RCW, stand level research can be interpreted readily in terms of benefit to both RCW habitat function and to forest restoration.

As a result of fire suppression or exclusion, the historically dominant longleaf pine has been replaced by other less fire-tolerant species, especially loblolly pine. Fire maintained longleaf pine woodlands and savannas, with herbaceous ground layer vegetation and little or no mid-story hardwoods, provided ideal habitat for the RCW and a variety of other rare animals and plants (Walker 1993, 1998). In contrast, loblolly stands often include abundant hardwoods in the mid-story and have lost much of the characteristic ground layer that produces fine fuels critical for fire management. Compared to loblolly, longleaf pine is longer lived, less susceptible to a variety of pests and diseases, and preferred by RCWs. Additionally, longleaf stands are conducive to management with prescribed fire, an ecologically and economically desirable management strategy. Thus, managers are eager to restore longleaf pine to sites it once occupied. Although longleaf pine is readily established after clearcutting the loblolly canopy, loblolly pines currently provide habitat for RCWs in sites spanning the previous longleaf range. In stands providing RCW habitat, longleaf pine restoration must be accomplished while retaining habitat value, specifically mature canopy trees. The project addressed the need for stand conversion protocols.

In many areas of the southeast, reports of pine stands exhibiting symptoms of poor health have raised questions about the longevity of existing RCW habitat in loblolly stands. For example, Fort Benning contains around 36,000 ha of upland pine forests, including almost 4,000 ha classified as longleaf and the balance dominated by primarily loblolly. Forest managers observed that “off-site” loblolly pine trees are either dying prematurely or are showing symptoms of stress and poor health. Premature senescence could adversely affect the recovery of RCWs on the base because approximately two thirds of the active RCW clusters currently depend on loblolly stands. Without effective management intervention, ongoing forest decline could limit habitat needed to meet RCW recovery responsibilities and, consequently, constrain the training mission at Fort Benning. Given the broad geographic extent of longleaf pine and the natural variability in site conditions, it is unlikely that protocols will be immediately exportable from site to site. In order to understand the transportability of protocols to various kinds of sites it is necessary to understand the ecological factors that control the process of regeneration under an existing canopy of loblolly pines.

Because longleaf pine seedling growth decreases as canopy cover increases, it was expected that restoration protocols would likely include some level of canopy removal. Leaving the individual trees likely to live the longest would optimize RCW habitat through time, but individual tree mortality is a complex process that is difficult to predict. Additionally, managing landscapes would also require selecting which stands to treat, and in landscapes with declining loblolly pine stands selection must be based in part on stand vulnerability or condition. To select stands, managers need a firm understanding of the relationships between stand conditions, site conditions, and management history.

1.2. Research questions and technical objectives

The overall goal of this project was to develop stand level management recommendations for longleaf pine restoration while retaining habitat value for RCWs at Fort Benning, Camp Lejeune, and by extension to other Southeastern installations. We approached this goal by addressing three research questions that proceeded concurrently. The following is a list of specific objectives (O-1 through O-11) organized by research questions (Q-1 through Q-3). Question 1 was addressed through a field experiment at Fort Benning and Camp Lejeune. Questions 2 and 3 pertain to Fort Benning only.

Q-1: What are optimal silvicultural practices for restoring longleaf pine to loblolly pine stands while retaining mature trees and enhancing the herbaceous ground layer? Eight component objectives were required to fully address this question.

O-1. Quantify the effects of canopy abundance after harvest treatments and cultural treatments on planted longleaf pine.

O-2. Quantify the effects of canopy abundance after harvest treatments and cultural treatments on natural loblolly pine regeneration.

O-3. Quantify the effects of canopy abundance after harvest treatments and cultural treatments on ground-layer and mid-story vegetation structure and abundance.

O-4. Describe the effects of canopy abundance after harvest treatments and cultural treatments on ground-layer vegetation richness and composition.

O-5. Quantify the effects of gap size and within-gap position on ground layer vegetation.

O-6. Quantify the effects of canopy density and distribution on light availability, soil moisture and temperature, and soil nitrogen in pine stands.

O-7. Quantify the relationships between resource availability and planted longleaf pine seedling survival and early growth.

O-8. Quantify the effects of canopy and cultural treatments on fine fuel production, fire behavior, and short-term fire effects.

Q-2: Which stand or environmental factors are associated with declining loblolly pine canopy health at Fort Benning?

O-9. Quantify loblolly pine canopy health in relation to stand condition, site characteristics (physiography, slope, aspect, soil texture, soil nutrient status), and recent management history (burning and thinning).

O-10. Assess the effects of pine canopy distribution on individual loblolly pine canopy health and mortality.

Q-3: Can individual tree mortality at Fort Benning be predicted?

O-11. Develop a model to predict the timing and probability of individual loblolly pine stem mortality based on annual radial growth patterns.

1.3. Organization of this report

In Section 2 we present the background and general research approaches for the overall project. Because the organizing questions and specific objectives require a variety of methods, we present any detailed technical background, methods, results and discussions for each question and objectives within each question separately, beginning with research Question 1 in Section 3. Section 3 is further divided to present results related to individual research objectives. In addition to the sub-sections linked to each objective, we provide a comparison of results from Fort Benning and Camp Lejeune and discuss similarities and differences in the context of forest restoration. Questions 2 and 3 are addressed in Sections 4 and 5, respectively. Section 6 provides recommendations for continued monitoring of experimental plots. In Section 7 we present a project synthesis that includes models of expected outcomes from selected management scenarios and a discussion of the application of study results to other parts of the longleaf pine range. Section 8 includes literature cited in the report. Numerous appendices include supplemental information and are referenced throughout the report where applicable. We call attention Appendix A-1.1.1 (p. 369) because it presents information specific to restoring the herbaceous component of longleaf pine woodlands. This appendix describes a pilot study that measured the effects of field experimental treatments on the establishment of planted native grasses at Fort Benning and Camp Lejeune.

2. Background

This section explains the need for the research and presents what was known about the problem at that time the project was initiated.

2.1. Problem overview

As a result of fire suppression and exclusion, the historically dominant longleaf pine (*Pinus palustris* Mill.) has been replaced by other, less fire-tolerant species, especially loblolly pine (*P. taeda* L.). Fire-maintained longleaf pine woodlands and savannas, with herbaceous ground layer vegetation and little or no mid-story hardwoods, provide ideal habitat for the red-cockaded woodpecker (RCW; *Picoides borealis*) and a variety of other rare animals and plants (Walker 1993; USFWS 2003). In contrast, loblolly pine stands often include abundant hardwoods in the mid-story and have lost much of the characteristic ground layer that produces fine fuels critical for fire management. Compared to loblolly pine, longleaf is longer lived, less susceptible to a variety of pests and diseases, and preferred by RCWs. Additionally, longleaf stands are conducive to management with prescribed fire, an ecologically and economically desirable management strategy. So managers are eager to restore longleaf to sites it once occupied. However, longleaf pine seedlings are considered intolerant of competition for resources (Boyer 1990a), and therefore traditional silviculture for stand conversion to longleaf pine often includes clearcutting the existing canopy followed by artificial regeneration (e.g. Boyer 1988, Brockway et al. 2006, Knapp et al. 2006). This approach is not desirable in stands that provide current RCW habitat or other ecological benefits that require the presence of canopy trees. In loblolly pine stands providing RCW habitat, longleaf pine restoration must be accomplished while retaining habitat value, specifically mature canopy trees. This research was designed to meet the need for such stand conversion protocols.

Forest conditions at Fort Benning exemplified the management problem. Fort Benning has about 36,000 ha of upland pine forests, of which less than 4,000 ha are classified as longleaf stands. Because of historical land use and forestry practices, loblolly pine currently dominates many upland pine sites. Estimates at the beginning of the project indicated that two thirds of the upland loblolly habitat is experiencing some level of forest decline. Specifically, loblolly pine trees that were considered “off-site” were either dying prematurely or are stressed and expected to die prematurely. Premature senescence could adversely affect the recovery of the RCW on the base because two thirds of the 330 active RCW clusters currently depend on loblolly pine and as many as 70% of the RCW cavity trees are loblolly pines. Without effective management intervention, ongoing forest decline could limit habitat needed to meet RCW recovery responsibilities and, consequently, constrain the training mission at Fort Benning. Given the broad geographic extent of longleaf pine and the natural variability in site conditions, it is unlikely that protocols will be immediately exportable from site to site, so it was important to understand the ecological factors that control the process of regeneration under an existing canopy.

Because longleaf seedlings do not thrive under closed forest canopies, restoration protocols will require partial canopy removal. Leaving the trees likely to live the longest would secure the most

RCW habitat value through time, but there was no good way to forecast individual tree mortality. Managing landscapes would also require selecting which stands to treat, and in landscapes with declining loblolly stands selection must be based in part on stand vulnerability or condition. To select stands, managers needed a firm understanding of the relationships between stand conditions, site conditions, and management history.

2.2. Uneven-aged longleaf pine forest as a management template

Although longleaf pine is commonly managed using even-aged silvicultural methods, naturally regenerating longleaf forests typically develop as an uneven-aged mosaic of even-aged patches (Platt and Rathburn 1993). Natural regeneration is commonly observed within canopy gaps (Gagnon et al. 2004), and frequent lightning strikes or other small scale disturbance events often create favorable conditions for natural regeneration (Palik and Pederson 1996). Interactions between fire effects and competition with canopy trees likely contribute to the gap-phase regeneration of longleaf pine. The natural regeneration process suggests the potential for uneven-aged management and for regenerating longleaf pine in the presence of mature trees. Indeed, the "Stoddard-Neel" system exemplifies a successful silvicultural system that can be used to create and maintain open, uneven aged longleaf forests. The silvicultural method used in the system resembles "thinning from below"(Moser et al. 2002), and the key features include maintaining densities below 15 m^2/ha, managing the overstory with removal from below, maintaining a reproduction component in the stand (that is, in gaps) and allowing transition from reproduction to overstory on some small proportion of the area. Although the system is designed for existing longleaf pine stands, it might be modified to convert even-aged loblolly stands into uneven-aged loblolly and longleaf pine mixed stands, and eventually uneven-aged longleaf pine stands.

2.3. Overstory retention and longleaf pine regeneration

Overstory retention is increasingly used in forests traditionally managed for even-aged structure. By maintaining some overstory trees during a regeneration harvest, silviculturists create uneven-aged stands over one or more rotations (e.g., Franklin et al. 1997, Halpern et al. 1999, Loewenstein 2005). One rationale for retention is that residual stand structure better resembles the complex structure of forests after natural disturbances, helping to perpetuate ecosystem functions dependent on that structure (Hansen et al. 1995, Franklin et al. 1997, Seymour and Hunter 1999). The benefits of retention come at a cost of reduced survival and growth of regeneration because of competition with residual trees (Birch and Johnson 1992, Hansen et al. 1995). This is especially true for longleaf pine, which is intolerant and sensitive to competition for light, moisture and nutrients (Boyer 1990a).

Previous studies have explored alternative silvicultural methods for regenerating longleaf within existing longleaf pine canopies and have commonly reported that seedling growth is reduced by the presence of canopy trees. For instance, Palik et al. (1997) reported a negative, exponential relationship between overstory density and seedlings size, and seedling size increased substantially with less than 8 m^2/ha of overstory basal area. According to RCW habitat guidelines, recommended optimal habitat requires overstory basal area between 9 to 14 m^2/ha (USFWS 2003). Retaining an overstory of mature loblolly for the benefit of RCW habitat may negatively affect the restoration of longleaf in the same stand. Previous studies of canopy effects on regeneration were conducted in established longleaf pine stands; the interaction between a loblolly overstory and planted longleaf seedlings may or may not resemble the well-documented relationships in longleaf pine dominated stands. Longleaf pines have more extensive and deeper root systems than loblolly, and the feeding roots of loblolly pines are increasingly concentrated on top soils with aging (Baker and Langdon 1990, Boyer 1990a). Rooting habit differences may reduce competition intensity between overstory loblolly and planted longleaf pine seedlings. How this difference would translate into gap resource availability and improved growth of planted longleaf seedlings was unknown when this study was initiated. A study of planting longleaf pines under slash pine was published soon after RC-1474 was started (Kirkman et al. 2007), and provides a reference point for this study.

2.4. Regenerating longleaf pine in canopy gaps

Understanding the regeneration dynamics of longleaf pine in gaps is critical for developing an uneven-aged silvicultural system for restoring longleaf pine to current loblolly stands while maintaining the transitional stand as functional RCW habitat. Recent studies have examined the growth of naturally established and planted longleaf pine seedlings in canopy gaps of various sizes (Palik et al. 1997, 2003; Brockway and Outcalt 1998, McGuire et al. 2001, Gagnon et al. 2003, Rodriguez-Trejo et al. 2003). These studies report an influence zone between 15-36 m from the gap edge, and recommend minimum gap sizes of 0.1 to 0.2 ha to minimize intraspecific competition. In natural, uneven-aged longleaf forests, tree fall gaps ranging from 40 to 50 m in diameter are common (Brockway and Outcalt 1998). Gaps of these sizes result from mortality of several trees as gaps resulted from single tree mortality are typically < 30 m in diameter, suggesting that group selection may be an appropriate silvicultural method for regenerating longleaf pine. However, these results are derived from studies conducted in longleaf pine forests and the applicability to loblolly forests was not known.

Various studies have shown that adult longleaf pine trees negatively affect growth and/or survival of longleaf pine seedlings established within a distance of 15 m (e.g., Grace and Platt 1995, McGuire et al. 2001, Gagnon et al. 2003, Palik et al. 2003); however the underlying mechanisms are still debated. Light limitation has proven to be important in most studies, and longleaf seedlings respond positively to increased light reaching the understory in a gap (Palik et al. 1997, McGuire et al. 2001). In studying the pattern of naturally regenerated longleaf seedlings in gaps, however, Brockway and Outcalt (1998) attributed an observed seedling exclusion zone to intraspecific root competition. They proposed the “root gap” to explain the concentration of longleaf pine seedlings in the gap center and speculated that reduced competition for soil moisture in a “root gap” should increase growth and survival of longleaf seedlings. However, no corroborating patterns in soil moisture (measured as volumetric water content) were observed in relation to distance from the gap edge or direction within gaps (McGuire et al. 2001, Gagnon 2003, Palik et al. 2003). Given the heterogeneity of soil and the dynamics of soil moisture, it is arguable that water potential in planted longleaf seedlings would be a better indicator of local soil moisture supply, but no study has yet reported the water potential of planted seedlings. Increased N availability in the canopy gap has positively affected the growth of planted longleaf (e.g., McGuire et al. 2001, Palik et al. 2003), though the gain is small compared to the effect of light. Although the status of foliage nutrients of planted longleaf pine seedlings can also serve as a good indicator of local nutrient availability, previous studies did not examine how canopy retention or gap size affect seedling nutrient status.

As found in other species (e.g., De Steven 1991, Chhin and Wang 2004a), longleaf pine seedlings planted in gaps exhibit a trade-off between survival and growth, especially under extreme drought (e.g., Rodriguez-Trejo et al. 2003). Partial shade improved the survival of planted longleaf seedlings during the initial 1-2 years despite its negative effect on growth (McGuire et al. 2001, Gagnon et al. 2003, Rodriguez-Trejo et al. 2003). Because of this trade-off, Gagnon et al. (2003) suggested that the best location for planted longleaf seedlings during the first two years was located between 20-30 m from the gap edge. We note that the optimum range is likely to change through time because of the growth of seedlings and the dynamics of vegetation within the gap, and that gaps created in declining loblolly pine stand likely have different dynamics than those in longleaf pine forests due to a higher rate of canopy mortality. Over time, these gaps could enlarge and provide more resources for planted longleaf seedlings. This anticipated dynamic could provide an advantage to seedlings planted near the gap edge or into the forest.

Platt et al. (1988) suggested that along with resource availability, fire is an important factor regulating gap-phase regeneration and resulting in aggregating naturally regenerated seedlings towards the gap centers. Several lines of evidence support this hypothesis. Competition near mature longleaf pine reduces the growth of seedlings, and smaller seedlings are more susceptible to fire (Boyer 1974, Grace and Platt 1995). Also greater needle fall near mature longleaf has been associated with more intense fire (Rebertus et al. 1989, Williamson and Black 1991, Grace and Platt 1995). In short, higher-intensity fire combined with smaller seedlings due to resource competition spatially segregates seedlings from mature longleaf trees (e.g., Avery et al. 2004). However, the effect of fire on the survival of planted longleaf pine seedlings under a retained canopy or in a gap has not been verified experimentally.

Palik et al. (1997) reported that optimum growth of longleaf seedlings occurs at a residual basal area below 6 m^2/ha; however, a basal area between 9-14 m^2/ha is recommended for high quality RCW habitat. The distribution of the residual basal area may be manipulated to meet these conflicting management needs. Harrington et al. (2003) reported that reducing basal area to 10 m^2/ha was not sufficient to increase herb layer performance in young (13-15 years old) longleaf stands, where residual trees were uniformly dispersed across the stand. Alternatively, a target basal area could be obtained using a group selection method that would result in aggregated residual trees. In this way, fewer but larger gaps can be created (Palik et al. 1997). Because of reduced competition from the overstory, large gaps created by aggregating residuals provided more resources (light, moisture and/or nutrients) to the growth of planted longleaf seedlings compared to small gaps (Palik et al. 2003).

2.5. The importance of restoring ground layer vegetation

High-quality RCW habitat also requires intact native ground layer vegetation (USDI FWS 2003), which is dominated by grasses, legumes, and composites in upland sites (Walker 1998). In terms of ecosystem function, the ground layer provides fine fuels to carry the surface fires that sustain the ecosystem and supports a diverse arthropod community (Folkerts et al. 1993, Hermann et al.

1998, Hanula and Engstrom 2000). Recent research reports link the condition of ground layer vegetation to RCW fecundity and population health. Red-cockaded woodpecker groups defending territories with predominantly grassy or herbaceous ground layers had higher fecundity than nearby groups in shrub-dominated territories (James et al. 1997, Hardesty et al. 1997). When restoring longleaf on loblolly-occupied sites, it is also important to protect and restore native ground layer vegetation.

As elaborated in the previous section, planted longleaf seedlings require relatively large gaps to achieve optimal growth. However, needle fall from mature pine trees extends only 4-5 m from the gap edge (Boyer 1974, Farrar 1996, Brockway and Outcalt 1998). Needle-fall is considered an important fuel source for fire management (Mitchell et al. 2006, Kirkman et al. 2007), and when gap management was proposed fire managers at Fort Benning expressed concerns about the ability to burn in stands thinned to low residual basal area, particularly within large gaps. In natural, open longleaf stands, abundant growth of grasses helps to maintain a frequent surface fire regime. Therefore, the restoration of longleaf pine to loblolly stands where grasses are not well represented, may benefit from seeding native grasses such as little bluestem *(Schizachyrium scoparium)* or wiregrasses *(Aristida stricta, A. beyrichiana)* (Walker and Silletti 2006). Establishing or enhancing grass cover may be important in large gaps created for the optimum growth of longleaf pine seedlings, where fine fuels from herbaceous layers must carry surface fires through the gap. In addition to affecting fire behavior, the seeded grass is likely to compete with planted longleaf seedlings and other herbaceous species. Little is known about the magnitude of this competition.

2.6. Cultural practices and longleaf pine regeneration

Cultural practices, such as competition control and fertilization, may be applied to reduce the effects of root competition from overstory trees and to compensate for sub-optimum light conditions. Herbaceous weed control has proven effective in promoting the growth and thus the early emergence from the grass stage for longleaf pine seedlings planted in the open, although its effect on survival has not been consistent in past reports (Haywood 2000, Ramsey et al. 2003). Fertilization alone or in combination with herbaceous weed control did not improve the growth of longleaf planted in an old field (Ramsey et al. 2003); however, hand weeding and fertilization increased the growth of longleaf seedlings planted in a longleaf forest canopy gap by > 40% during the first two years (Gagnon et al. 2003). Compared to old fields, soil fertility of Gagnon's study sites was inherently lower. Various methods can be used to control competition, e.g., hand weeding, herbicide application, and/or mulching. Haywood (2000) found that application of herbicide (hexazinone, at 1.12 ai kg/ha) or mulches significantly increased height growth and shortened the grass stage. For applying overtop of longleaf seedlings, Ramsey and Jose (2004) recommended the use of hexazinone at 0.56 kg ai/ha for controlling herbaceous vegetation.

2.7. Factors influencing loblolly pine decline

Loblolly pine decline is the name applied to a syndrome in which canopy trees are characterized by a gradual deterioration in health and vigor that frequently ends in death. Decline symptoms include short chlorotic needles, sparse crowns, and reduced radial growth by stand age 40-50, with mortality occurring two to three years after symptoms appear (Hess et al. 2002). Several pathogens (e.g., *Phytophthora cinnamomi* and *Leptographium* spp.) associated with the syndrome are vectored by root-feeding bark-beetles and weevils. The expression of decline symptoms is apparently associated with significant environmental stressors. Working on a project for the Talladega National Forest, Eckhardt and Menard (2008) developed a GIS model that showed decline associated with relatively well-drained sandy soils and south-facing aspects with slope > 20%, and they applied the same modeling parameters to develop a preliminary risk assessment tool for Fort Benning. This work provided preliminary information about the factors associated with possibly declining forests at Fort Benning, but the risk assessment did not provide enough information for understanding possible causes or management factors associated with declining forest health.

Loblolly pine stands at Fort Benning display a range of stand attributes (e.g., stocking, age) and site conditions (e.g., site quality, aspect, slope, soil texture) that are likely to influence their vulnerability to decline. In addition, common management practices, especially thinning and burning, may influence vulnerability in unpredictable ways. Thinning equipment may damage roots, attract root-feeders, and increase mortality rates. Alternatively, thinning may reduce competition for moisture or nutrients on extreme sites (Smith et al. 1997) and increase resistance.

Frequent burning reduces tree growth and effectively reduces hardwoods and understory vegetation (e.g., Boyer 1990b, Boyer and Miller 1994), both factors significantly correlated with loblolly decline (Eckhardt 2003). Managers are using a prescribed fire management regime (frequent, low intensity fires) that might be appropriate for longleaf pine, but loblolly is less fire-tolerant because it has shallower feeding roots, especially for mature trees (Baker and Langdon 1990, Boyer 1990a). In addition to possible canopy scorch and cambium damage, burning, even prescribed at a low intensity, could kill some feeding roots and reduce water and nutrient absorption. In addition to negatively affecting root absorption, fire may increase soil bulk density and reduce soil water-holding capacity (Boyer and Miller 1994). These negative effects could be further magnified on dry and nutrient poor soils, which are typical at Fort Benning. Because loblolly pine is much more nutrient demanding than longleaf (Baker and Langdon 1990, Boyer 1990a), nutrient deficiency may also contribute to loblolly decline. Fire also increases attacks by root-feeding bark beetle and weevil, which, in turn, vector disease *(Leptographium* spp.*)* into the loblolly pine root system (Eckhardt 2003).

2.8. Modeling individual tree mortality in the context of loblolly pine decline

Tree mortality is a complex phenomenon. The process of dying often takes decades driven by a sequence of multiple stress factors (Villalba and Veblen 1998). A variety of empirical approaches has been used to model tree mortality at both stand and individual tree scales. For individual-based models, characteristics such as tree size (e.g., diameter or height), tree growth rate (e.g., ring widths or basal area increment), crown condition (e.g., leaf area index or crown defoliation), tree age, and competition are often used to predict tree mortality (e.g., Wyckoff and Clark 2000, Bigler and Bugmann 2003). Tree ring data have proven to be useful for addressing mortality issues, since tree rings are integrators of biotic and abiotic influences that reflect the entire growth history of a tree (Fritts 1976), and reduced radial growth often occurs prior to visual symptoms of crown decline (Buchman et al. 1983, Hamilton 1986). Low growth levels are often characteristic of stressed or dying trees, and it is well know that prolonged periods of strongly reduced stem growth increase a tree's risk of dying (e.g., Kozlowski et al. 1991, Pedersen 1998, Monserud and Serba 1999, Wyckoff and Clark 2002).

Most mortality models are based on radial growth 1-5 years prior to death (e.g., Wyckoff and Clark 2000). However, recent theoretical and empirical findings have shown that considering long-term growth trends may be needed for assessing many mortality issues, especially for forest decline (Bigler et al. 2004). A combination of growth level, growth trend, and/or relative growth has been shown to increase the reliability of mortality predictions (Bigler and Bugmann 2003, 2004). For example, low growth levels or relative growth combined with negative growth trends indicated impending tree death of Norway spruce (Bigler and Bugmann 2003).

Based on growth level, growth trend, and/or relative growth, tree-ring series of dead and living trees can be used to fit a logistic regression model,

$$\Pr\left(Y_{i,t} = 1 \middle| X_{i,t}\right) = \frac{1}{1 + \exp(X_{i,t}\beta)^{-1}}$$

with $Y_{i,t}$ being the status of tree *i* at time *t* (Y = 1 means the tree is alive, Y = 0 means the tree is dead). $\Pr(Y_{i,t} = 1 \mid X_{i,t})$ is survival probability in the interval [0,1], $X_{i,t}\beta$ is a linear combination of the independent variables *(X)* and the regression coefficients *(β).* This model can be used to calculate the mortality probability for every year of the life of the tree (Bigler and Bugmann 2003, Bigler and Bugmann 2004, Bigler et al. 2004). In addition to growth related variables, site quality, management history, and other factors affecting loblolly pine decline may also be important predictors of loblolly mortality. Adding these variables would capture a site-specific pattern of tree mortality. Combining tree ring analyses with stand and site conditions represent a novel approach, which we believe will improve the ability to forecast mortality significantly.

3. What are optimal silvicultural practices for restoring longleaf pine to loblolly pine stands while retaining mature trees and enhancing the herbaceous ground layer? (Question 1)

Section 3 is the longest section of the Final Report. Here we present the details of a replicated field experiment installed at both Fort Benning and Camp Lejeune. The first sub-section describes details of the setting up the experiment to test the effects of various canopy manipulations and cultural treatments to enhance longleaf pine seedling establishment and growth. Subsequent sub-sections address separate but related research objectives.

3.1. Field experiment implementation

This study was replicated at two ecologically distinct locations within the natural longleaf pine range: Fort Benning Military Installation (~32.38º N, 84.88º W) in Chattahoochee and Muscogee Counties, GA and Russell County, AL and Marine Corps Base Camp Lejeune in Onslow County, NC (~34.68º N, 77.33º W) (Figure 3.1.1).

Fort Benning falls within two ecological land units: the northeastern two thirds of the installation are within the Sand Hills Subsection of the Lower Coastal Plains and Flatwoods Section and the southwestern one third of the installation is classified as the Upper Loam Hills Subsection within the Middle Coastal Plain Section (Bailey 1995). Common soil series of the Sand Hills include Troup sandy loam (loamy, kaolinitic, thermic Grossarenic Kandiudults), Wagram loamy sand (loamy, kaolinitic, thermic Arenic Kandiudults) and Vaucluse loamy sand (fine-loamy, kaolinitic, thermic Fragic Kanhapludults). These soils are sandy in the surface layers and loamy in the subsoil, with low natural fertility and low organic matter content (Green 1997). Soils of the Upper Loam Hills tend to be finer textured and more productive although they share the characteristics of being low in organic matter and natural fertility (Mason 2003), with common soils including Maxton loamy sand (fine-loamy over sandy or sandy-skeletal, siliceous, subactive, thermic Typic Hapludults) and Wickham sandy loam (fine-loamy, mixed, semiactive, thermic Typic Hapludults). The key to soil names associate with study plots on Fort Benning are shown in Appendix A-3.1.1. The terrain is predominately rolling and highest in the Sand Hills of the northeast (225 m above sea level) and lowest near the Chattahoochee River in the southwest (58 m above sea level). Mean annual precipitation at Fort Benning is 1230 mm with a mean temperature of 18.4ºC (Garten et al. 2003).

Camp Lejeune is located in the Atlantic Coastal Flatlands Section of the Outer Coastal Plains Mixed Forest Province (Bailey 1995). Study areas were primarily dominated by Norfolk loamy fine sand (fine-loamy, kaolinitic, thermic Typic Kandiudult), Baymeade fine sand (loamy, siliceous, semiactive, thermic Arenic Hapludult), and Wando fine sand (thermic, coated Typic Quartzipsamment). All soils are well- to excessively-drained, with low to moderate water holding capacity and low nutrient holding capacity (Barnhill 1992). The key to soil names associate with study plots on Camp Lejeune are shown in Appendix A-3.1.8. Slopes typically range from 0 to 6 percent and rarely from 6 to 15 percent, with elevation from 7 to 21 m above sea level. The climate is classified as warm humid temperate, with average annual precipitation of 1420 mm and average annual temperature of 13ºC (MCBCL 2006).

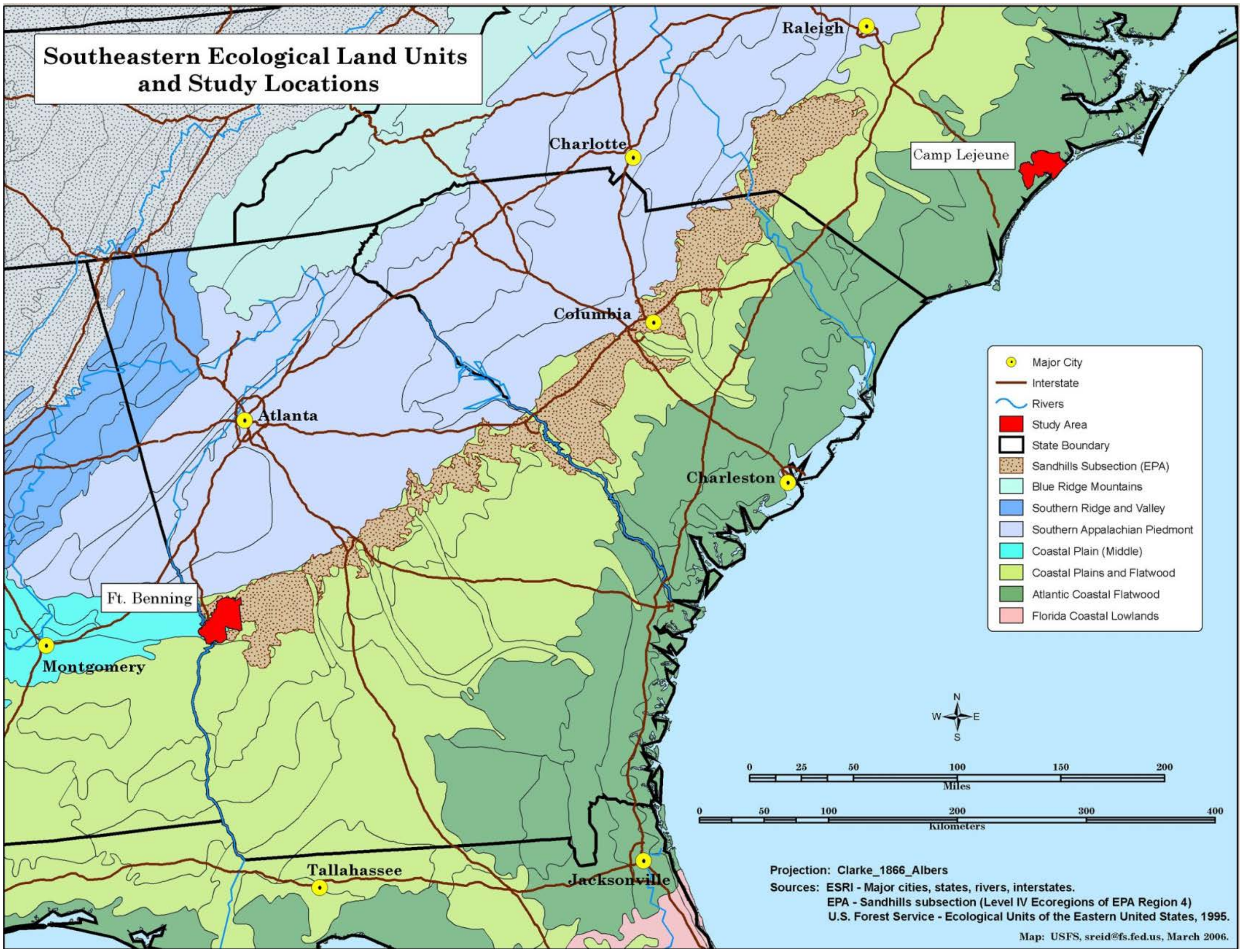


Figure 3.1.1. Map showing the locations of Fort Benning, GA and Camp Lejeune, NC with respect to the Southeastern Ecological Land Unit classifications, major cities, and major roads.

At both installations, study areas were selected from upland loblolly pine stands that were targeted for conversion to longleaf pine, as determined by base forestry personnel. At Fort Benning, this included equal representation of sites in the Sand Hills and the Upper Loam Hills (Figure 3.1.2). Past management had included the use of frequent prescribed burning following RCW habitat guidelines. Common understory species included bunchgrasses (e.g. *Andropogon* spp., *Schizachyrium scoparium* (Michx.) Nash, *Sorghastrum* spp.) and herbaceous species such as legumes (e.g. *Desmodium* spp., *Lespedeza* spp.) and composites (e.g. *Eupatorium* spp., *Solidago* spp.). Woody species, including sweetgum (*Liquidambar styraciflua* L.), persimmon (*Diospyros virginiana* L), oaks (*Quercus* spp.), and hickories (*Carya* spp.), were common in the understory and infrequent in the midstory.

At Camp Lejeune, we established plots in two types of loblolly pine stand. The first type (Blocks 1-4) was a large plantation previously established following a beetle kill (Figure 3.1.3). The stand had been prescribed burned infrequently since establishment, and encroachment of sweetgum was widespread. Common understory vegetation included graminoids such as bluestems and panic grasses (e.g. *Panicum* spp, *Dichanthelium* spp.) and herbaceous species within the family Asteraceae. The other blocks (Blocks 5, 7, and 8) were established in older pine stands (~60 years old) that had not recently been burned. In the absence of fire, these plots had developed a dense midstory layer dominated by sweetgum, loblolly pine, and shrubs such as wax myrtle (*Morella cerifera* (L.) Small), horse sugar (*Symplocos tinctoria* (L.) L'Hér), and redbay (*Persea borbonia* (L.) Spreng). None of the study sites had wiregrass present prior to the study.

Baseline soils information, including chemical and physical properties, was collected from each study block (Table 3.1.1). We obtained soil series information from Geographic Information Systems (GIS) provided by each installation (Appendices A-3.1.1 - A-3.1.12), and one soil sample was collected from each soil series that occurred in each plot. Soil chemistry, cation exchange capacity (CEC), organic matter (%), and soil pH were determined by the Agricultural Services Laboratory at Clemson University. Soil bulk density was determined gravimetrically from soil samples of known volume, and soil texture was calculated by the Bouyoucos hydrometer method (Milford 1997).

Climate data from the study period was obtained from the National Climatic Data Center web service, with data for Fort Benning collected at the Columbus GA Regional Airport and data for Camp Lejeune collected at the Wilmington, NC National Airport. Monthly precipitation and mean monthly temperature data for each site during the study period is plotted in Figures 3.1.4 and 3.1.5.

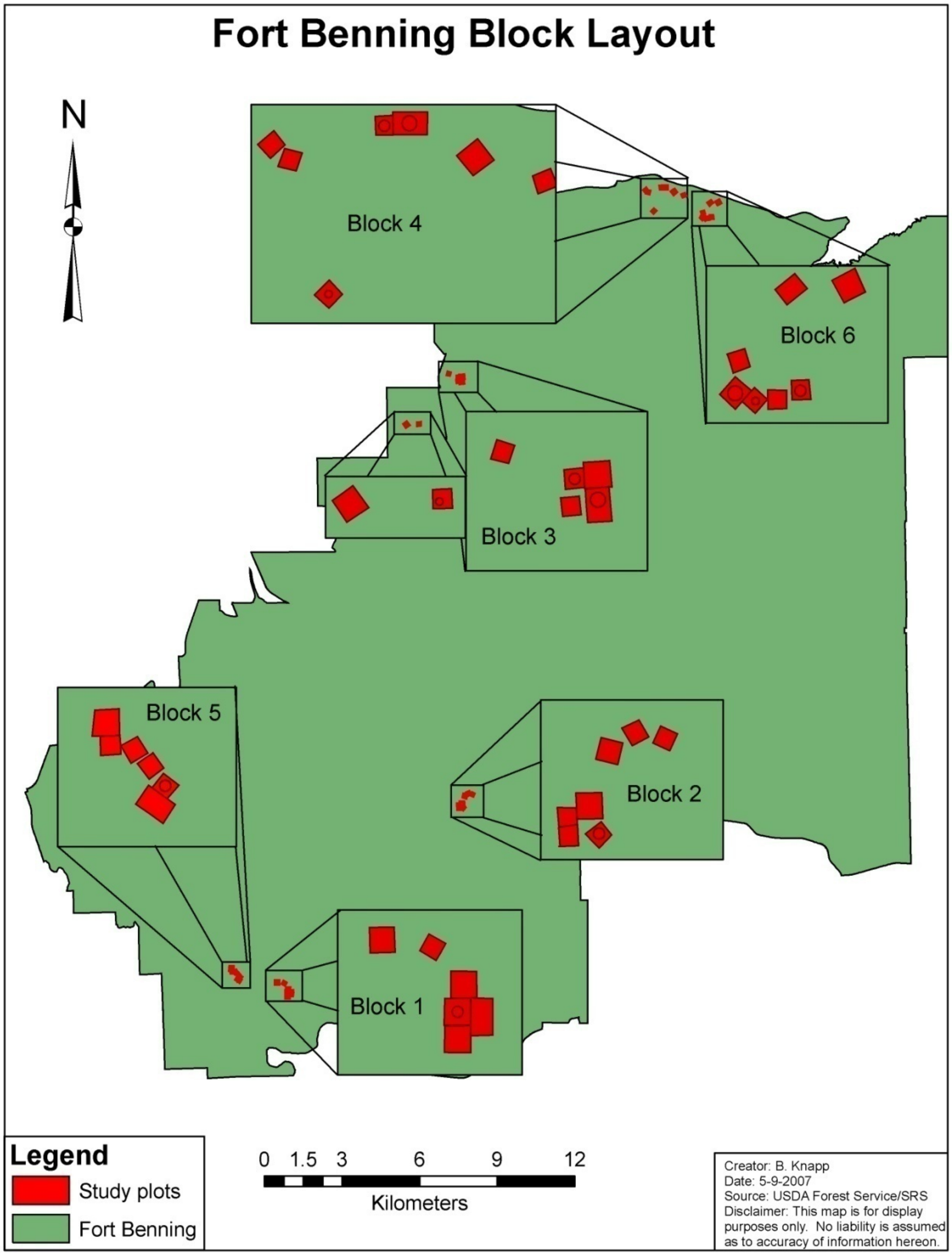


Figure 3.1.2. Map showing block and plot locations at Fort Benning, GA.

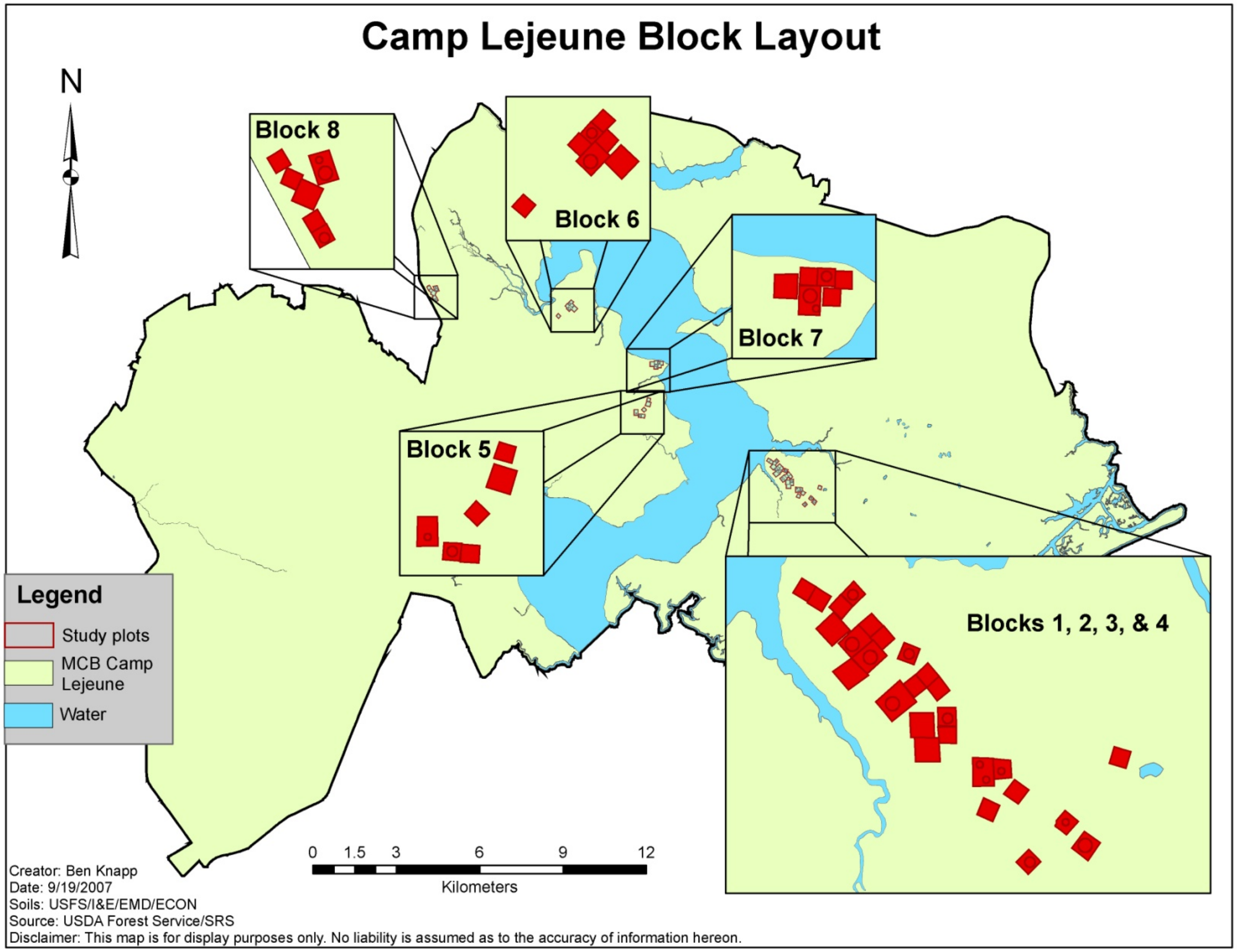


Figure 3.1.3. Map showing block and plot locations at Camp Lejeune, NC. Block 6 was excluded from analyses because of a wildfire in summer 2009.

Table 3.1.1. Soil chemical and physical properties of study areas at Fort Benning and Camp Lejeune. Mean values at the block level are presented from soil samples taken from each soil type that occurred within each study plot, and mean values at the study site level were tested for statistical difference between sites (p-values)

Site	Block	Total N (%)	Total C (%)	C:N ratio	Soil pH	Organic matter (%)	P (ppm)	K (ppm)	Mg (ppm)	Ca (ppm)	CEC	Bulk density (g/cm^3)	Sand (%)	Silt (%)	Clay (%)
Fort Benning	1	0.05	0.91	16.26	5.41	1.15	26.25	89.75	119.00	442.63	7.36	1.33	71.8	13.9	14.3
	2	0.06	1.50	25.76	4.73	1.61	5.00	116.14	239.57	397.00	19.27	1.24	73.2	11.9	14.9
	3	0.03	0.91	32.67	5.01	0.87	8.22	49.11	31.33	186.56	5.69	1.27	88.1	6.6	5.3
	4	0.02	0.73	28.98	4.93	0.53	10.11	52.89	25.00	110.11	4.17	1.39	88.9	5.8	5.3
	5	0.04	0.72	17.82	4.96	0.50	7.56	84.44	191.33	296.56	10.96	1.44	68.0	13.0	19.0
	6	0.02	0.77	34.61	5.08	0.41	8.25	53.50	38.13	165.25	4.16	1.46	88.5	6.4	5.1
	Mean	0.04	0.92	26.02	5.02	0.85	10.90	74.31	107.39	266.35	8.60	1.36	79.8	9.6	10.7
Camp Lejeune	1	0.05	1.21	26.35	4.90	1.44	10.29	53.86	34.86	209.29	9.21	0.95	75.2	19.0	5.8
	2	0.04	1.48	34.98	4.67	1.36	5.14	48.86	34.86	205.43	12.97	1.22	71.2	22.0	6.8
	3	0.05	1.46	30.67	4.79	1.46	4.89	53.78	42.33	244.89	8.68	1.22	63.5	30.1	6.4
	4	0.04	1.56	33.38	4.50	1.57	5.29	46.86	38.71	196.29	11.94	1.27	67.7	26.5	5.8
	5	0.04	1.36	34.34	4.37	1.09	11.14	41.86	30.00	117.00	9.84	1.18	90.8	5.4	3.8
	7	0.04	0.98	25.73	4.40	0.70	28.29	39.14	29.14	107.86	10.99	1.21	92.4	3.5	4.1
	8	0.04	0.94	25.70	4.68	0.81	18.75	45.75	29.50	135.63	7.26	1.29	91.6	3.9	4.5
	Mean	0.04	1.28	30.16	4.62	1.20	11.97	47.16	34.20	173.77	10.13	1.19	78.9	15.8	5.3
	p-value	**0.3699**	**0.0404**	**0.2110**	**0.0048**	**0.1116**	**0.7283**	**0.2370**	**0.0571**	**0.1195**	**0.5046**	**0.0252**	**0.8963**	**0.2299**	**0.0448**

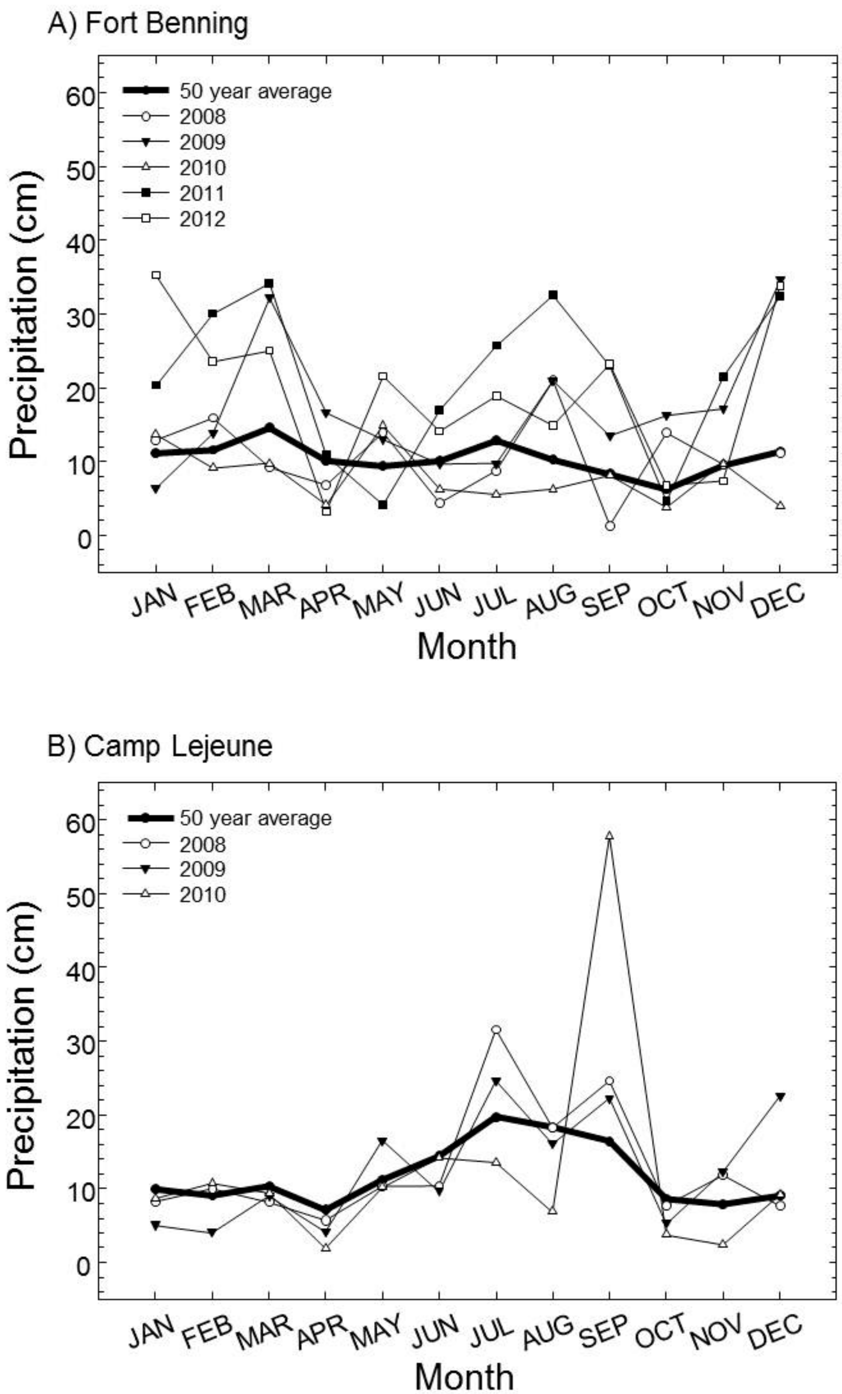


Figure 3.1.4. Precipitation data during the study period and the 50 year average at A) Fort Benning and B) Camp Lejeune.

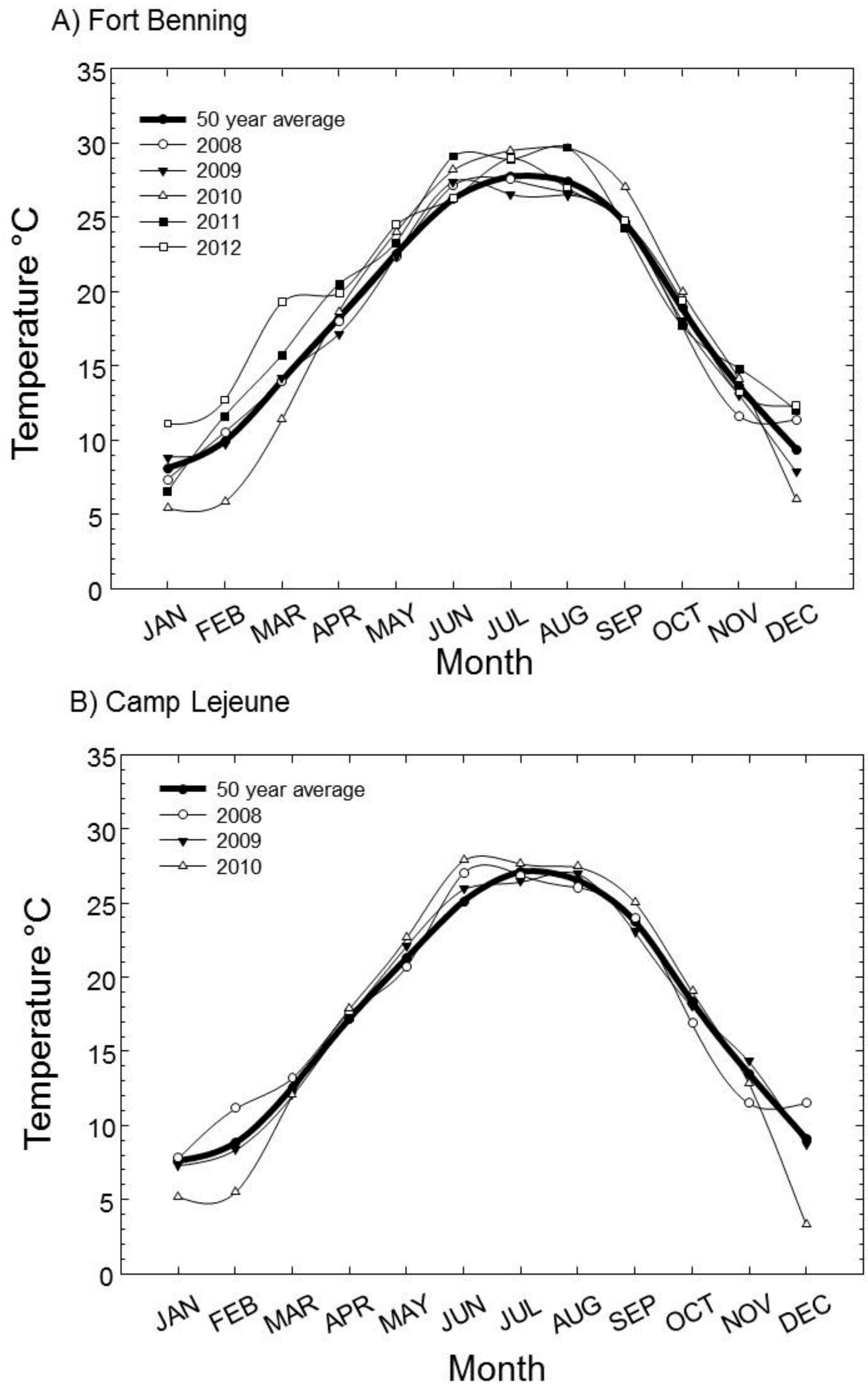


Figure 3.1.5. Mean monthly temperature data during the study period and 50 year average at A) Fort Benning and B) Camp Lejeune.

3.1.1. Experimental design

The experiment uses a randomized, complete block, split-plot design with location as the block factor. Each block was divided into seven main treatment plots and each main-plot received an overstory treatment. Main-plots were 100 x 100 m (1 ha), with the exception of the Clearcut plots, which were 141 x 141 m (2 ha) to create clearcut conditions in the plot center. The overstory treatments, described below, generate different competitive conditions commonly created by silvicultural practices.

3.1.1.1 Overstory treatments

- Control – Uncut control; basal area ≥ 14 m^2/ha
- MedBA – Single-tree selection to create uniform canopy with target basal area of 9 m^2/ha
- LowBA – Single-tree selection to create uniform canopy with target basal area of 5 m^2/ha
- Clearcut – All trees removed to basal area 0 m^2/ha
- SG – Group selection to create circular “small” canopy gap (1257 m^2; radius = 20 m)
- MG – Group selection to create circular “medium” canopy gap (2827 m^2; radius = 30 m)
- LG – Group selection to create circular “large” canopy gap (5027 m^2; radius = 40 m)

Because of the uniform distribution of the canopy in the Control, MedBA, LowBA, and Clearcut plots, we refer to these treatments collectively as “Uniform” treatments, and we refer to SG, MG, and LG plots as “Gap” treatments.

Timber marking in uniform plots was done by base forestry personnel with the objective of thinning from below to uniformly distribute the canopy and reach the desired level of canopy density. Thinning resulted in significantly different levels of basal area for the treatments at each location, with residual density around gaps not different from the Controls (Figure 3.1.6). More information on residual stand structure is provided in Appendices A-3.1.13 – A-3.1.18. The logging operations were contracted out following standard installation procedures and operators were monitored to insure minimal damage to residual trees during logging. For the most part, tops and slash were removed from the experimental units during harvest. Harvesting was completed throughout 2007.

Split-plot treatments include additional cultural practices designed to enhance ecosystem restoration, through either improvement of short- or long-term growing conditions for planted longleaf seedlings or changes to ground layer vegetation. Main-plot treatments Control, MedBA, LowBA, and Clearcut were each divided into four equal sections for cultural treatment application (Figure 3.1.7). Within each section, split-plot treatments were applied to a 30 x 30 m area centered on a 20 x 20 m measurement plot. Within each gap, split-plot treatments were applied directly to three selected rows of planted longleaf seedlings, each oriented along the north/south aspect (Figure 3.1.8).

3.1.2.2 Culture treatments

- NT – Control, no treatment applied
- H – Competition control with herbicide treatment
- H+F – Competition control with herbicide treatment (H) plus fertilizer

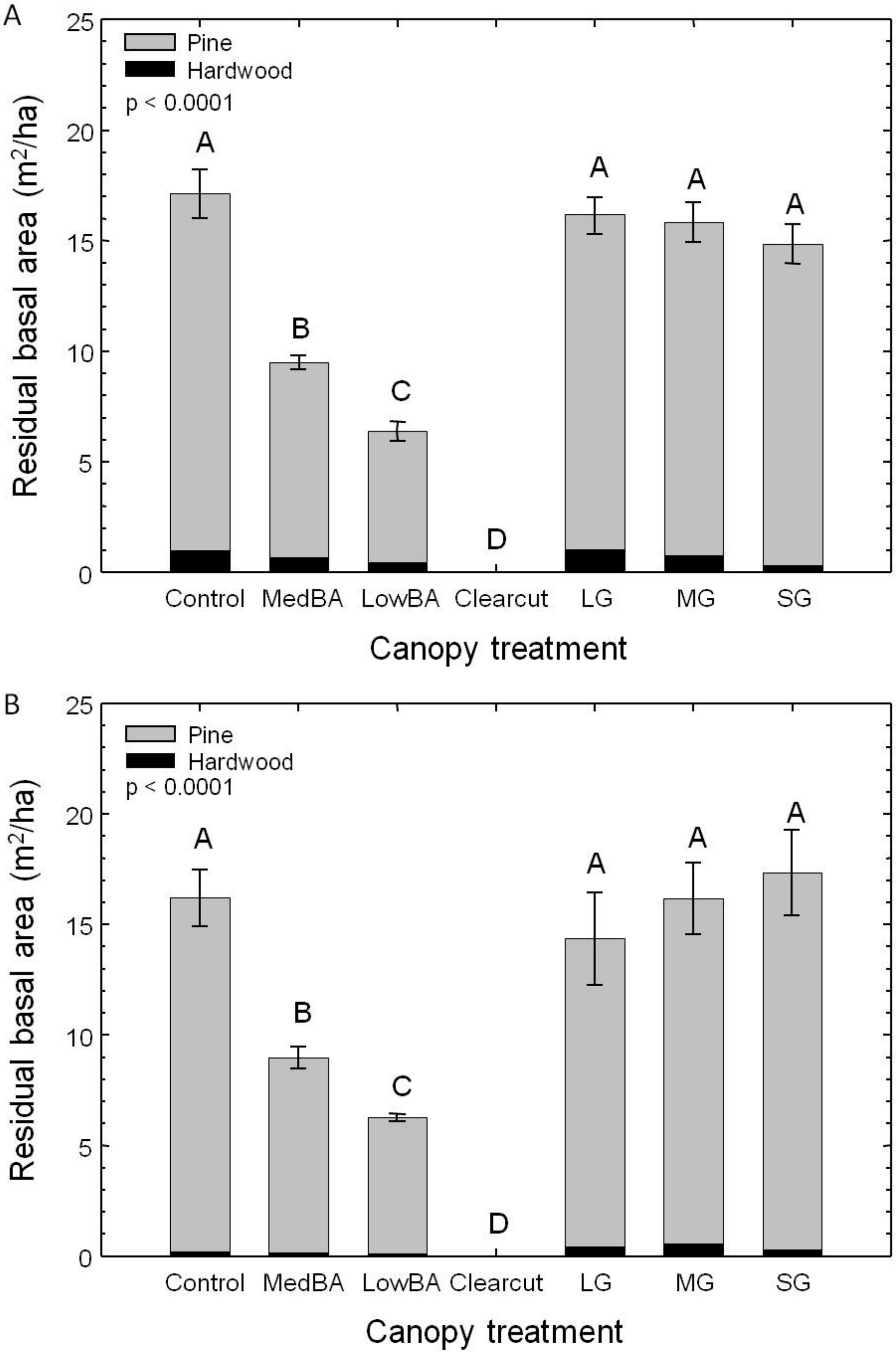


Figure 3.1.6. Residual basal area of each canopy treatment and the forest surrounding gaps, separated by pine and hardwood at A) Fort Benning and B) Camp Lejeune.

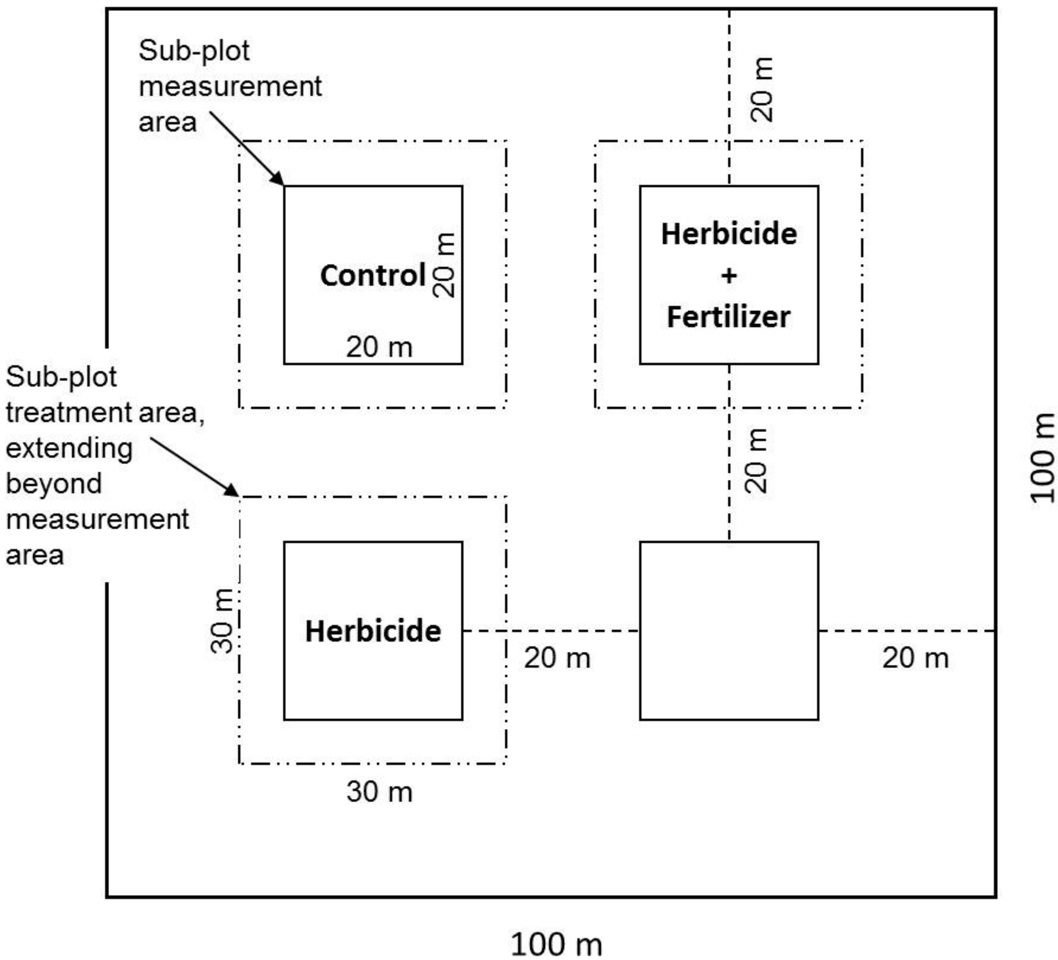


Figure 3.1.7. Example of layout of split-plots within each uniform main plot. Note: Clearcut main plots are 141 x 141 m to create clearcut conditions in plot center.

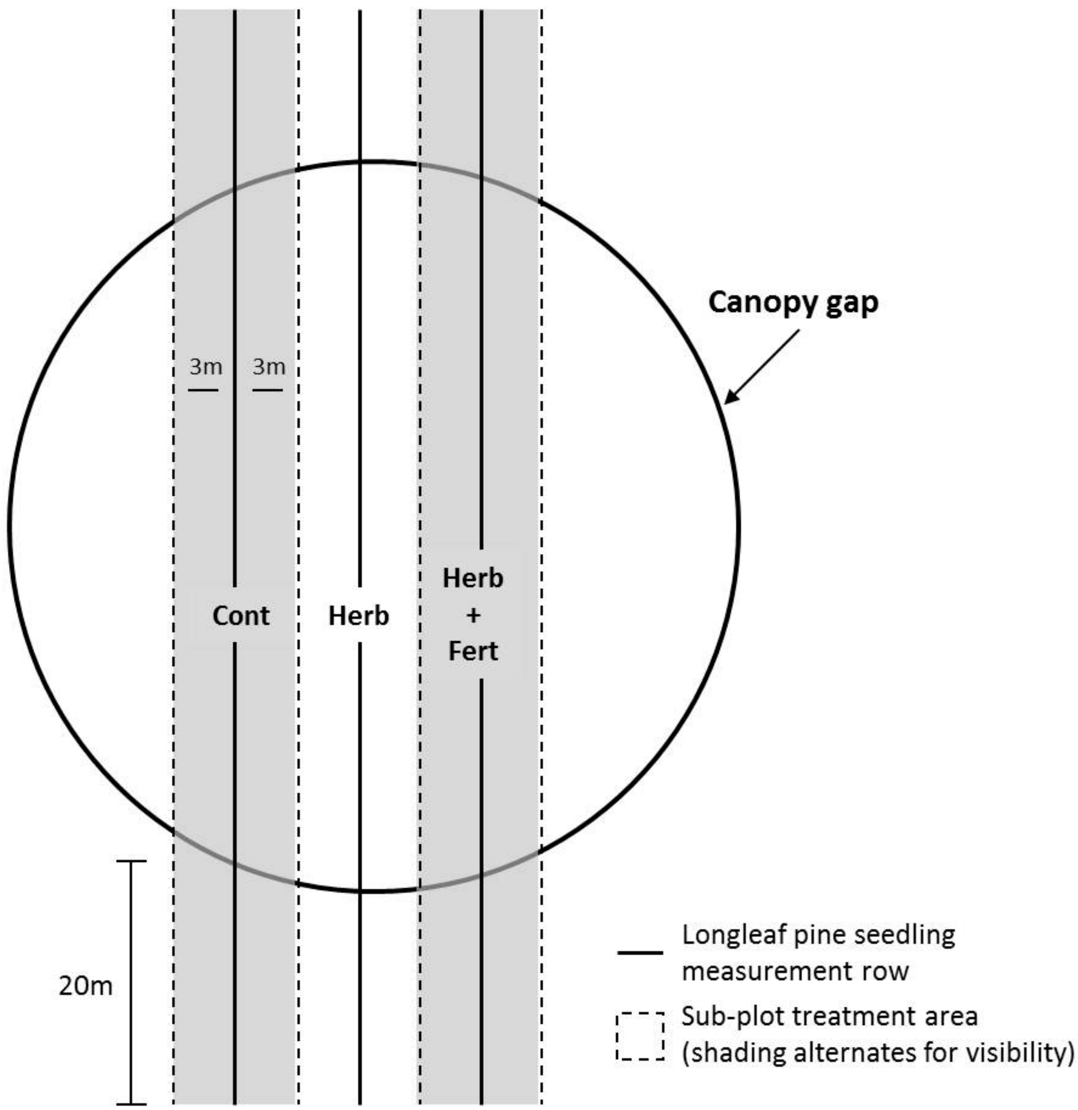


Figure 3.1.8. Example of layout of split-plots within each gap main plot.

The herbicide treatment was designed to improve conditions for planted longleaf pine seedlings by reducing competition from surrounding vegetation. We consulted with Matt Nespeca of the Conservation Land Company, Inc. for herbicide recommendations, and we prescribed a direct spray of 1% imazapyr (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-3-pyridinecarboxylic acid) plus 0.25% non-ionic surfactant in October 2008 to control woody vegetation occurring in the application area at both study locations. At Fort Benning, herbaceous vegetation dominated study areas and provided additional competition to longleaf pine seedlings. We applied an additional granular mix of 63.2% hexazinone [3-cyclohexyl-6-(dimethylamino)-1-methyl-1,3,5-triazine-2,4(1H,3H)-dione] and 11.8% sulfometuron methyl {Methyl 2-[[[[(4,6-dimethyl-2-pyrimidinyl)amino]-carbonyl]amino]sulfonyl]benzoate} at a rate of 0.84 kg/ha, sprayed in approximately 1 m wide bands over top of longleaf pine seedlings in March 2009 at Fort Benning only.

The H+F treatment included the herbicide treatments described above as well as an application of 280 kg/ha 10-10-10 NPK granular fertilizer. We selected this prescription to approximately double the nitrogen mineralization rates that have been reported within the North Carolina Coastal Plain (Vitousek and Matson 1985; Li et al. 2003), while also alleviating phosphorus limitations common to the region. The fertilizer treatment was broadcast by hand, with care taken to evenly distribute fertilizer throughout each treatment area in April 2009 at both study sites.

All study treatments were initially replicated in 6 blocks at Fort Benning and 8 blocks at Camp Lejeune. However, at Camp Lejeune the LG treatment was not included in Block 5 due to technical problems, MedBA was eliminated by military training in Block 4, and Block 6 was lost to wildfire in 2009. One other plot, MedBA in Block 3, was cut too heavily and reclassified as LowBA. In 2011, a wildfire burned through Block 1 of Fort Benning, and therefore that block was dropped from the design for 2012 analyses.

3.1.2. Site preparation and planting

Following timber harvest, study sites were prepared in accordance with standard management procedures used for longleaf pine establishment at each installation, with the objectives of removing woody competitors and preparing the sites for planting container-grown longleaf pine seedlings. At Fort Benning, site preparation included an herbicide treatment of 2.34 l/ha imazapyr mixed with 2.24 kg/ha glyphosate and applied in September 2007, followed by prescribed fire in November 2007. At Camp Lejeune, all standing vegetation was cut to ground level and mulched with a Fecon® Bull Hog rotary mower in July/August of 2007, followed by prescribed burning in November. Restrictions on burning in 2007 limited application of prescribed fire to days when conditions were not ideal, resulting in patchy fuel consumption and incomplete burns. Effects of the mulching site preparation on fuels and fire behavior may have also contributed to the patchiness of the burns (Glitzenstein et al. 2006). At Camp Lejeune, Block 8 was unable to be burned due to its proximity to a highway and burn restrictions.

Study sites were planted by contracted crews at each installation and followed standard management procedures. At Fort Benning, container grown longleaf pine seedlings were planted at 1.8 x 3.7 m spacing, for a total of 1495 seedlings per hectare. Planting crews began in mid-

November 2007 and completed planting by January 2008. At Camp Lejeune, container-grown longleaf pine seedlings were planted 1.8 x 3.0 m spacing, resulting in a density of 1795 seedlings per hectare. Planting was completed in November 2007.

3.1.3. Dormant season prescribed burn (2010)

All study areas were burned with dormant season prescribed fire applied between the second and third growing season (January – April 2010). At Fort Benning, prescribed fires were ignited by land management and The Natural Conservancy personnel using backing and strip-head firing techniques; similar firing techniques were applied by Camp Lejeune base forestry personnel. Efforts were made to completely burn the study plots, and areas of patchy fire movement were re-ignited as needed. However, weather conditions during burns differed among the study blocks (Table 3.1.2.), resulting in varying levels of burn completeness. Effects of study treatments on fuels, fire behavior, and some fire effects are presented in Section 3.9.

Table 3.1.2. Weather conditions from the 2010 dormant season prescribed fires at Fort Benning and Camp Lejeune. Data at Fort Benning were collected with a Kestrel 3000 Pocket Weather Meter at the time of ignition; data from Camp Lejeune were acquired from the North Carolina Division of Forest Resources, Remote Automated Weather Station at the Sandy Run station (34.61º N, 77.49º W)

Site	Block	Treatment	Burn date	Temp. °C	Relative Humidity (%)	Average wind speed (km/hr)	Max gust wind speed (km/hr)	Wind direction
Fort Benning	1	All	7-Mar-2010	16.7	15	7.9	17.6	West
	2	All	5-Apr-2010	26.9	44	3.2	4.7	Southwest
	3	Clearcut	17-Feb-2010	7.8	49	14.4	28.8	West
	3	LowBA, MedBA, Control, Gap	25-Feb-2010	7.2	26	4.7	10.1	Northwest
	4	Clearcut, LowBA, Gap	18-Feb-2010	12.0	28	4.7	11.2	West
	4	MedBA, Control	25-Feb-2010	6.1	27	17.6	30.6	Northwest
	5	All	8-Mar-2010	24.0	26	2.9	4.7	North
	6	All	18-Feb-2010	14.4	26	6.5	13.0	Northwest
Camp Lejeune	1	All	5-Jan-2010	2.2	45	14.4	27.7	Northwest
	2	All	5-Jan-2010	2.2	45	14.4	27.7	Northwest
	3	All	5-Jan-2010	2.2	45	14.4	27.7	Northwest
	4	All	27-Feb-2010	11.1	31	9.7	24.1	West
	5	All	10-Mar-2010	22.8	39	11.2	25.9	South
	7	All	15-Mar-2010	16.7	47	14.4	32.0	Northwest
	8	All	26-Feb-2010	7.8	33	14.4	32	West

3.2. Effects of harvesting and cultural treatments on planted longleaf pine seedlings at Fort Benning and Camp Lejeune

This section details the effects of harvesting and cultural treatments on planted longleaf pine seedlings (research objective O-1). Previously reported results from sampling in 2008-2010 (Hu et al. 2012; Knapp et al. 2013) are included along with 2012 sampling results. Specific objectives were to: 1) determine the effects of harvesting treatments that vary the distribution and density of residual canopy trees on planted longleaf pine seedling survival and growth; 2) determine the effects of cultural treatments designed to improve longleaf pine restoration on planted longleaf pine seedling survival and growth; and 3) determine the effects of gap direction and position on planted longleaf pine seedling survival and growth.

3.2.1. Methods

See Section 3.1 for details on study sites, experimental design, and treatment installation.

3.2.1.1. Data collection

In June 2008, we selected a sub-sample of longleaf pine seedlings in each split-plot, and we permanently marked each seedling with an aluminum tag for repeated measurements. In uniform canopy plots (Control, MedBA, LowBA, and Clearcut), we randomly selected a sample of 30 seedlings (approximately half of what was planted in each 20 x 20 m measurement area), and in gap plots we tagged every seedling that occurred on each split-plot measurement row, extending 20 m into the forest on either end. Therefore, the total number of seedlings marked in each gap varied with gap size.

We monitored seedling survival at the end of the first, second, third, and fifth growing seasons after planting (October 2008, 2009, 2010, and 2012). Root collar diameter (RCD) of each seedling was measured at two perpendicular axes with digital calipers, and the average of the two measurements was calculated to account for irregularity in RCD shape. Seedling height was measured as the distance from the RCD to the tip of the terminal bud. Because all seedlings were in the grass stage in 2008, seedling heights were measured only in 2009, 2010, and 2012.

3.2.2.2. Data analysis

We tested effects of management treatments on the average longleaf pine response at the plot level during each year. Mean mortality and growth variables were calculated at the main-plot level in 2008 and at the split-plot level in 2009, 2010, and 2012. Because one block was eliminated from the study in 2012 at Fort Benning, treatment means are not directly comparable from 2010 to 2012 at Fort Benning. For the height growth analyses, we considered seedlings to be in height growth when the terminal bud was at least 15 cm from the root collar. We calculated, for each split-plot, the percentage of all living seedlings measured in height growth.

We used Analysis of Variance (ANOVA) to determine significant treatment effects in each year, using one-way ANOVA in 2008 but split-plot ANOVA in 2009, 2010, and 2012. We conducted repeated measures ANOVA with the autoregressive order 1 covariance structure to determine the effect of time on longleaf pine mortality and root collar diameter. Because split-plot treatments were applied during different years we only included the control split-plot (NT) data for the repeated measures analyses, and only the five blocks remaining in 2012 were used for the repeated measures analyses at Fort Benning. Treatment differences were determined used Tukey's LSD approach, and degrees of freedom were calculated using the Satterthwaite approximation. When necessary, transformations were used to meet assumptions of normality and constant variance.

In gap plots, we tested the effects of gap position on longleaf pine seedling mortality and root collar diameter in two ways: 1) we compared seedling response in the north vs. the south half of gaps, and 2) we tested the effect of gap position (10 m intervals) on seedling response along the north/south transects. We calculated mean values for each direction and 10-m interval position by grouping data into bins for analysis. Split-plot data were grouped together for the analysis because we found no interactions between split-plot and gap position or direction.

We used an initial split-plot ANOVA with gap size as the main-plot effect and direction as the split-plot effect to test for interactions between gap size and direction. In the absence of an interaction, we tested the effects of gap direction on response variables with data from all gaps combined. We used ANOVA to test effects of gap position in 10-m intervals for each gap separately because gap size differed (and therefore the number of positions per gap differed). For all analyses, we used $\alpha = 0.05$ to determine statistical significance.

3.2.2. Results

3.2.2.1. Overall treatment effects

Cumulative mortality was significantly affected by main-plot treatments at the end of each growing season, with the exception of after the fifth growing season at Fort Benning only (Table 3.2.1). By the end of five growing seasons, mortality at Fort Benning ranged from 49.5% on the SG treatments to 62.3% on the LG treatments and from 30.1% on the Clearcut treatments to 55.8% on the MG treatments at Camp Lejeune (Figure 3.2.1). Among the uniform treatment, mortality tended to increase as canopy density decreased at Fort Benning during the first three growing seasons, but the opposite pattern was observed at Camp Lejeune. There were no interactions between main-plot and split-plot effects in 2009, 2010, or 2012 at either site (Table 3.2.1), and no split-plot treatment effects were observed, although the split-plot effect was nearly significant in 2010 and 2012 at Camp Lejeune. Mean mortality for all split-plots at Fort Benning was 29.8% in 2008, 37.1% in 2009, 52.9% in 2010, and 54.5% in 2012; at Camp Lejeune, mean mortality among split-plots was 9.3% in 2008, 23.3% in 2009, 33.3% in 2010, and 44.8% in 2012 (Figure 3.2.2).

The pattern of mortality observed at Fort Benning was driven primarily by mortality during the first growing season, from which mortality in the Clearcut plots was 47.9% compared to 8.8% in Control plots (Figure 3.2.1). Mortality at Camp Lejeune was evenly distributed over the three

Table 3.2.1. Results from ANOVA to determine effects of main-plot and split-plot treatments on longleaf pine seedling mortality at Fort Benning and Camp Lejeune at the end of the 2008, 2009, 2010, and 2012 growing seasons

Year	Site	Effect	Num DF	Den DF	F-value	p-value	Transformation
2008	Fort Benning	main	6	30.0	8.59	<0.0001	none
	Camp Lejeune	main	6	33.9	3.61	0.0071	arcsin($\sqrt{x}$)
2009	Fort Benning	main	6	30.0	6.75	0.0001	none
		split	2	70.0	0.34	0.7162	none
		main* split	12	70.0	0.7	0.7504	none
	Camp Lejeune	main	6	33.5	5.72	0.0004	arcsin($\sqrt{x}$)
		split	2	81.5	1.54	0.2199	arcsin($\sqrt{x}$)
		main* split	12	81.5	0.60	0.8350	arcsin($\sqrt{x}$)
2010	Fort Benning	main	6	30.0	3.97	0.0048	arcsin($\sqrt{x}$)
		split	3	70.0	0.4	0.6714	arcsin($\sqrt{x}$)
		main* split	18	70.0	0.83	0.6180	arcsin($\sqrt{x}$)
	Camp Lejeune	main	6	33.5	6.86	0.0009	arcsin($\sqrt{x}$)
		split	2	81.5	2.21	0.1159	arcsin($\sqrt{x}$)
		main* split	12	81.5	5.01	0.5447	arcsin($\sqrt{x}$)
2012	Fort Benning	main	6	24.0	1.15	0.3645	none
		split	2	56.0	0.93	0.4003	none
		main* split	12	56.0	0.88	0.5722	none
	Camp Lejeune	main	6	34.4	2.64	0.0328	none
		split	2	78.4	2.83	0.0652	none
		main* split	12	78.4	1.06	0.4048	none

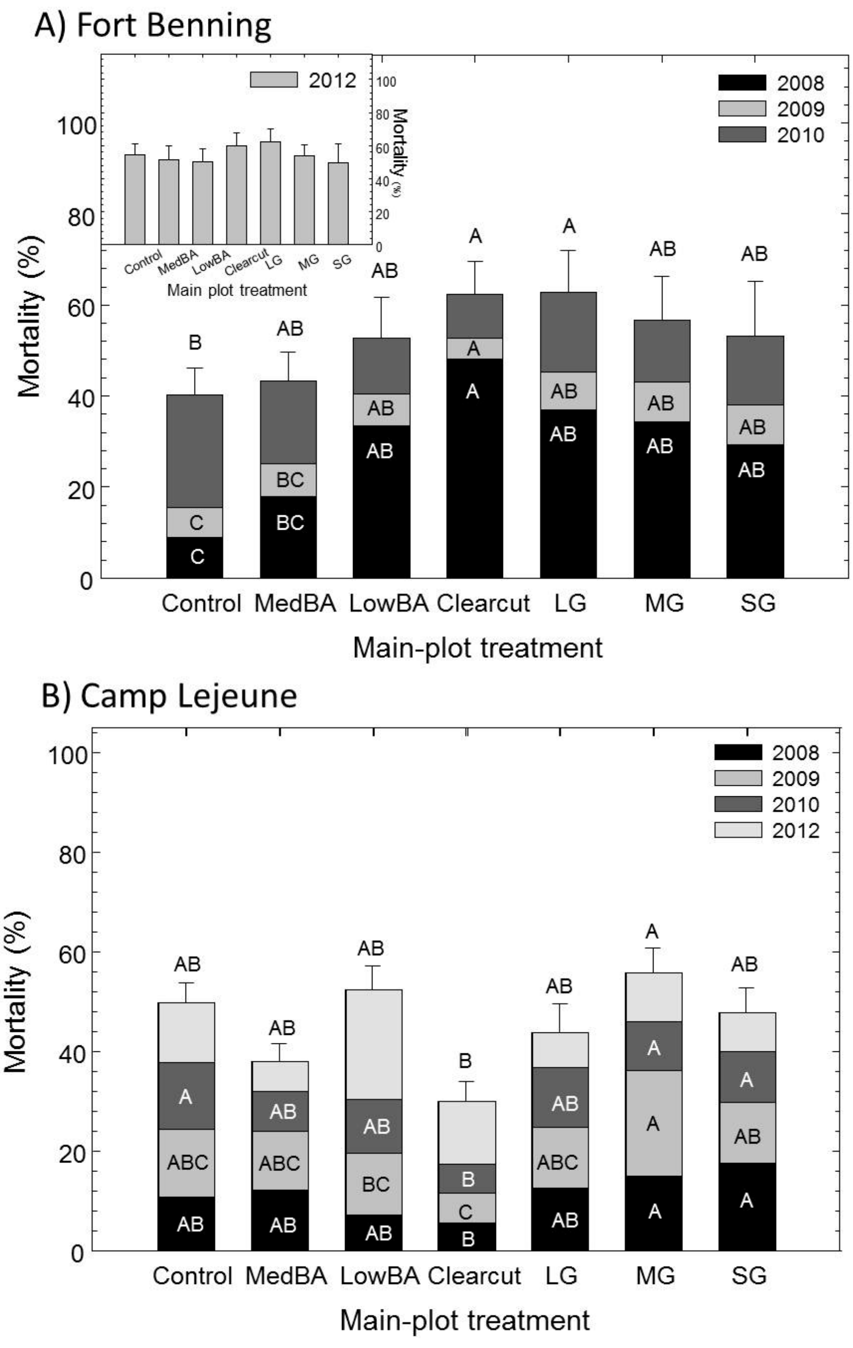


Figure 3.2.1. Longleaf pine seedling cumulative mortality (mean ± one standard error) at the end of the 2008, 2009, 2010, and 2012 growing seasons at A) Fort Benning and B) Camp Lejeune. Cumulative mortality for 2012 at Fort Benning is inset because one study block was lost from the design. The same letter indicates no difference in cumulative mortality after each growing season surveyed at Fort Benning and Camp Lejeune.

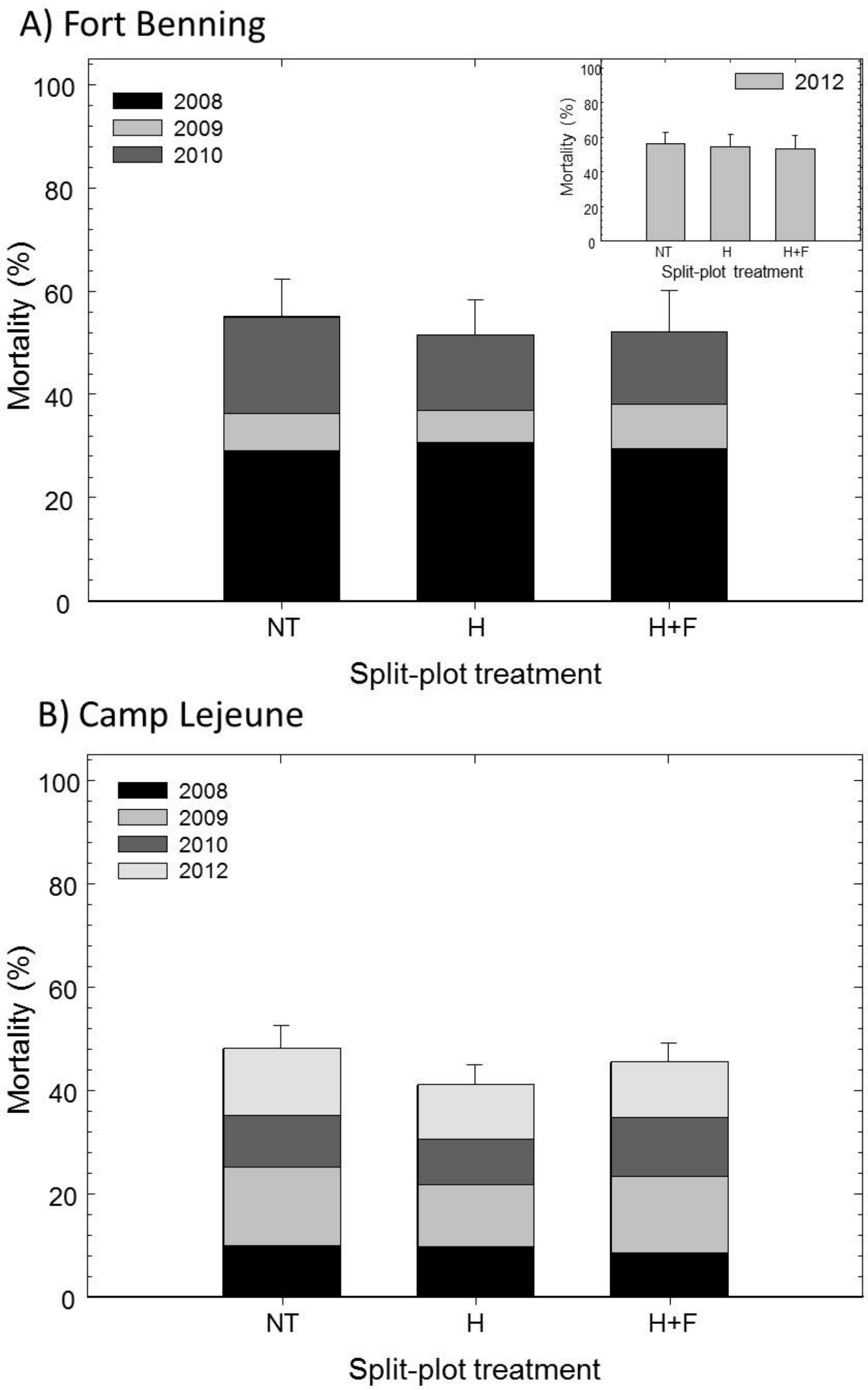


Figure 3.2.2. Longleaf pine seedling mortality (mean ± one standard error) by split-plot in 2008, 2009, 2010, and 2012 at A) Fort Benning and B) Camp Lejeune. Cumulative mortality for 2012 at Fort Benning is inset because one study block was lost from the design.

growing seasons (Figure 3.2.1). Results from the repeated measures analysis demonstrate that cumulative mortality was significantly higher each subsequent year (at Fort Benning $F = 62.41$, $p < 0.0001$; at Camp Lejeune $F = 40.19$, $p < 0.0001$). Although there was not a significant interaction of time*treatment at Fort Benning ($F = 1.91$; $p = 0.0749$), survival in the Control plots was highest among the treatments following the first growing season but dropped sharply in the third and fifth growing seasons, resulting in the lowest survival in Controls and Clearcuts after five years at Fort Benning (Figure 3.2.3).

Root collar diameter of longleaf pine seedlings was significantly affected by main-plot treatments in all years at Fort Benning and Camp Lejeune (Table 3.2.2). At both sites, the range of root collar diameters was small among canopy treatments following the first growing season (Figure 3.2.4). However, seedling root collar diameter was largest on Clearcut treatments and smallest on Control treatments following each growing season. After five growing seasons, mean root collar diameter ranged from 21.2 mm on Control plots to 43.2 mm on Clearcut plots at Fort Benning and from 21.7 mm on Control plots to 35.1 mm on Clearcut plots at Camp Lejeune.

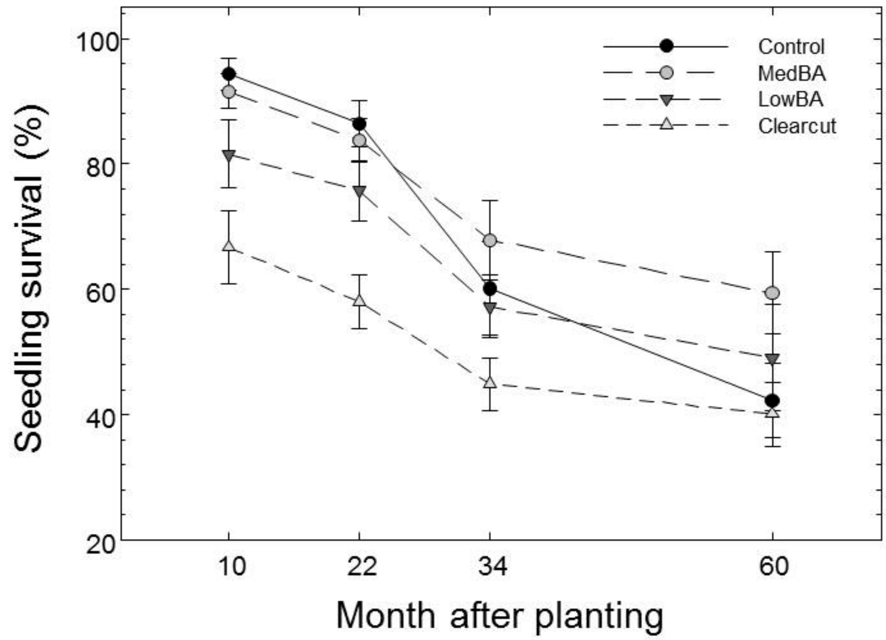
There was no effect of the split-plot treatments in 2009 at Fort Benning, but at Camp Lejeune the split-plot treatments that included herbicide (H and H+F) had larger mean root collar diameters than the untreated split-plot (NT; Table 3.2.2 and Figure 3.2.5). This pattern was also observed at both Fort Benning and Camp Lejeune after the fifth growing season (Table 3.2.2 and Figure 3.2.5). In 2010, there were significant main-plot by split-plot interaction effects at both Fort Benning and Camp Lejeune (Table 3.2.2). Generally, main-plot treatments with canopy reduction and split-plot treatments with herbicide generally had larger root collar diameters than other treatments, and the interaction appeared to be caused by inconsistencies in the split-plot effects within main-plots (Figure 3.2.6).

In 2009, the percentage of seedlings in height growth was greatest on Clearcut plots at Fort Benning but was not significantly different among main-plot or split-plot treatments at Camp Lejeune (Table 3.2.3). There were no significant interactions between main-plot and split-plot treatments for any measure of seedlings in height growth ($p > 0.2043$). By the end of five growing seasons, over 85% of surviving seedlings were in height growth on Clearcut plots compared to nearly zero on Control plots at Fort Benning, with nearly 60% of surviving seedlings in height growth on Clearcut plots at Camp Lejeune. The split-plot treatments that included herbicide had a slightly higher percentage of seedlings in height growth than those without at both sites in 2010 and at Camp Lejeune in 2012 (Table 3.2.3).

3.2.2.2. Effects of gap direction and position

At Fort Benning, there were no interactions between gap size and direction effects on seedling mortality in any year (2008 $F = 0.45$, $p = 0.6449$; 2009 $F = 0.17$, $p = 0.8423$; 2010 $F = 0.32$, $p = 0.7300$; 2012 $F = 0.45$, $p = 0.6477$). Cumulative mortality was significantly higher in the north half of gaps than the south half in 2008 and 2009 but the differences were no longer significant in 2010 or 2012 (Figure 3.2.7), with a difference of 10% in 2008, 9% in 2009, 4% in 2010, and 3% in 2012. This pattern was not evident at Camp Lejeune, where gap direction had no significant effect on longleaf pine seedling mortality ($p \geq 0.2168$; Figure 3.2.7).

A) Fort Benning



B) Camp Lejeune

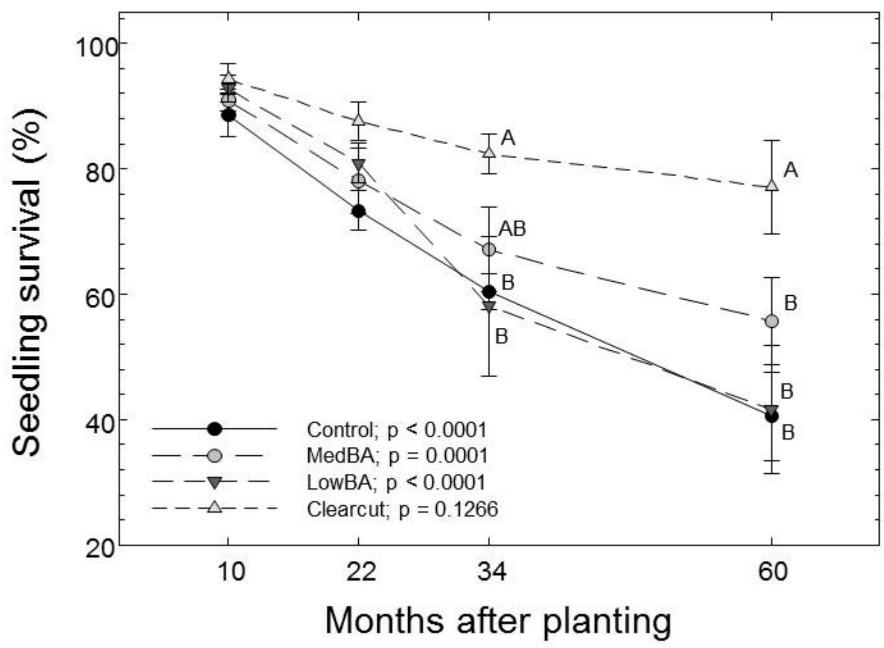


Figure 3.2.3. Seedling survival (mean ± one standard error) in October 2008, 2009, 2010, and 2012 in uniform plots at A) Fort Benning and B) Camp Lejeune. Results shown are from the repeated measures analyses, using only NT split-plot treatments due to the timing of split-plot treatment application. The same letter indicates no significant difference in pair-wise comparisons among main-plot treatments within a time period.

Table 3.2.2. Results from ANOVA to determine effects of main-plot and split-plot treatments on longleaf pine seedling root collar diameter at Fort Benning and Camp Lejeune at the end of the 2008, 2009, 2010, and 2012 growing seasons

Year	Site	Effect	Num DF	Den DF	F-value	p-value	Transformation
2008	Fort Benning	main	6	156.0	8.4	<0.0001	
	Camp Lejeune	main	6	131.0	9.62	<0.0001	Log10(x)
2009	Fort Benning	main	6	30.0	8.94	<0.0001	
		split	2	70.0	1.65	0.2004	
		main*split	12	70.0	1.27	0.2576	
	Camp Lejeune	main	6	34.6	3.34	0.0106	Log10(x)
		split	2	82.0	11.30	<0.0001	Log10(x)
		main* split	12	82.0	0.89	0.5562	Log10(x)
2010	Fort Benning	main	6	30.1	7.87	<0.0001	
		split	2	67.7	2.48	0.0909	
		main* split	12	67.7	2.12	0.0266	
	Camp Lejeune	main	6	33.9	5.36	0.0006	Log10(x)
		split	2	80.0	31.20	<0.0001	Log10(x)
		main* split	12	80.0	1.89	0.0486	Log10(x)
2012	Fort Benning	main	6	24	13.33	<0.0001	
		split	2	56	5.36	0.0074	
		main* split	12	56	1.23	0.2871	
	Camp Lejeune	main	6	34.0	4.85	0.0011	
		split	2	76.2	31.86	<0.0001	
		main* split	12	76.2	1.25	0.2670	

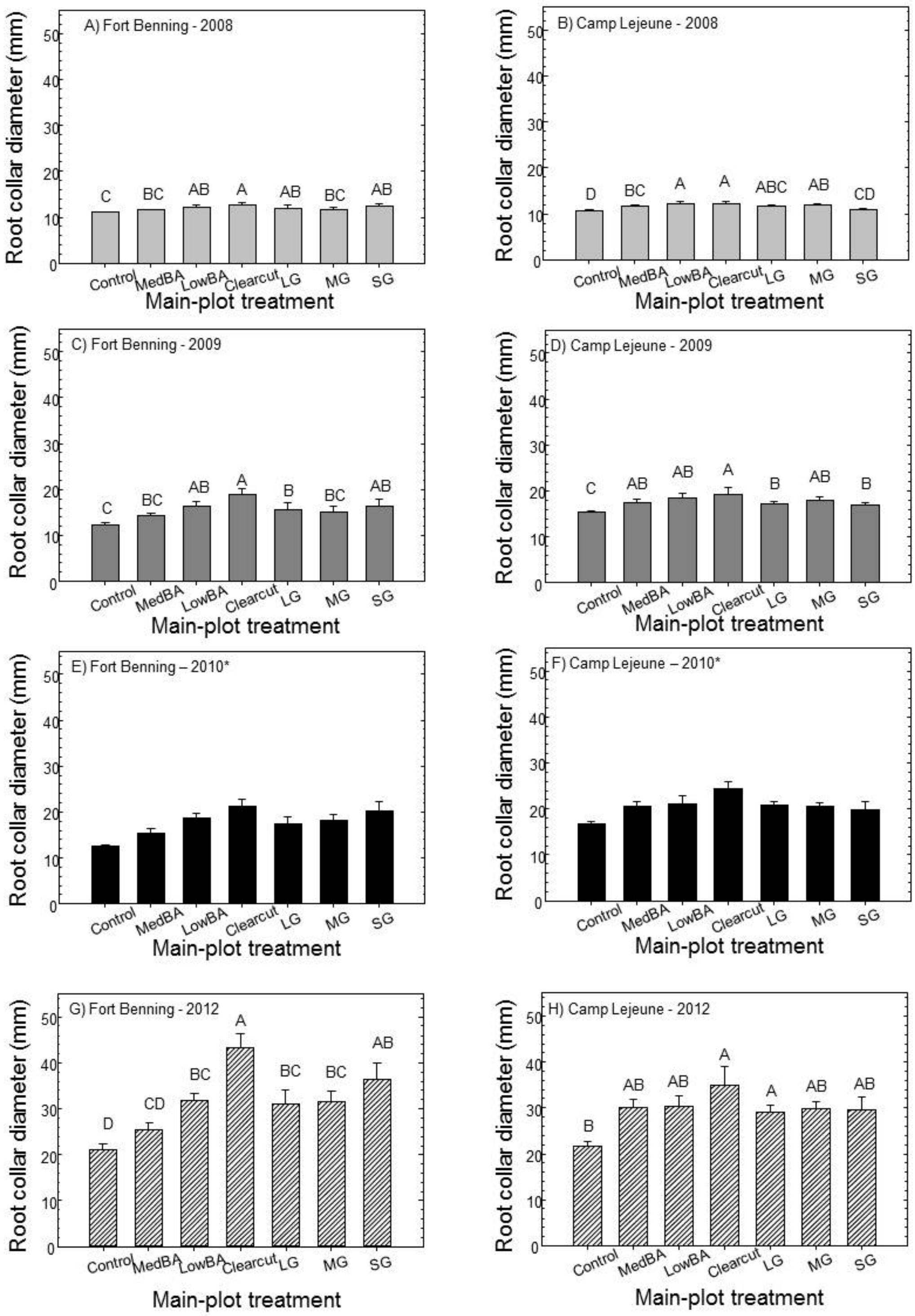


Figure 3.2.4. Longleaf pine seedling root collar diameter (mean ± one standard error) measured in October 2008, 2009, 2010, and 2012 at Fort Benning (panels A, C, E, and G, respectively) and Camp Lejeune (panels B, D, F, and H, respectively). The same letter indicates no significant differences among pair-wise comparisons. Panels E and F do not include letters of significance because there were main*split-plot interactions for each site in 2010.

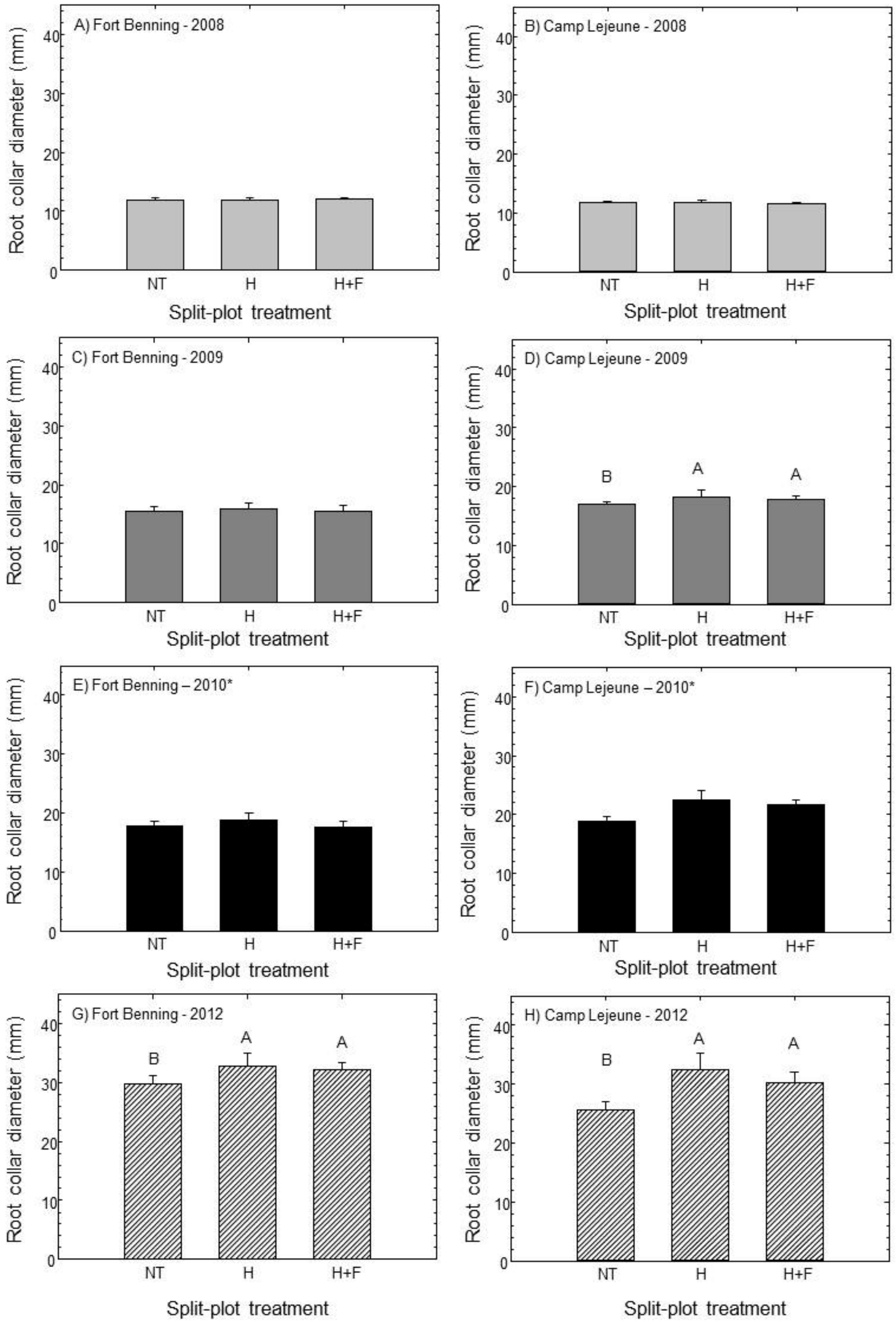


Figure 3.2.5. Longleaf pine seedling root collar diameter (mean ± one standard error) by split-plot treatment, measured in October 2009, 2010, and 2012 at Fort Benning (panels A, C, E, and G, respectively) and Camp Lejeune (panels B, D, F, and H, respectively). The same letter indicates no significant differences among pair-wise comparisons. Panels E and F do not include letters of significance because there were main*split-plot interactions for each site in 2010.

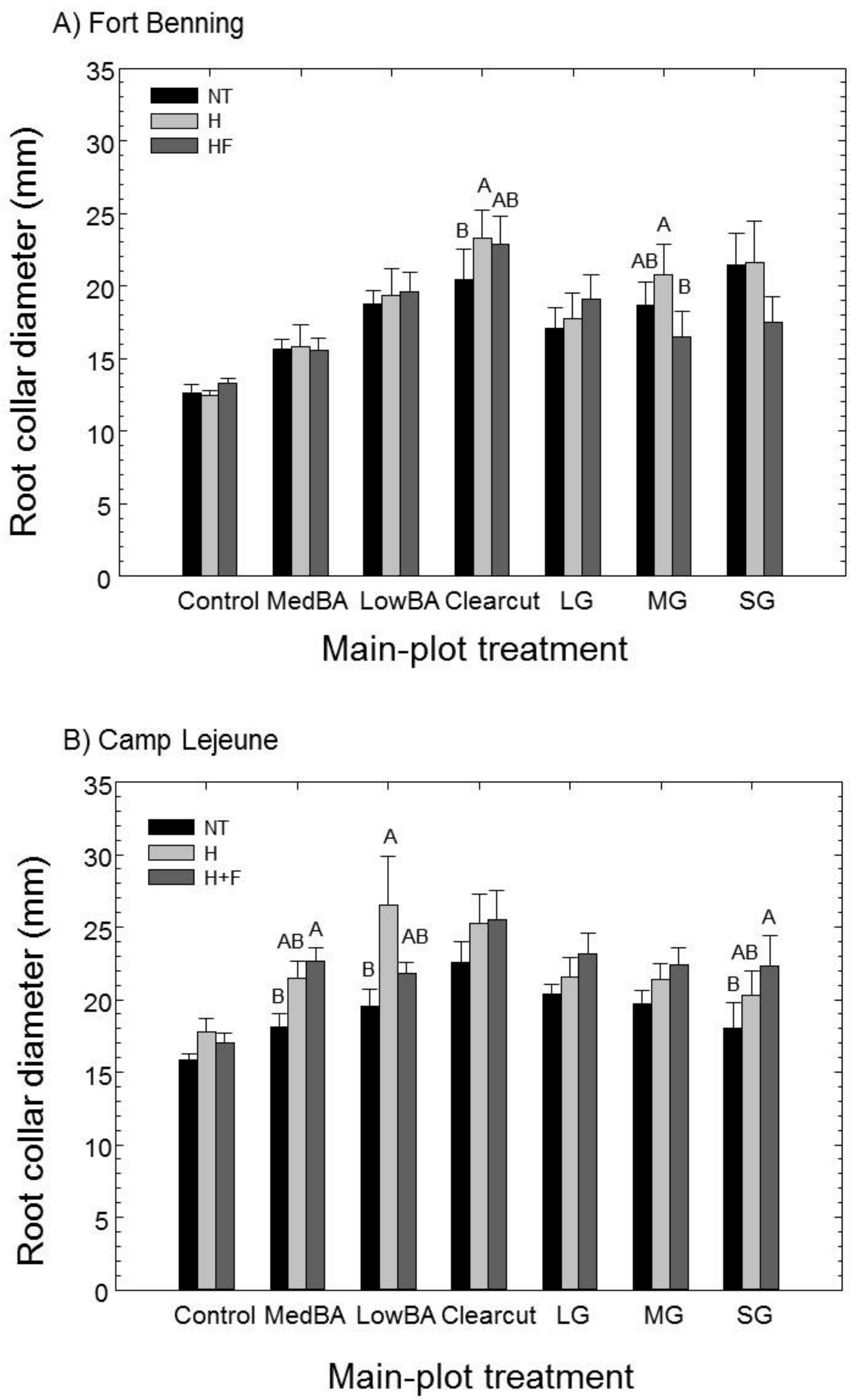


Figure 3.2.6. Root collar diameter (mean ± one standard error) by main-plot and split-plot treatment in October 2010 at A) Fort Benning and B) Camp Lejeune, where significant main*split-plot interactions were present. The same letter indicates no significant difference in pair-wise comparisons among split-plot treatments within each main-plot treatment.

Table 3.2.3. Percentage of seedlings in height growth in October 2009, 2010, and 2012 at Fort Benning and Camp Lejeune. The same letter indicates no significant difference in pair-wise comparisons among treatments for each effect

			Height growth (%)					
			2009		2010		2012	
Site	Effect	Treatment	Mean	SE	Mean	SE	Mean	SE
Fort Benning	Main-plot	Control	0.00[b]	0	0.23[c]	0.23	2.97[d]	2.00
		MedBA	0.76[b]	0.76	3.38[bc]	1.63	22.96[cd]	5.92
		LowBA	3.31[ab]	1.8	16.04[ab]	3.9	61.70[ab]	7.18
		Clearcut	8.50[a]	3.54	34.59[a]	9.18	86.61[a]	4.92
		LG	1.78[ab]	1.24	11.94[abc]	5.33	50.77[bc]	14.16
		MG	3.54[ab]	1.98	12.48[abc]	5.9	54.80[b]	5.46
		SG	5.53[a]	2.3	23.31[a]	8.59	65.36[ab]	11.06
		p-value	**0.0177**		**<0.0001**		**<0.0001**	
	Split-plot	NT	3.27	0.83	10.25[ab]	3.48	43.44	6.40
		H	3.29	1.5	18.14[a]	5.78	51.94	6.90
		H+F	3.47	1.58	15.31[ab]	4.4	52.55	4.44
		p-value	**0.9722**		**0.0224**		**0.0664**	
Camp Lejeune	Main-plot	Control	0.42	0.29	1.11[b]	0.64	13.32[b]	5.08
		MedBA	1.21	0.55	12.96[a]	2.77	45.53[a]	9.73
		LowBA	3.26	2.73	12.86[a]	2.91	46.43[a]	9.76
		Clearcut	6.15	2.09	26.47[a]	5.02	56.88[a]	8.81
		LG	0.76	0.41	8.27[a]	1.74	43.06[a]	2.5
		MG	2.2	0.75	12.63[a]	2.03	45.60[a]	6.33
		SG	1.72	0.84	10.54[ab]	2.9	40.87[a]	8.28
		p-value	**0.2677**		**0.0003**		**0.0003**	
	Split-plot	NT	1.22	0.5	8.14[c]	1.83	28.46[b]	4.75
		H	3.63	1.59	14.29[b]	2.72	47.18[a]	7.56
		H+F	2.18	0.67	18.54[a]	2.47	52.10[a]	5.23
		p-value	**0.1454**		**< 0.0001**		**<0.0001**	

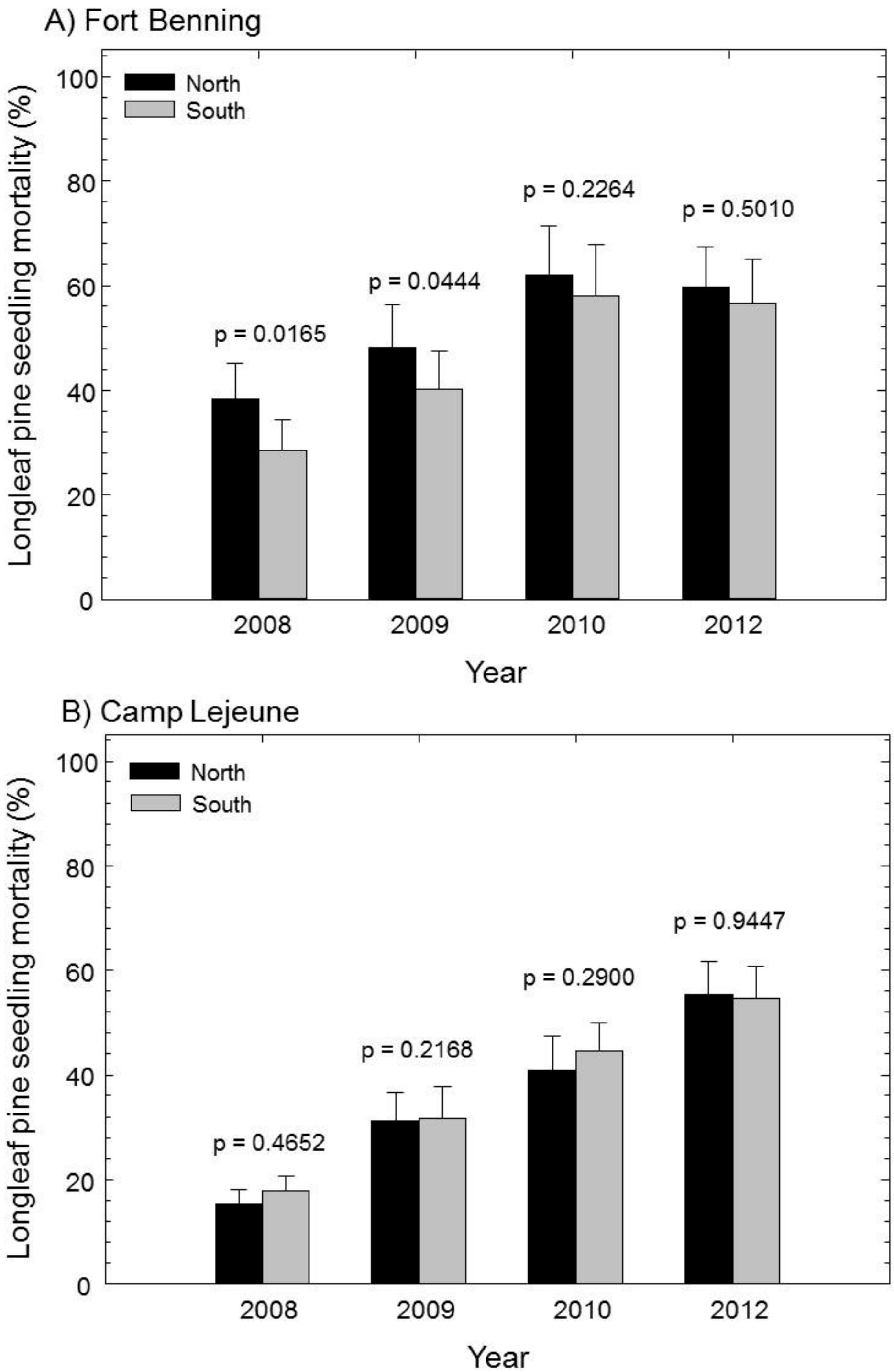


Figure 3.2.7. Longleaf pine seedling mortality by gap direction (mean ± one standard error) in 2008, 2009, 2010, and 2012 at A) Fort Benning and B) Camp Lejeune. *P*-values test for differences in root collar diameter between the north and south half of gaps within each year.

At Fort Benning, we observed a general pattern of increasing mortality associated with gap position, where mortality was lowest within the forest and increased toward gap center (Figure 3.2.8). Patterns of cumulative mortality at the end of each year appeared to strongly follow the initial patterns of mortality from 2008. At Camp Lejeune, there was no effect of gap position on seedling mortality in the SG plots or in the MG gap plots in any year. During years with significant position effects in LG plots, there was no clear pattern to explain the observed mortality, although mortality was generally highest beneath the forest canopy on the south side of the gaps (Figure 3.2.8).

The only significant interaction effect between gap size and gap direction on root collar diameter that we observed was in 2010 at Fort Benning ($F = 4.50$; $p = 0.0294$), where seedlings on the north side of MG plots (20.9 mm) were larger than those on the south side of the MG plots (17.2 mm) but gap direction did not affect seedling size for LG or SG plots. For other years, root collar diameter was not significantly affected by gap direction at Fort Benning or Camp Lejeune (Figure 3.2.9). At Fort Benning, gap position significantly affected root collar diameter in only LG plots in 2008, but seedling size increased from beneath the canopy to the center of canopy gaps of each size in 2009, 2010, and 2012 (Figure 3.2.10). There were not clear patterns of seedling size related to gap position at Camp Lejeune.

3.2.3. Discussion

Patterns of seedling mortality differed largely between Fort Benning and Camp Lejeune. Similar to previous studies, the majority of longleaf pine seedling mortality at Fort Benning occurred during the first growing season (Boyer 1988, Knapp et al. 2006), but mortality at Camp Lejeune occurred throughout the study period. Generally, container-grown longleaf pine seedlings are considered the most vulnerable to mortality during the first year of establishment because the seedlings must become adjusted to the new growing environment. The 2008 growing season was drier than the 50-year average at each study location, creating conditions in which seedling plugs could have dried out. At Fort Benning, the low water holding capacity and coarse soils may have exacerbated water stress, but higher soil water content at Camp Lejeune (see Section 3.1.1) may have contributed to lower mortality rates in the first year after planting.

At Fort Benning, seedling mortality in the first two years appeared to be associated with canopy removal, as suggested by the pattern of increasing mortality with heavier canopy removal in uniform plots. In each of these years, the Control plots had significantly lower cumulative mortality than the LowBA or the Clearcut plots, and the MedBA plots had significantly lower mortality than the Clearcut plots. Patterns within gaps also support this association, in which mortality increased from within the forest to the gap center. Previous studies have reported high early mortality for longleaf pine seedlings planted in canopy gaps, especially in periods of drought (McGuire et al. 2001, Rodriguez-Trejo et al. 2003, Gagnon et al. 2003). In southwestern Georgia, McGuire et al. (2001) reported survival rates of around only 10% after two growing seasons for longleaf pine seedlings planted in canopy gaps of different sizes. The significant direction effect in canopy gaps at Fort Benning, in which mortality in the north half of gaps was higher than mortality in the south half of gaps, suggests that seedling mortality may have been related to increased exposure to solar irradiance (see Section 3.7). Similar to our study, both Rodriguez-Trejo et al. (2003) and Gagnon et al. (2003) found that longleaf

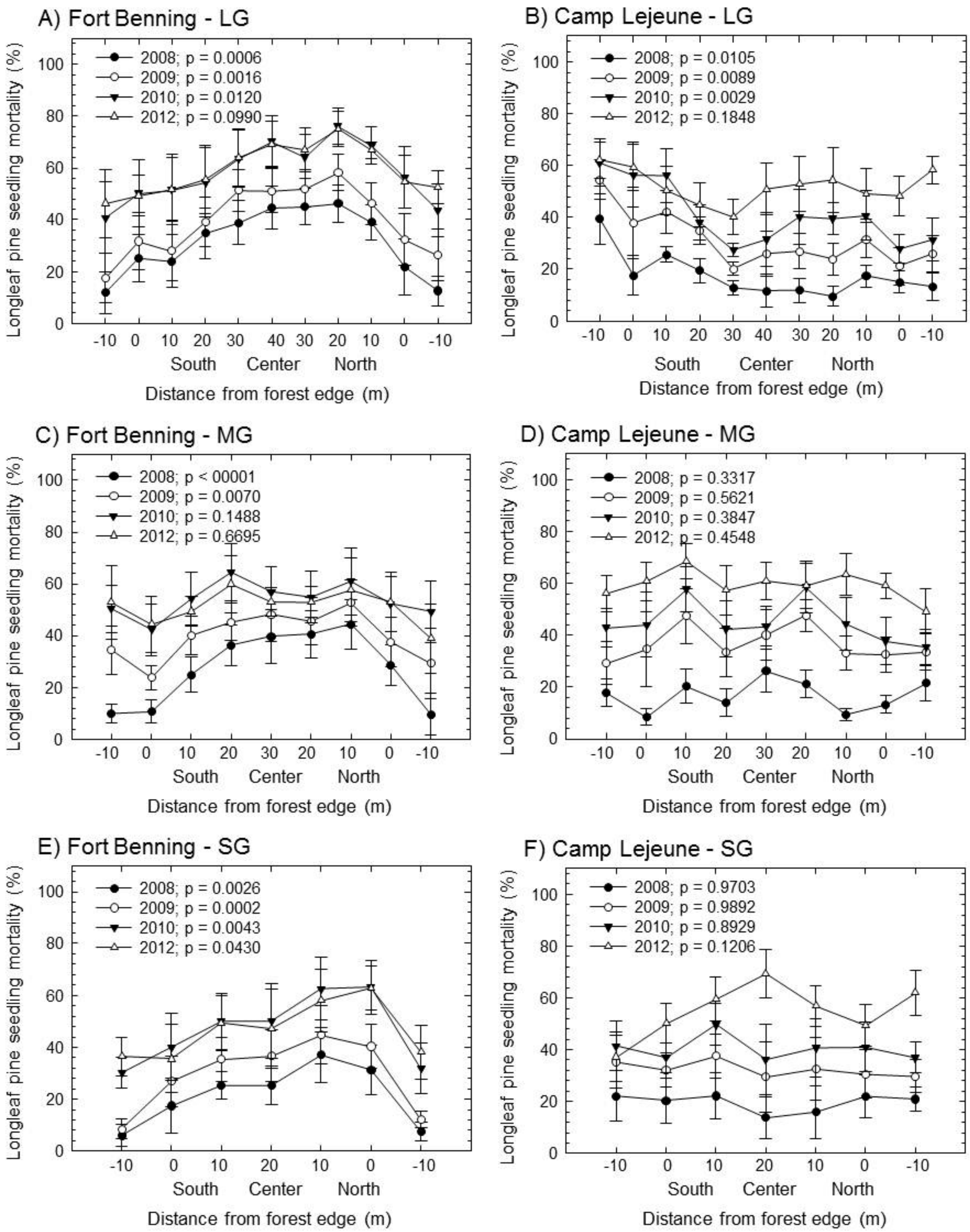


Figure 3.2.8. Longleaf pine seedling cumulative mortality (mean ± one standard error) by gap position (10 m interval) in 2008, 2009, 2010, and 2012 for A) Fort Benning large gap, B) Camp Lejeune large gap, C) Fort Benning medium gap, D) Camp Lejeune medium gap, E) Fort Benning small gap, and F) Camp Lejeune small gap.

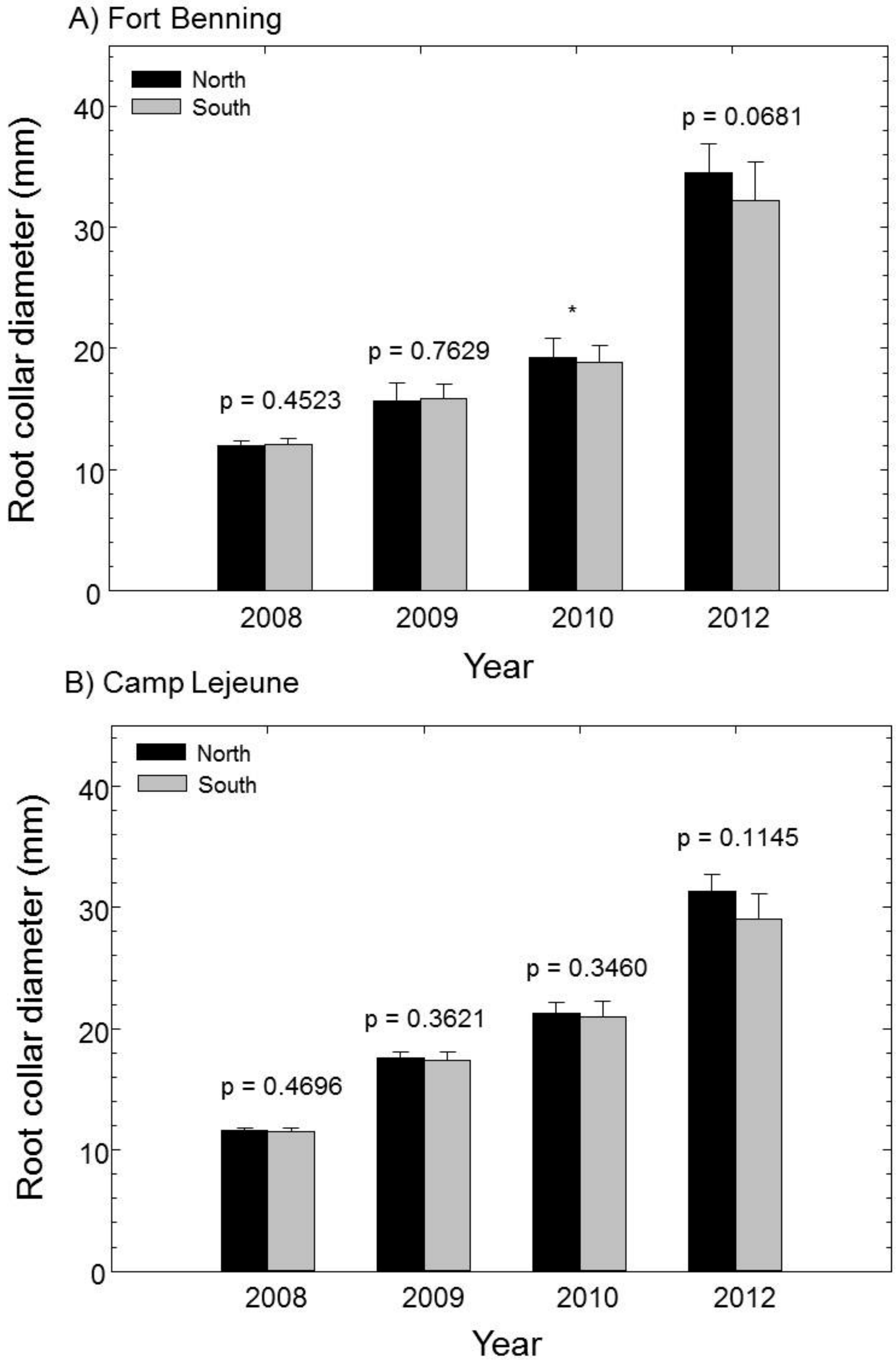


Figure 3.2.9. Longleaf pine seedling root collar diameter by gap direction (mean ± one standard error) in 2008, 2009, 2010, and 2012 at A) Fort Benning and B) Camp Lejeune. *P*-values test for differences in root collar diameter between the north and south half of gaps within each year. * indicates significant interaction within the model therefore no *P*-value is reported.

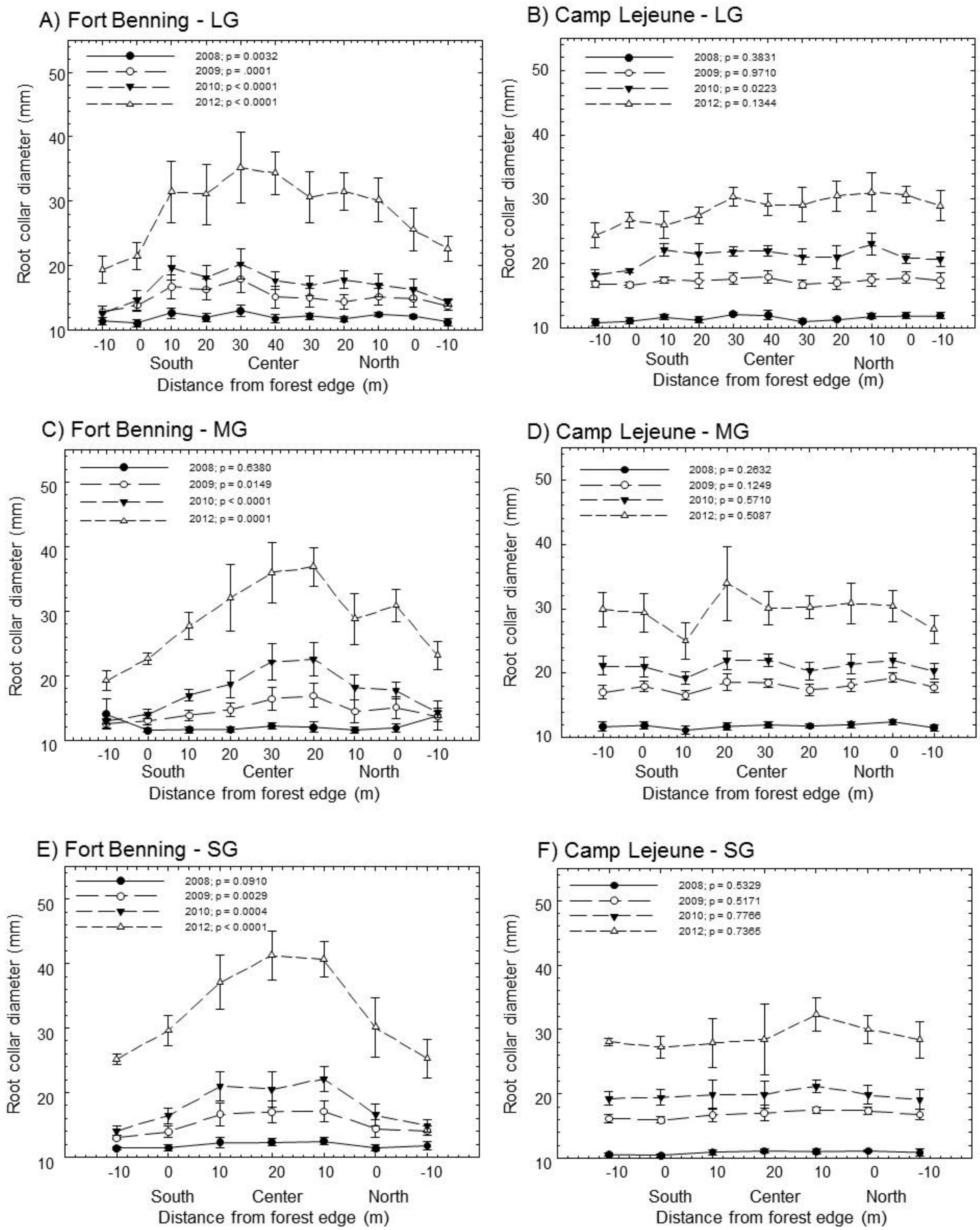


Figure 3.2.10. Longleaf pine seedling root collar diameter (mean ± one standard error) by gap position (10 m interval) in 2008, 2009, 2010, and 2012 for A) Fort Benning large gap, B) Camp Lejeune large gap, C) Fort Benning medium gap, D) Camp Lejeune medium gap, E) Fort Benning small gap, and F) Camp Lejeune small gap.

pine seedling mortality was highest near the center of canopy gaps and decreased closer to the forest canopy in studies located in southwestern Georgia and northwestern Florida, respectively.

The association between canopy removal and early longleaf pine seedling mortality observed at Fort Benning was not apparent at Camp Lejeune. In fact, mortality was lowest on the Clearcut plots and generally did not differ with gap position or direction. As opposed to evidence that supports a facilitation effect of canopy trees on early seedling survival at Fort Benning, the pattern of seedling mortality at Camp Lejeune may have been driven by competition with canopy trees. Competition with canopy pines is one explanation for the low density of natural longleaf pine regeneration under intact canopies (Platt et al. 1988, Boyer 1993, Grace and Platt 1995), although few previous studies have associated artificially regenerated seedling mortality with competition with mature trees (Kirkman and Mitchell 2006). Our results from Fort Benning, which suggest a facilitation effect of canopy pines on early seedling survival, also show a sharp increase in mortality on Control plots over time. By the end of five growing seasons, the mortality observed on Control plots was similar to that on Clearcut plots, suggesting that the facilitation effects of high levels of canopy retention may be transient as competition-induced mortality increases over time.

Although our results showed no effect of herbicides or fertilizer on longleaf pine seedling mortality, previous studies have reported variable results of such treatments. Ramsey et al. (2003) found that a tank mix of hexazinone and sulfometuron methyl initially increased seedling survival compared to an untreated control, but treatment effects were no longer present after two growing seasons. However, Freeman and Jose (2009) found that both imazapyr and a mix of hexazinone and sulfometuron methyl resulted in lower survival when compared to an untreated control. Fertilizer has more commonly been found to reduce survival when compared to untreated areas, often associated with increased growth of competing vegetation (Bengston 1976, Ramsey et al. 2003). However, when fertilizers are applied following competition control (e.g. weeding or herbicides), as was done in our study, effects on seedling survival have been mixed (e.g., Gagnon et al. 2003, Haywood 2007). It is likely that the effectiveness of herbicides, as well as the differences reported in previous studies, is related to the competitive pressure of surrounding vegetation.

Results from both study locations illustrate the sensitivity of longleaf pine seedling growth to competition from canopy trees. Longleaf pine seedlings are commonly considered intolerant to competition from surrounding vegetation (Boyer 1990), and many previous studies have reported reduced growth of natural regeneration (Boyer 1963, Platt et al. 1988, Grace and Platt 1995) and artificial regeneration (Palik et al. 1997, Palik et al. 2003) associated with canopy density. Palik et al. (1997) found that seedling growth increased exponentially as canopy basal area decreased, with substantial increases in growth at basal areas below 6 m^2/ha. The basal area of the LowBA treatment in our study is near this threshold, although we found no differences between the LowBA and the MedBA plots. However it is clear that the density of uncut loblolly pine stands strongly limits longleaf pine seedling growth at both these study area.

Ground layer and/or midstory vegetation can provide an important source of competition for longleaf pine seedlings as well. We generally found that ground layer vegetation, and especially woody species, was more abundant at Camp Lejeune than at Fort Benning (see Section 3.1.1).

Controlling woody vegetation is often an objective of longleaf pine restoration (Jose et al. 2008, Freeman and Jose 2009) with implications for increasing longleaf pine seedling growth (Boyer 1985). We found that split-plot treatments that included herbicides had a stronger effect on seedling growth at Camp Lejeune than at Fort Benning, suggesting that the greater competitive pressure of woody vegetation at Camp Lejeune played an important role in reducing seedling growth. However, results from previous studies have also demonstrated the potential for reductions in growth or survival of longleaf pine seedlings caused by competition from herbaceous vegetation (Nelson et al., 1985; Ramsey et al., 2003; Berrill and Dagley, 2011). It is likely that the site preparation treatments used at each site contributed to the abundance and composition of competing species during the duration of our study. The herbicides used for site preparation at Fort Benning provided initial control of woody competitors and reduced the need for extensive woody control as a study treatment. We expect that the magnitude of the effects of the herbicide split-plot treatments on longleaf pine seedling response would have been greater at Fort Benning if woody vegetation control was not achieved with an herbicide site preparation treatment. The comparison of responses between the two study sites demonstrates that although the use of herbicides for longleaf pine release may be effective for increasing seedling growth (e.g. Ramsey et al. 2003, Haywood 2007, Freeman and Jose 2009), management decisions must consider the abundance and composition of ground layer vegetation when determining if herbicides are needed.

The growth differences among main-plot treatments and the effects of herbicides on growth became much more pronounced through time, suggesting that long term monitoring will be important to understand the ultimate development of these stands. Longleaf pine has the potential to remain in the grass stage for many years, and emergence from the grass stage is essential for stand establishment. We found that patterns in emergence from the grass stage were similar to those observed with root collar diameter size, with the highest percentage of seedlings in height growth on Clearcut plots. Underplanting longleaf pine seedling in uncut Control plots, with essentially no seedlings in height growth, does not appear to be a feasible option for longleaf pine establishment in loblolly pine stands.

3.2.4. Restoration implications

The differences observed in longleaf pine seedling response between the two study locations indicate that one set of silvicultural prescriptions may not be appropriate for all sites within the longleaf pine range. Early seedling survival appears to be especially variable and may be dependent on site conditions and related stressors such as water availability or local weather patterns. On dry, coarsely textured soils like those at Fort Benning, canopy removal can be expected to reduce seedling survival. Likewise, large canopy gaps may result in greater mean seedling mortality than a series of small canopy gaps, although treatment differences in mortality among gap sizes were not significant in this study. Palik et al. (2002) report that cutting a few large gaps within a stand will result in larger average seedling size at the stand level than cutting many smaller gaps or using single-tree selection to achieve the same residual basal area. We found seedling growth to be similar in gaps that ranged from 0.12 ha to 0.52 ha, suggesting that small gaps can be used to successfully establish longleaf pine seedlings. Moreover, single-tree selection may be a viable option for underplanting longleaf pine, especially for ecological restoration where slight reductions in seedling growth are acceptable. The retention of canopy trees provides additional benefit through continuous input of fine fuels from needlefall, as well as facilitation for longleaf pine seedling survival on dry sites. Herbicide release treatments can increase longleaf pine seedling growth, but managers should consider the competitive pressure of ground layer vegetation as well as the effects of herbicides on ground layer composition and structure (see Sections 3.1.1 and 3.2.3). However, we found no benefit of using fertilizer in longleaf pine restoration on these sites. Our results suggest that various management options are available for restoring longleaf pine to loblolly pine sites, but additional monitoring will provide essential information for understanding long-term implications of these silvicultural alternatives.

3.3. Restoring longleaf pine in loblolly pine stands: effects of restoration treatments on natural loblolly pine regeneration

This section includes early results previously published in *Forest Ecology and Management* (Knapp et al. 2011) as well as data from the 2012 field season. It reports the effects of experimental silvicultural treatments on loblolly pine, a species likely to compete with planted longleaf pine seedlings (research objective O-2).

3.3.1. Introduction

Because longleaf pine seedlings begin height growth more slowly than other southern pine species, and they have a low tolerance of competition from other vegetation, restoring longleaf pine within existing loblolly pine stands presents unique challenges that have not been addressed by previous research. The silvical characteristics of loblolly pine make it an easier species to regenerate than longleaf pine, a fact that has contributed to the current dominance of loblolly pine throughout the southeastern U.S. (Schultz 1999). Natural loblolly pine regeneration can be successfully achieved using various even-aged silvicultural methods, including shelterwood, seed-tree, and clearcut techniques (Langdon 1981). Good seed crops are typically produced every 3 to 6 years (Baker and Langdon 1990, Shelton and Cain 2000), and the large trees likely to be retained for ecological value are also the most prolific seed producers (Schultz 1997). Large seed crops can range from 200,000 seeds/ha to over 2,000,000 seeds/ha, while marginal to poor seed crops are generally considered to be less than 100,000 seeds/ha (Baker and Langdon 1990, Shelton and Cain 2000). Seed-to-seedling ratios depend on site and climatic conditions but have been reported to be as low as 5:1 (Cain 1986), suggesting that even a ‘poor’ seed crop can result in abundant loblolly pine regeneration during longleaf pine restoration.

In addition to partial or whole canopy removal, longleaf pine restoration in stands with significant midstory or undesirable understory species often requires chemical or mechanical site preparation (Boyer 1988, Knapp et al., 2006), and prescribed burning is a standard practice prior to planting container-grown longleaf pine seedlings. Natural loblolly pine seedling establishment increases following soil disturbances caused by logging, and prescribed fire further improves the seedbed by increasing exposure of mineral soil (Cain 1987, Schultz 1997). Additional treatments designed to benefit planted longleaf pines through competition reduction are likewise expected to increase growth of loblolly pine from local seed sources (Haywood 1986, Wittwer et al. 1986, Bacon and Zedaker 1987, Miller et al. 1991) and may heighten the risk of site dominance by fast-growing loblolly pine regeneration before longleaf pine seedlings can emerge from the grass stage. Therefore, effective control of loblolly pine regeneration is critical to the success of restoring longleaf pine in loblolly pine stands.

Prescribed fire is the primary tool land managers can use to control loblolly pine regeneration during the first few years after planting longleaf pine. Loblolly pines less than 2.5 m tall with ground line diameters less than 5 cm experience high levels of mortality when exposed to surface fires (Cain 1985, Cain 1993), while longleaf pine seedlings are considered tolerant of fire throughout most of the grass stage (Boyer 1990). However, the effectiveness of prescribed fire for controlling loblolly pine seedlings may be quite variable, depending on fire behavior. Artificially regenerated longleaf pine stands are typically burned within two or three years after planting, and it is critical that early prescribed fires effectively minimize loblolly pine competition.

This study was designed to test how loblolly pine regeneration is affected by silvicultural treatments prescribed to restore longleaf pine to existing loblolly pine stands while retaining canopy trees for ecological benefit. Prescribed fires were applied to the study sites following the second growing season after planting longleaf pine seedlings (2010), and loblolly pine mortality was monitored. This study was replicated at two ecologically distinct locations within the longleaf pine range that may differ in loblolly pine seed production and site quality (Fort Benning, GA and Camp Lejeune, NC). Because the 2010 prescribed fires at Camp Lejeune did not sufficiently control loblolly pine regeneration, the Camp Lejeune sites were again treated with dormant season prescribed fire prior to the 2012 growing season (four years after initial logging treatments). We predicted that: 1) loblolly pine seedling density in the first year following management (logging and site preparation) would be highest on treatments with light harvest because many seed trees would remain and the logging disturbance would expose mineral soil; 2) harvesting treatments that reduce competition from overstory trees would result in increased growth of loblolly pine seedlings; 3) loblolly pine mortality following the prescribed fires would be related positively to canopy density because fallen needles would increase fine fuels and mortality would be higher for small seedlings (expected under denser canopies in 2) than large seedlings; and 4) loblolly pine regeneration grown through four growing seasons at Camp Lejeune would differentially survive prescribed fire based on reaching a threshold size.

3.3.2. Methods

This study was a part of the field experiment replicated at Fort Benning and Camp Lejeune. A complete description of study sites, experimental design and treatments is provided in Section 3.1. For data through three growing seasons, we only used the untreated split-plots (NT) and tested effects of main plot canopy treatments only. All study blocks at Fort Benning were used for this study, but only Blocks 1, 2, and 7 were used at Camp Lejeune because of access restrictions by military training prevented sampling. All uniform treatment plots and medium gap treatments were included. For the fifth growing season data (2012) at Camp Lejeune only, the split-plot treatments were included in the analyses and Blocks 1, 2, 5, and 7 were used.

3.3.2.1. Data collection

We randomly located twenty 1 m^2 sampling quadrats in uniform treatment plots (Control, MedBA, LowBA, Clearcut) to quantify initial establishment of loblolly pine seedlings following timber harvest and site preparation. In each quadrat, we counted the number of loblolly pine seedlings in May and September 2008, representing the start and the end of the first growing season after treatment. Throughout this paper, the term “seedling” is used to refer to any loblolly pine individual that established following site preparation, regardless of seedling size.

Loblolly seedling density and size were quantified again in May 2010, following the dormant season prescribed fires. In each uniform plot, we established one 20 m x 20 m measurement area with 15 m long sampling transect running from the plot center to each corner (n = 4 transects per plot). At the 4, 8, and 12 m distances along each transect, we established one 1 m^2 sampling quadrat and measured the height of all loblolly pine seedlings >10 cm tall whose center at the groundline was within the quadrat. We chose the height threshold of 10 cm because we were interested in assessing seedlings that had become established in previous years (prior to the 2010 prescribed burns), and field observation indicated that a 10-cm height effectively separated new germinants from established seedlings. Each seedling was classified as living or dead, and observed mortality was assumed to be fire-caused. At Fort Benning, many quadrats contained no loblolly pine seedlings, so to increase the number of individuals sampled per plot, the sampling area was expanded to a 2 m wide belt that was centered on, and ran the length of, each transect. Additionally, we tallied the number of newly established seedlings (germinants; individuals <10 tall)) in each sampling area.

In each gap plot, we established one transect extending from the gap center to 10 m into the forest (40 m total transect length) along each cardinal direction (azimuths of 0, 90, 180, and 270 degrees). We sampled loblolly pine regeneration at 10 m intervals along each transect (positions are described by distance from the forest edge to gap center: -10, 0, 10, 20, and 30 m). At each interval position, three 1 m^2 sampling quadrats (subsamples) were established along the transect, with 30 cm between each quadrat (that is, quadrats centered at 8.7, 10, and 11.3 m were used to sample the 10 m position along each transect). The height and mortality status of each seedling > 10 cm tall within each quadrat were recorded, as well as the number of new germinants present. At Fort Benning, we sampled a 2-m belt centered on each transect to supplement low numbers of seedlings measured in each quadrat.

We quantified the area burned (%) in each uniform treatment plot immediately following the prescribed burns. As another measure of area burned, we recorded evidence of burning (char or consumed fuels) as either present or absent at each meter point along each of the four transects (n = 60 points per plot).

At Camp Lejeune, loblolly pine regeneration was sampled again in 2012, following dormant season prescribed burning. In each split-plot of uniform plots in Blocks 1, 2, 5, and 7, the survival, groundline diameter (GLD), and diameter at breast height (DBH; when applicable) were recorded for each seedling occurring within a 2 m belt transect established for mid-story stem counts in the vegetation analysis (see Section 3.6). Height was recorded for each seedling in Block 2 and regression was used to determine relationships between height and GLD for seedlings <1.37 m tall and between height and DBH for seedlings >1.37 m tall for the remainder of the dataset. In gap plots, the survival, GLD, and DBH of each seedling within a 2 m x 4 m wide belt centered along each seedling row were recorded.

3.3.2.2. Data analyses

We calculated mean seedling density (number of seedlings/ha) at the plot level in May and September 2008 and used mixed model analysis of variance (ANOVA) with a random block effect to test for differences in initial density among the uniform canopy treatments. Data collected following the prescribed fires of 2010 were separated into two groups for analyses. Based on field observations of fire behavior and effects, we assume that no loblolly pine seedlings were completely consumed by the low intensity surface fires. Based on this assumption, the combined dataset of live and dead seedlings represents regeneration demographics two growing seasons following harvesting and site preparation. For both the pre-fire dataset and the live seedlings remaining after the fires, we calculated mean seedling height and density at the plot level (using quadrat data at Camp Lejeune and transect data at Fort Benning). The distribution of loblolly pine seedlings was quantified as the percentage of quadrats sampled that contained at least one loblolly pine seedling (frequency, n = 12 quadrats per plot at each location). We tested effects of uniform canopy treatments on response variables (seedling height, density, and frequency) using plot level means with mixed model ANOVA and a random block effect. Similarly, plot level means of seedling size were determined following the fifth growing season, and split-plot ANOVA was used to test for significant treatment effects.

Data from the gap plots were analyzed to determine effects of distance from canopy trees on loblolly pine seedling height and density. At Fort Benning, seedling data collected along each 2 m wide belt transect were grouped into the nearest 10 m interval position, and at Camp Lejeune the mean of the three sampled quadrats was calculated for each position. Initial analyses indicated no effect of transect direction on any response variable, so data from all four transects were pooled and effects of gap position on seedling height and density were analyzed using mixed model ANOVA with a random block effect.

We calculated the mortality rate from the prescribed fires as the percentage of dead seedlings out of the total number of seedlings counted at the plot level. The percent of the study area that burned was calculated as the percentage of points with evidence of fire out of the total number of points observed at the plot level. Relationships between loblolly pine mortality and percent area burned were tested with linear regression models. Uniform harvesting treatment effects on area burned and on the number of germinants established following prescribed fires (May 2010) were analyzed using mixed model ANOVA with a random block effect. We tested for differences between study sites for all response variables using t-tests and site-level means, with data from uniform plots and data from gap plots tested separately. All statistical analyses were conducted with SAS statistical software (version 9.1; SAS Institute, Inc., Cary, NC). Transformations were used when necessary to satisfy assumptions of normality and constant variance, and we used α = 0.05 to determine significant treatment effects.

3.3.3. Results

3.3.3.1. Initial seedling establishment following management

At Fort Benning, there was a significant effect of canopy treatment on loblolly pine seedling density at the start of the first growing season after treatment (May 2008), and the Control plots had more seedlings present than the Clearcut plots (Table 3.3.1). By the end of the first growing season, however, seedling density had dropped on all plots and there was no longer a treatment effect. At Camp Lejeune, variability within treatments was high, and there were no treatment effects on seedling density in May or September 2008. Seedling density was higher at Camp Lejeune than Fort Benning in May (t = 2.76, p = 0.0200), with mean densities of 94,489 seedlings/ha and 7,784 seedlings/ha, respectively. Seedling densities remained different between the study sites in September (t = 3.88, p = 0.0031), with a mean density of 66,054 seedlings/ha at Camp Lejeune and a mean density of 3,901 seedlings/ha at Fort Benning.

Table 3.3.1. Density of loblolly pine seedlings in May and September 2008, the first year following harvesting and site preparation, and the density of new germinants in May 2010, following the dormant season prescribed fire. Different letters within a study location indicate statistically different least square means at α = 0.05

		May 2008		September 2008		May 2010	
Site	Treatment	Mean	*St. error*	Mean	*St. error*	Mean	*St. error*
Fort Benning	Control	12,166^{A}	*2007*	6000	*1538*	8208^{A}	*3190*
	MedBA	7973^{AB}	*1130*	3855	*1190*	10,458^{A}	*5096*
	LowBA	6833^{AB}	*2747*	3333	*1564*	2319^{AB}	*730*
	Clearcut	4166^{B}	*963*	2417	*970*	167^{B}	*78*
	p-value	**0.0422**		**0.2289**		**0.0096**	
Camp Lejeune	Control	75,278	*30,123*	69,483	*21,409*	329,167	*113,604*
	MedBA	165,548	*123,904*	97,523	*58,639*	259,167	*42,544*
	LowBA	56,798	*21,731*	34,035	*4996*	151,944	*75,741*
	Clearcut	80,333	*37,648*	63,177	*8846*	32,083	*32,083*
	p-value	**0.5584**		**0.4325**		**0.0994**	

3.3.3.2. Loblolly pine regeneration density and height two years after logging (pre-fire)

After two growing seasons, the density of loblolly pine seedlings > 10 cm tall was not significantly affected by canopy density in uniform plots at Fort Benning or at Camp Lejeune (Table 3.3.2). Similar to initial seedling establishment, mean seedling density at Camp Lejeune (27,500 seedlings/ha) remained much higher than that at Fort Benning (2,010 seedlings/ha) (t = 3.05, p = 0.0122). Seedling frequency was also higher at Camp Lejeune (mean of 58.0%) than at Fort Benning (mean of 14.9%) (t = 5.55, p < 0.0001), with no effect of canopy treatment at either site (Table 3.3.2). Seedling size following two growing seasons was significantly affected by the canopy treatments at Fort Benning (F = 12.24, p = 0.0003) and Camp Lejeune (F = 8.80, p = 0.0193), with loblolly pine seedlings largest on Clearcut plots (mean of 54.0 cm tall at Fort Benning and mean of 82.4 cm at Camp Lejeune) and smallest on the Control plots (mean of 18.9 cm at Fort Benning and mean of 29.5 cm at Camp Lejeune; Figure 3.3.1A). Seedling size did not differ between the study sites (t = 1.08, p = 0.2862).

In gap plots, the density of loblolly pine seedlings did not differ with distance from forest edge at either location, although the distance effect was nearly significant at Fort Benning (Table 3.3.3). Seedling size gradually increased from 10 m in the forest interior to the gap center (30 m from the forest edge) at Fort Benning, with the size of seedlings in the gap significantly larger than those in the forest (F = 4.29, p = 0.0036). A distance effect was present at Camp Lejeune as well (F = 6.89, p = 0.0009), where seedlings 10 m in the forest interior were smaller than all other positions measured (Figure 3.3.1B). Mean seedling size in gaps was greater at Camp Lejeune than at Fort Benning (t = 2.85, p = 0.0072).

3.3.3.3. 2010 fire effects on loblolly pine regeneration

The uniform harvesting treatments did not affect the percentage of loblolly pine seedlings killed by the prescribed fires at either study location (Table 3.3.2). At Fort Benning, the fires killed 70.6 percent of the loblolly pine regeneration in uniform plots compared to 64.3 percent mortality at Camp Lejeune, although the difference was not significant (t = 0.47, p = 0.6426). For gaps, a slight trend of reduced mortality with distance from the forest edge was evident at both study locations, although mortality was not significantly affected by gap position at either site (Table 3.3.3). Average loblolly pine mortality in forest gaps was lower at Camp Lejeune (38.1 percent) than at Fort Benning (74.4 percent) (t = 2.89, p = 0.0112).

For the range of loblolly pine seedling sizes observed two years after treatment, there is little evidence that seedling size affected the likelihood of mortality from the prescribed fires at either location (Figure 3.3.2 and Figure 3.3.3). Mortality occurred for seedlings of virtually all sizes up to 2 m tall. Few seedlings were killed that were taller than 1.5 m, but the number of seedlings that were in that size class was low; at Fort Benning there were only two seedlings and no mortality, and at Camp Lejeune only six out of 22 seedlings in that size class were killed by fire. The area burned was significantly affected by harvesting treatment at Fort Benning (F = 7.34, p = 0.003), with nearly 100 percent of the Control and MedBA plots burned, compared to 78 percent burned on Clearcut plots (Figure 3.3.4). A similar pattern among the treatments was evident at Camp Lejeune, although no treatment effect was detected (F = 1.97, p = 0.2197). The percent area burned was significantly related to loblolly pine mortality at each study site (Figure 3.3.5). The relationship was much stronger at Camp Lejeune than Fort Benning, because Fort Benning had some plots with high percent area burned but relatively low loblolly pine mortality.

Table 3.3.2. Density and frequency of occurrence of loblolly pine seedlings > 10 cm (mean and standard error) by uniform harvesting treatment before and after the 2010 prescribed fires at Fort Benning and Camp Lejeune. Prescribed fire mortality values were calculated at the plot level for analysis and may differ slightly from that calculated at the treatment level with data in the table. *P*-values are from ANOVA tests of treatment effects for each site

		Total seedlings (pre-fire)				Live seedlings (post-fire)				Prescribed fire	
		Density (number/ha)		Frequency (%)		Density (number/ha)		Frequency (%)		mortality (%)	
Site	Treatment	Mean	*St. Error*	Mean	*St. Error*	Mean	*St. Error*	Mean	*St. Error*	Mean	*St. Error*
Fort	Control	722	*249*	11.1	*5.1*	222	*109*	5.6	*3.5*	69.2	*14.1*
Benning	MedBA	2264	*1203*	19.4	*9.8*	181	*119*	4.2	*4.2*	94.0	*3.6*
	LowBA	3583	*2448*	22.2	*7.0*	1125	*738*	9.7	*3.4*	66.2	*8.5*
	Clearcut	1472	*488*	6.9	*5.4*	333	*195*	1.4	*1.4*	64.8	*18.4*
	p - value	**0.5225**		**0.3931**		**0.2739**		**0.3301**		**0.3069**	
Camp	Control	8056	*3737*	38.9	*16.9*	4167	*3005*	25.0	*21.0*	60.3	*30.7*
Lejeune	MedBA	42,778	*26,581*	66.7	*12.7*	7222	*2650*	30.6	*7.3*	66.3	*17.4*
	LowBA	23,333	*11,345*	47.2	*14.7*	6111	*4547*	19.4	*10.0*	70.3	*26.2*
	Clearcut	35,833	*6667*	79.2	*12.5*	16,250	*14,583*	41.7	*25.0*	60.5	*30.6*
	p - value	**0.3240**		**0.3248**		**0.5148**		**0.6552**		**0.9853**	

Table 3.3.3. Density of loblolly pine seedlings > 10 cm (mean and standard error) relative to the forest edge in gap plots before and after the 2010 prescribed fires at Fort Benning and Camp Lejeune. Prescribed fire mortality values were calculated at the plot level for analyses and may differ slightly from that calculated at the treatment level with data in the table. *P*-values are from ANOVA tests of treatment effects for each site

		Total seedlings (pre-fire) Density (number/ha)		Live seedlings (post-fire) Density (number/ha)		Prescribed fire mortality (%)	
Site	Distance from forest edge (m)	Mean	*St. Error*	Mean	*St. Error*	Mean	*St. Error*
Fort	-10	2958	*1218*	542	*255*	87.0	*7.5*
Benning	0	3333	*892*	896	*429*	71.3	*11.7*
	10	4333	*1121*	292	*79*	90.0	*3.2*
	20	2875	*796*	938	*232*	65.3	*9.1*
	30	1969	*579*	719	*309*	58.5	*21.0*
	p - value	**0.0763**		**0.2017**		**0.1020**	
Camp	-10	38,333	*19,867*	12,424	*5,524*	45.3	*28.2*
Lejeune	0	33,611	*7276*	27,500	*7,120*	36.7	*24.1*
	10	25,833	*5367*	17,500	*5,537*	38.3	*29.4*
	20	29,722	*5278*	15,277	*3,110*	32.0	*28.0*
	30*	.	.	.	.	.	.
	p - value	**0.4156**		**0.1155**		**0.2118**	

*Data was not taken in gap centers at Camp Lejeune due to concerns about the disturbance created at the intersection of four sampling transects.

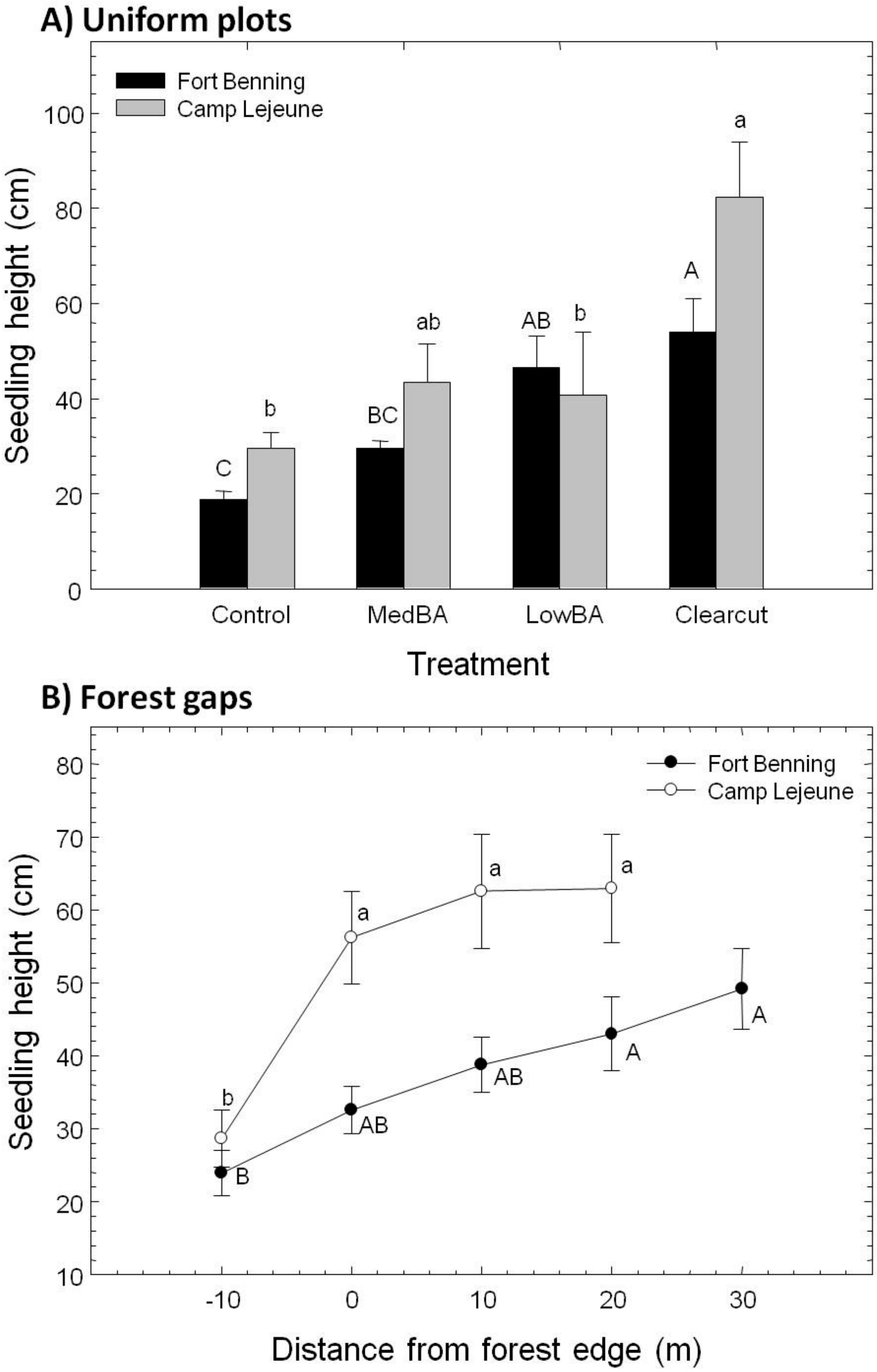


Figure 3.3.1. Height of loblolly pine natural regeneration (mean ± standard error) two growing seasons after harvest and site preparation at Fort Benning and Camp Lejeune by A) harvesting treatment in uniform plots and B) distance from forest edge in gap plots. Measurements were not taken in gap centers at Camp Lejeune due to concerns about the disturbance created at the intersection of four sampling transects. Different letters within a study location indicate statistically different least square means at $\alpha = 0.05$.

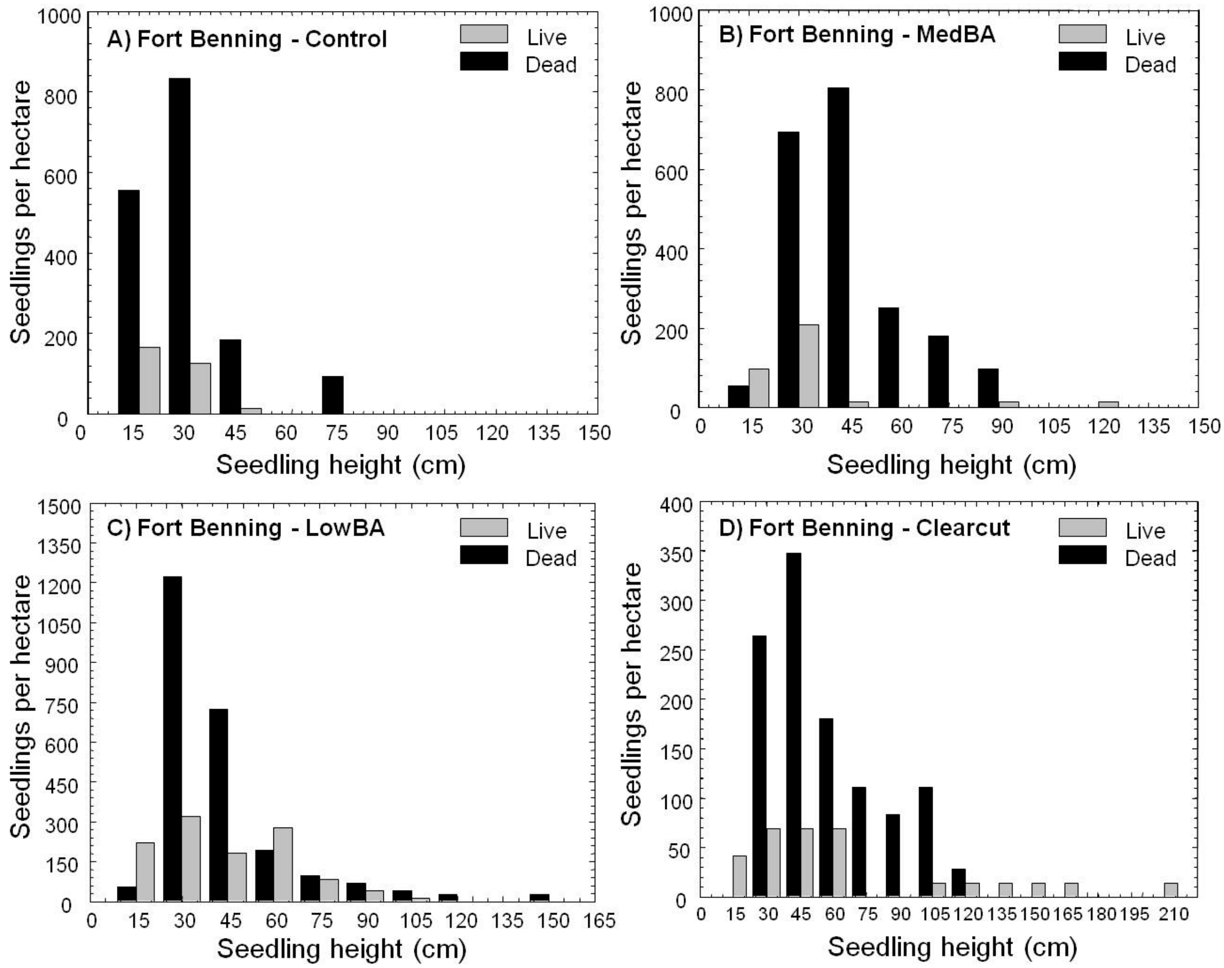


Figure 3.3.2. Density (seedlings per hectare) of live and dead loblolly pine seedlings by size following 2010 prescribed fires for A) Control, B) MedBA, C) LowBA, and D) Clearcut plots at Fort Benning. Note: scales of y-axes are not consistent for each treatment.

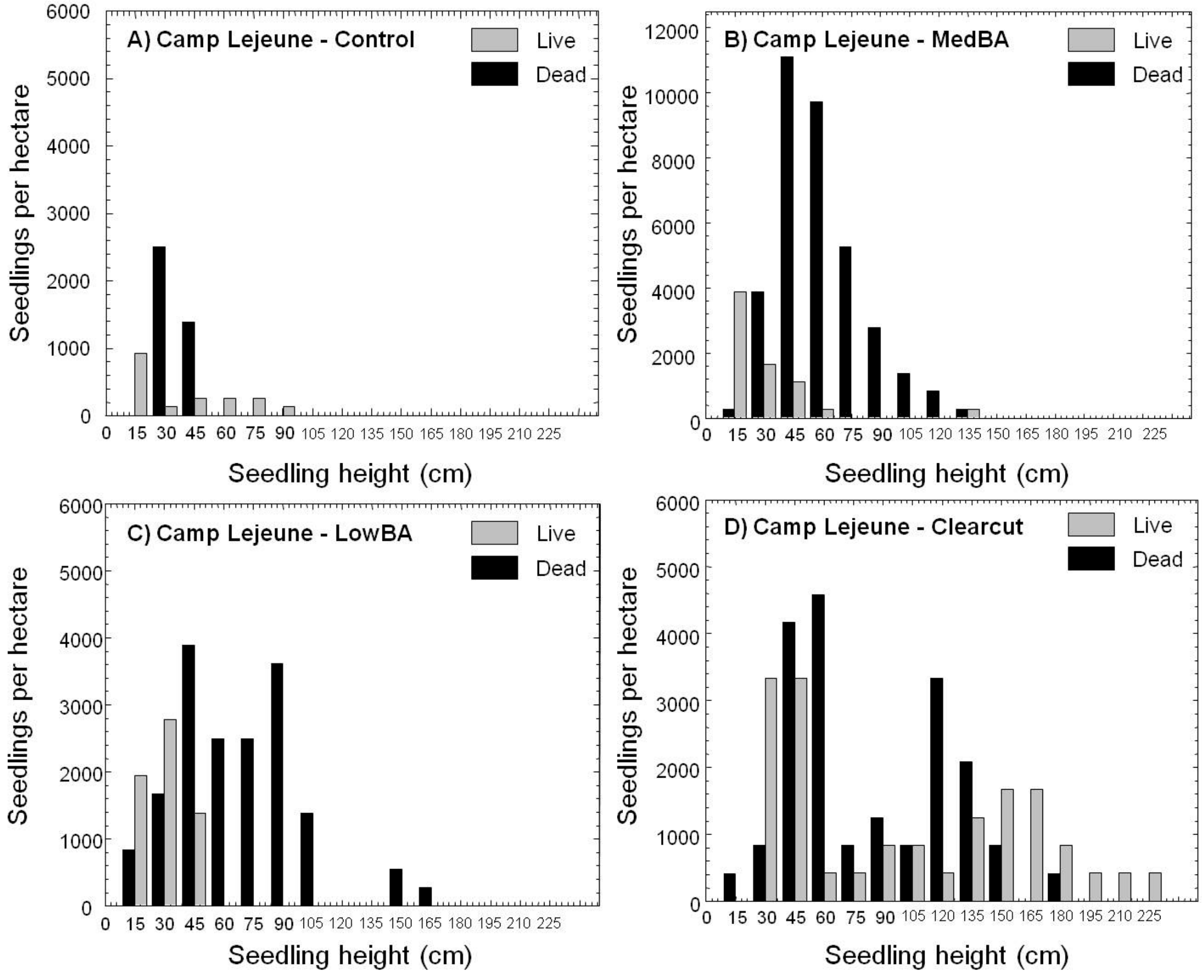


Figure 3.3.3. Density (seedlings per hectare) of live and dead loblolly pine seedlings by size following 2010 prescribed fires for A) Control, B) MedBA, C) LowBA, and D) Clearcut plots at Camp Lejeune. Note: scales of y-axes are not consistent for each treatment.

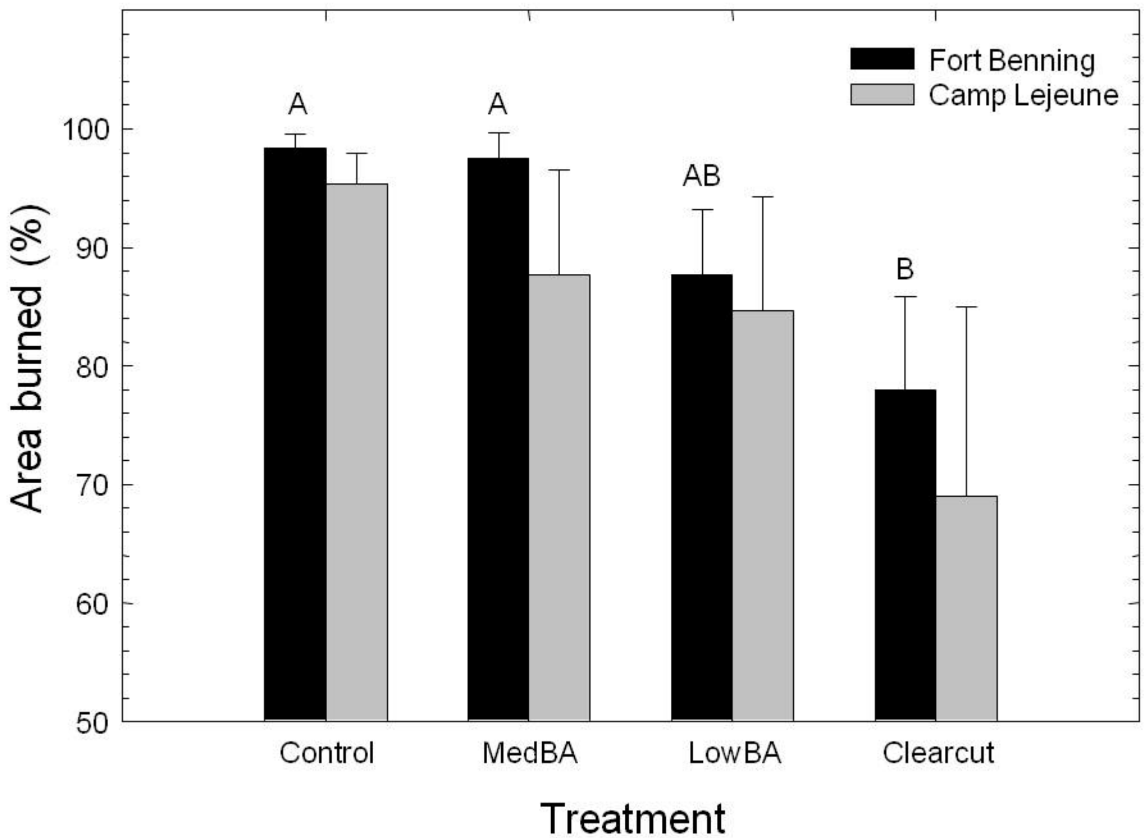


Figure 3.3.4. Percent area burned by 2010 prescribed fires (mean ± standard error) for each uniform harvesting treatment at Fort Benning and Camp Lejeune. Different letters within a study location indicate statistically different least square means at $\alpha = 0.05$.

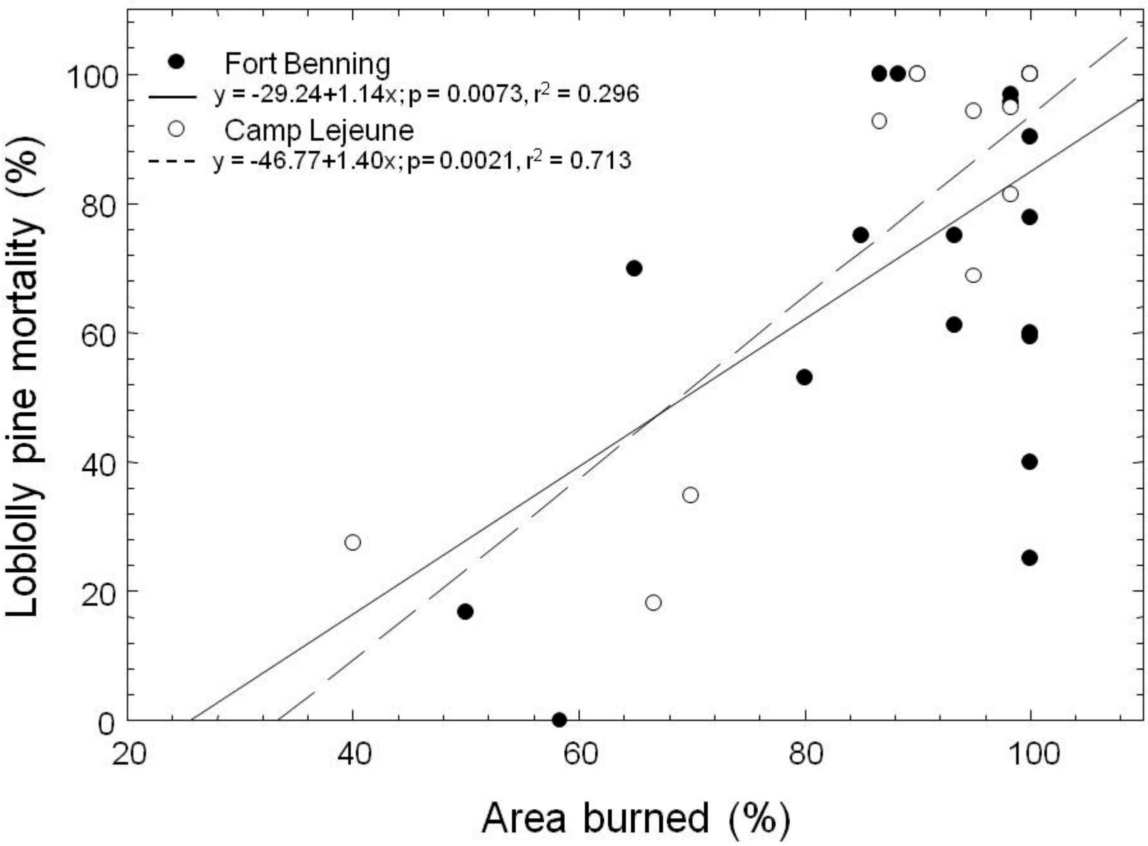


Figure 3.3.5. Scatterplots and least square mean lines for the percent area burned and loblolly pine seedling mortality for each study plot at Fort Benning (filled circles) and Camp Lejeune (open circles).

3.3.3.4. Post-fire loblolly pine regeneration density and height

After the prescribed fires of 2010, there were no significant treatment effects on the number of live seedlings or the frequency of loblolly pine seedlings in the uniform plots at either study location (Table 3.3.2). Fort Benning averaged 465 remaining loblolly pine seedlings per hectare, with only around 5 percent frequency, and Camp Lejeune averaged 8438 seedlings per hectare and 29.2 percent frequency. Both measures of seedling abundance were greater at Camp Lejeune than Fort Benning (density: $t = 2.62$; $p = 0.0252$, frequency: $t = 3.14$; $p = 0.0093$). We found no significant treatment effects on seedling size at Fort Benning ($F = 2.11$, $p = 0.1744$), despite an increase from 15.2 cm on Control plots to 41.6 cm on Clearcut plots (Figure 3.3.6A). Size of the live seedlings at Camp Lejeune was significantly affected by harvesting treatment ($F = 5.76$, $p = 0.0213$), with seedlings in Clearcut plots averaging 79.6 cm, compared to an average of 25.8 among the other three treatments. In gap plots, the density of live seedlings following the prescribed fires was not affected by distance from the forest edge at Fort Benning or Camp Lejeune (Table 3.3.3). Patterns of seedling size and distance to forest edge were similar to those before the prescribed fires (Figure 3.3.1B and Figure 3.3.6B), with a significant position effect at both sites after the prescribed fires ($F = 4.23$, $p = 0.0063$ at Fort Benning and $F = 5.61$, $p = 0.0037$ at Camp Lejeune).

The density of new germinants following the 2010 prescribed fires in uniform plots was highest on the MedBA and Control plots, with very little recruitment in the Clearcut plots at Fort Benning. The treatment effect was only marginally significant at Camp Lejeune, despite a range from 329,167 seedlings/ha on Control plots to 32,083 seedlings per hectare on Clearcut plots (Table 3.3.1). There were significantly more new germinants at Camp Lejeune than at Fort Benning after the prescribed fires ($t = 4.26$; $p = 0.0017$).

3.3.3.5. Loblolly pine regeneration size and density four years after logging

Using the population of all loblolly pine seedlings (live and dead) present at Camp Lejeune prior to the fifth growing season after logging, we found that seedling density was not significantly affected by the main-plot treatment ($F = 1.35$; $p = 0.3058$) despite seedling densities that ranged from 2000 seedlings per hectare on Control plots to 9531 seedlings per hectare on Clearcut plots (Table 3.3.4). The split-plot treatments had a significant effect on seedling density ($F = 3.56$; $p = 0.0444$), with higher loblolly pine seedling density on Herbicide plots than on Control plots (Table 3.3.4). There were no significant main-plot or split-plot treatment effects on any measure of seedling growth ($p \geq 0.2888$; Table 3.3.5).

3.3.3.6. 2012 prescribed fire effects on loblolly pine regeneration

Although we found no significant effects of main-plot treatments on the percent mortality of loblolly pine regeneration from the 2012 prescribed burns ($F = 2.51$; $p = 0.0860$), there was nearly complete mortality (99.8% mortality) on Control plots and only 53.5% mortality on Clearcut plots (Table 3.3.4). There was no effect of the split-plot treatments on the mortality of loblolly pine regeneration ($F = 0.78$; $p = 0.4724$).

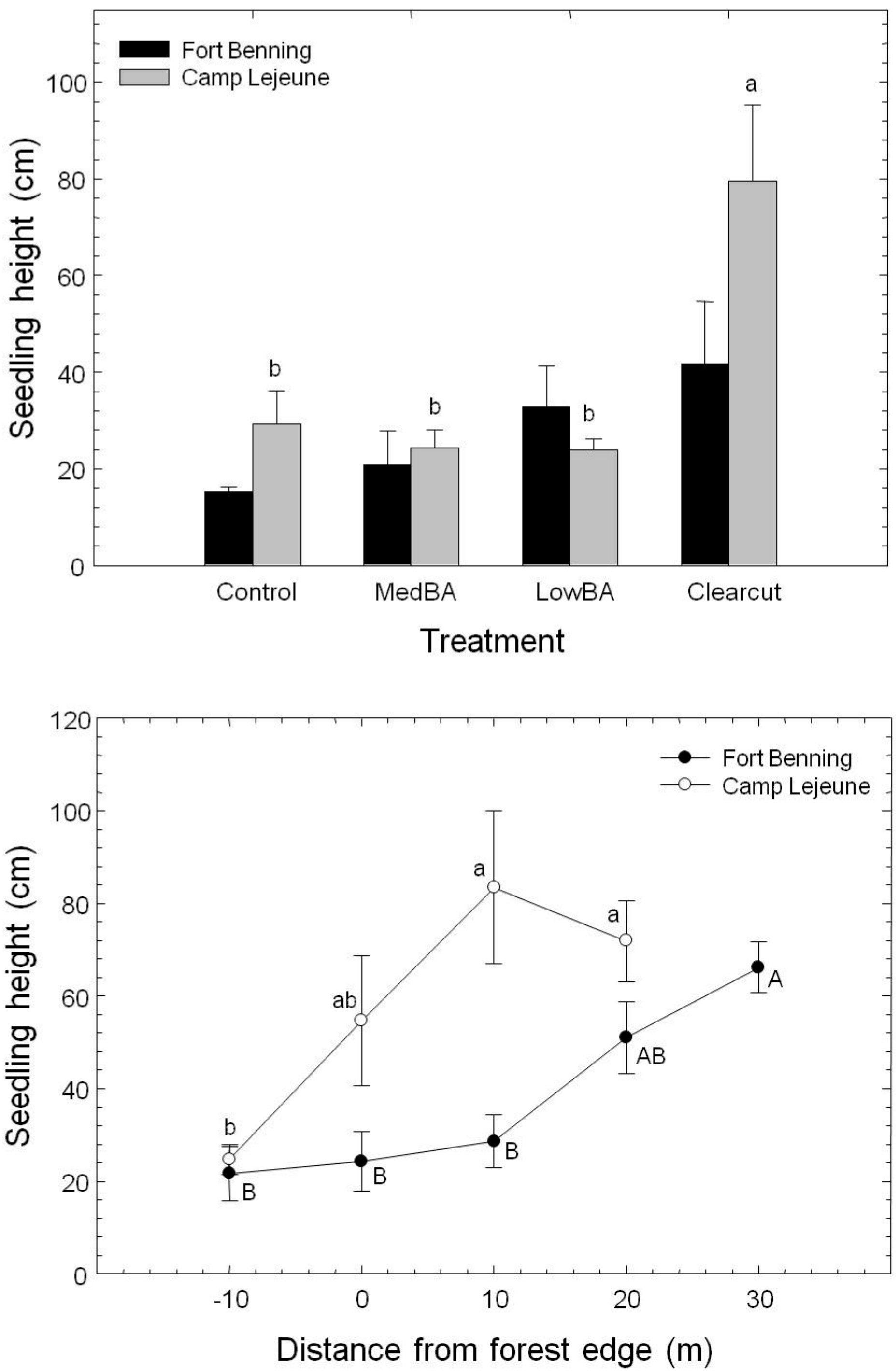


Figure 3.3.6. Height of live loblolly pine natural regeneration (mean ± standard error) remaining after 2010 prescribed fires at Fort Benning and Camp Lejeune by A) harvesting treatment in uniform plots and B) distance from forest edge in gap plots. Measurements were not taken in gap centers at Camp Lejeune due to concerns about the disturbance created at the intersection of four sampling transects. Different letters within a study location indicate statistically different least square means at $\alpha = 0.05$.

Table 3.3.4. Density of loblolly pine seedlings by uniform harvesting treatment before and after the 2012 prescribed fires at Camp Lejeune. Prescribed fire mortality values were calculated at the plot level for analysis and may differ slightly from that calculated at the treatment level with data in the table. *P*-values are from ANOVA tests of treatment effects, and the same superscript letter indicates no difference among treatment levels within an effect

		Total seedlings (pre-fire) Density (seedlings/ha)		Live seedlings (post-fire) Density (seedlings/ha)		Prescribed fire mortality (%)	
Effect	Level	Mean	*St. Error*	Mean	*St. Error*	Mean	*St. Error*
Main-plot	Control	2000	*1161*	10^{B}	*10*	99.8	*0*
	MedBA	5760	*1992*	885^{AB}	*421*	73.3	*17*
	LowBA	6969	*3656*	771^{AB}	*580*	79.7	*12*
	Clearcut	9531	*3238*	3219^{A}	*929*	53.5	*7*
	p-value	**0.3058**		**0.0124**		**0.0860**	
Split-plot	NT	3070^{B}	*1297*	531	*111*	59.5	*18*
	H	7992^{A}	*1185*	1727	*197*	61.3	*12*
	H+F	7133^{AB}	*1648*	1406	*675*	83.9	*10*
	p-value	**0.0444**		**0.2086**		**0.4724**	

Table 3.3.5. Ground-line diameter, diameter at breast height, and height of all loblolly pine regeneration (live and dead) measured prior to the fifth growing season after logging (2012) at Camp Lejeune. *P*-values are from ANOVA tests of treatment effects

		Ground-line diameter (mm)		Diameter at breast height (mm)		Height (cm)	
Effect	Level	Mean	*St. Error*	Mean	*St. Error*	Mean	*St. Error*
Main-plot	Control	29.0	*9.32*	14.3	*3.59*	197.6	*42.95*
	MedBA	31.6	*3.51*	18.2	*4.10*	212.4	*18.46*
	LowBA	45.6	*8.80*	24.5	*5.98*	283.0	*46.36*
	Clearcut	46.2	*1.88*	33.4	*9.21*	287.3	*11.14*
	p-value	**0.3045**		**0.3413**		**0.2888**	
Split-plot	NT	39.9	*5.59*	24.6	*4.27*	252.6	*27.51*
	H	43.2	*4.60*	23.1	*2.97*	271.1	*25.31*
	H+F	39.4	*6.26*	23.1	*4.56*	253.2	*31.81*
	p-value	**0.5588**		**0.7128**		**0.5576**	

With the exception of the ground-line diameter and height of loblolly pine regeneration on Control plots, the population of seedlings killed by the prescribed fire was significantly smaller in each measure of seedling size than the population of surviving seedlings (Figure 3.3.7). Across canopy treatments, the mean ground-line diameter was 26 mm for dead seedlings compared to 58 mm for live seedlings; mean diameter at breast height was 11 mm for dead seedlings compared to 35 mm for live seedlings; mean height was 184 cm for dead seedlings compared to 342 cm for live seedlings. The logistic regression analyses indicated that the main-plot treatments significantly affected the probability of loblolly pine seedling mortality based on ground-line diameter ($\chi^2 = 72.363$; $p < 0.0001$), diameter at breast height ($\chi^2 = 48.510$; $p < 0.0001$), and height ($\chi^2 = 65.740$; $p < 0.0001$) (Figure 3.3.8). For each seedling size variable, the probability of survival was highest at a given size in Clearcut plots and lowest in Control plots. For example, the probability of seedling survival was 0.75 for seedlings greater than 60 mm in ground-line diameter on Clearcut plots, but on Control plots the probability of survival for similar sized seedlings was 0.06; ground-line diameter of seedlings with a survival probability of 0.75 was 105 mm on Control plots. Because Clearcut plots had the greatest number of loblolly pine seedlings among the treatments, survival probabilities for when the data was pooled across all treatments was most similar to that for Clearcut plots (Figure 3.3.8).

3.3.4. Discussion

The large difference in initial loblolly pine seedling density (May 2008) between Fort Benning and Camp Lejeune, in which nearly 10 times as many seedlings were present at Camp Lejeune, may be attributed to multiple factors. Seed production is often a reliable predictor of first year pine density (Cain 1991), and it is well understood that loblolly pines experience large annual variation in seed crops (Wenger 1957, Cain 1991). Cain and Shelton (2001) reported complete failure (zero sound seeds/ha) one year, followed by a bumper crop of over 2 million sound seeds per hectare the following year in an Arkansas study. Generally, seed crops are larger and more consistent in the lower Coastal Plain than in the upper Coastal Plain or Piedmont (Wakeley 1947, Brender and McNab 1972, Schultz 1997), so it is possible that differences in seedling density between the two study sites were associated with differences in seed production in 2007 (prior to the treatment). Additionally, site conditions during germination and early establishment play an important role in regeneration success. At both study locations, precipitation early in the first growing season (March – June 2008) was well below the 50-year average (Camp Lejeune: 346 vs. 430 mm, respectively; Fort Benning: 343 vs. 442 mm, respectively). Forest soils are typically drier at Fort Benning than at Camp Lejeune, and the dry conditions during the period of early seedling establishment may have been more inhibitive for seedling establishment at Fort Benning than at Camp Lejeune. Finally, it is unclear how the different site preparations used at each location may have affected the recruitment of loblolly pine on these sites.

Generally, loblolly pine seedling establishment increases following disturbances that reduce vegetation cover and expose mineral soil (Pomeroy and Trousdell 1948, Cain 1991, Schultz 1997), and therefore we expected initial loblolly pine recruitment to be highest on harvested treatments that still retain some canopy trees as a seed source. However, we did not see evidence that disturbance from logging further improved the seedbed over that provided by site preparation (mechanical or chemical vegetation control plus fire) at either site. The importance of seedbed preparation is reduced during years of high seed production because abundant seed

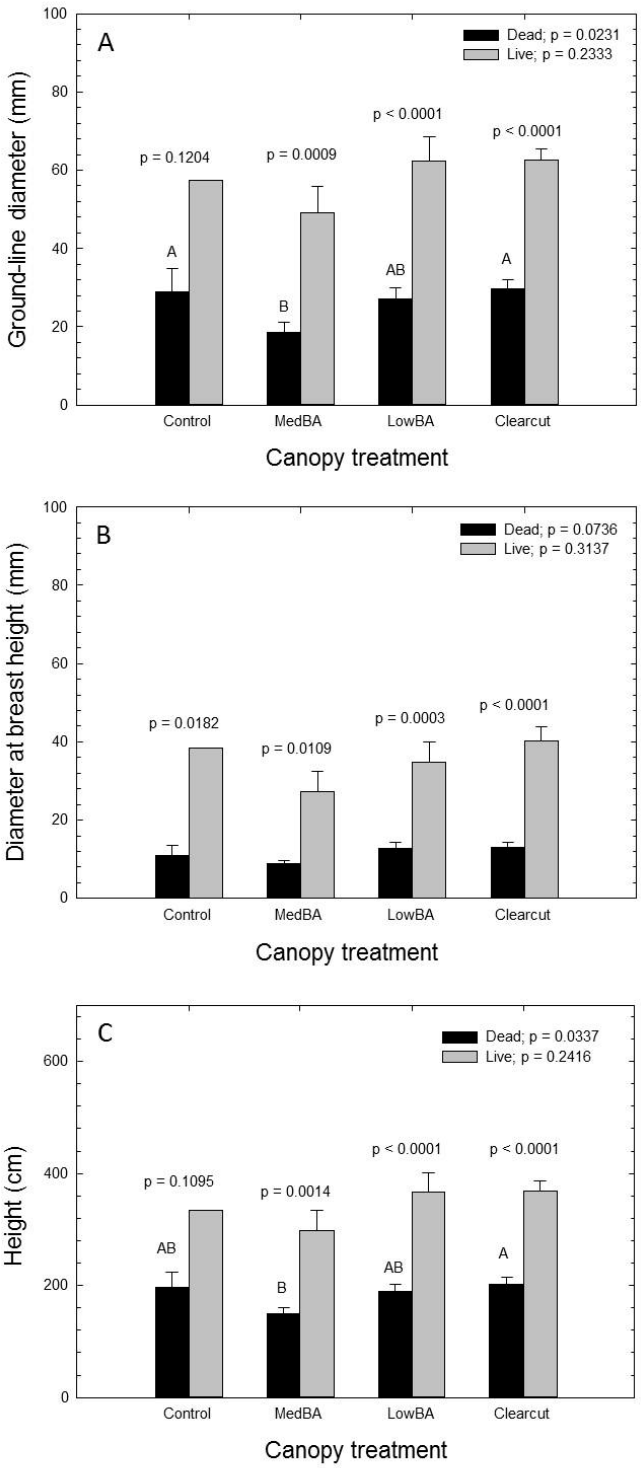


Figure 3.3.7. Loblolly pine ground-line diameter (A), diameter at breast height (B), and height (C) prior to the fifth growing season and following the 2012 dormant season prescribed burns. Similar letters indicate no difference among main-plot effects within mortality status; *p*-values are for differences between the size of dead and living seedlings for each canopy treatment.

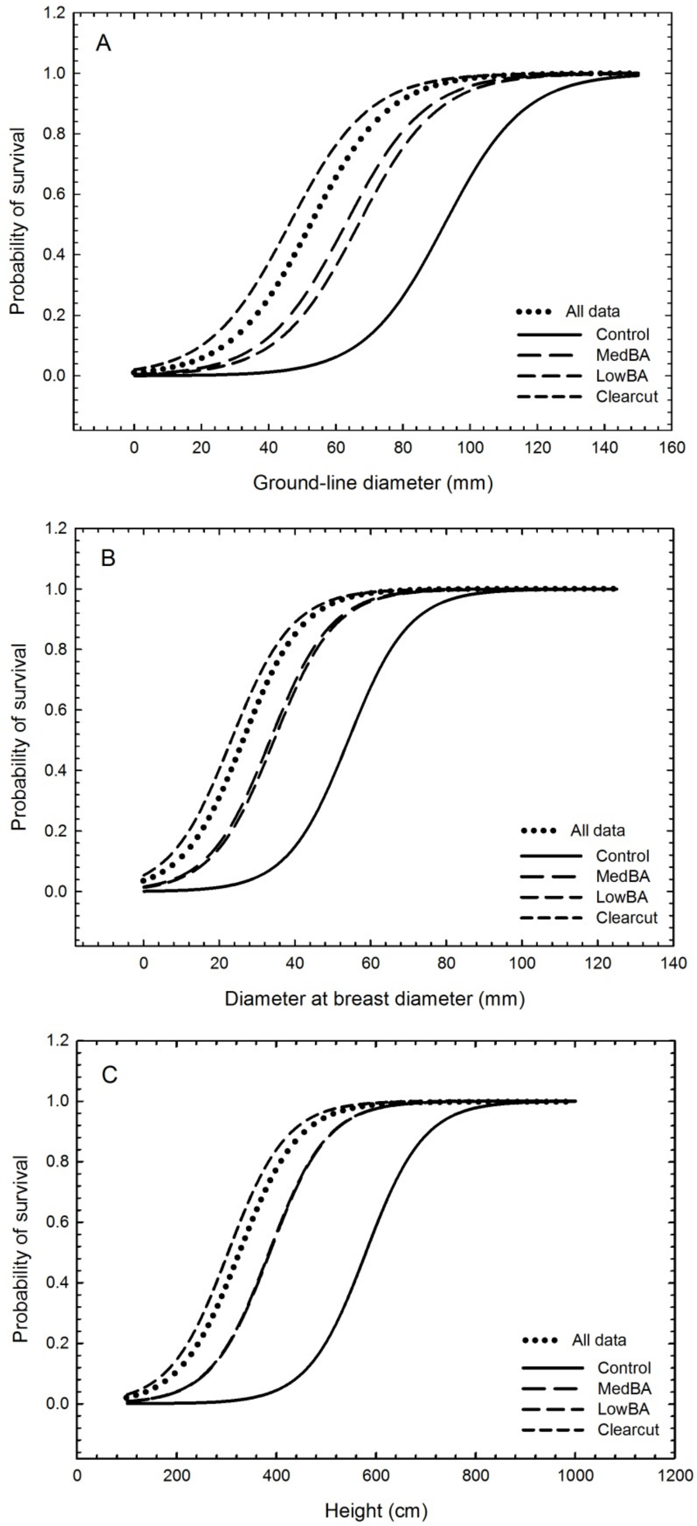


Figure 3.3.8. Probability of survival from logistic regression for all data together and each treatment separately based on A) ground-line diameter (mm), B) diameter at breast height (mm), and C) height (cm).

rain increases the likelihood that all suitable microsites are occupied (Trousdell, 1963). Although seed production was not directly measured, the high density of seedlings at Camp Lejeune suggests that seed production was high the previous year. On the other hand, lower seed production at Fort Benning may have increased the importance of canopy trees as a seed source, resulting in a higher number of established seedlings on uncut plots than those in which canopy trees had been removed. Additionally, the shade of canopy trees may have facilitated seedling establishment at Fort Benning by improving microsite conditions for seedling establishment during the dry summer of 2008.

We found a high number of loblolly pine seedlings in Clearcut plots at Camp Lejeune, despite complete removal of the seed source. Loblolly pine seed dispersal is reported to occur 60 m from seed trees, with diminishing recruitment out to 100 m (Pomeroy 1949, Wenger and Trousdell 1958, Schultz 1997). Because our Clearcut plots were 2 ha in size (141 x 141 m), the centers of the plots were only 70 m from the nearest forest edge and were not out of range of seed dispersal. Very few loblolly pine seeds remain viable from one year to the next (Little and Somes 1959, Baker and Langdon 1990, Cain and Shelton 1997), so it is not likely that residual seeds contributed to initial seedling density. It is possible that loblolly pine regeneration came from seedlings that had not been killed during logging or site preparation. Although we did not measure loblolly pine seedling density before timber harvest, field observations following site preparation indicated that loblolly pine regeneration was not abundant at the start of 2008, and contributions from previously established seedlings were not likely significant.

As expected, we found that canopy thinning and gap harvesting, both used to reduce overstory competition with planted longleaf pine seedlings, increased the growth of natural loblolly pine regeneration through the third growing season. Hu (1983) compared growth of natural loblolly pine regeneration following various regeneration techniques (clearcut, shelterwood, seed tree, selection cutting) and reported results similar to ours, with the greatest growth on clearcuts and reduced growth associated with canopy competition. Although we found no significant effects of uniform canopy density on loblolly seedling size in the fifth growing season, our data indicated clear patterns of increasing loblolly pine size from Control plots to Clearcuts (Table 3.3.5). For example, mean ground-line diameter was over 50% greater on Clearcut plots than on Control plots. It is likely that the treatment effects were not statistically significant because of the variability among blocks, with some blocks having no loblolly pine present in the Control plots. Results from the gap plots show that seedling size through two growing seasons increased from within the forest to the gap center, although the rate of increase differed between the study sites. At Fort Benning, we noted a gradual increase in seedling size associated with the distance from the forest edge, but at Camp Lejeune seedling size increased rapidly from 10 m into the forest to the forest edge and remained constant toward the gap center. The ability of a species to respond to increased resource availability is often controlled by limitations of other resources (Teskey et al. 1987), and differences in site quality (nutrients and moisture) between the study sites are likely responsible for the observed growth patterns.

The susceptibility of loblolly pine seedlings to fire-induced mortality decreases with seedling size, and previous research suggests that once loblolly pine seedlings reach 2.5 m in height they become resistant to fire (Cain 1985, Cain and Shelton 2002). By the end of two growing seasons, no measured seedlings had reached that size threshold, and we found little evidence that seedling size affected the likelihood of survival following our prescribed fires because fire-induced mortality was observed for nearly all size classes. Data from the 2012 prescribed burns at Camp Lejeune, however, included a wide range of seedling sizes, and our results indicate that prescribed burning at this point differentially affected loblolly pine seedlings based on seedling size. When pooling the loblolly pine seedling data together, we found that there was a 75% chance of seedling survival for ground-line diameters greater than 6.6 cm, for diameter at breast height of at least 3.6 cm, and heights of at least 3.9 m. These results are similar to that reported by Crow and Shilling (1980), who suggest that resistance is developed when ground-line diameter exceeded 7.6 cm and heights ranged between 3.7 and 4.6 m tall. Therefore, the ability of forest managers to control loblolly pine development with prescribed burning is dependent on loblolly pine size, with the threshold size for loblolly pine resistance attainable during the first four growing seasons after loblolly pine establishment in some sites (Camp Lejeune).

Fires in frequently burned pine systems can be quite heterogeneous at fine scales, depending on fuel distributions and micro-site conditions (Gibson et al. 1990, Thaxton and Platt 2006, Hiers et al. 2009), and interactions between seedling size and the heterogeneity of prescribed burns may affect fire-induced mortality at the stand level. We expected loblolly pine seedling mortality to be highest on sites with more canopy trees present because inputs from needlefall would improve the continuity of the fuelbed, resulting in more uniform, complete burns. We found that prescribed fires burned more completely in treatments with intact canopies, with evidence of burning in nearly 100% of the observation points in the Control plots at both sites, compared to 78% and 69% on Clearcut plots at Fort Benning and Camp Lejeune, respectively. We attribute the lack of a treatment effect on loblolly pine mortality rates in uniform plots in 2010 to fine-scale heterogeneity in prescribed fire intensity, which was not accounted for in the measurement of area burned. However, the relationships between the percent area burned and loblolly pine mortality (Figure 3.3.5) demonstrate the importance of complete burns for loblolly pine control, as mortality tended to decrease abruptly with modest decreases in the area burned. Moreover, although not statistically significant, we observed nearly 100% mortality of loblolly pine regeneration in Control plots following the 2012 prescribed burns, compared to 53% mortality in Clearcut plots. The logistic regression models indicated that the relationship between seedling size and fire-induced mortality varied with canopy density, suggesting that differences in fire behavior resulting from canopy retention (e.g., fuel loading) further affected the size at which loblolly pine seedlings become resistant to mortality from burning.

We found a general pattern of higher loblolly pine mortality under the forest canopy than in the center of canopy gaps at both study sites, although this trend was not statistically significant in either case. Previous research has suggested that canopy gaps may be a useful silvicultural technique for longleaf pine restoration in stands in which canopy retention is desirable (Palik et al. 1997, Palik et al. 2003). However, the loss of the fine fuels associated with needlefall may affect the movement of fire across canopy gaps, with potentially long-term effects on fire management (Mitchell et al. 2006). We think it likely that the observed patterns of loblolly pine mortality were related to fire behavior within the gaps and that control of loblolly pine regeneration with fire will be more difficult farther from the forest edge or with reduced canopy density. However, a complete analysis of the role of pine needles as a fuel source, the effects of canopy trees on fuel properties (e.g. fuel moisture), and the interactions of those factors is beyond the scope of this study.

One consequence of using prescribed fire to control loblolly pine regeneration is that the seedbed is again improved for loblolly pine seed germination and seedling establishment. Additionally, loblolly pine seed production may be stimulated by release of seed trees through timber harvest (Wenger 1954, Schultz 1997), increasing the likelihood of a good seed crop coinciding with the first prescribed fire after planting longleaf pine seedlings in thinned stands. Following the 2010 prescribed fires, the density of newly germinated seedlings was similar to that observed during initial establishment at Fort Benning and generally higher than that observed during initial establishment at Camp Lejeune. At both study sites, our results show that additional loblolly pine seedlings will become established after each prescribed fire, and consequently managers must use prescribed fire at two to three year intervals to control each cycle of loblolly pine recruitment.

3.3.5. Management implications

Restoring the longleaf pine ecosystem in many areas of the southeastern United States requires conversion of existing loblolly pine stands to longleaf pine forests. When silvicultural prescriptions include the retention of canopy trees, managers must be prepared for natural loblolly pine regeneration and need to understand the implications of that regeneration on stand development. The comparison of two ecologically distinct study sites demonstrates that initial loblolly pine seedling establishment may be highly variable both between sites (e.g., higher seedling density at Camp Lejeune than at Fort Benning) and within sites indicated by high standard error values for seedling density for most treatments at both sites. Seed crop size and successful establishment of loblolly pine regeneration are contingent on numerous factors that include the year (e.g. seed production, weather patterns), site quality (e.g. climate, soil characteristics), stand age, and seedbed preparation. Regional differences in seed production of loblolly pines affect the likelihood of abundant regeneration, with larger and more consistent seed crops in the lower Coastal Plain (e.g., Camp Lejeune). Consequently, the feasibility of longleaf pine restoration in loblolly pine stands may depend on location, site quality, and initial loblolly pine seedling establishment. By using knowledge of site characteristics and trends in recent seed production (Wenger 1957, Cain and Shelton 2001), managers may be able to time longleaf pine restoration to coincide with poor seed crops to minimize initial loblolly pine establishment. Moreover, the majority of viable loblolly pine seeds are typically dispersed by the end of December (Cain 1991), and additional control may be provided by applying a site preparation burn after seedfall has occurred. Although managers should consider ways to minimize loblolly pine regeneration during restoration, some level of recruitment is inevitable, and managers must be prepared to control it with prescribed burning.

Frequent prescribed burning is fundamental to longleaf pine ecosystem management but becomes paramount in the presence of fast-growing loblolly pine seedlings. During the early years of longleaf pine seedling development (i.e., prior to emergence from the grass stage), the ability to control loblolly pine regeneration with fire will largely determine which pine species will dominate a site. Given the heterogeneous nature of fire behavior, we expect the survival of some loblolly pine seedlings following prescribed fire. The development of mixed stands may be acceptable during ecological restoration, provided that longleaf pine makes up a significant portion of the new cohort and that subsequent thinning operations select loblolly pines for removal. However, the success of such a model is contingent on the development of competitive longleaf pine seedlings, and managers can maximize the likelihood of longleaf pine establishment with effective prescribed burning. Fire management decisions should therefore consider the control of loblolly pine regeneration as a principle objective, especially while artificially regenerated longleaf pine seedlings are in the stemless grass stage and vulnerable to competition from faster growing species.

The complex interactions among needlefall as a fine fuel, fire behavior, and loblolly pine seedling size suggest that control of loblolly pine regeneration with fire may be more difficult following removal of some canopy trees. Silvicultural treatments that include complete canopy removal (e.g. gaps or clearcuts) maximize growth of established loblolly pine seedlings, increase the probability of surviving prescribed burning for a given seedling size, and shorten the window of opportunity for control with prescribed fire. For example, in Clearcut plots at Camp Lejeune, seedlings that survived the 2010 prescribed fires averaged around 80 cm tall with mean densities in excess of 1.5 seedlings per square meter; by 2012, mean seedling height in Clearcut plots at Camp Lejeune was nearly 3 m and resulted in only 50% mortality following the 2012 prescribed burns. In such cases, the fire return interval may have to be shortened or additional mechanical treatments may be required to control loblolly pine regeneration, with the potential risk of damage to planted longleaf pine seedlings.

Ultimately, developing appropriate silvicultural prescriptions for converting loblolly pine stands to longleaf pine will require information on how harvesting treatments affect ecosystem components that include longleaf pine seedling establishment, ground layer vegetation composition, stand structure, fuel complexes, and the ability for sustained management with prescribed fire. This study addresses one potential source of competition for longleaf pine seedlings that will have major implications for stand development following restoration treatments. In general, our results suggest that site and stand conditions may be more important for controlling loblolly pine seedling density than the harvesting treatments used in this study. However, canopy retention is expected to increase the continuity of prescribed fire and therefore allow the manager greater flexibility in the use of prescribed fire to control loblolly pine regeneration. Overall, the challenges posed to longleaf pine restoration by natural regeneration in loblolly pine stands should not be insurmountable with the proper use of prescribed fire and adaptive management applied on a stand-specific basis.

3.4. Effects of canopy density and cultural treatments on ground-layer and mid-story vegetation

This sections addresses research objective O-3.

3.4.1. Introduction

The characteristic stand structure of frequently burned longleaf pine forests includes an open canopy dominated by longleaf pine, conspicuously few midstory stems, and a ground layer that is dominated by herbaceous species. This structure is important to the ecological integrity of the system by providing high quality habitat for many of the endangered faunal species associated with longleaf pine. For example, the gopher tortoise (*Gopherus polyphemus*) and many other herpetofaunal specialists in longleaf pine habitats require open stands for foraging herbaceous ground layer plants (Guyer and Bailey 1993). Perhaps the most well-known faunal species associated with these ecosystems is the federally endangered red-cockaded woodpecker (RCW; *Picoides borealis*), which uses live longleaf pine trees for nesting cavities and prefers open stands for foraging (USFWS 2003). Moreover, recent research shows that RCWs defending territories with predominantly grassy or herbaceous ground layers had higher fecundity than nearby groups in shrub-dominated territories (James et al. 1997, Hardesty et al. 1997). Herbaceous ground layers support diverse arthropod communities that provide food for RCW populations as well as other faunal species (Folkerts et al. 1993, Hermann et al. 1998, Hanula and Engstrom 2000).

Functionally, the ground layer vegetation serves as a critical fuel source for maintaining the frequent fire regime required to sustain the longleaf pine ecosystem (Peet and Allard 1993). The 'canopy' of the ground layer is typically dominated by large bunchgrasses that create a matrix of overlapping plant tissue and form an often continuous layer of well-aerated fuels. When combined with needlefall from canopy pines, this fuel layer burns readily as low-intensity surface fires (e.g. Clewell 1989, Noss 1989, Glitzenstein et al. 1995). Frequent surface fire reduces encroachment from hardwood species and maintains the dominance of herbaceous species. The importance of ground-layer vegetation (particularly large bunchgrasses) as a fuel source, coupled with the dependence of the structure of the vegetation layer on a frequent fire regime for self-perpetuation, represents a positive feedback system that becomes difficult to re-establish once disrupted (Mitchell et al. 2009).

Existing loblolly pine stands often appear very different from that described above. Midstory encroachment by hardwoods is a common occurrence in the absence of frequent fire, and the presence of a midstory component can further reduce the pyrogenicity of a pine dominated forest. As hardwood species gain dominance, herbaceous species such as grasses and forbs are often shaded out and their contribution as fine fuels is reduced. In such cases, management objectives must include the control of midstory hardwoods to shift the balance to an herbaceous dominated ground layer.

Despite an understanding of the importance of ground layer vegetation in this ecosystem, longleaf pine restoration efforts often focus on establishing longleaf pine seedlings. Restoration must also consider other aspects of stand structure, and a complete understanding of how management actions prescribed to improve longleaf pine seedling establishment will affect overall stand structure is required. This study was designed to determine how longleaf pine restoration management affects ground layer vegetation during the first few years after harvesting. Our specific objectives were to determine: 1) how canopy density affects ground layer vegetation cover and biomass; 2) how cultural treatments used for longleaf pine ecosystem restoration affect ground layer cover and biomass; and 3) how ground layer vegetation cover changes through time in response to canopy density manipulation and prescribed fire.

3.4.2. Methods

A complete description of study sites, experimental design and treatments is provided in Section 3.1.

For this section, we only used the uniform main plot treatments (Control, MedBA, LowBA, Clearcut) because the sampled area of uniform and gap plots had different coverages of the herbicide split-plot treatment at Fort Benning. In all study plots, the March treatment of hexazinone/sulfometuron methyl was applied in 1-m wide bands overtop of planted longleaf pine seedlings. In uniform plots, sampling of vegetation cover was done randomly throughout each plot, but in gap plots sampling was centered over the longleaf pine seedling rows. Consequently, the herbicide treatment covered 100% of the sampling area within gap plots but only around 30% of the sampling area within uniform plots.

3.4.2.1. Data collection

In each split-plot of each uniform main-plot, we randomly located two transects (each 20 m in length) that ran parallel to one split-plot boundary (Figure 3.4.1). Along each transect, we randomly selected ten numbers ranging from 2 to 17 to serve as starting points (m) for sampling quadrats. Each randomly selected number represented a distance from the start of the transect (0 m). We did not sample from the edges of the transects to avoid potential disturbance from transect establishment and plot layout.

At each randomly selected sampling location, we established a 1 m x 1 m sampling quadrat and recorded ocular estimates of percent cover of all vegetation < 1 m tall that occurred within the quadrat. We estimated cover as the percentage of the plot that would be shaded if the sun were positioned directly overhead. Cover was recorded using the following cover classes: 1 = trace, 2 = 0-1%, 3 = 1-2%, 4 = 2-5%, 5 = 5-10%, 6 = 10-25%, 7 = 25-50%, 8 = 50-75%, 9 = 75-95%, and 10 = 95-100%, and total cover for a quadrat could sum to over 100% if vegetation overlapped. We estimated cover by functional group (graminoids, ferns, forbs, woody shrubs/trees, and woody vines). Ground layer vegetation cover was recorded in October 2008, 2009, 2010, and 2012. A prescribed fire (described in Section 3.1) was applied to all study plots in the dormant season before the 2010 growing season and a second prescribed fire was applied to all study plots in the dormant season before the 2012 growing season at Camp Lejeune.

In August 2009, we destructively sampled biomass of graminoids, forbs, and woody vegetation in the ground layer (< 1 m tall). In each split-plot (NT, H, H+F) we used the two sampling transects (Figure 3.4.1) to randomly located five quadrats that were not used for measuring

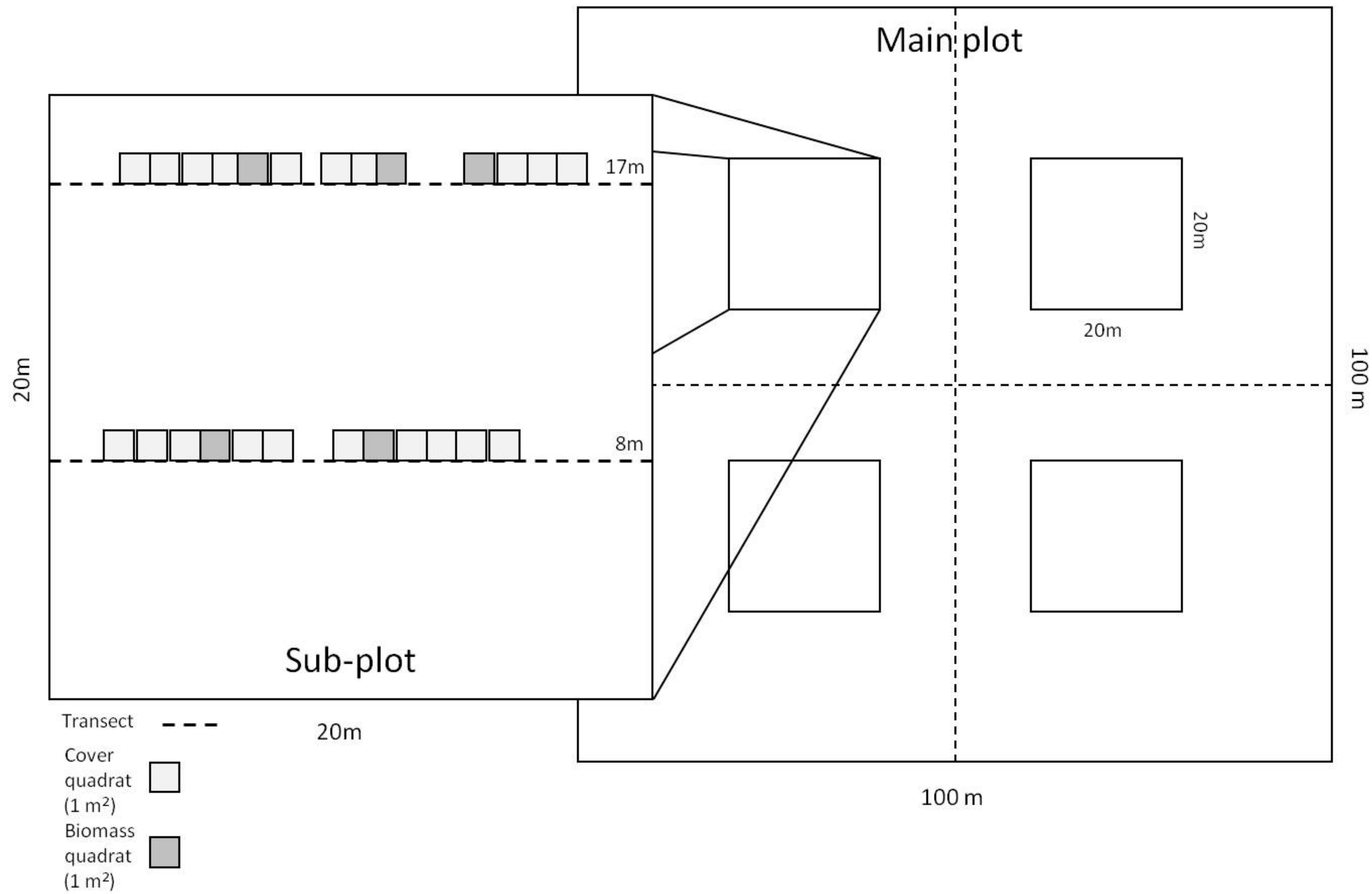


Figure 3.4.1. Illustration of sampling design for vegetation cover and biomass in uniform plots.

vegetation cover, and we clipped all vegetation that occurred within the quadrat. For individuals rooted outside the quadrat, all vegetation that occurred within the quadrat was clipped. Estimates of cover were also made for each functional group using the cover classes described above. All plant material was returned to the laboratory, dried to a constant mass at 70º C, and weighed to determine biomass.

During the vegetation sampling in 2008, 2009, 2010, and 2012, we counted midstory (> 1 m tall) woody stems by species along belt transects. Each belt transect was 2 m wide and centered on transect established for sampling vegetation cover (n = 2 per split-plot; each 20 m long x 2 m wide = 80 m^2 sampled per split-plot treatment). In 2012, only four blocks (Blocks 1, 2, 5 and 7) were sampled for loblolly pine stem densities at Camp Lejeune due to the high abundance of midstory loblolly pines in the plots.

3.4.2.2. Data analyses

Cover data were converted to the mid-point of each class, and we calculated mean values at the split-plot level for analyses. Mean midstory stem density was calculated at the split-plot level for hardwoods (including shrubs), loblolly pines, and all woody stems. We used split-plot ANOVA with a random block effect to test for main-plot effects, split-plot effects, and main*split-plot interaction effects on total vegetation cover, herbaceous vegetation cover, woody vegetation cover, vegetation cover by functional group, and the number of stems per hectare of hardwoods, loblolly pines, and all woody species. Analyses were conducted for each year separately because the timing of split-plot treatment application differed. In 2008, no split-plot treatments had been applied and we tested for only main-plot effects, but in 2009 we applied the herbicide and fertilizer treatments and compared NT, H, and H+F treatments. We used repeated measures ANOVA with autoregressive order one covariance structure to test for year effects and year*main-plot treatment effects. For the repeated measures test we used only NT split-plot treatments because the split-plots were applied at different times.

Mean biomass for total vegetation, graminoids, forbs, and woody vegetation was calculated at the split-plot level. We tested for main-plot effects, split-plot effects, and main*split-plot interactions for vegetation biomass in each category using split-plot ANOVA with a random block effect. To understand how closely estimates of vegetation cover and vegetation biomass are related, we used simple linear regression to determine relationships between percent cover estimates of vegetation and total vegetation biomass calculated at the split-plot level.

3.4.3. Results

Total vegetation cover was significantly affected by canopy density in every year at both study sites, with the exception of 2012 at Camp Lejeune (Figure 3.4.2). Generally, vegetation cover was greater on treatments with canopy removal than on treatments with intact canopy, with the highest values of vegetation cover on the Clearcut plots and the lowest values on the Control plots. By the end of the fifth growing season, only the Control plots were significantly different from the other study treatments at Fort Benning, and there was no effect of canopy density on total cover at Camp Lejeune. At both sites, we found significant split-plot effects on total vegetation cover the first year after treatment (2009). At Fort Benning, H plots had significantly

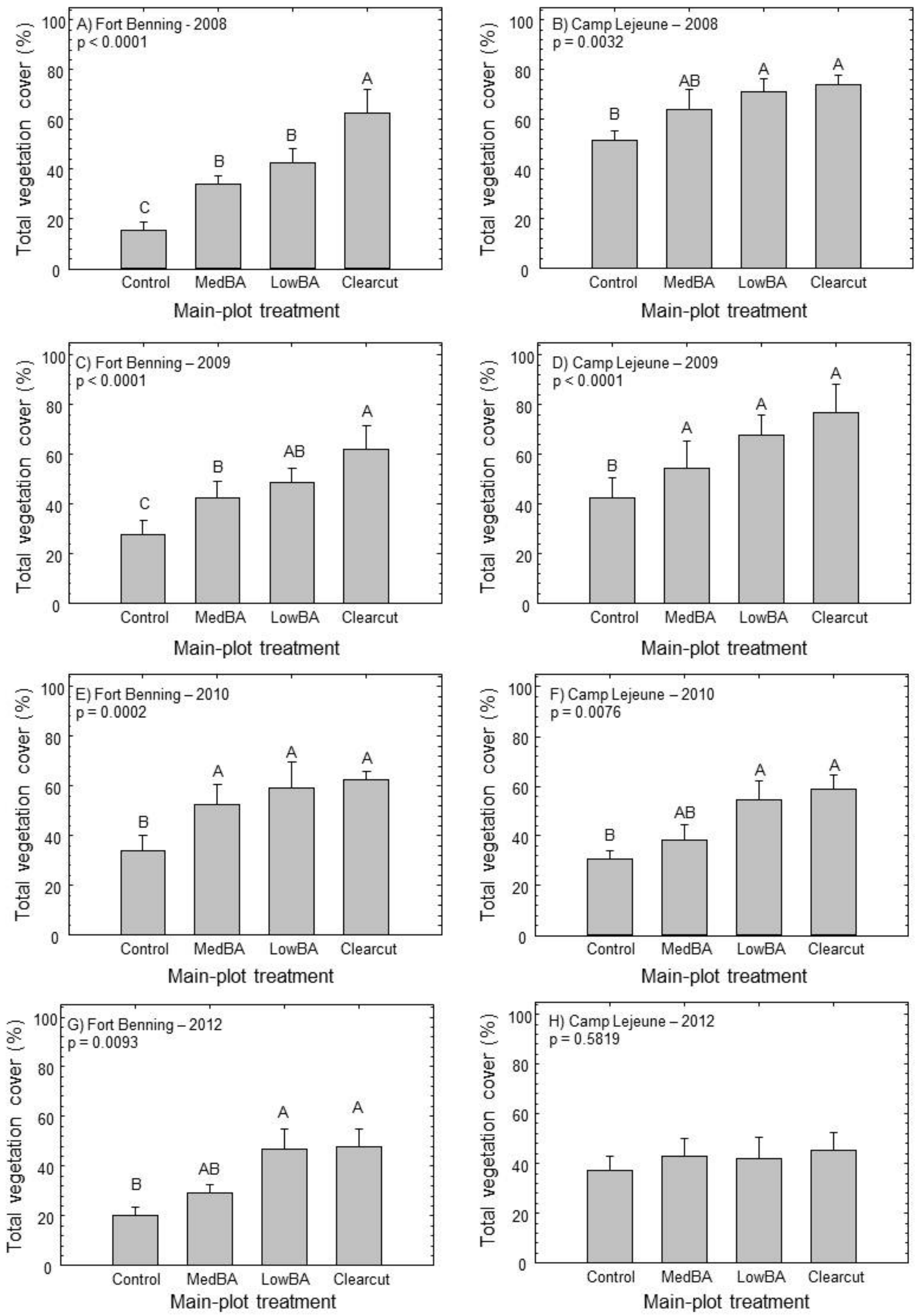


Figure 3.4.2. Total vegetation cover (mean and one standard error) by main-plot treatment in 2008, 2009, 2010, and 2012 at Fort Benning (A, C, E, and G) and Camp Lejeune (B, D, F, and H). The same letter indicates no significant difference at $p = 0.05$.

less vegetation cover than H+F plots, and NT plots were intermediate; at Camp Lejeune, both H and H+F treatments reduced vegetation cover when compared to NT plots (Figure 3.4.3). We found no significant split-plot effect at Fort Benning in 2010 or in 2012. At Camp Lejeune, the split-plot treatments that included herbicide resulted in lower total vegetation cover through the end of the 2012 growing season. The addition of fertilizer appeared to increase total cover when compared to herbicide alone at Fort Benning in 2009 but had no other effects on total cover in any year at either site.

At Fort Benning, there was higher cover of herbaceous vegetation than of woody vegetation in each measurement season (Figure 3.4.4). There were significant main-plot treatment effects on both herbaceous and woody vegetation in most years, with generally increasing cover for both vegetation groups associated with canopy removal. There was no effect of canopy density on herbaceous cover after three growing seasons at Fort Benning, but a treatment effect was significant after five growing seasons. At Camp Lejeune, there tended to be greater woody vegetation cover than herbaceous cover. Canopy density significantly affected herbaceous vegetation in 2008 but only affected woody vegetation in 2009 and 2010 (Figure 3.4.4). There were no effects of canopy density on herbaceous or woody vegetation in 2012 at Camp Lejeune. Similar to patterns at Fort Benning, cover generally increased with canopy removal. Among the split-plot treatments, we found that H reduced herbaceous vegetation compared to NT and H+F treatments at Fort Benning in 2009, although we found no split-plot treatment effects on 2009 woody vegetation cover or on either group in 2010 or 2012 at Fort Benning (Figure 3.4.5). There was a strong split-plot treatment effect on woody vegetation cover at Camp Lejeune, with less vegetation cover on H and H+F plots than on NT plots in all years. In addition, there was greater cover of herbaceous vegetation on H plots than on NT plots in 2012 at Camp Lejeune.

The analysis of functional groups indicated that cover of graminoids, forbs, and woody shrubs/trees were significantly affected by canopy density at Fort Benning in 2008, but only graminoids were significantly affected at Camp Lejeune (Table 3.4.1). Similar trends persisted in 2009 and 2010 for graminoids and woody shrubs/trees at Fort Benning and for woody shrubs/trees at Camp Lejeune, where canopy removal generally increased vegetation cover for each group (Tables 3.4.2 and 3.4.3). After five growing seasons, canopy density only affected woody shrubs/trees at Fort Benning and none of the functional groups at Camp Lejeune (Table 3.4.4). There were no effects of split-plot treatments on vegetation cover of any functional group in 2009 or 2012 at Fort Benning, and in 2010 only woody vine cover was increased on H plots. At Camp Lejeune, H and H+F split-plot treatments significantly reduced vegetation cover of graminoids, woody shrubs/trees, and woody vines when compared to the NT treatment in 2009. In contrast, forb cover was greater on the H and H+F plots than on the NT plots. The effect of the herbicide treatment on woody shrubs/trees persisted through 2010 and 2012 but was no longer significant in 2012 for woody vines. By the end of the fifth growing season, graminoid cover was higher on H plots than NT plots, and there were no longer significant differences in forb cover among the split-plot treatments (Table 3.4.4).

The repeated measures ANOVA resulted in no year*main-plot treatment interactions for any variable at Fort Benning or Camp Lejeune (Table 3.4.5). There were significant year effects for total vegetation cover, herbaceous vegetation cover, and woody vegetation cover at both sites. At Fort Benning, total vegetation cover gradually increased from 2008 through 2010, with a

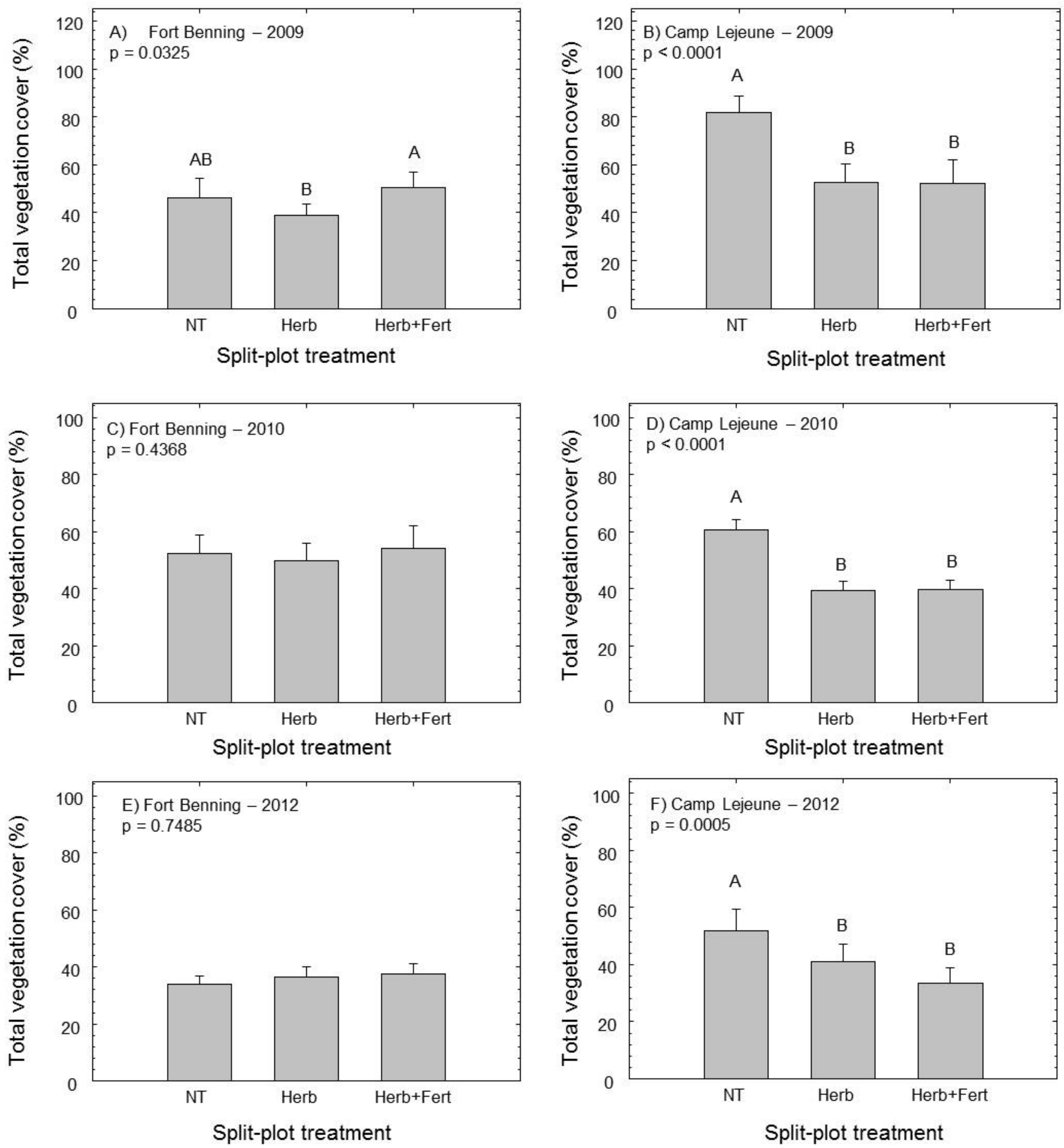


Figure 3.4.3. Total vegetation cover (mean and one standard error) by split-plot treatment in 2009, 2010, and 2012 at Fort Benning (A, C, and E) and Camp Lejeune (B, D, and F). The same letter indicates no significant difference at $p = 0.05$.

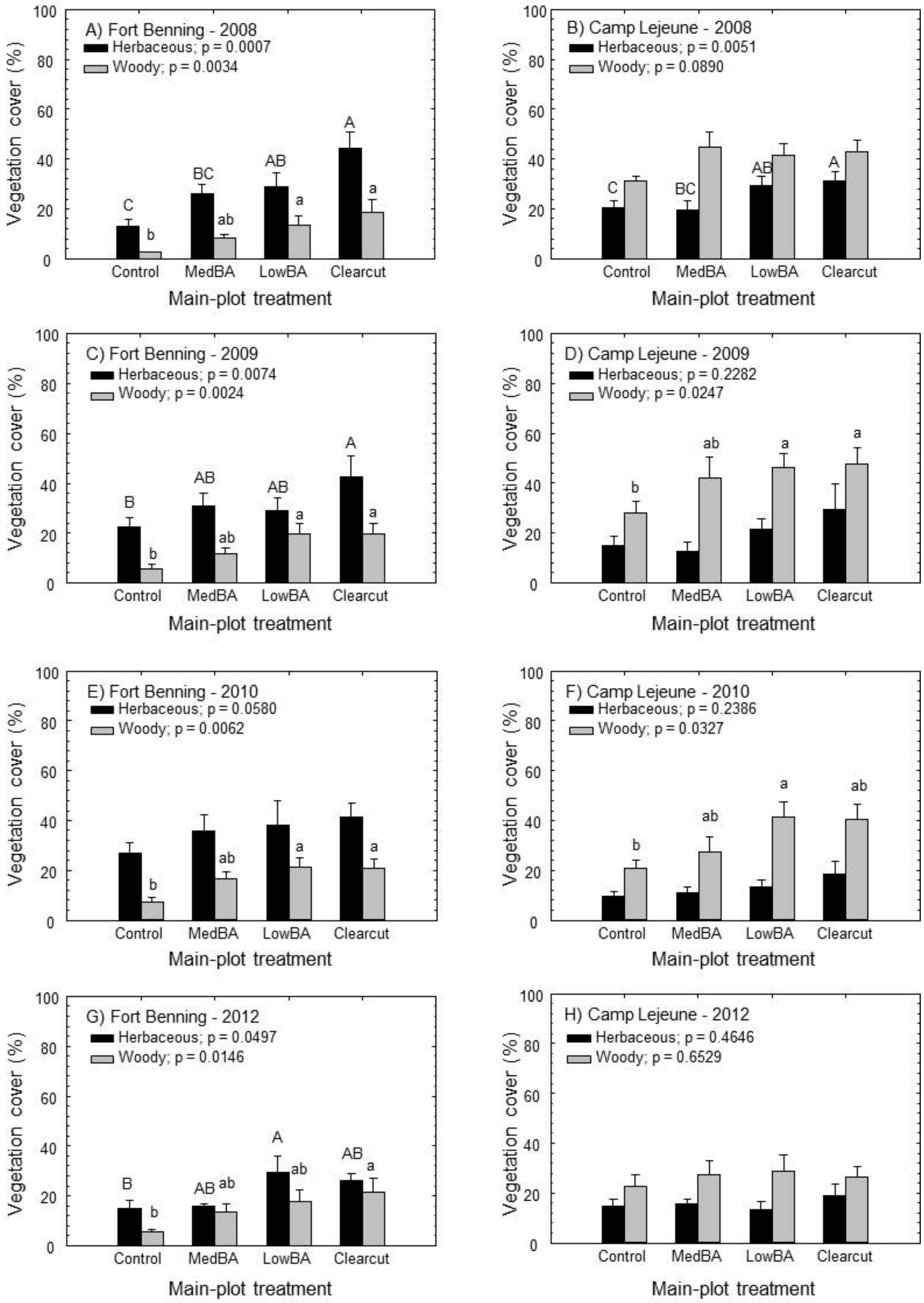


Figure 3.4.4. Herbaceous and woody vegetation cover (mean and one standard error) by main-plot treatment in 2008, 2009, 2010, and 2012 at Fort Benning (A, C, E, and G) and Camp Lejeune (B, D, F, and H). The same letter indicates no significant difference at $p = 0.05$.

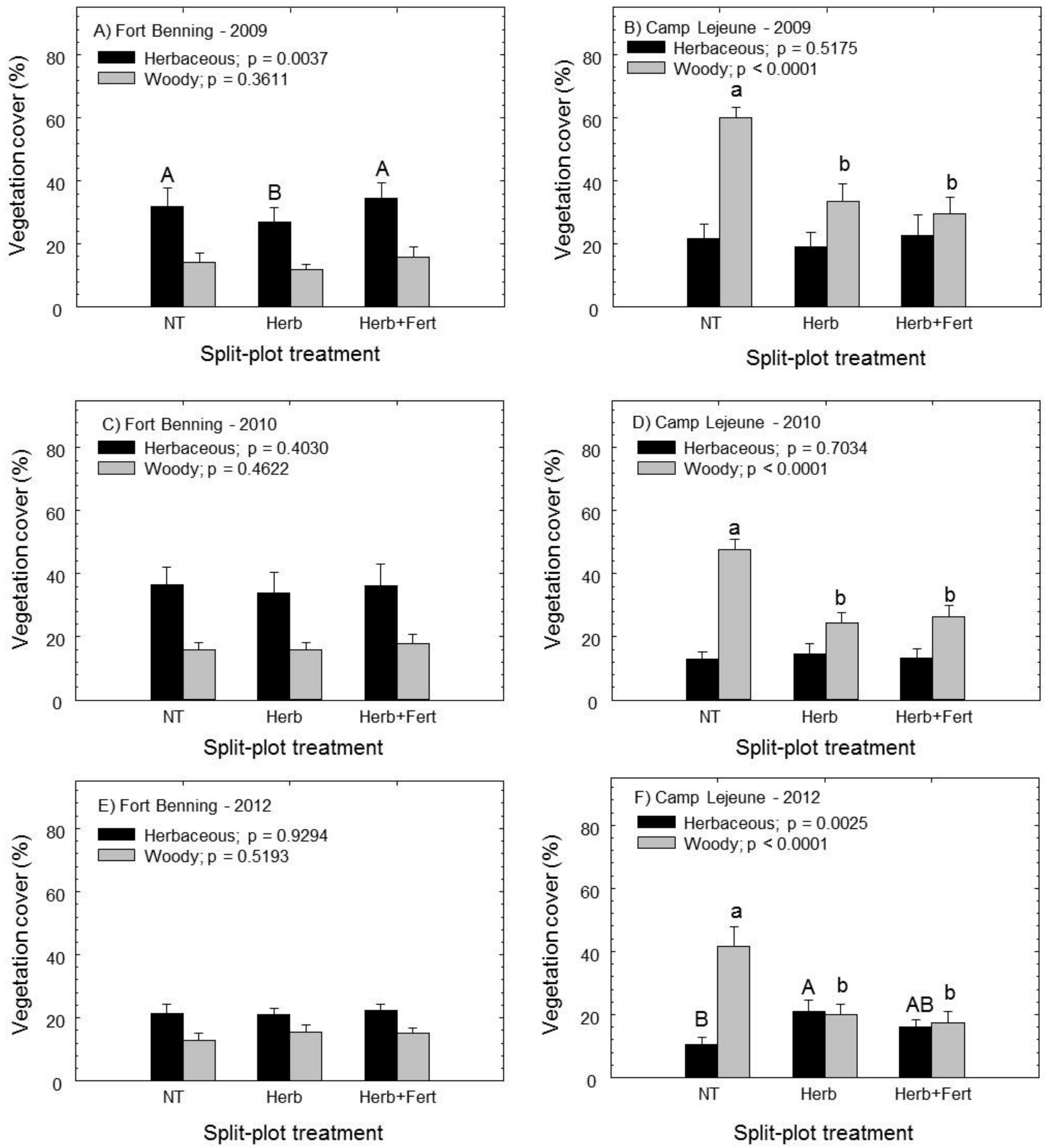


Figure 3.4.5. Herbaceous and woody vegetation cover (mean and one standard error) by split-plot treatment in 2009, 2010, and 2012 at Fort Benning (A, C, and E) and Camp Lejeune (B, D, and F). The same letter indicates no significant difference at $p = 0.05$.

Table 3.4.1. Mean and standard error of vegetation cover by functional group in 2008 for each main-plot at Fort Benning and Camp Lejeune. *P*-values refer to each group of main-plot treatments, and different letters indicate significant differences among treatments

2008

			Graminoids		Forbs		Ferns		Woody		Woody vine	
Site	Effect	Treatment	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Fort Benning	Main plot	Control	3.4^{b}	0.8	9.1^{b}	2.5	0.5	0.3	2.3^{b}	0.3	0.2	0.1
		MedBA	6.2^{b}	0.5	18.3^{ab}	2.7	1.5	1.4	7.0^{ab}	1.1	1.0	0.4
		LowBA	6.8^{b}	1.4	19.8^{ab}	5.0	2.4	1.7	12.8^{a}	4.0	0.5	0.3
		Clearcut	17.5^{a}	4.2	26.1^{a}	4.3	0.5	0.3	17.6^{a}	5.2	0.8	0.4
		p-value	**0.0004**		**0.0066**		**0.5041**		**0.0032**		**0.1799**	
Camp Lejeune	Main plot	Control	16.5^{b}	2.3	3.9	1.3	0.1	0.0	28.9	2.0	2.2	0.5
		MedBA	17.0^{ab}	4.0	2.4	0.9	0.0	0.0	41.4	5.7	3.1	0.9
		LowBA	24.0^{a}	3.0	5.2	2.7	0.1	0.1	37.8	3.7	3.8	1.8
		Clearcut	25.0^{a}	2.6	6.0	1.5	0.2	0.2	38.9	4.1	4.2	2.6
		p-value	**0.0109**		**0.2810**		**0.8188**		**0.1474**		**0.9100**	

Table 3.4.2. Mean and standard error of vegetation cover by functional group in 2009 for each main-plot and split-plot at Fort Benning and Camp Lejeune. *P*-values refer to each group of main- or sub-plot treatments, and different letters indicate significant differences among treatments

2009

			Graminoids		Forbs		Ferns		Woody		Woody vine	
Site	Effect	Treatment	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Fort Benning	Main Plot	Control	11.5[b]	3.0	10.4	2.1	0.4	0.2	5.2[b]	1.9	0.4	0.2
		MedBA	14.6[ab]	3.3	15.9	2.3	0.5	0.4	10.4[ab]	2.0	1.0	0.6
		LowBA	10.9[b]	1.6	16.1	3.7	1.9	1.5	18.7[a]	4.4	1.0	0.7
		Clearcut	23.6[a]	5.9	18.1	3.4	0.7	0.3	18.4[a]	4.2	1.1	0.8
		p-value	**0.0235**		**0.1240**		**0.5134**		**0.0056**		**0.6198**	
	Split Plot	NT	15.9	3.9	15.0	2.0	1.1	0.6	13.2	3.2	1.0	0.7
		H	12.7	3.2	13.4	1.6	0.8	0.4	11.0	1.7	1.0	0.4
		H+F	16.9	2.1	16.9	3.3	0.6	0.4	15.3	3.1	0.6	0.4
		p-value	**0.2273**		**0.1668**		**0.2784**		**0.4161**		**0.3462**	
Camp Lejeune	Main Plot	Control	9.6	2.8	5.0	2.4	0.1	0.1	26.6[b]	4.5	1.3	0.4
		MedBA	7.7	3.0	4.6	2.4	0.0	0.0	38.7[ab]	7.3	3.3	1.4
		LowBA	14.9	3.7	6.3	2.4	0.2	0.1	43.2[a]	5.3	3.1	1.1
		Clearcut	23.3	8.6	5.7	1.6	0.3	0.3	46.5[a]	6.5	1.0	0.3
		p-value	**0.1792**		**0.5831**		**0.8654**		**0.0205**		**0.4722**	
	Split Plot	NT	19.6[a]	4.2	1.9[b]	0.7	0.3	0.2	55.3[a]	2.6	4.6[a]	1.4
		H	12.0[b]	3.6	6.8[a]	2.5	0.2	0.1	33.1[b]	5.5	0.6[b]	0.1
		H+F	14.8[b]	5.1	7.7[a]	2.5	0.0	0.0	28.7[b]	5.3	0.9[b]	0.3
		p-value	**0.0004**		**0.0001**		**0.2435**		**<0.0001**		**<0.0001**	

Table 3.4.3. Mean and standard error of vegetation cover by functional group in 2010 for each main-plot and split-plot at Fort Benning and Camp Lejeune. *P*-values refer to each group of main- or split-plot treatments, and different letters indicate significant differences among treatments

2010

			Graminoids		Forbs		Ferns		Woody		Woody vine	
Site	Effect	Treatment	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Fort Benning	Main plot	Control	13.8^{b}	2.5	11.7	2.9	1.2	0.7	6.8^{b}	1.9	0.6	0.4
		MedBA	17.7^{ab}	3.8	16.8	2.9	1.3	1.1	15.1^{ab}	2.6	1.5	0.8
		LowBA	15.8^{ab}	3.5	18.8	5.9	3.4	2.1	20.0^{a}	4.2	1.2	0.8
		Clearcut	23.6^{a}	4.7	16.8	2.9	1.1	0.7	19.9^{a}	3.9	1.1	0.7
		p-value	**0.0310**		**0.1390**		**0.5954**		**0.0070**		**0.6695**	
	Split plot	NT	18.4	3.2	16.0	3.1	2.1	1.1	14.9	2.4	1.0^{b}	0.8
		H	16.5	3.7	15.2	2.9	2.1	1.0	14.5	2.4	1.4^{a}	0.6
		H+F	18.3	3.0	16.8	4.0	1.2	0.6	17.0	2.7	0.9^{b}	0.5
		p-value	**0.4662**		**0.6909**		**0.6783**		**0.6269**		**0.0187**	
Camp Lejeune	Main plot	Control	7.5	1.8	1.8	0.4	0.4	0.3	19.1^{b}	2.6	1.7	0.8
		MedBA	7.3	1.0	3.8	1.7	0.0	0.0	23.7^{ab}	5.6	3.5	1.4
		LowBA	9.7	2.9	3.2	1.0	0.5	0.2	37.4^{a}	4.7	3.8	2.1
		Clearcut	14.3	3.7	3.7	1.1	0.6	0.6	38.1^{a}	5.7	2.1	1.1
		p-value	**0.2616**		**0.3375**		**0.8750**		**0.0217**		**0.6702**	
	Split plot	NT	10.6	1.9	1.5^{b}	0.3	0.8	0.4	42.9^{a}	2.5	4.6^{a}	1.4
		H	10.3	2.1	4.0^{a}	1.1	0.3	0.2	22.6^{b}	3.2	1.9^{bc}	0.8
		H+F	9.6	2.7	3.7^{ab}	1	0.2	0.1	25.0^{b}	3.4	1.2^{c}	0.7
		p-value	**0.7479**		**0.0130**		**0.0563**		**<0.0001**		**0.0003**	

Table 3.4.4. Mean and standard error of vegetation cover by functional group in 2012 for each main-plot and split-plot at Fort Benning and Camp Lejeune. *P*-values refer to each group of main- or split-plot treatments, and the same letter indicates no significant difference at p = 0.05

2012

			Graminoids		Forbs		Ferns		Woody		Woody vine	
Site	Effect	Treatment	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Fort Benning	Main Plot	Control	9.2	3.3	5.0	0.9	0.6	0.4	4.7^{b}	0.8	0.6	0.3
		MedBA	8.0	1.1	6.4	0.7	1.5	1.5	12.3^{ab}	2.6	1.2	0.6
		LowBA	16.1	3.2	11.0	4.9	2.1	1.7	16.0^{ab}	4.7	1.6	1.0
		Clearcut	15.6	2.0	10.3	3.1	0.3	0.2	20.5^{a}	5.3	1.0	0.4
		p-value	**0.0639**		**0.3675**		**0.5799**		**0.0148**		**0.8612**	
	Split Plot	NT	12.6	3.1	7.3	1.0	1.4	0.9	11.8	2.6	1.0	0.7
		H	10.7	0.9	9.3	2.3	1.1	0.7	14.2	2.2	1.3	0.4
		H+F	13.4	2.1	8.0	1.2	0.8	0.5	14.2	1.4	0.9	0.4
		p-value	**0.4383**		**0.7472**		**0.6918**		**0.4602**		**0.2027**	
Camp Lejeune	Main Plot	Control	9.5	2.0	4.7	1.5	2.5	1.6	20.9	3.8	2.6	0.8
		MedBA	12.2	1.9	3.3	0.9	3.6	1.4	24.1	5.1	4.6	1.4
		LowBA	8.6	2.3	4.9	1.3	3.6	1.9	26.4	6.4	3.2	1.3
		Clearcut	12.0	3.1	7.0	2.0	3.5	0.0	24.0	4.4	3.5	1.1
		p-value	**0.5808**		**0.3560**		**0.8098**		**0.6924**		**0.3110**	
	Split Plot	NT	7.2^{b}	1.4	3.6	0.6	4.3^{a}	1.8	38.2^{a}	5.6	4.2	1.3
		H	14.7^{a}	3.0	6.3	1.1	1.5^{b}	0.8	17.6^{b}	3.0	3.6	1.0
		H+F	10.5^{ab}	1.8	4.8	1.2	2.5^{ab}	1.3	16.1^{b}	3.3	2.4	0.8
		p-value	**0.0118**		**0.0539**		**0.0271**		**<0.0001**		**0.1034**	

Table 3.4.5. Results from the repeated measures ANOVA test for total vegetation cover, herbaceous vegetation cover, and woody vegetation cover at Fort Benning and Camp Lejeune

Site	Variable	Effect	Num DF	Den DF	F-value	p-value	Transformation
Fort Benning	Total	year	3	44.1	6.54	0.0009	
		treatment	3	17	9.19	0.0008	
		year*treatment	9	44.1	0.87	0.5615	
	Herbaceous	year	3	43.8	6.29	0.0012	
		treatment	3	12.7	3.45	0.0494	
		year*treatment	9	43.8	1.14	0.3578	
	Woody	year	3	46.7	6.16	0.0013	$x^{1/2}$
		treatment	3	12.8	4.08	0.0308	$x^{1/2}$
		year*treatment	9	46.7	0.68	0.726	$x^{1/2}$
Camp Lejeune	Total	year	3	59.6	8.36	0.0001	
		treatment	3	26.1	6.38	0.0022	
		year*treatment	9	59.7	1.17	0.3301	
	Herbaceous	year	3	60.9	3.26	0.0273	$x^{1/2}$
		treatment	3	25.5	2.8	0.0604	$x^{1/2}$
		year*treatment	9	60.9	0.78	0.6395	$x^{1/2}$
	Woody	year	3	62.7	11.23	<0.0001	$x^{1/2}$
		treatment	3	22.5	2.43	0.0915	$x^{1/2}$
		year*treatment	9	63.1	1.98	0.0566	$x^{1/2}$

reduction in cover in 2012 (Figure 3.4.6). Cover at Fort Benning was fairly evenly split among graminoids, forbs, and woody shrubs/trees in each year. At Camp Lejeune, total cover was significantly higher in 2009 than in any other year. Woody shrubs/trees dominated vegetation cover at Camp Lejeune in each year (Figure 3.4.6).

Total biomass from 2009 followed similar patterns observed for vegetation cover. At both sites, total biomass was significantly affected by main-plot treatments, with greater biomass on Clearcut plots than on Control plots (Figure 3.4.7). At Camp Lejeune, graminoid and forb biomass were not affected by main-plot treatments, but all vegetation groups were affected by canopy density at Fort Benning. The H split-plots had lower total biomass than NT and H+F plots at Fort Benning, but both herbicide treatments (H and H+F) had lower total biomass than NT plots at Camp Lejeune. At Camp Lejeune, patterns of total biomass were largely driven by biomass of woody vegetation (trees and shrubs) while at Fort Benning total biomass was more evenly distributed among graminoids, forbs, and woody species. We found significant, positive relationships between split-plot level mean total vegetation cover and mean total vegetation biomass at both study sites (Figure 3.4.8), although the relationship was stronger at Fort Benning (r^2 = 0.817) than at Camp Lejeune (r^2 = 0.518).

There were no interactions between main-plot and split-plot treatments on stem density of loblolly pines, hardwoods, or all woody species in any year ($p \geq 0.1385$). At Fort Benning, hardwoods were more abundant than loblolly pines on most of the treatments in each year, and stem densities were higher on Clearcut or LowBA plots than on Control plots in most years (Figure 3.4.9). Similarly, loblolly pine densities were highest on Clearcut plots and lowest on Control plots in 2012. By the end of the fifth growing season, there were nearly 5000 woody stems per hectare in the midstory on Clearcut plots at Fort Benning, with almost 4000 of those hardwoods. At Camp Lejeune, shrubs were dominant in the midstory in 2008, but loblolly pine densities increased over time. After the first growing season, canopy density did not affect the abundance of hardwoods in the midstory layer, but loblolly pine densities were higher on Clearcut plots than on Control plots in all years except 2012. Generally, midstory stem densities were much higher at Camp Lejeune than at Fort Benning, with over 12,000 stems per hectare compared to nearly 5000 stems per hectare in Clearcut plots for each respective site in 2012.

The split-plot treatment significantly affected hardwood stem densities at both sites in 2009 and 2010, with lower stem densities on H and H+F plots than NT plots (Figure 3.4.10). In 2012, the same pattern was observed at Camp Lejeune but not at Fort Benning. At both sites, the densities of loblolly pine were higher on H and H+F plots than on NT plots in 2012. Because loblolly pine and hardwood densities were generally affected in opposite directions by the split-plot treatments, total stem densities in 2012 did not differ among the split-plot treatments.

3.4.4. Discussion

Removal of canopy trees reduces direct competition with sub-canopy vegetation, typically resulting in an increase in resource availability and greater abundance of ground-layer plants (e.g., Anderson et al. 1969, Ares et al. 2010). Grelen and Enghardt (1973) reported increases in herbaceous vegetation of longleaf pine communities that was proportional to the intensity of canopy thinning. In 8- to 11-year old longleaf pine plantations at the Savannah River Site, GA,

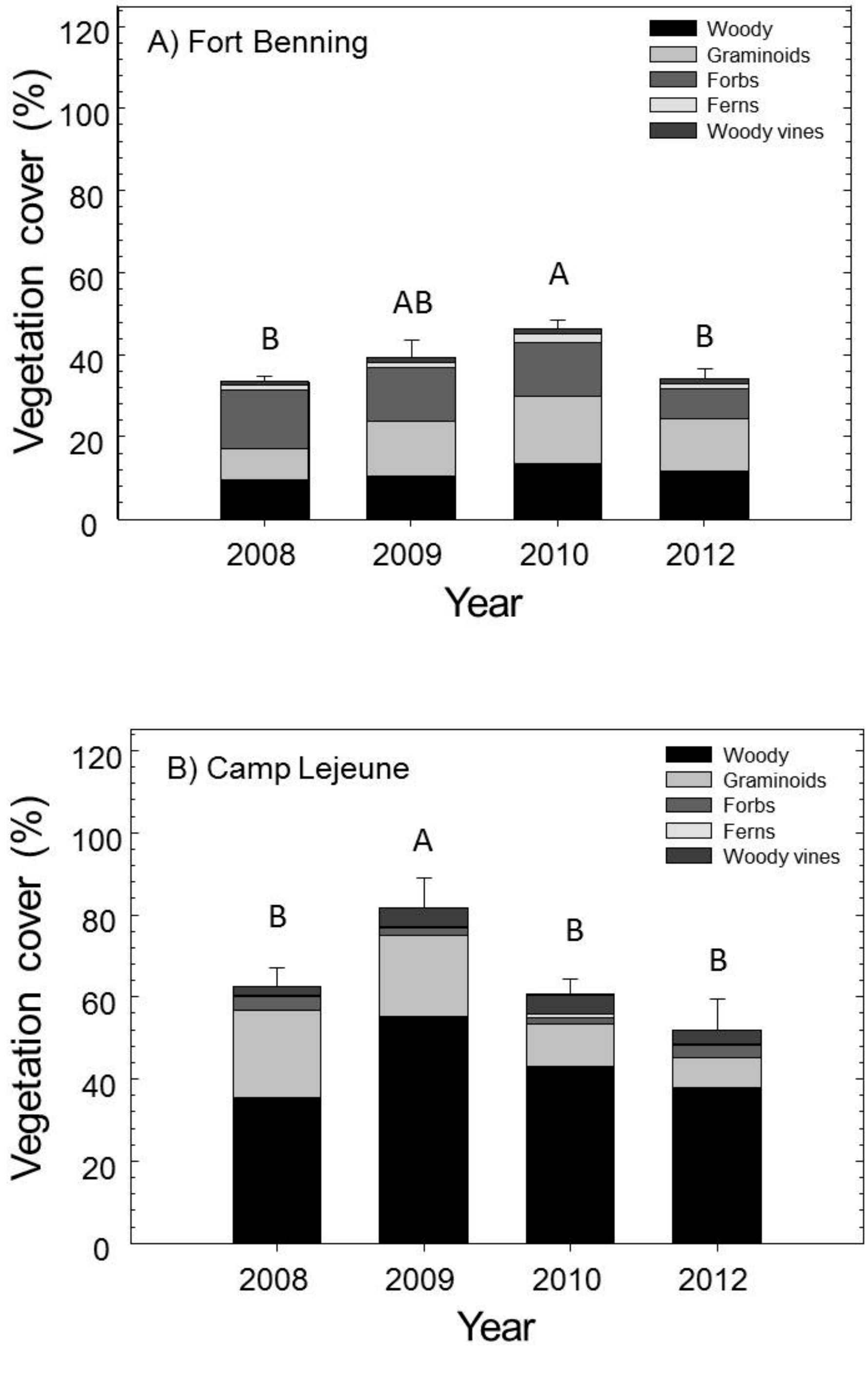


Figure 3.4.6. Total vegetation cover (mean ± one standard error) and contribution by functional group by year for A) Fort Benning and B) Camp Lejeune. The same letter indicates no significant difference in total vegetation among years at $p = 0.05$.

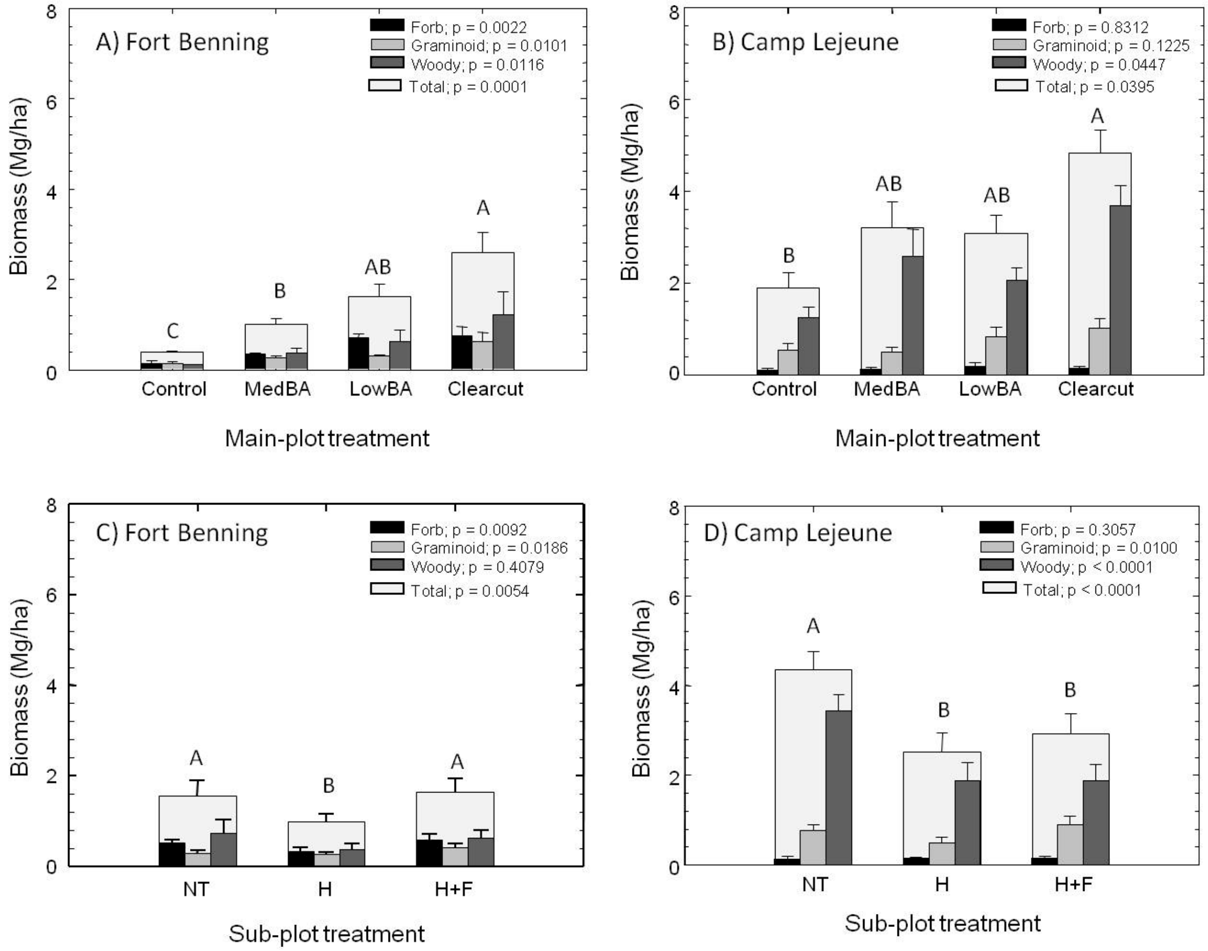


Figure 3.4.7. Biomass of ground layer vegetation (mean and standard error) in 2009 by main-plot treatment at A) Fort Benning and B) Camp Lejeune and by sub-plot treatment at C) Fort Benning and D) Camp Lejeune for total vegetation and by functional group. The same letter indicates no significant difference in total vegetation among years at $p = 0.05$.

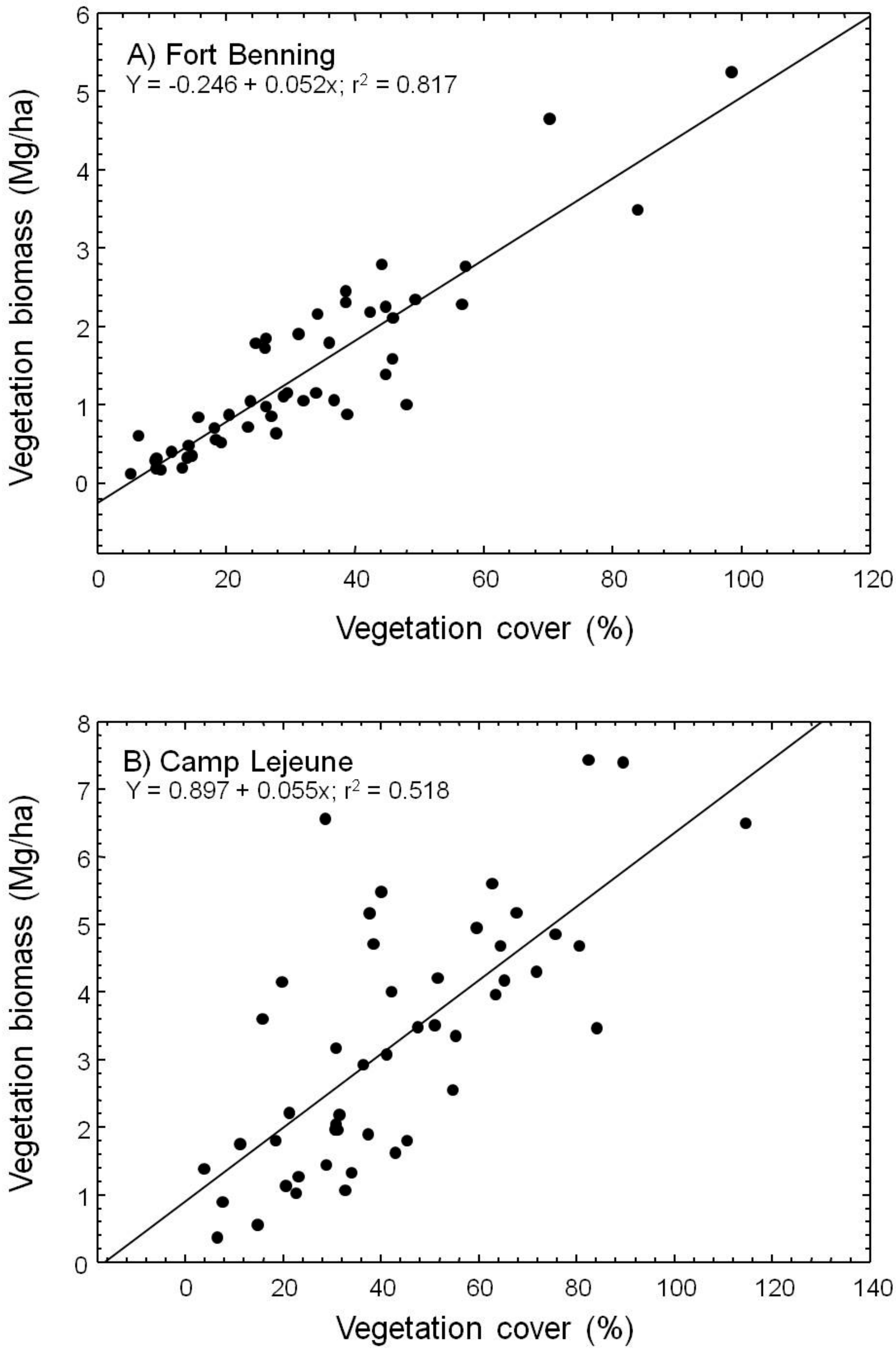


Figure 3.4.8. Scatterplots and linear regression relationship between percent vegetation cover and total vegetation biomass at A) Fort Benning and B) Camp Lejeune.

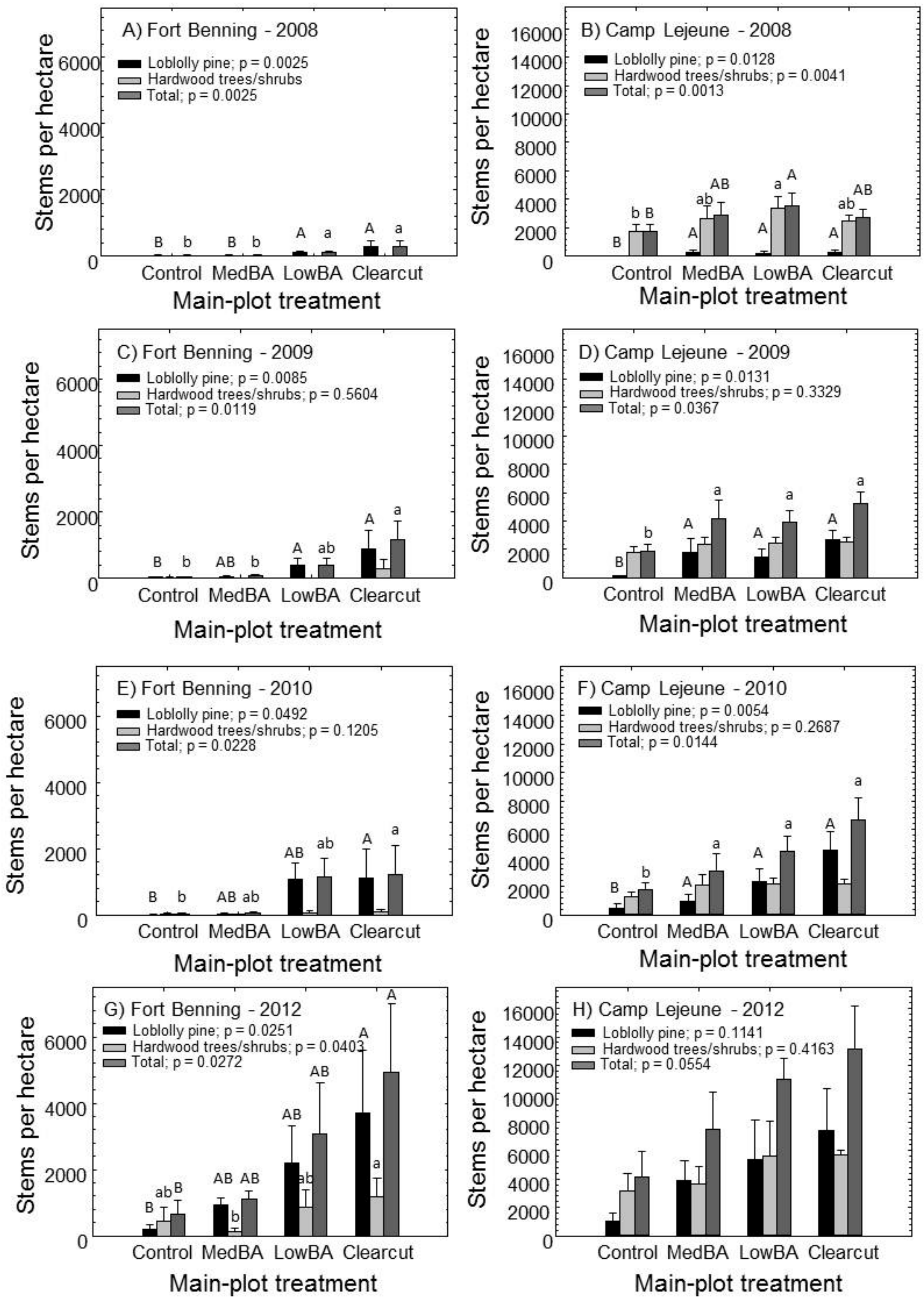


Figure 3.4.9. Number of loblolly pine, hardwood trees and shrubs, and total mid-story stems (> 1 m tall; mean and one standard error) by main-plot treatment in 2008, 2009, 2010, and 2012 at Fort Benning (A, C, E, and G) and Camp Lejeune (B, D, F, and H). The same letter within a species or group indicates no significant difference among years at $p = 0.05$

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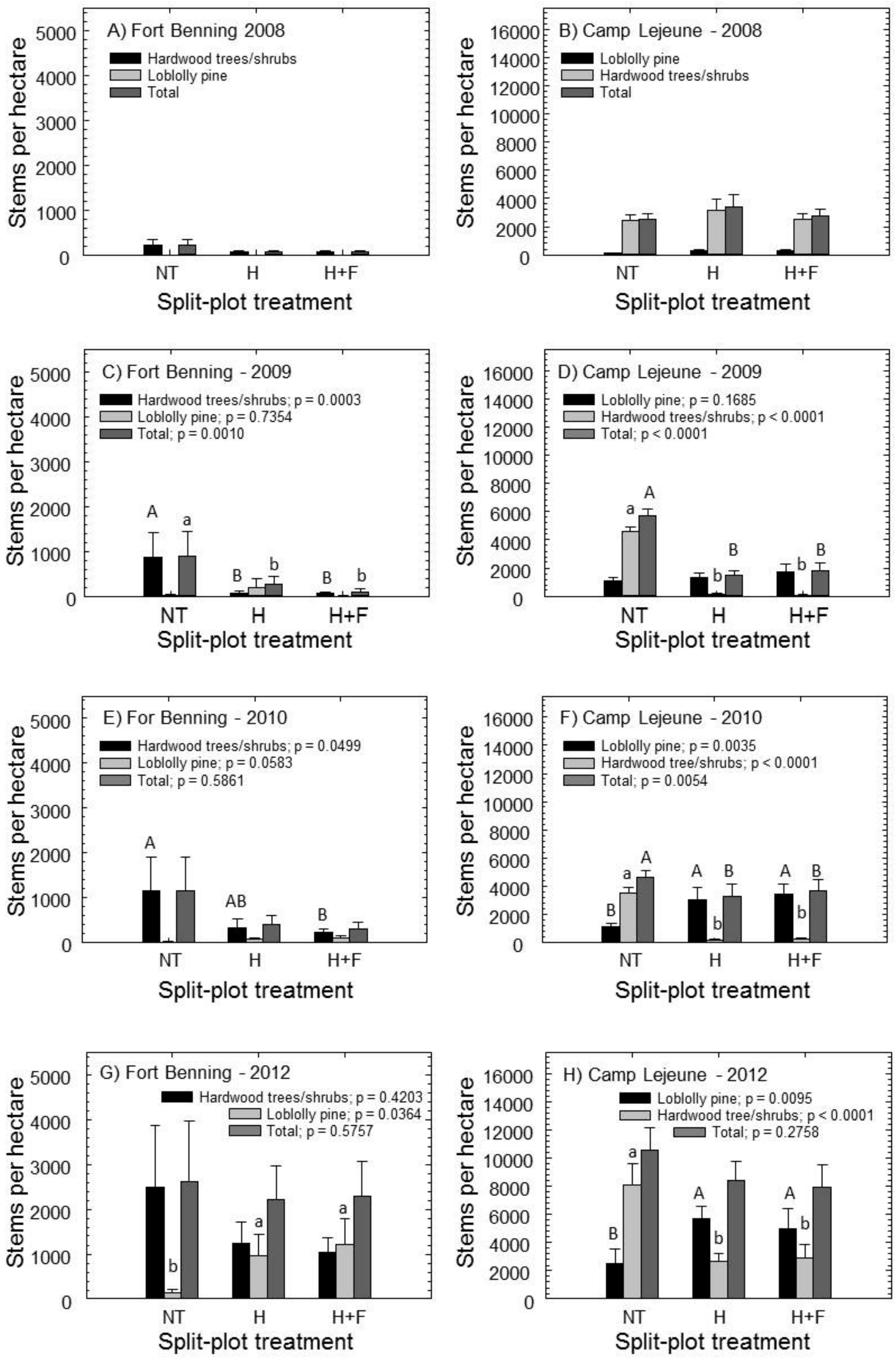


Figure 3.4.10. Number of loblolly pine, hardwood trees and shrubs, and total mid-story stems (> 1 m tall; mean and one standard error) by split-plot treatment in 2008, 2009, 2010, and 2012 at Fort Benning (A, C, E, and G) and Camp Lejeune (B, D, F, and H). The same letter within a species or group indicates no significant difference among years at $p = 0.05$. Note the different y-axis scales for Fort Benning and Camp Lejeune.

Harrington and Edwards (1999) found that forb, grass, vine, and shrub cover increased following experimental reductions of canopy density in longleaf pine plantations. They determined that the increased light availability strongly controlled increases in herbaceous vegetation but that increased soil moisture was also important.

Results from our study support previous findings that canopy removal leads to increased growth of ground layer vegetation in upland pine communities. We found this pattern for most functional groups and in most years at Fort Benning and Camp Lejeune. However, canopy density effects on total vegetation cover appeared to be strongest in the first year after thinning, especially at Fort Benning. At Camp Lejeune, total vegetation cover was not different among the MedBA, LowBA, or Clearcut treatments in 2008 or 2009, suggesting that even light levels of thinning may stimulate increased ground layer growth.

The study locations differed in dominant forms of ground layer vegetation, with herbaceous cover dominant at Fort Benning and woody vegetation cover dominant at Camp Lejeune. Such differences in ground layer composition have long-term implications for stand development and longleaf pine restoration management. Target stand structure for longleaf pine restoration includes little to no midstory and a ground-layer dominated by herbaceous species. An herbaceous ground cover provides important fine fuels for fire management, and the abundance of shrubs at Camp Lejeune is likely to decrease the ability of land managers to apply frequent prescribed fire to the stands.

Because longleaf pine restoration can be hampered by an abundance of woody vegetation, previous studies have explored various methods of woody vegetation control for restoration (e.g., Provencher 2001, Haywood 2009). Herbicides that target woody vegetation can be used to shift the dominance of ground-layer vegetation from woody to herbaceous species. Freeman and Jose (2009) evaluated the effects of different herbicide treatments on a north Florida flatwoods longleaf pine community and reported that imazapyr reduced initial shrub cover and increased herbaceous cover (also see Jose et al. 2008). At the Savannah River Site in GA, Harrington and Edwards (1999) found that herbicides successfully reduced woody vegetation but had variable effects on herbaceous species over two years. However, forb and grass cover had increased compared to untreated controls after two years following treatment, and total herbaceous cover had increased by 16% in response to woody vegetation control.

The herbicide treatments used in this study were prescribed for hardwood control (imazapyr) at Camp Lejeune and for both hardwood (imazapyr) and herbaceous control (hexazinone and sulfometuron methyl) at Fort Benning. We used different prescriptions to address the vegetation composition for each site, and it is likely that the site differences in dominant vegetation affected the relative impact of the split-plot treatments used in our study. At Camp Lejeune, the persistent herbicide effect on the dominating woody vegetation cover resulted in a reduction in total cover on split-plots with herbicide. Because woody vegetation was not abundant at Fort Benning, it is not surprising that we found no effect of herbicides on woody vegetation cover. We note that the site preparation treatment at Fort Benning included an herbicide application that targeted (and killed) woody vegetation, whereas the mulching treatment at Camp Lejeune initiated sprouting rather than mortality. Because the composition and abundance of the ground layer vegetation differed greatly between the two study areas, and the herbicide prescriptions for the split-plot treatments differed for the two study areas, the interpretation of the split-plot treatments themselves should be considered within the context of each study location.

The herbicide treatments had strong effects on the midstory hardwood stem densities at both study sites. The control of hardwood stems resulted in a concurrent increase in loblolly pine densities, especially at Camp Lejeune. As a result, total midstory stem density did not differ among the split-plot treatments after five growing seasons, suggesting that control of natural regeneration of loblolly pine is critical for reaching vegetation structure objectives (Section 3.3).

The development of midstory woody vegetation often conflicts with longleaf pine restoration objectives, and our results suggest that midstory development may be highly variable across sites. In general, we observed at least twice the density of midstory stems at Camp Lejeune when compared to Fort Benning, with a considerably higher amount of loblolly pine (see Section 3.3). Previous studies have discussed the importance of canopy retention for suppressing the development of woody plants in longleaf pine forests (Jack et al. 2006, Kirkman and Mitchell 2006, Kirkman et al. 2007, Pecot et al. 2007). Our results in loblolly pine stands generally support these findings, although there are several important points to note from our research. First, midstory stem densities were highly variable within and between sites. Within each study location, there was high variability among the study blocks, which limited our ability to detect treatment differences in some cases. Second, patterns of hardwood density in relation to canopy density were inconsistent between sites. We suspect that differences in site preparation may contribute to these different responses: at Fort Benning, the herbicide site preparation reduced the initial hardwood population but at Camp Lejeune the mulching treatment resulted in vigorous sprouting of shrubs. Because sprouts rely on carbohydrate reserves for initial growth, it was likely that the woody stem density was able to recover quickly regardless of canopy density on Camp Lejeune sites.

Interestingly, the herbicide treatment decreased herbaceous cover when compared to the herbicide plus fertilizer at Fort Benning in the first year after application. Because the herbaceous herbicide treatment was applied in bands over longleaf pine seedlings, approximately 30% of the measurement unit was treated. It is likely that untreated vegetation within the H+F plots responded to the fertilizer application with increased growth. We would expect a broadcast application of hexazinone and sulfo-meturon methyl to reduce vegetation cover more strongly than what we observed in our study. However, band application may be desirable during longleaf pine restoration to reduce competition at the local seedling level, while minimizing the reduction of herbaceous cover at the stand level (Brockway et al. 1998).

We applied prescribed fire to all study plots in the dormant season between 2009 and 2010, and again between 2011 and 2012 at Camp Lejeune. Although we cannot directly assess fire effects on vegetation, our results suggest differential fire effects at Camp Lejeune compared to Fort Benning, and we suggest that the differences are related to pre-fire vegetation structure. Total vegetation cover was significantly reduced between 2009 and 2010 at Camp Lejeune but did not change at Fort Benning. Measurements of cover vary with the time since burning, but unlike herbaceous vegetation that does not accumulate secondary growth and dies back to the ground every winter, woody vegetation accumulates biomass and increases in size every year post-burning. If pre-fire measurements represent more than one season's growth, it would be expected that post-burn measurements would show greater woody vegetation reduction than in the herbaceous component (which can only ever accumulate one-year's biomass). Unlike Fort Benning with very little woody vegetation, the Camp Lejeune sites were dominated by woody vegetation (shrubs), and their removal by fire drove the observed post-fire change. Similarly, the herbicide treatment at Camp Lejeune had a significant and persistent reducing effect on woody vegetation. Although fire did not increase the herbaceous layer after the first fire, it may have contributed to the significant increase in herbaceous cover in the herbicide split-plot compared to the NT split-plot after the 2011 fire. After a second fire, the shrub cover was further reduced in the herbicide treated plots and herbaceous cover increased. Repeated fires are often required for long-term changes in vegetation structure, specifically a shift from woody to herbaceous vegetation (e.g., Glitzenstein et al. 1995, 2001; Brockway and Lewis 1997, Haywood 2001). In our sites, early evidence suggests that herbicide treatments to reduce the woody vegetation will support this desirable transition.

Studies of ground layer vegetation often use cover to quantify relative differences in vegetation abundance, but biomass may more accurately represent measures of site productivity, vegetation abundance, and/or competitive pressures provided by vegetation. We found good relationships between vegetation cover and biomass, especially at Fort Benning, suggesting that estimates of cover are an acceptable method for quantifying vegetation abundance. Moreover, treatment effects were generally found to be the same from cover data and from biomass data. Total ground layer biomass at Fort Benning was within the range reported from studies in southwestern Georgia (McGuire et al. 2001, Pecot et al. 2007), but biomass in Clearcut plots at Camp Lejeune was quite high. Mitchell et al. (1999) found that aboveground primary productivity of ground layer vegetation in longleaf pine forests is strongly controlled by soil moisture, and it is likely that the generally higher soil moisture levels at Camp Lejeune are related to greater soil moisture at Camp Lejeune.

3.4.5. Conclusions

Ground layer vegetation is a critical component of the longleaf pine ecosystem, and restoration efforts must work to reduce woody species abundance and increase herbaceous dominance. We found that canopy removal increases vegetation cover and biomass at two ecologically distinct study sites. On sites where woody vegetation is dominant, herbicide treatments may be used to successfully reduce woody cover, but we found few effects of herbicides for herbaceous control at Fort Benning. Prescribing herbicide treatments for longleaf pine restoration requires consideration of site conditions; however, the herbicide treatments used in our study resulted in persistent reductions in woody vegetation cover and an increase in herbaceous vegetation after five growing seasons at Camp Lejeune. Although the herbicide treatments reduced the density of midstory (> m tall) woody stems, the growing space was subsequently occupied by regenerating loblolly pines (Section 3.3), indicating the importance of controlling natural loblolly pine regeneration during stand conversion. Given the importance of prescribed fire in longleaf pine management, we need a better understanding of how our prescribed fires interact with other management activities to affect vegetation responses. Our results provide information on short-term effects of our treatments on ground layer and midstory vegetation, but long-term studies are required when considering management effects on vegetation response throughout stand development.

3.5. Ground layer vegetation richness and composition following experimental restoration treatments

This section addresses objective O-4.

3.5.1. Introduction

The longleaf pine (*Pinus palustris* Mill.) ecosystem of the southeastern United States is recognized as one of the most floristically diverse ecosystems in North America (Mitchell et al. 2006, Peet 2006). The characteristic stand structure of fire-maintained longleaf pine forest includes a canopy dominated by longleaf pine and little to no midstory layer, and the exceptional diversity of this system is found primarily in the ground layer vegetation. For example, Walker and Peet (1983) identified over 40 species within 0.25 m^2 in the Green Swamp of the lower coastal plain of North Carolina, and Peet (2006) described many areas with greater than 100 species occurring within 1000 m^2. Such levels of diversity are comparable with those found in the Smoky Mountain cove forests (Mitchell et al. 2006) and contribute to a unique biological legacy of the longleaf pine ecosystem.

High levels of floristic diversity in the longleaf pine ecosystem are dependent on frequent surface fires (Provencher et al. 2001, Kirkman et al. 2004). Fire exclusion and changes in land use have resulted in widespread reduction and fragmentation of the longleaf pine ecosystem, with many upland sites converted from longleaf to loblolly pine (Frost 1993). In addition to altered structure (Section 3.4) the overall diversity of many of these sites has decreased and species composition shifted. Treatments used to re-establish longleaf pine, like thinning the canopy and burning, would be expected to benefit the ground layer; however, effects of cultural treatments, for example, using herbicides to control competition, are not so clear.

This study was designed to determine the effects of silvicultural treatments for restoration on the diversity and composition of ground layer vegetation at two ecologically distinct sites. Specific objectives were to: 1) determine effects of canopy density on species richness of ground layer vegetation; 2) determine effects of herbicides and fertilizer on species richness of ground layer vegetation; and 3) identify factors affecting composition of ground layer communities following restoration management.

3.5.2. Methods

See Section 3.1 for details on study sites, experimental design, and treatment installation. We used only uniform treatment plots (Control, MedBA, LowBA, and Clearcut) and three split-plot treatments (NT, H, and H+F) for this study.

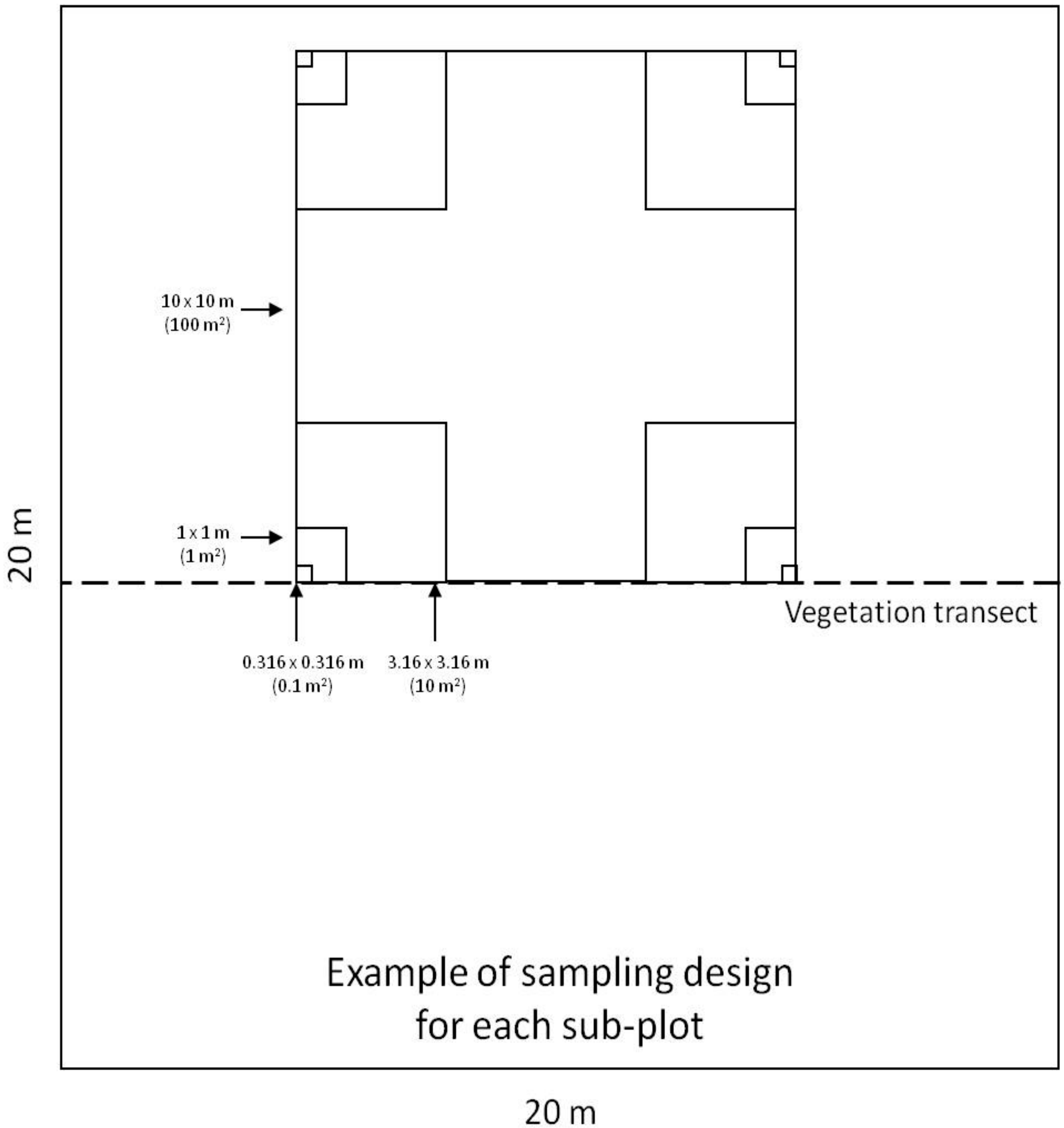


Figure 3.5.1. Example of sampling design for quantifying species richness at areas of 0.1 m^2, 1 m^2, 10 m^2, and 100 m^2.

3.5.2.1. Data collection

In each sampled split-plot, we used a nested-scale sampling design to quantify species richness and composition at different scales (Figure 3.5.1). We established a 10 x 10 m (100 m^2) at a random starting location along Transect 1 from the ground layer vegetation cover measurements (Section 3.4). In each corner of the 10 x 10 m sampling area, we established nested sampling areas at 0.316 x 0.316 m (0.1 m^2), 1 x 1 m (1 m^2) and 3.16 x 3.16 m (10 m^2). We sampled plots at each corner starting with the smallest area (0.1 m^2) and progressing through increasing sample areas. We recorded the presence of each species occurring in the smallest scale and additional species at each subsequent scale for each corner of the sampling area. All additional species occurring within the entire sample 100 m^2 plot were recorded.

Species that could not be positively identified in the field were collected (from outside study plots when possible) and immediately pressed for laboratory identification. We worked with personnel of the Clemson Herbarium to identify field unknowns. Some species could not be positively identified because they lacked the required features (e.g. flowering or seed structures). In such cases, species were commonly identified to the genus and grouped for analyses; this was most common for functionally similar graminoids such as *Dichanthelium* spp. and *Rhynchospora* spp.

3.5.2.2. Data analyses

We calculated the total number of species (species richness) occurring at each scale for all species, all woody species, all herbaceous species, and selected functional groups (graminoids, forbs, ferns, woody trees and shrubs, and woody vines). Functional groups were assigned to each species based on classifications from the USDA PLANTS Database (http://plants.usda.gov/java/). We used split-plot ANOVA to test for effects of main-plot treatments (canopy density), split-plot treatments (herbicide/fertilizer) and main*split-plot treatment interactions, with a significance level of $\alpha = 0.05$. We treated Block as a random effect in the analysis. We used a series of t-tests to compare results from the site locations.

We used non-metric multidimensional scaling (NMS) to identify patterns in species composition at Fort Benning and Camp Lejeune. The NMS procedure is an iterative process that orients data in ordination space to minimize the dissimilarity between the original data and the data in the reduced ordination space (McCune and Grace 2002). At the largest scale (100 m^2), each split-plot represented one point in ordination space (n = 72 at Fort Benning; n = 81 at Camp Lejeune). At each other scale, we sampled four locations within each 100 m^2 area, resulting in 288 sampled points at Fort Benning and 324 sampled points at Camp Lejeune.

In the analyses we considered explanatory variables that included measures of vegetation structure, environmental parameters, and soil properties (Tables 3.5.1-3.5.4) and used bi-plot overlays to represent the strength of the correlations between continuous explanatory variables and the ordination groups. We used a non-parametric multi-response permutation procedure (MRPP) to test for differences in species composition based on study block, main-plot treatment, and split-plot treatment at each location. The procedure produces a T statistic that is a measure of the grouping effect, and an associated *p*-value. We report the *p*-values; a significant *p*-value

Table 3.5.1. Block level summary of secondary matrix data used in non-metric multidimensional scaling analysis at Fort Benning.

Fort Benning	Block					
Variable	1	2	3	4	5	6
Basal area (m/ha)	8.9	8.3	7.9	7.3	9.8	7.3
DBH (cm)	38.0	29.2	25.7	33.9	41.5	32.4
Gap light index (%)	63.5	61.5	67.9	66.1	60.6	65.2
Soil moisture	11.3	7.3	2.8	1.2	7.0	5.8
Soil temperature	30.8	33.2	33.3	33.0	31.2	31.9
Total vegetation cover (%)	73.6	48.2	31.8	34.2	45.0	38.2
Herbaceous vegetation cover (%)	53.0	36.9	24.5	23.8	29.9	18.6
Woody vegetation cover (%)	20.6	11.3	7.3	10.4	15.2	19.5
Graminoid cover (%)	25.8	19.2	9.6	12.2	18.1	5.9
Forb cover (%)	26.1	14.9	13.6	11.5	11.8	12.6
Fern cover (%)	1.0	2.8	1.3	0.0	0.0	0.1
Shrub cover (%)	20.5	8.3	7.2	10.1	13.8	19.3
Woody vine cover (%)	0.1	3.0	0.1	0.3	1.4	0.3
Clay content (%)	16.1	10.1	7.5	5.8	9.9	6.8
Sand content (%)	66.7	75.9	87.2	88.7	76.1	86.9
Silt content (%)	17.2	14.0	5.3	5.5	14.0	6.3
Total soil N (%)	0.063	0.068	0.026	0.024	0.038	0.025
Total soil C (%)	1.084	1.680	0.913	0.703	0.668	0.848
Soil P (ppm)	14.9	5.3	6.9	12.4	10.3	7.5
Soil K (ppm)	87.4	127.5	48.0	53.3	76.5	55.6
Soil pH	5.5	4.7	5.0	4.9	5.0	5.1
Soil organic matter (%)	1.425	1.700	0.863	0.563	0.350	0.525
Cation exchange capacity	8.9	20.0	5.3	3.9	8.0	4.5

Table 3.5.2. Block level summary of secondary matrix data (means) used in nonmetric multidimensional scaling analysis at Camp Lejeune.

Camp Lejeune	Block						
Variable	1	2	3	4	5	7	8
Basal area (m/ha)	6.9	7.5	6.6	7.1	7.2	7.7	10.1
DBH (cm)	25.4	21.6	19.8	18.2	30.9	28.3	33.2
Gap light index (%)	72.8	66.1	71.7	71.8	70.5	68.9	62.7
Soil moisture	7.9	9.6	8.6	7.6	5.4	6.0	6.8
Soil temperature	25.7	27.3	27.0	25.9	26.4	25.9	26.8
Total vegetation cover (%)	48.2	45.4	51.6	51.4	39.4	35.3	57.6
Herbaceous vegetation cover (%)	9.2	9.9	18.0	15.8	18.6	4.9	16.7
Woody vegetation cover (%)	39.0	35.5	33.6	35.5	20.7	30.3	40.8
Graminoid cover (%)	5.3	7.7	12.7	13.3	15.9	3.4	10.9
Forb cover (%)	3.9	2.0	3.9	1.5	2.5	1.5	5.8
Fern cover (%)	0.0	0.2	1.4	1.0	0.2	0.0	0.0
Shrub cover (%)	34.6	32.6	32.9	34.9	20.3	28.0	34.0
Woody vine cover (%)	4.5	2.9	0.7	0.6	0.5	2.3	6.9
Clay content (%)	16.2	20.0	30.1	30.5	5.1	3.5	4.1
Sand content (%)	78.3	73.1	63.4	63.4	91.3	93.0	92.0
Silt content (%)	5.5	7.0	6.5	6.2	3.6	3.5	3.9
Total soil N (%)	0.043	0.043	0.050	0.043	0.034	0.044	0.036
Total soil C (%)	1.043	1.325	1.381	1.193	1.264	0.993	0.980
Soil P (ppm)	6.8	5.3	5.0	4.7	11.9	27.4	17.6
Soil K (ppm)	54.5	47.8	53.8	47.3	42.8	39.6	46.9
Soil pH	5.1	4.8	4.8	4.8	4.3	4.4	4.7
Soil organic matter (%)	1.100	1.025	1.375	1.300	0.988	0.845	0.900
Cation exchange capacity	6.6	12.3	8.2	9.2	10.3	11.1	6.8

Table 3.5.3. Main-plot treatment level summary of secondary matrix data (means) used in nonmetric multidimensional scaling analysis at Fort Benning and Camp Lejeune.

	Main plot treatment							
	Fort Benning				Camp Lejeune			
Variable	Control	MedBA	LowBA	Clearcut	Control	MedBA	LowBA	Clearcut
Basal area (m/ha)	17.5	10.0	5.5	0.0	16.0	9.0	6.4	0.0
DBH (cm)	31.0	35.6	33.8	.	33.1	37.8	34.1	.
Gap light index (%)	38.5	55.1	68.5	94.5	48.2	61.4	69.4	94.3
Soil moisture	7.1	6.9	5.9	4.7	7.9	7.7	7.7	6.4
Soil temperature	31.2	31.9	31.8	33.8	26.9	26.6	26.3	26.3
Total vegetation cover (%)	27.9	42.3	48.5	61.9	31.7	38.4	54.6	58.8
Herbaceous vegetation cover (%)	22.3	30.9	28.8	42.4	10.1	11.2	12.8	18.6
Woody vegetation cover (%)	5.6	11.4	19.7	19.5	21.6	27.2	41.8	40.2
Graminoid cover (%)	11.5	14.6	10.9	23.6	7.8	7.3	9.3	14.3
Forb cover (%)	10.4	15.9	16.1	18.1	1.9	3.8	3.0	3.7
Fern cover (%)	0.4	0.5	1.9	0.7	0.4	0.0	0.4	0.6
Shrub cover (%)	5.2	10.4	18.7	18.4	19.8	23.7	38.4	38.1
Woody vine cover (%)	0.4	1.0	1.0	1.1	1.7	3.5	3.4	2.1
Clay content (%)	11.0	8.8	8.7	8.9	15.7	9.7	17.0	16.7
Sand content (%)	77.4	81.4	80.7	81.6	78.8	85.7	77.5	78.5
Silt content (%)	11.7	9.8	10.6	9.5	5.5	4.7	5.5	4.8
Total soil N (%)	0.040	0.044	0.038	0.040	0.050	0.041	0.046	0.029
Total soil C (%)	0.987	0.923	0.982	1.038	1.373	1.167	1.366	0.754
Soil P (ppm)	7.8	9.1	9.6	11.6	10.4	11.5	8.8	14.8
Soil K (ppm)	71.0	65.9	83.5	78.4	50.9	43.2	46.8	48.6
Soil pH	4.9	5.1	5.1	5.1	4.8	4.6	4.6	4.8
Soil organic matter (%)	1.017	0.792	0.825	0.983	1.110	1.010	1.313	0.800
Cation exchange capacity	9.4	7.6	9.0	7.8	10.3	9.2	10.8	6.3

Table 3.5.4. Split-plot treatment level summary of secondary matrix data (means) used in nonmetric multidimensional scaling analysis at Fort Benning and Camp Lejeune.

	Sub plot treatment					
	Fort Benning			Camp Lejeune		
Variable	NT	H	HF	NT	H	HF
Basal area (m/ha)	8.2	8.5	8.1	7.7	7.7	7.3
DBH (cm)	32.1	35.2	33.0	25.7	25.7	25.3
Gap light index (%)	63.6	65.2	63.7	68.0	69.2	70.2
Soil moisture	6.4	6.2	5.7	7.8	7.1	7.3
Soil temperature	31.9	32.4	32.3	26.2	26.7	26.5
Total vegetation cover (%)	46.3	38.9	50.3	58.5	40.1	42.0
Herbaceous vegetation cover (%)	32.1	26.9	34.3	12.5	14.1	13.4
Woody vegetation cover (%)	14.2	12.0	16.0	46.0	26.0	28.7
Graminoid cover (%)	15.9	12.7	16.9	10.3	9.7	9.6
Forb cover (%)	15.0	13.4	16.9	1.5	4.1	3.7
Fern cover (%)	1.1	0.8	0.6	0.7	0.3	0.1
Shrub cover (%)	13.2	11.0	15.3	41.3	24.0	27.3
Woody vine cover (%)	1.0	1.0	0.6	4.7	1.9	1.4

rejects the hypothesis of within group distance no smaller than expected by chance. We also report the *A*-statistic that describes the within-group homogeneity of the group; $A = 1$ when all items in the group are identical and $A = 0$ when the heterogeneity in the group is equal to that expected by chance. In ecology, values of A that are greater than 0.3 are considered fairly high (McCune and Grace 2002). Indicator species analysis was used to identify species with high importance values for treatments. We analyzed all data together at the 100 m^2 scale at each location but found that the strong effect of the study blocks on composition (Figures 3.5.6, 3.5.7) masked main and split-plot treatments. Consequently, we analyzed data for each block separately at the 10 m^2 scale to demonstrate localized effects of study treatments.

3.5.3. Results

3.5.3.1. Treatment effects on species richness

Overall, total species richness and herbaceous species richness were significantly greater at Fort Benning then at Camp Lejeune at each spatial scale, but woody species richness was greater at Camp Lejeune than at Fort Benning at each spatial scale (Table 3.5.5). At Fort Benning, there was nearly three times the number of herbaceous species as woody species in each of the spatial scales, but at Camp Lejeune total species richness was split evenly between woody and herbaceous species (Table 3.5.5, Figure 3.5.2). As a result, there were approximately 11 more species at Fort Benning than at Camp Lejeune at the 100 m^2 scale, but the difference in herbaceous richness was nearly 20 more species at Fort Benning.

We found no significant interaction effects at any scale for total species richness, herbaceous species richness, or woody species richness at Fort Benning ($p= 0.4556$, $p= 0.3932$, and $p= 0.4524$, respectively) or at Camp Lejeune ($p= 0.2783$, $p= 0.5255$, $p= 0.3506$, respectively). There were no significant main-plot treatment effects on total species richness, herbaceous species richness, or woody species richness at either site (Figures 3.5.2 and 3.5.3).

The split-plot treatments significantly affected species richness at Camp Lejeune but had few effects at Fort Benning (Figures 3.5.4 and 3.5.5). At Camp Lejeune, split-plot treatments that included herbicide (H and H+F) resulted in significantly fewer woody species present when compared to untreated plots (NT) at each spatial scale. The H treatment resulted in an increase in herbaceous species richness at the 1, 10 and 100 m^2 scales, and herbaceous species richness on the H+F plots did not differ from either NT or H at the 0.1, 1 and 100 m^2 scales. Total species richness at Camp Lejeune was significantly lower on the H and H+F plots than the NT plots at the 0.1 m^2 scale but only different between the H+F and NT plots at the 1 and 10 m^2 scales.

Table 3.5.5. Results of t-test to determine differences between mean total species richness, herbaceous species richness, and woody species richness between Fort Benning and Camp Lejeune at each sampling scale

					Fort Benning		Camp Lejeune	
Variable	Scale	DF	t-value	p-value	Mean	SE	Mean	SE
Total species richness	0.1 m^2	131	2.78	0.0063	5.27	0.12	4.66	0.18
	1 m^2	135	2.64	0.0092	12.63	0.30	11.25	0.43
	10 m^2	148	4.50	<0.0001	27.32	0.64	23.26	0.63
	100 m^2	135	6.66	<0.0001	55.93	1.36	44.55	1.04
Herbaceous species richness	0.1 m^2	148	9.24	<0.0001	4.11	0.12	2.42	0.14
	1 m^2	148	10.05	<0.0001	9.90	0.26	5.76	0.31
	10 m^2	148	14.19	<0.0001	20.67	0.50	11.03	0.46
	100 m^2	135	14.12	<0.0001	41.33	1.07	22.44	0.81
Woody species richness	0.1 m^2	141	-7.96	<0.0001	1.16	0.08	2.24	0.11
	1 m^2	131	-10.17	<0.0001	2.72	0.15	5.49	0.23
	10 m^2	148	-12.95	<0.0001	6.65	0.28	12.23	0.33
	100 m^2	148	-10.58	<0.0001	14.60	0.54	22.12	0.47

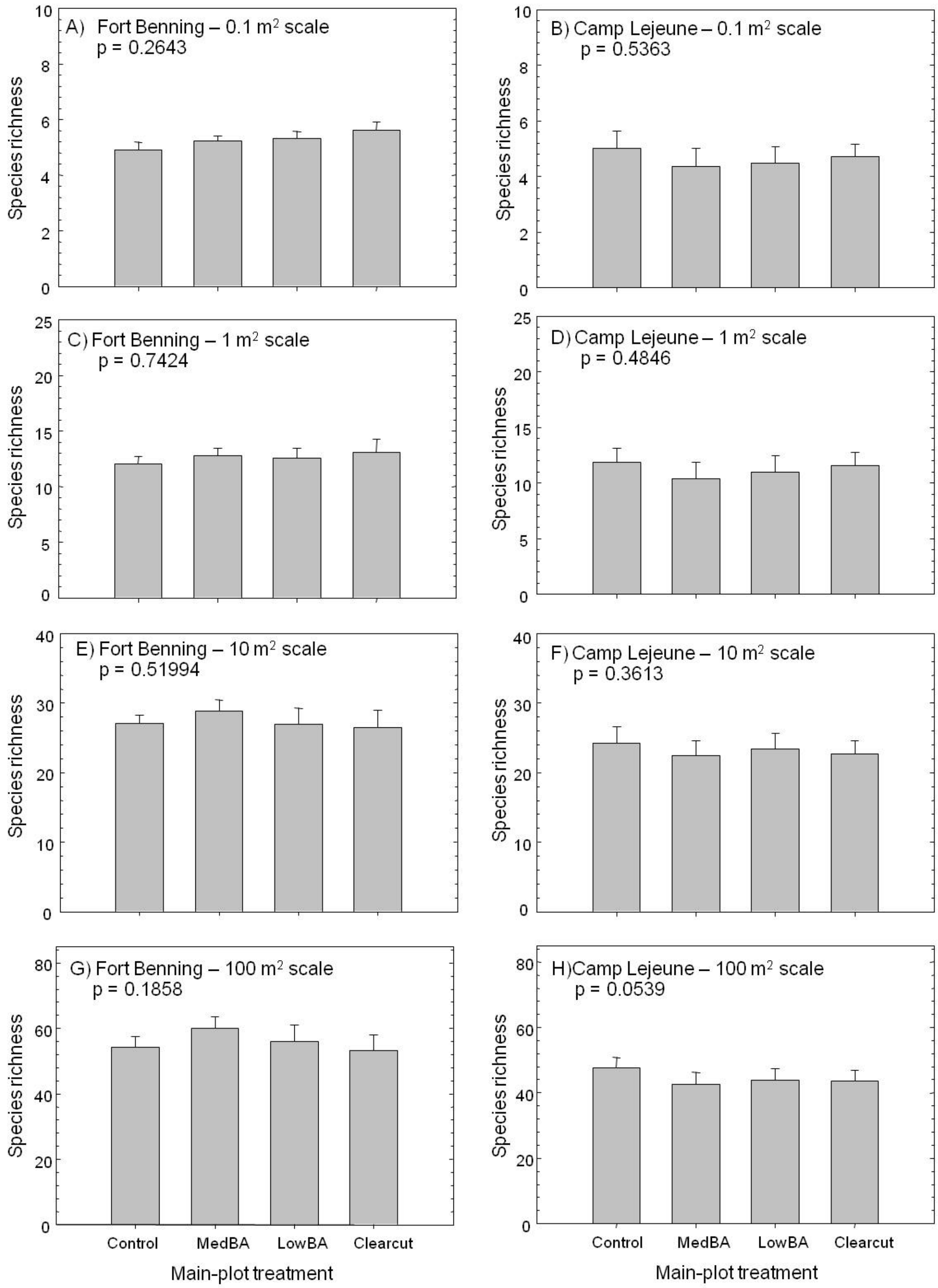


Figure 3.5.2. Total species richness (number of species; mean ± one standard error) by main-plot treatment at spatial scales of 0.1 m^2, 1 m^2, 10 m^2, and 100 m^2 for Fort Benning (A, C, E, and G) and Camp Lejeune (B, D, F, and H).

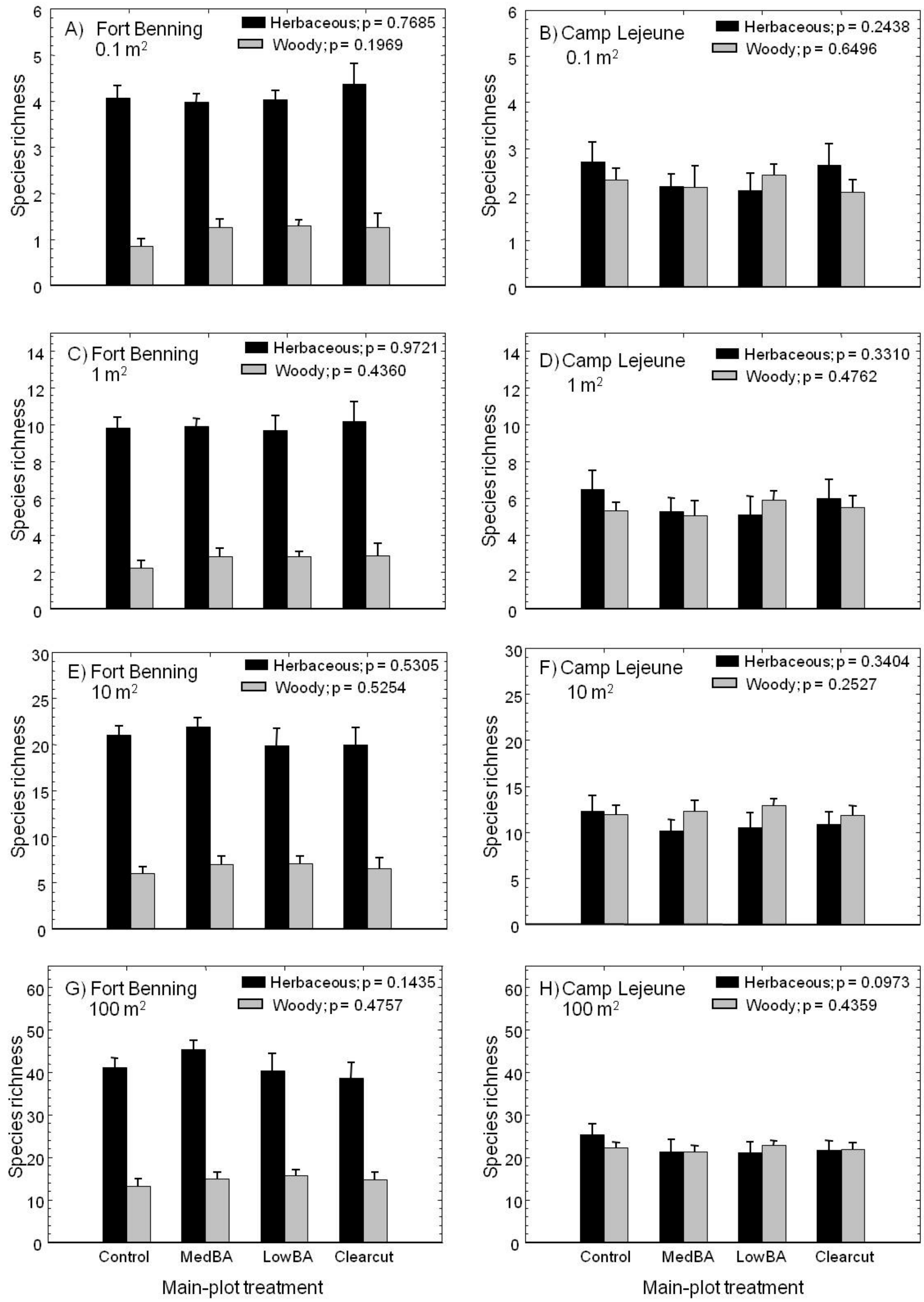


Figure 3.5.3. Species richness (number of species; mean ± one standard error) of herbaceous and woody vegetation by main-plot treatment at spatial scales of 0.1 m^2, 1 m^2, 10 m^2, and 100 m^2 for Fort Benning (A, C, E, and G) and Camp Lejeune (B, D, F, and H).

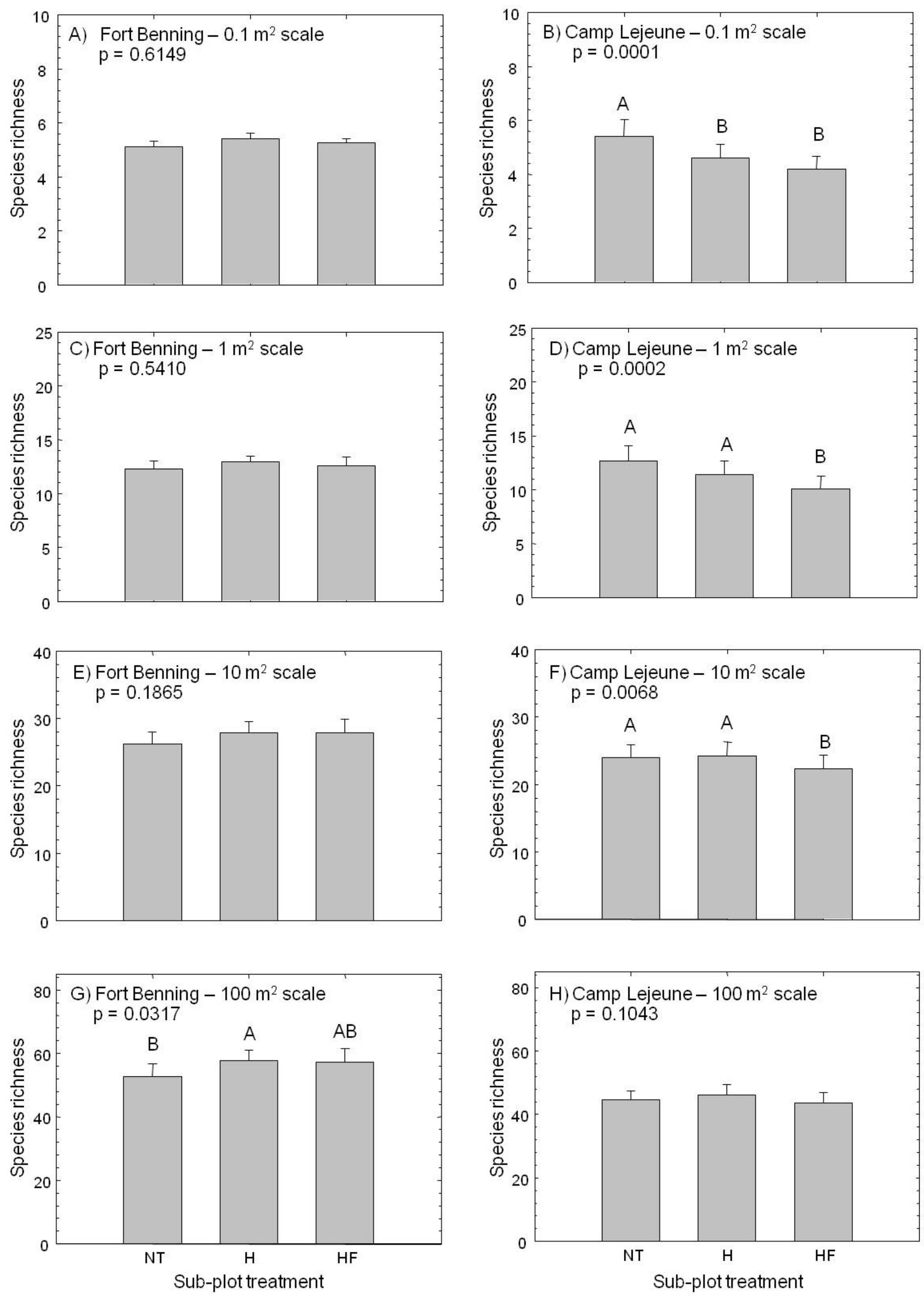


Figure 3.5.4. Total species richness (number of species; mean ± one standard error) by split-plot treatment at spatial scales of 0.1 m^2, 1 m^2, 10 m^2, and 100 m^2 for Fort Benning (A, C, E, and G) and Camp Lejeune (B, D, F, and H). Different letters indicate significant differences at $\alpha = 0.05$.

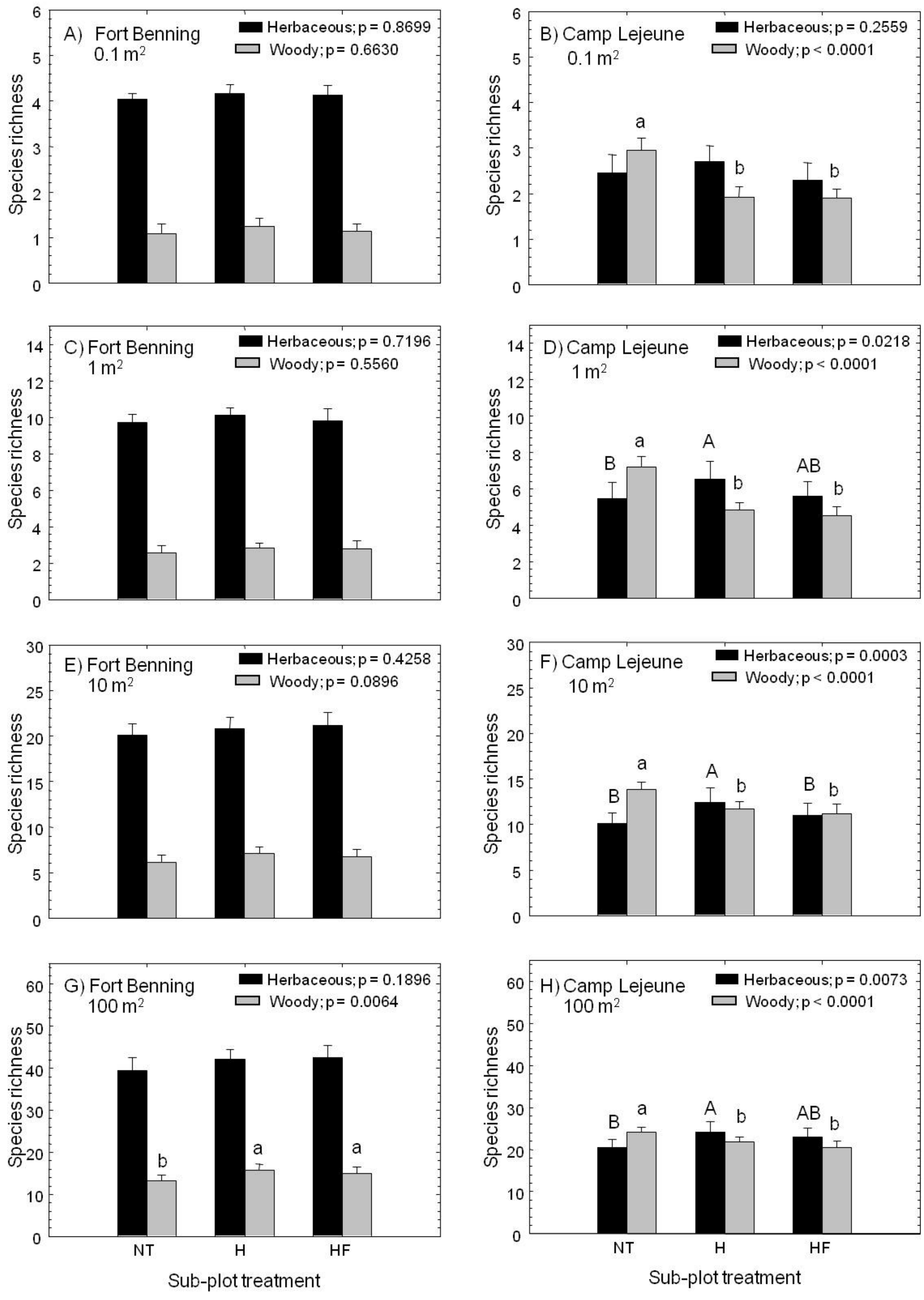


Figure 3.5.5. Species richness (number of species; mean ± one standard error) of herbaceous and woody vegetation by split-plot treatment at spatial scales of 0.1 m^2, 1 m^2, 10 m^2, and 100 m^2 for Fort Benning (A, C, E, and G) and Camp Lejeune (B, D, F, and H). Different letters indicate significant differences within a vegetation type at $\alpha = 0.05$.

3.5.3.2. Factors controlling species composition

At Fort Benning, we determined that a 2-dimensional solution was most appropriate for ordination of the composition data at the 100 m^2 scale. When plotted in ordination space, the plot data was most strongly grouped by study block, and we found that sample units were not aggregated by main-plot treatment or split-plot treatment (Figure 3.5.6). The MRPP test confirmed these results, with significant effects of study block on the ordination of plots (A = 0.2071; $p < 0.0001$), but no significant effects of main-plot treatment (A = 0.0058; p = 0.1326) or split-plot treatment (A = 0.0003; p = 0.4141). The variable from the secondary matrix that most strongly affected the compositional similarity of study plots was the percent sand content, accounting for 51.7% of the variability in Axis 1 (Table 3.5.6). The ordination analysis indicated that a 3-dimensional solution best fit the data at Camp Lejeune, and the results from Camp Lejeune were similar to those from Fort Benning. Study plots separated according to study block (A = 0.2268; $p < 0.0001$) but were not strongly affected by main-plot treatments (A = 0.0053; p = 0.1549) or split-plot treatments (A = 0.0059; p = 0.0973) (Figure 3.5.7). Soil texture, particularly the silt content of the soil, was the variable from the secondary matrix that most strongly affected the distribution of plots along Axis 1 (Table 3.5.7).

When each block was analyzed at the 10 m^2 scale, the MRPP analyses indicated significant main-plot effects and split-plot effects on community composition in all blocks at Fort Benning and at Camp Lejeune (Table 3.5.8). At both sites, plots were more homogeneous within main-plot treatments than within split-plot treatments, as indicated by the higher *A*-statistics for main-plot treatments. Ordination from the block with the highest *A*-value from each site is shown in Figures 3.5.8 and 3.5.9. At Fort Benning, overstory basal area explained 71.3% of the variance in axis 2, while soil phosphorus content explained the most variation in axis 3 (29.0%). At Camp Lejeune, soil moisture was the variable that explained the most variation in axis 1 (36.3%), while soil temperature explained 71.3% of the variation in axis 3. Ordination plots by main-plot and split-plot treatment for the other blocks, as well as the correlation variables from their respective secondary matrices, are included as Appendices A-3.5.1-A-3.5.26.

The indicator species analyses from Fort Benning included primarily perennial forbs as indicators of Control plots, as well as the perennial graminoid *Danthonia sericea* (Table. 3.5.9). In contrast, species associated with the Clearcut plots primarily included annuals that are common following disturbance events. The majority of the indicator species at Fort Benning were significant in only 2 of the 6 blocks, but at Camp Lejeune *Mitchella repens* was a significant indicator of Control plots in 4 of the 7 study blocks. Other indicators at Camp Lejeune included species with a range of growth form and duration habits; for example, Clearcut plots included trees, low growing graminoids (*Dichanthelium* spp.) and one annual species (Table 3.5.9). The importance values and p-values for each species identified by treatment in the indicator species analyses are included as Appendices A-3.5.27-A-3.5.36.

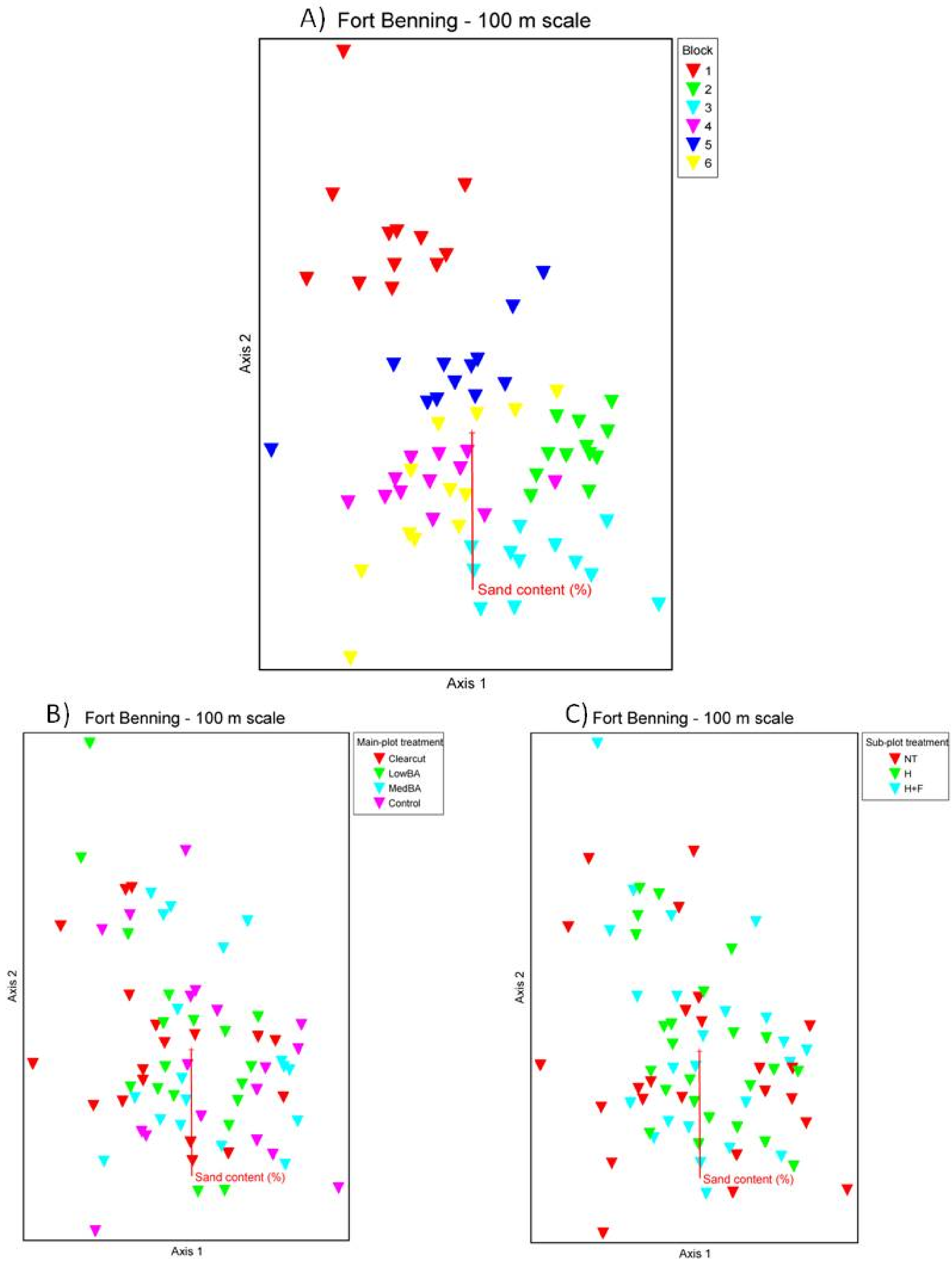


Figure 3.5.6. Ordination plots of species data at the 100 m^2 using non-metric multidimensional scaling and grouped by A) study block, B) main-plot treatment, and C) split-plot treatment at Fort Benning.

Table 3.5.6. Summary of Pearson and Kendall tau correlations with ordination axes at the 100 m scale from Fort Benning.

	Axis 1			Axis 2		
Variable	r	r-square	tau	r	r-square	tau
Basal area (m/ha)	0.269	0.072	0.182	0.013	0.000	0.024
DBH (cm)	0.062	0.004	-0.084	0.155	0.024	0.188
Gap light index (%)	-0.301	0.091	-0.180	-0.017	0.000	-0.057
Soil moisture	-0.051	0.003	0.005	0.613	0.376	0.426
Soil temperature	0.068	0.005	0.070	-0.069	0.005	-0.306
Total vegetation cover (%)	-0.278	0.077	-0.175	0.634	0.401	0.387
Herbaceous vegetation cover (%)	-0.250	0.063	-0.112	0.518	0.269	0.282
Woody vegetation cover (%)	-0.180	0.032	-0.119	0.483	0.234	0.355
Graminoid cover (%)	-0.161	0.026	-0.036	0.393	0.154	0.297
Forb cover (%)	-0.320	0.103	-0.211	0.478	0.229	0.171
Fern cover (%)	0.238	0.057	0.153	-0.029	0.001	0.030
Shrub cover (%)	-0.234	0.055	-0.153	0.480	0.230	0.340
Woody vine cover (%)	0.343	0.117	0.315	0.074	0.006	0.014
Clay content (%)	-0.109	0.012	0.038	0.705	0.497	0.481
Sand content (%)	0.059	0.004	-0.035	-0.719	0.517	-0.547
Silt content (%)	-0.023	0.001	0.001	0.694	0.482	0.562
Total soil N (%)	0.177	0.031	0.113	0.518	0.268	0.456
Total soil C (%)	0.404	0.164	0.253	0.081	0.007	0.048
Soil P (ppm)	-0.556	0.309	-0.447	0.439	0.193	0.157
Soil K (ppm)	0.200	0.040	0.050	0.338	0.114	0.456
Soil pH	-0.560	0.314	-0.435	0.469	0.220	0.240
Soil organic matter (%)	0.293	0.086	0.174	0.251	0.063	0.146
Cation exchange capacity	0.462	0.213	0.253	0.168	0.028	0.252

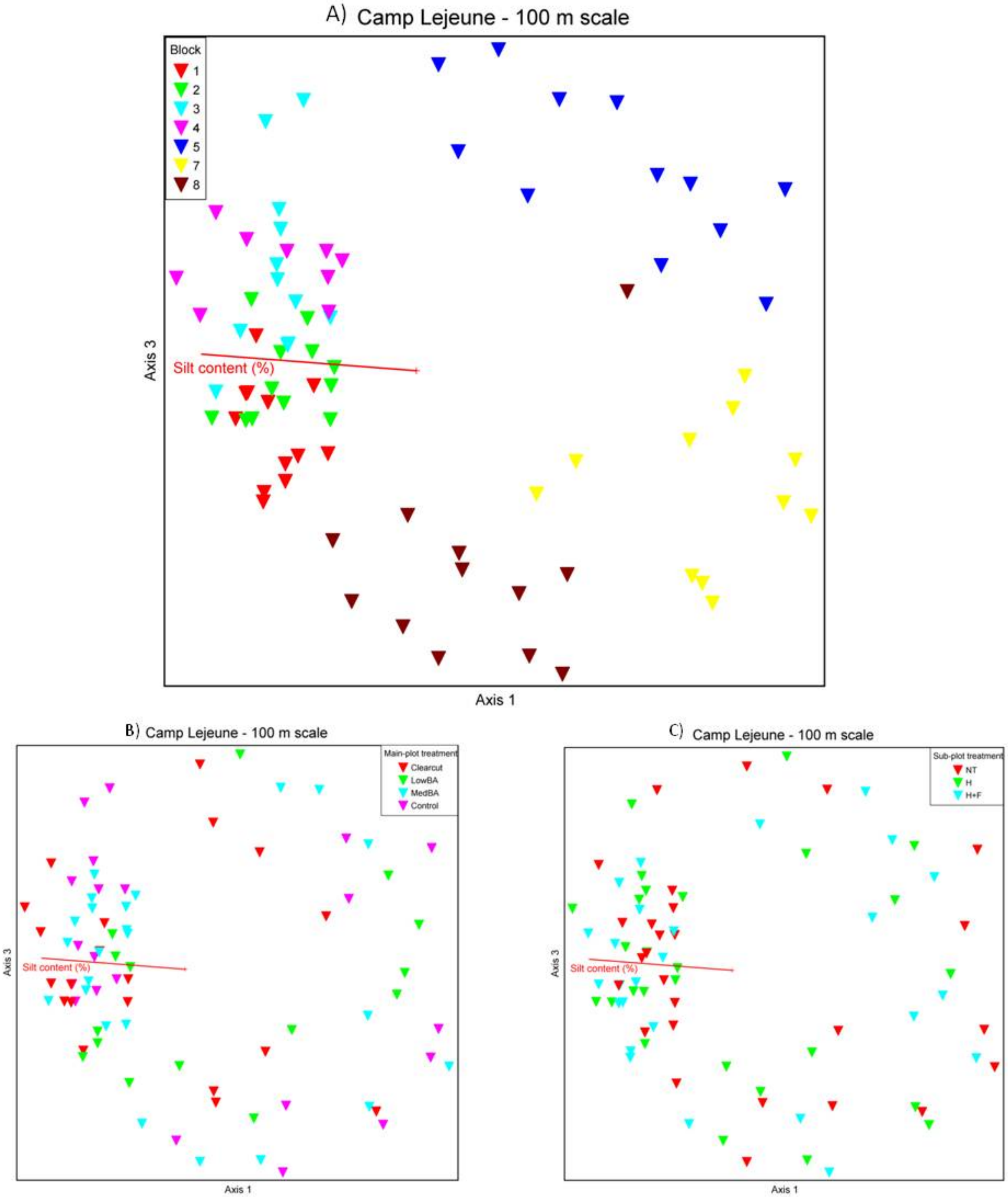


Figure 3.5.7. Ordination plots of species data at the 100 m^2 using non-metric multidimensional scaling and grouped by A) study block, B) main-plot treatment, and C) split-plot treatment at Camp Lejeune.

Table 3.5.7. Summary of Pearson and Kendall tau correlations with ordination axes at the 100 m scale from Camp Lejeune.

Camp Lejeune	Axis 1			Axis 2			Axis 3		
Variable	r	r-square	tau	r	r-square	tau	r	r-square	tau
Basal area (m/ha)	-0.051	0.003	0.004	-0.061	0.004	0.060	-0.102	0.010	-0.071
DBH (cm)	0.108	0.012	0.211	-0.007	0.000	0.071	-0.140	0.020	-0.198
Gap light index (%)	0.050	0.002	0.010	0.065	0.004	-0.076	0.088	0.008	0.075
Soil moisture	-0.440	0.194	-0.268	-0.475	0.225	-0.232	0.185	0.034	0.126
Soil temperature	-0.173	0.030	-0.096	0.427	0.182	0.307	-0.008	0.000	0.003
Total vegetation cover (%)	-0.182	0.033	-0.069	-0.156	0.024	-0.132	-0.102	0.010	-0.046
Herbaceous vegetation cover (%)	-0.073	0.005	-0.068	0.175	0.034	0.200	0.327	0.107	0.299
Woody vegetation cover (%)	-0.151	0.023	-0.058	-0.260	0.067	-0.231	-0.279	0.078	-0.166
Graminoid cover (%)	-0.054	0.003	-0.026	0.080	0.006	0.199	0.451	0.203	0.339
Forb cover (%)	-0.023	0.001	-0.147	0.329	0.108	0.187	-0.145	0.021	0.010
Fern cover (%)	-0.242	0.059	-0.297	-0.063	0.004	-0.031	0.384	0.147	0.355
Shrub cover (%)	-0.150	0.022	-0.079	-0.285	0.081	-0.234	-0.197	0.039	-0.098
Woody vine cover (%)	-0.151	0.023	-0.058	-0.260	0.067	-0.231	-0.279	0.078	-0.166
Clay content (%)	-0.770	0.593	-0.550	-0.231	0.053	-0.080	0.391	0.153	0.368
Sand content (%)	0.792	0.628	0.602	0.241	0.058	0.098	-0.380	0.145	-0.337
Silt content (%)	-0.822	0.675	-0.546	-0.274	0.075	-0.096	0.229	0.052	0.172
Total soil N (%)	-0.220	0.048	-0.237	-0.299	0.090	-0.120	-0.052	0.003	0.019
Total soil C (%)	-0.228	0.052	-0.177	-0.184	0.034	-0.008	0.255	0.065	0.141
Soil P (ppm)	0.693	0.480	0.584	0.053	0.003	0.183	-0.401	0.161	-0.286
Soil K (ppm)	-0.517	0.267	-0.364	-0.068	0.005	-0.020	0.075	0.006	0.024
Soil pH	-0.594	0.353	-0.402	-0.001	0.000	-0.029	-0.264	0.069	-0.158
Soil organic matter (%)	-0.327	0.107	-0.192	-0.256	0.065	-0.035	0.265	0.070	0.145
Cation exchange capacity	0.113	0.013	0.030	-0.313	0.098	-0.118	0.190	0.036	0.056

Table 3.5.8. Results from Multi-Response Permutation Procedures testing effects of main-plot and split-plot treatments on community composition for each block at Fort Benning and Camp Lejeune

Site	Block	Effect	T-stat	A	p-value
Fort Benning	1	main	-14.345	0.139	<0.0001
		sub	-9.808	0.077	<0.0001
	2	main	-16.256	0.118	<0.0001
		sub	-2.861	0.017	0.0081
	3	main	-16.502	0.128	<0.0001
		sub	-3.872	0.024	0.0011
	4	main	-16.635	0.136	<0.0001
		sub	-5.462	0.036	<0.0001
	5	main	-15.019	0.119	<0.0001
		sub	-2.838	0.018	0.0081
	6	main	-17.493	0.166	<0.0001
		sub	-3.097	0.024	0.0092
Camp Lejeune	1	main	-9.248	0.073	<0.0001
		sub	-11.347	0.072	<0.0001
	2	main	-9.505	0.072	<0.0001
		sub	-7.795	0.048	<0.0001
	3	main	-15.019	0.128	<0.0001
		sub	-6.617	0.046	<0.0001
	4	main	-7.835	0.063	<0.0001
		sub	-6.205	0.050	<0.0001
	5	main	-15.311	0.144	<0.0001
		sub	-3.701	0.028	0.0023
	7	main	-13.309	0.125	<0.0001
		sub	-3.079	0.023	0.0046
	8	main	-12.935	0.106	<0.0001
		sub	-6.091	0.040	<0.0001

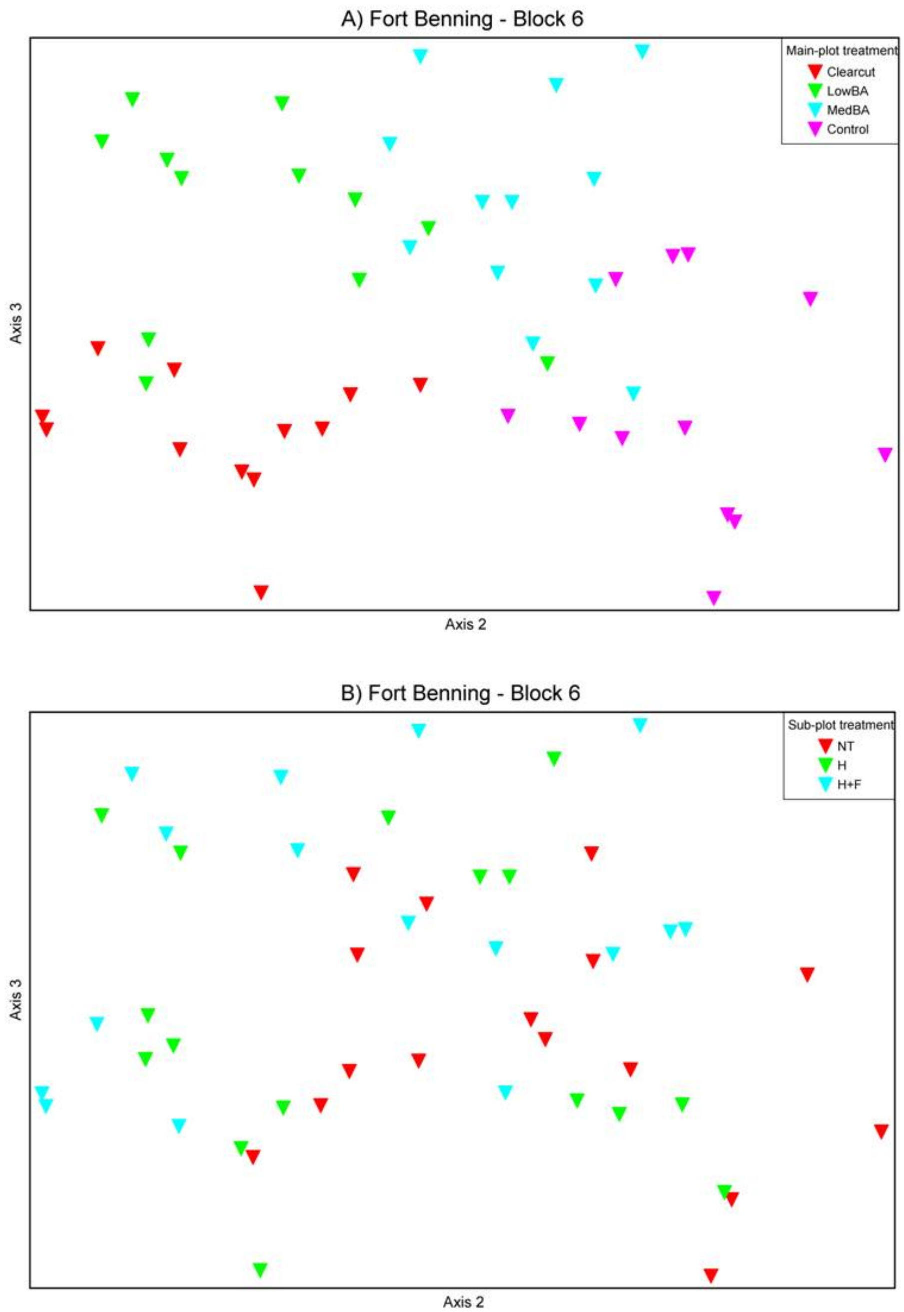
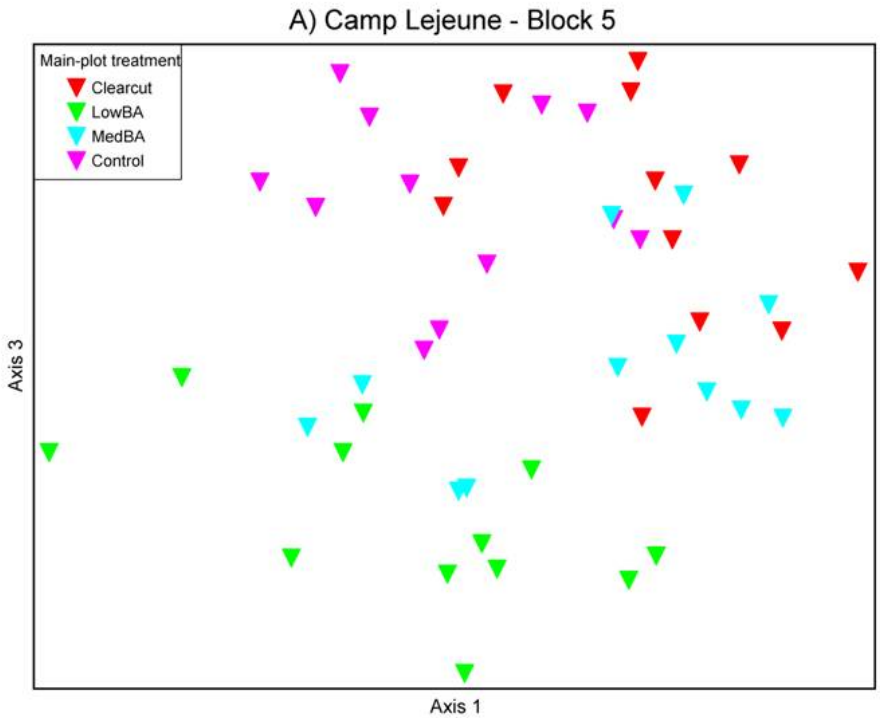


Figure 3.5.8. Ordination plots of species data at the 10 m^2 using non-metric multidimensional scaling and grouped by A) main-plot treatment, and b) split-plot treatment in Block 6 at Fort Benning.



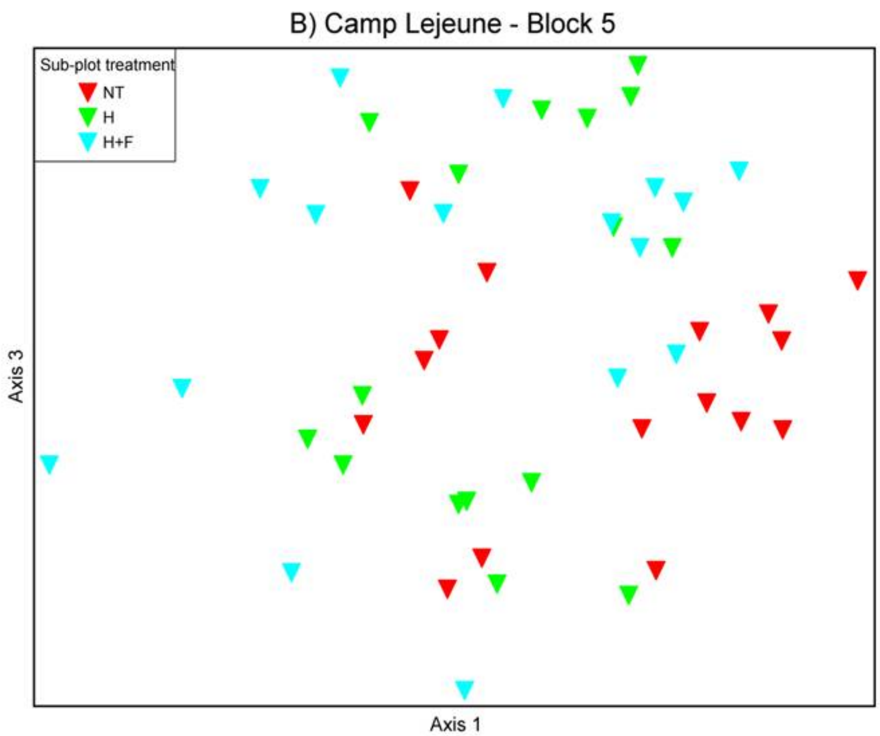


Figure 3.5.9. Ordination plots of species data at the 10 m^2 using non-metric multidimensional scaling and grouped by A) main-plot treatment, and b) split-plot treatment in Block 6 at Camp Lejeune.

Table 3.5.9. Significant indicator species in more than one block from each main-plot treatment at Fort Benning and Camp Lejeune.

Site	Treatment	Species	Growth form	Duration	No. of blocks
Fort Benning	Control	*Ageratina aromatica*	Forb/herb	Perennial	2
		Danthonia sericea	Graminoid	Perennial	2
		Desmodium ciliare	Forb/herb	Perennial	2
		Elephantopus tomentosus	Forb/herb	Perennial	2
		Tephrosia spicata	Forb/herb	Perennial	2
	MedBA	*Saccharum alopecuroides*	Graminoid	Perennial	3
		Ambrosia artemisiifolia	Forb/herb	Annual	2
		Campsis radicans	Vine	Perennial	2
		Eupatorium hyssopifolim	Forb/herb	Perennial	2
	LowBA	*Campsis radicans*	Vine	Perennial	2
		Dichanthelium acuminatum	Graminoid	Perennial	2
		Liquidambar styraciflua	Tree	Perennial	2
		Smilax glauca	Shrub/vine	Perennial	2
	Clearcut	*Agalinis fasciculata*	Forb/herb	Annual	2
		Hypericum gentianoides	Forb/herb	Annual	2
		Lespedeza stuevei	Forb/herb	Perennial	2
		Polypremum procumbens	Forb/herb	Annual	2
Camp Lejeune	Control	*Mitchella repens*	Subshrub/forb/herb	Perennial	4
		Acalypha gracilens	Forb/herb	Annual	2
		Carya pallida	Tree	Perennial	2
		Centella erecta	Forb/herb	Perennial	2
		Chamaecrista nictitans	Subshrub/forb/herb	Annual/perennial	2
		Chasmanthium sessiliflorum	Graminoid	Perennial	2
		Elephantopus tomentosus	Forb/herb	Perennial	2
		Rubus spp.	Subshrub	Perennial	2
		Solidago fistulosa	Forb/herb	Perennial	2
	MedBA	*Bignonia capreolata*	Vine	Perennial	2
		Dichanthelium aciculare	Graminoid	Perennial	2
		Smilax rotundifolia	Shrub/vine	Perennial	2
	LowBA	*Callicarpa americana*	Shrub	Perennial	2
	Clearcut	*Quercus marilandica*	Tree	Perennial	3
		Dichanthelium acuminatum	Graminoid	Perennial	2
		Dichanthelium commutatum	Graminoid	Perennial	2
		Liriodendron tulipifera	Tree	Perennial	2
		Pseudognaphalium obtusifolium	Forb/herb	Annual/biennial	2

3.5.4. Discussion

Patterns in species composition and richness emerged not from experimental treatments, but from differences among treatment blocks. Tobler's (1970) first law of geography states that everything is [spatially] related to everything, but near things are more related than distant things. The similarity among blocks at both Camp Lejeune and Fort Benning show this relationship: blocks that are close in space are also close in ordination space. Various factors may contribute to the spatial dependence of similarity (Nekola and White 1999), and in the context of our study two are notable: (1) physical environments diverge with distance, and (2) sources for species establishment (and persistence when infusions of propagules are necessary for persistence) also change through space. At Camp Lejeune blocks 1-4 are adjacent (Figure 3.1.3), carved from a large area where similar environments, e.g. soils, produced similar vegetation. These blocks are tightly grouped, contrasting with the greater separation among blocks 5, 7, and 8. This latter group was more dispersed on the landscape and had more variable soils. They also were areas that had experienced long periods of fire exclusion, so that any differences in the physical environment plus happenstances of historical composition could have been magnified without the "resetting" function of prescribed fire. At Fort Benning, the blocks nearest to each other (Figure 3.1.2), blocks 1 and 5, and blocks 4 and 6 were closest in ordination space indicating their compositional similarities. Their proximity could have ensured a similar species pool as the communities were assembled, and the physical environments could be similar within those pairs. Blocks 1 and 5 are located in the southwest portion of the base in the Upper Loam Hills Subsection within the Middle Coastal Plain Section (Section 3.1.1; Bailey 1995); 4 and 6 are in the northeast part of base, well within Sand Hills Subsection of the Lower Coastal Plains and Flatwoods Section the sandhills fall line area. Blocks 2 and 3 are intermediate in the ordination, and location. While it is tempting to attribute Fort Benning differences to differences in ecoregion, we have not sampled in a way that can support that idea. We are able to say the proximity is associated with similarity, and the differences in composition are likely related to both physical environment and history.

In addition to the similarity by proximity ideas of Tobler's first law, species in the longleaf pine ecosystem tend to be long lived, at least perennial, and canopy changes based on treatments were conceivably within the range of natural disturbances in these systems. Thus, even if a treatment favored some species over others, the loss of any species may take a long time to occur and the relatively short monitoring period may have been too short to detect the extinction process. We might look for evidence in substantial compositional changes if a treatment effectively eliminated a species or group of species, or explicitly favored the recruitment of new species. The inclusion of ruderal annuals as indicator species in Fort Benning clearcuts is an example of the latter. The persistent and significant woody species reduction in herbicide treated plots at Camp Lejeune may eventually show shifts in composition, especially with continued frequent prescribed burning.

Previous research indicates that diversity of longleaf pine plantations is lower than diversity in reference sites at small scales, with important differences in the composition of the stands (Smith et al. 2002, Walker et al. 2010). In many stands requiring conversion from loblolly pine to longleaf pine, it is likely that the ground layer composition has already diverged from that of remnant longleaf pine stands, particularly in areas with a history of agricultural land use.

Hedman et al. (2000) compared the composition of longleaf pine stands, including second-growth forests, to loblolly pine and slash pine stands on International Paper land in southwestern Georgia and found that longleaf pine stands had significantly higher herbaceous richness and diversity than the other southern pine stands, but that a history of agriculture was most strongly related to changes in ground layer composition. Clearly, the starting condition of the ground layer must be considered when determining the intensity of management to use for restoring of longleaf pine stands.

Overall, species richness was higher at Fort Benning than at Camp Lejeune, with a dominance of herbaceous species at Fort Benning and woody species at Camp Lejeune. However, total richness at each site was similar to levels reported in the literature for similar site types (Peet 2006). For example, Mulligan and Hermann (2004) reported mean species richness of around 12 species/m^2 in upland longleaf pine sites at Fort Benning. Although harvesting intensity had no apparent effect on total, herbaceous, or woody species richness, it did affect the composition of the study plots. Plant species strongly associated with Clearcut plots, particularly at Fort Benning, included annuals that commonly occur on disturbed sites; at Camp Lejeune, opportunistic species such as *Liriodendron tulipifera* and *Dichanthelium* spp. were associated with Clearcut plots. In contrast, the variety of perennial forb species indicative of Control plots suggests the association of these species with largely undisturbed forest canopies. Mulligan and Hermann (2004) described species associated with reference longleaf pine communities at Fort Benning, and identified *Tephrosia spicata* as a possible indicator of habitat quality. Interestingly, *Elephantopus tomentosus*, another species listed by Mulligan and Hermann (2004), was strongly associated with Control plots at both study locations.

3.5.5. Conclusions

The silvicultural practices used in this study had few negative effects on ground layer richness and composition during restoration of longleaf pine stands at Fort Benning and Camp Lejeune. The condition of the ground layer community should be assessed before prescribing management treatments, as the initial condition will strongly control subsequent ground layer response. The herbicide control treatment used in this study effectively controlled woody vegetation at Camp Lejeune (see also Sections 3.4 and 3.6), resulting in potential concomitant increases in herbaceous species richness. In general, we observed compositional shifts in the vegetation communities associated with harvesting density, with ruderal, opportunistic species associated with canopy removal and perennial forb species associated with uncut Control plots.

3.6. Effects of gap size and within-gap position on ground layer vegetation cover

Results in this Section address research objective O-5.

3.6.1. Introduction

Previous research demonstrates that group selection may be a suitable management option for artificially regenerating longleaf pine while retaining canopy trees for other ecological services (e.g. Palik et al. 1997, Palik et al. 2002, Gagnon et al. 2003). Palik et al. (1997) reported that gap sizes of 1,400 m^2 were large enough to maximize seedling growth at gap center, and similar results were reported by McGuire et al. (2001) and supported by our study (Section 3.2). Although relatively small gap sizes may be sufficient for increasing longleaf pine seedling size, Palik et al. (2003) found that a few large canopy gaps within a stand will result in larger average seedling size than many small gaps in a stand cut to the same basal area, suggesting that rapid seedling growth may be realized through the use of fewer large gaps within a stand.

Canopy removal increases resource availability for ground layer vegetation as well as for longleaf pine seedlings (Harrington and Edwards 1999), and the gap dynamics of ground layer vegetation are not well-described. The removal of canopy trees reduces needle loading and potentially limits the effectiveness of frequent prescribed burning in pine stands (Mitchell et al. 2006). Moreover, reduced competition with canopy pines has been found to increase the growth of woody species, especially in the center of large gaps where root competition with canopy pines is eliminated (Kirkman and Mitchell 2006). More woody species within canopy gaps can further inhibit the ability of managers to apply prescribed fires and ultimately threaten longleaf pine restoration efforts.

This study presents findings on the effects of canopy removal and additional cultural treatments on ground layer vegetation response within canopy gaps. Our specific objectives are to: 1) determine effects of canopy gap size on ground layer vegetation abundance; 2) determine effects of cultural treatments used for longleaf pine restoration management (herbicide release, herbicide release plus fertilizer, control) on ground layer vegetation response; and 3) determine effects of canopy position (direction north vs. south and distance from forest edge) on ground layer vegetation response.

3.6.2. Methods

This study was a part of the field experiment replicated at Fort Benning and Camp Lejeune. Study sites, experimental design and treatments are described in Section 3.1.

For this section, we used the gap main-plot treatments (LG, MG, and SG). As detailed in Section 3.1, we selected three north/south oriented seedling rows for applying split-plot treatments. Split-plot treatments were randomly assigned to rows, one per treatment.

3.6.2.1. Data collection

We used longleaf pine seedling rows, which were oriented along north/south azimuths across each gap, to locate split-plot treatment areas in gaps. Three rows were selected and split-plot treatments were randomly assigned to each row. Along each row, we established ten 1 m^2 sampling quadrats that were evenly spaced from gap center to the north forest edge and ten 1 m^2 sampling quadrats that were evenly spaced from gap center to the south forest edge (Figure 3.6.1). At Fort Benning, we established additional sampling quadrats extending to 15 m beyond the forest edge in 2009.

At each 1 m^2 sampling quadrat, we recorded ocular estimates of percent cover for all vegetation < 1 m tall that occurred within the quadrat. We estimated cover as the percentage of the plot that would be shaded if the sun was positioned directly overhead. Cover was recorded using the following cover classes: 1 = trace, 2 = 0-1%, 3 = 1-2%, 4 = 2-5%, 5 = 5-10%, 6 = 10-25%, 7 = 25-50%, 8 = 50-75%, 9 = 75-95%, and 10 = 95-100%, and total cover for a quadrat could sum to over 100% if vegetation overlapped. We estimated cover by functional group (graminoids, ferns, forbs, woody shrubs/trees, and woody vines). Ground layer vegetation cover was recorded in October 2008, 2009, and 2010. A prescribed fire, described in Section 3.1, was applied to all study plots in the dormant season before the 2010 growing season. Prescribed fires were repeated in all study plots at Camp Lejeune in the dormant season before the 2012 growing season.

3.6.2.2. Data analyses

We converted cover class data to the mid-point of each class, and calculated mean values at the split-plot level for analyses. For the first analysis, we used split-split-plot analysis of variance (ANOVA) to determine effects of gap size (main-plot effect), cultural treatment (split-plot effect), and gap direction (split-split-plot effect) on total vegetation cover, total herbaceous cover, and total woody cover. We ran the analyses with Proc Mixed and a random block effect using SAS statistical software (version 9.1; SAS Institute, Inc., Cary, NC).

To determine the effect of gap position, we calculated mean cover values for each variable (total vegetation cover, total herbaceous vegetation cover, and total woody vegetation cover) by averaging across quadrats grouped within 10 m intervals and centered on each 10 m mark (e.g., seedlings located between 5 m and 15 meters were grouped into the 10-m group) across each gap (Figure 3.6.1). Analyses on gap position were run for each gap size separately because each gap included a different number of positions. We ran split-plot ANOVA to determine if interaction effects existed between gap position (main-plot effect) and cultural treatment (split-plot effect). In the event of a significant interaction (found for total vegetation cover in MG plots in 2010 at both sites, woody vegetation cover in MG plots in 2010 at Camp Lejeune, and woody vegetation cover in SG plots in 2009 and 2010 at Camp Lejeune), further analyses were conducted separately for each split-plot treatment. We also used split-plot ANOVA to test for interactions between gap direction (main-plot effect) and gap position (split-plot effect); no interactions were observed and data were pooled across directions (north/south) for analyses. As a result, we used repeated measures ANOVA with a random block effect and a first-order autoregressive covariance structure to determine the effect of measurement year and gap position in 10 m intervals from the forest edge to the gap center on total vegetation cover, total herbaceous

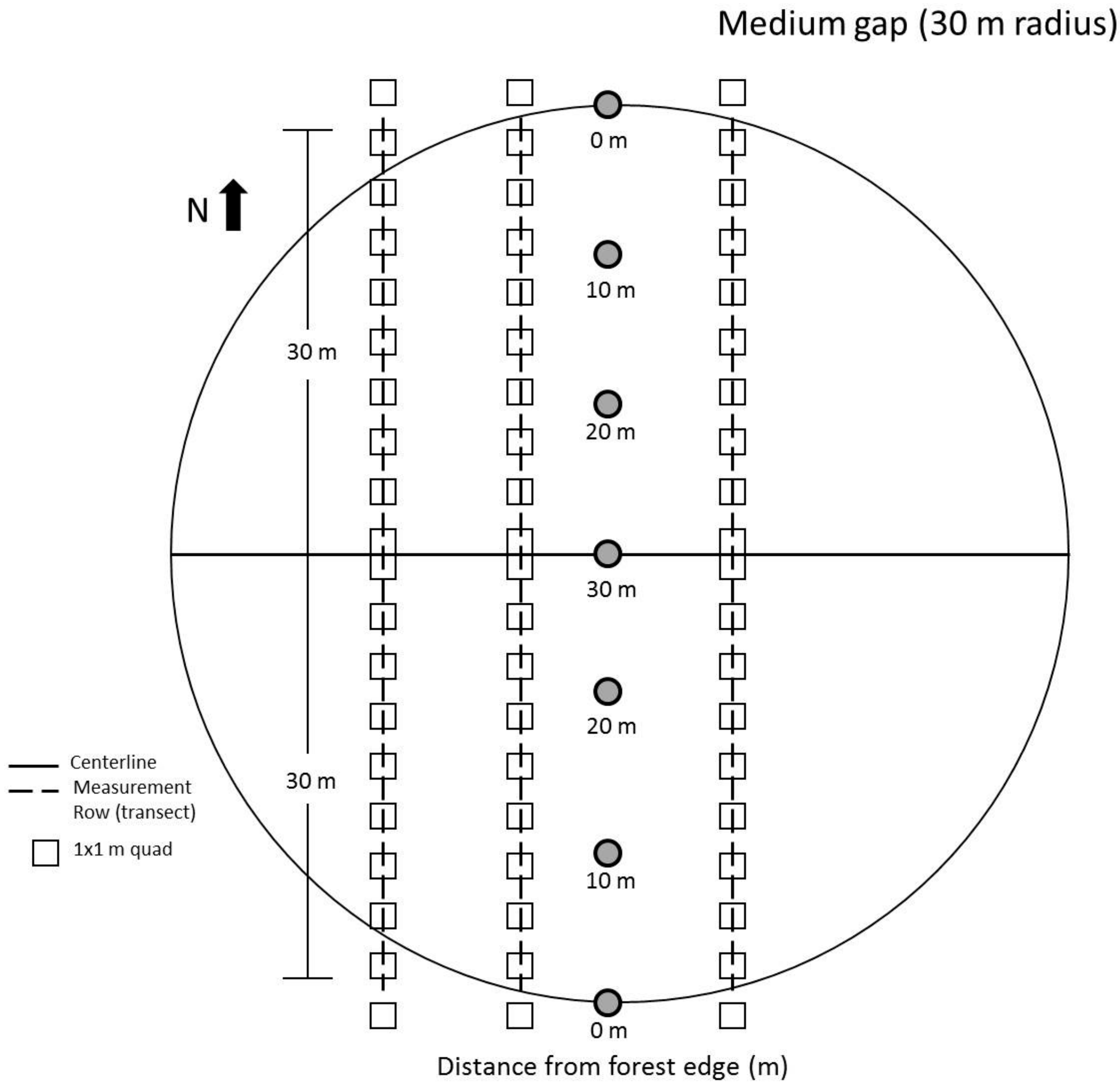


Figure 3.6.1. Sampling design for vegetation cover in gap plots, using MG as an example. The distance between sampling quadrats differed depending on the gap radius

vegetation cover, and total woody vegetation structure. For the repeated measures analyses, we used data from 2009, 2010, and 2012 but excluded data from 2008 because split-plot treatments had not yet been applied.

3.6.3. Results

We found no effect of canopy gap size on total vegetation cover in any year at Camp Lejeune (Figure 3.6.2), with mean cover of 76%, 83%, 69%, and 50% in 2008, 2009, 2010, and 2012 respectively. At Fort Benning, we found that LG plots had greater mean cover (51%) then SG plots (38%) in 2009 and the LG plots had greater mean cover (43%) than MG plots (33%) and SG plots (34%) in 2012. Although the pattern was not consistently significant, we observed a general trend of increasing cover associated with increasing gap size at Fort Benning. There was a significant interaction between main-plot and split-plot treatments in 2010 at Fort Benning (p = 0.0016), in which there were split-plot treatment effects in LG and SG plots but not in MG plots (Figure 3.6.3). There were no other significant interaction effects on total vegetation cover. In 2009, there were significant split-plot effects at Fort Benning and at Camp Lejeune; at both study locations, H and H+F plots had significantly less total vegetation cover than NT plots. This pattern was observed in 2010 at Camp Lejeune, but there were no longer significant split-plot effects at either location in 2012 (Figure 3.6.3). We found no significant interactions of gap size and direction ($p \geq 0.4885$) or cultural treatment and direction ($p \geq 0.1592$) at either location in any year. Gap direction had no significant effect on total vegetation cover in any year at Fort Benning or at Camp Lejeune (Table 3.6.1).

Similar to results from uniform plots (Section 3.4), we found that herbaceous vegetation dominated ground layer cover in gap plots at Fort Benning, but herbaceous and woody cover were more equally represented at Camp Lejeune (Figure 3.6.4). We found no effects of gap size on herbaceous or woody cover in any measurement year at Fort Benning or at Camp Lejeune. Herbaceous cover averaged 38%, 30%, 38%, and 19% in 2008, 2009, 2010, and 2012 at Fort Benning and averaged 34%, 34%, 28%, and 23% over the same years at Camp Lejeune, while woody vegetation cover averaged 15%, 16%, 19%, and 18% in 2008, 2009, 2010, and 2012 at Fort Benning as compared to 41%, 49%, 41%, and 26% during the same years at Camp Lejeune.

There were significant effects of cultural treatments on herbaceous vegetation cover in 2009 at both locations (Figure 3.6.5), and the H plots had significantly less cover than the H+F plots at both sites. Although herbaceous cover was greatest on NT plots at Fort Benning, it was not different from H and H+F plots at Camp Lejeune. There was no effect of cultural treatment on woody vegetation cover at Fort Benning, but at Camp Lejeune woody cover was significantly greater on NT plots than on both H and H+F plots in every year (Figure 3.6.5). We did observe a significant gap size*cultural treatment interaction for 2010 herbaceous vegetation cover at Fort Benning (p = 0.0080). Generally, we found slight reductions in herbaceous cover on H and H+F plots when compared to NT plots for LG and SG gaps, although the treatment differences were not consistent and likely responsible for the observed interaction (Figure 3.6.5e). There were no significant gap size*direction or cultural treatment*direction interactions for herbaceous or woody vegetation in any year at either location ($p \geq 0.2162$). Herbaceous cover was significantly greater on the north half of gaps than the south half of gaps at Camp Lejeune in 2010 and 2012, but direction effects were not significant for herbaceous cover at Fort Benning

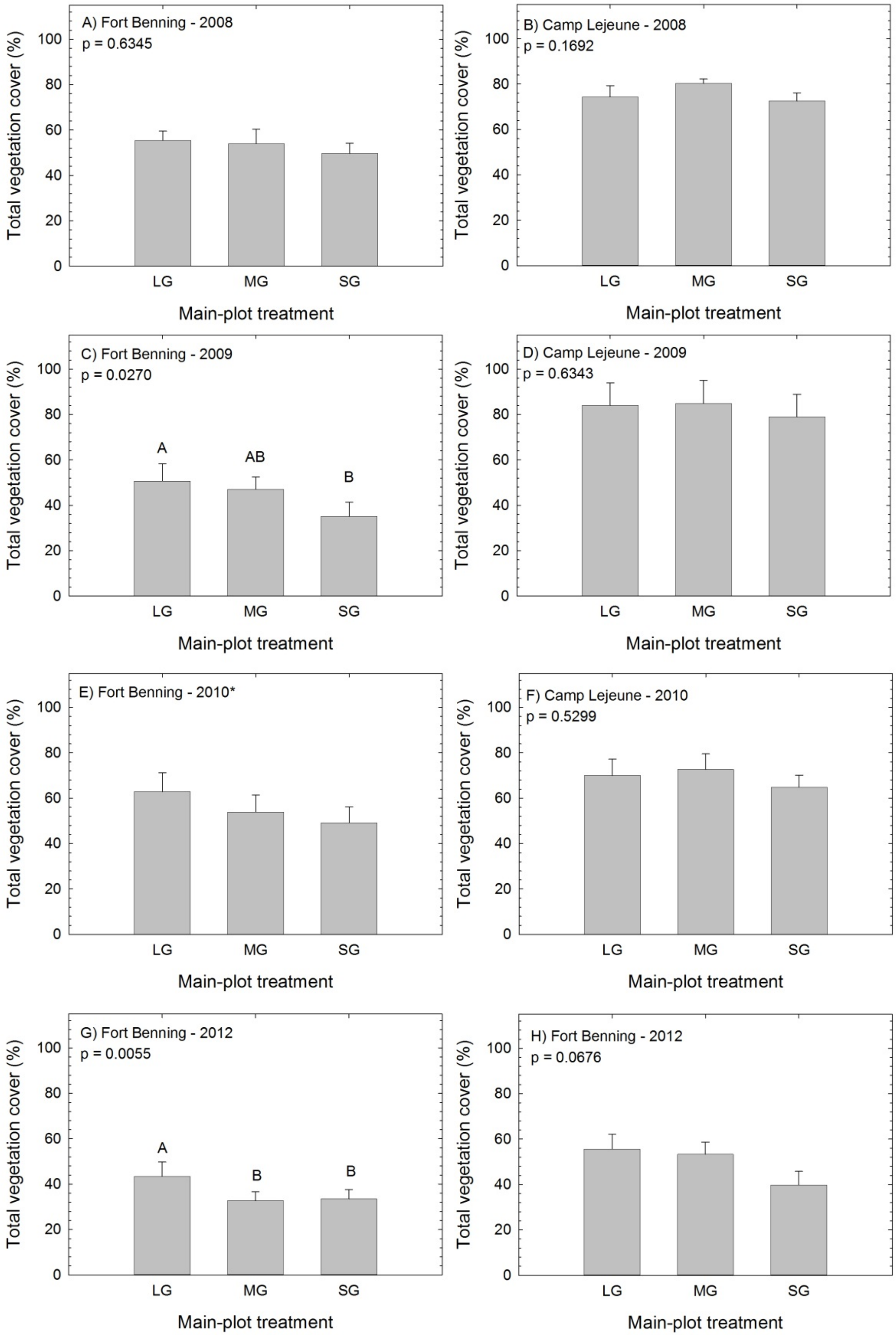


Figure 3.6.2. Total vegetation cover (mean ± one standard error) by gap size from Fort Benning in 2008, 2009, 2010, and 2012 (A, C, E, and G) and from Camp Lejeune (B, D, F, and H). The same letter means no significant difference in pair-wise comparisons at $\alpha = 0.05$.

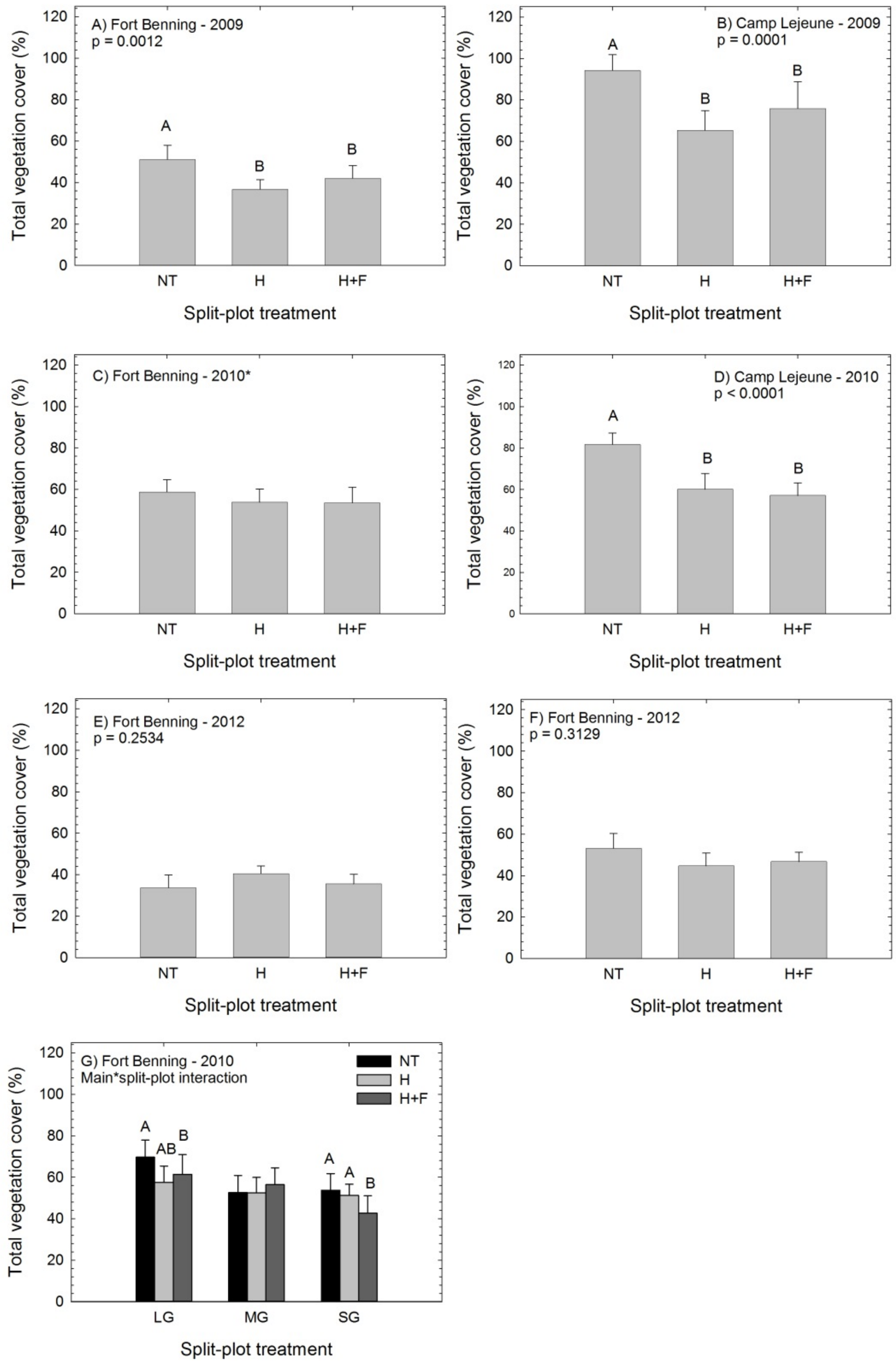


Figure 3.6.3. Total vegetation cover (mean + one standard error) by split-plot treatment from Fort Benning in 2009, 2010, and 2012 (A, C, and E) and from Camp Lejeune (B, D, and F). Panel G shows differences among split-plot treatments within each main-plot with the significant interaction of 2010. The same letter means no significant difference in pair-wise comparisons at $\alpha = 0.05$.

Table 3.6.1. Vegetation cover (total, herbaceous, woody; mean and one standard error) by gap direction in each year and associated *p*-values for a significant direction effect

			North		South		
Site	Year	Cover group	Mean	SE	Mean	SE	*p*-value
Fort Benning	2008	Total	54.4	3.3	51.7	4.7	0.2035
		Herbaceous	38.2	2.9	38.5	4.4	0.8909
		Woody	16.2	3.0	13.2	2.1	0.0090
	2009	Total	43.8	5.7	42.8	6.0	0.7290
		Herbaceous	29.1	4.5	28.9	4.2	0.9532
		Woody	14.7	2.1	13.9	2.5	0.6102
	2010	Total	55.1	5.9	55.5	7.1	0.8254
		Herbaceous	37.2	5.0	37.5	5.7	0.8272
		Woody	18.0	2.3	18.1	2.4	0.9495
	2012	Total	36.6	3.5	36.5	5.5	0.9656
		Herbaceous	19.7	3.5	18.8	3.7	0.6864
		Woody	17.8	1.3	18.6	2.5	0.7477
Camp Lejeune	2008	Total	75.5	3.6	76.3	1.9	0.6220
		Herbaceous	37.0	4.9	33.5	3.7	0.1968
		Woody	38.5	3.1	42.9	2.8	0.0261
	2009	Total	82.4	9.1	79.8	10.0	0.2804
		Herbaceous	35.3	6.0	31.5	6.0	0.5528
		Woody	47.1	5.1	48.3	5.4	0.6806
	2010	Total	66.4	6.6	33.2	6.8	0.7575
		Herbaceous	32.1	7.3	26.6	4.4	0.0131
		Woody	34.3	4.2	39.6	5.6	0.0068
	2012	Total	53.0	5.7	43.4	6.5	0.0281
		Herbaceous	26.4	5.7	18.7	3.2	0.0194
		Woody	26.6	4.2	24.6	5.0	0.4486

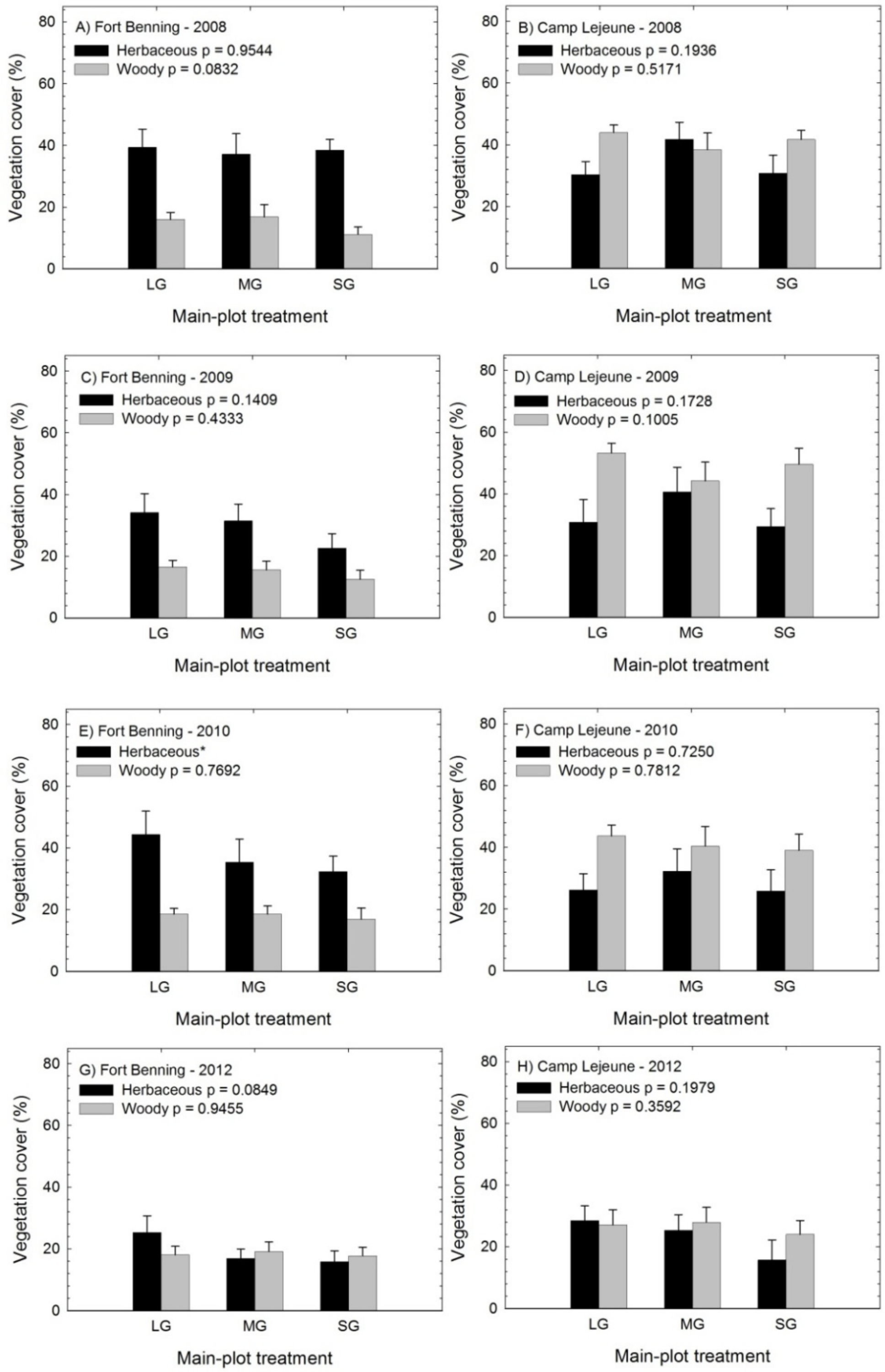


Figure 3.6.4. Herbaceous and woody vegetation cover (mean ± one standard error) by gap size from Fort Benning in 2008-2012 (A, C, and E) and from Camp Lejeune (B, D, and F). The same letter means no significant difference in pair-wise comparisons at α = 0.05;* = significant interaction

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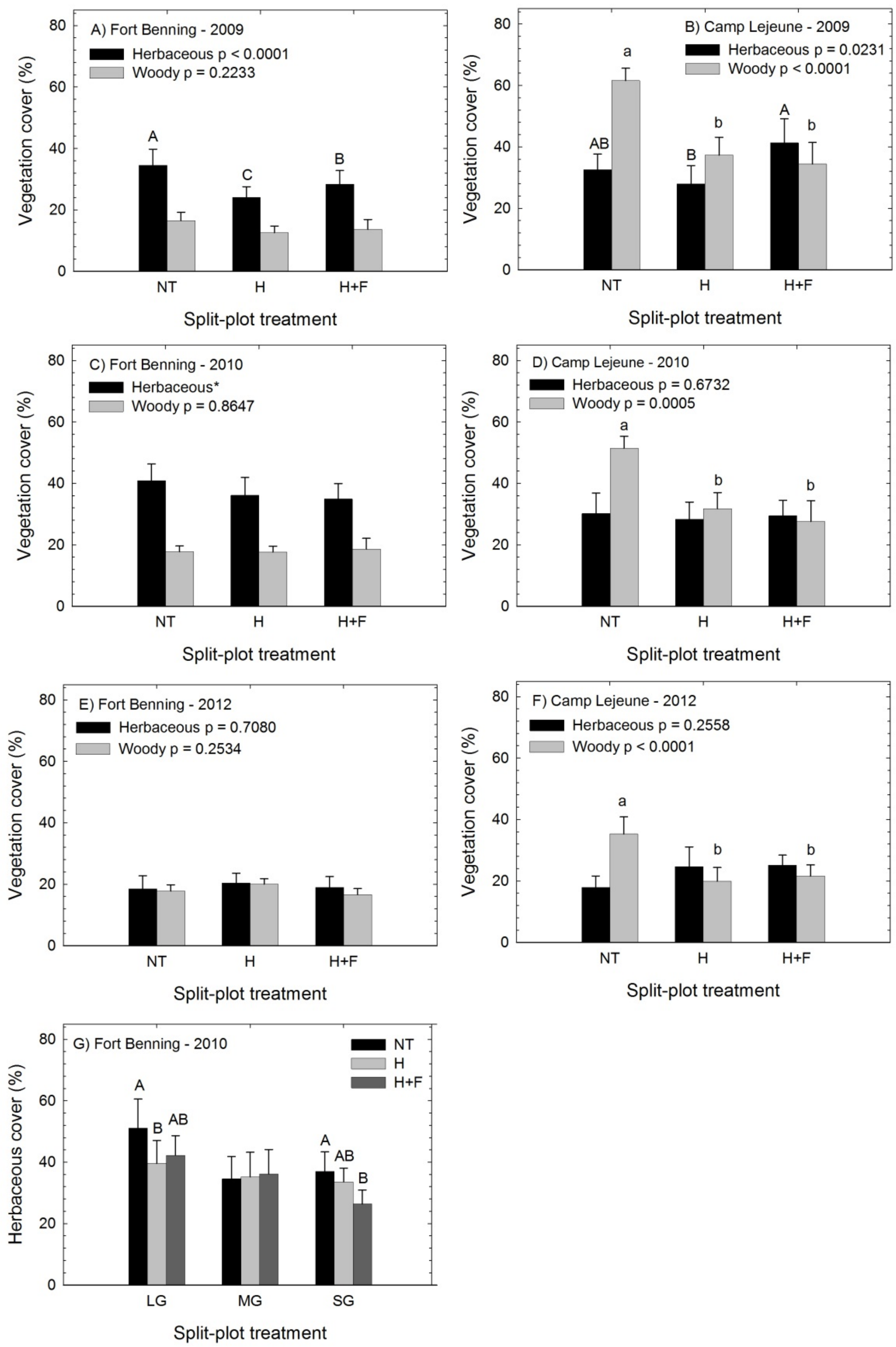

Figure 3.6.5. Herbaceous and woody vegetation cover (mean + one standard error) by split-plot treatment from Fort Benning in 2009, 2010, and 2012 (A, C, and E) and from Camp Lejeune (B, D, and F). Panel G shows a significant main*split-plot treatment interaction for herbaceous cover at Fort Benning in 2010. The same letter means no significant difference in pair-wise comparisons at $\alpha = 0.05$; * indicates significant interaction.

(Table 3.6.1). Woody cover was significantly greater on the north half of gaps than the south half of gaps at Fort Benning in 2008, but we found the opposite trend for woody vegetation in 2008 and 2010 at Camp Lejeune.

The initial analyses found no interaction of gap size and cultural treatment in LG plots ($p \geq 0.1185$), so data were pooled across cultural treatments for the repeated measures analyses. There were no interactions between year and canopy gap position in LG plots at either site for any vegetation cover variable ($p \geq 0.5022$). At Fort Benning, total vegetation cover and herbaceous vegetation cover increased from the forest edge into the gap center, but woody vegetation cover did not differ among gap positions (Figure 3.6.6). There were no effects of canopy gap position on vegetation cover in LG plots at Camp Lejeune. At both study locations, total vegetation cover decreased between 2010 and 2012 in LG plots. At Fort Benning, the decrease was driven by a reduction in herbaceous vegetation, and at Camp Lejeune there by a decrease in woody vegetation between 2010 and 2012 (Figure 3.6.6).

In MG plots, both herbaceous and woody vegetation increased from the forest edge to the gap interior at Fort Benning (Figure 3.6.7), but there were no significant increases from 10 m from the forest edge to gap center. At Fort Benning, herbaceous vegetation decreased from 2010 to 2012 in MG plots, but woody vegetation did not change. There was no effect of gap position on herbaceous vegetation at Camp Lejeune. At both sites, there were significant interactions between cultural treatment and canopy gap position on total vegetation cover in MG plots. At Fort Benning, total vegetation cover increased from the forest edge to the gap center for each of the cultural treatments, but at Camp Lejeune there was no effect of gap position on either NT or HF treatments (Figure 3.6.8). At Fort Benning, total cover decreased on each cultural treatment between 2010 and 2012, but total cover did not decrease on HF split-plots between 2010 and 2012 at Camp Lejeune.

Total vegetation cover, herbaceous vegetation cover, and woody vegetation cover increased from the forest edge to gap center in SG plots at Fort Benning (Figure 3.6.9). Total vegetation cover and herbaceous vegetation cover increased between 2009 and 2010 but then decreased by 2012, but woody vegetation cover increased each year. At Camp Lejeune, there was no effect of gap position on the cover of total vegetation or herbaceous vegetation, both of which decreased between 2010 and 2012 (Figure 3.6.9). There were significant interactions between the cultural treatments and canopy position effects on woody vegetation cover in MG and SG plots at Camp Lejeune. However, there were no significant effects of gap position on woody vegetation cover for any of the cultural treatments in MG or SG plots (Figure 3.6.10). For each of the cultural treatments, woody vegetation cover generally decreased from 2009 through 2012 in MG and SG plots at Camp Lejeune (Figure 3.6.10).

3.6.4. Discussion

The expected association between the amount of canopy removal and increased ground layer vegetation growth (Anderson et al. 1969, Grelen and Enghardt 1973, Ares et al. 2010; see Section 3.4) was not consistently observed when we compared mean ground layer cover among different sized gaps. At Fort Benning, such a trend was significant in 2009 and somewhat apparent in the other years, but there was no pattern in vegetation cover among the gap sizes at

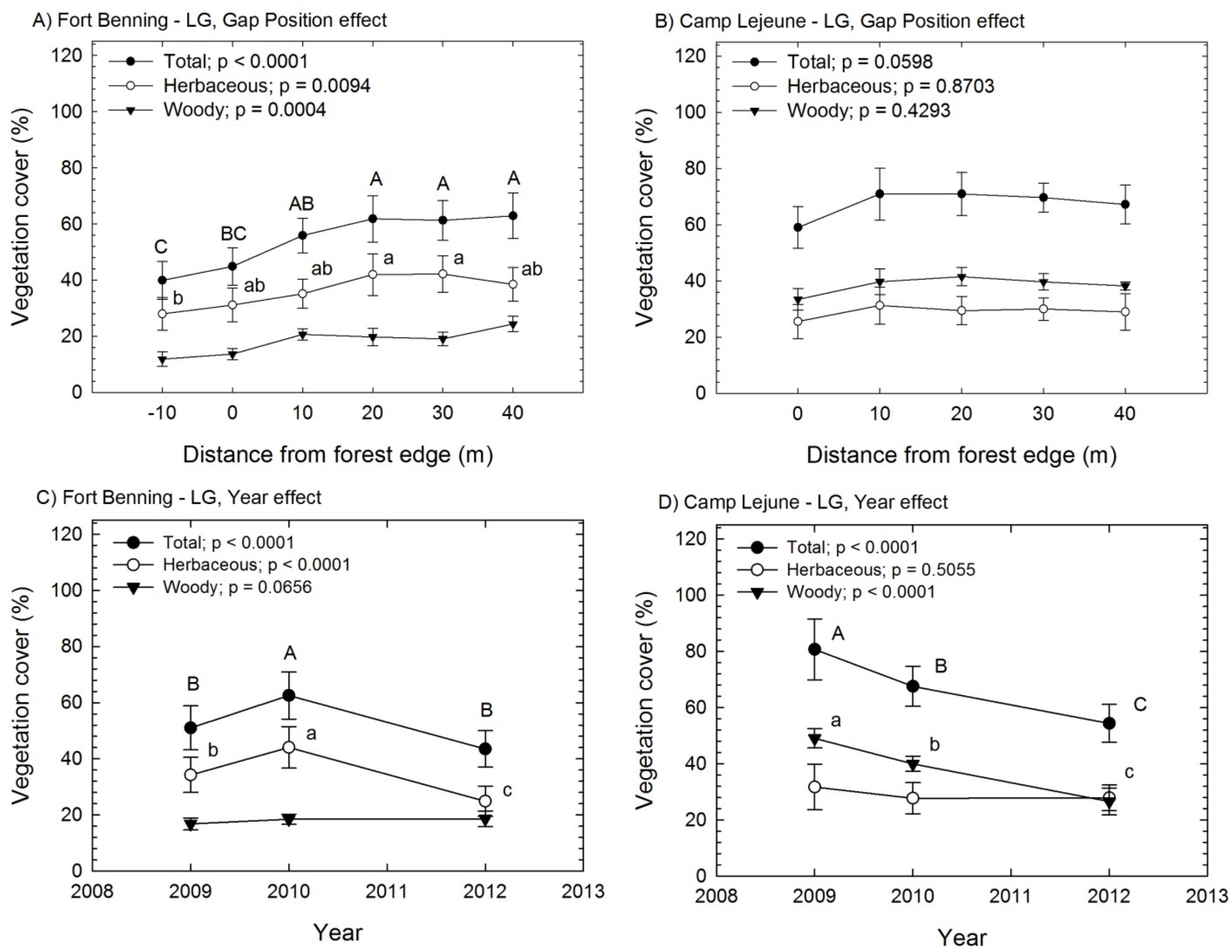

Figure 3.6.6. Cover (mean ± one standard error) of total vegetation, herbaceous vegetation, and woody vegetation in LG plots by A) canopy gap position at Fort Benning, B) canopy gap position at Camp Lejeune, C) year at Fort Benning, and D) year at Camp Lejeune. The same letter indicates no significant difference within a variable at $\alpha = 0.05$.

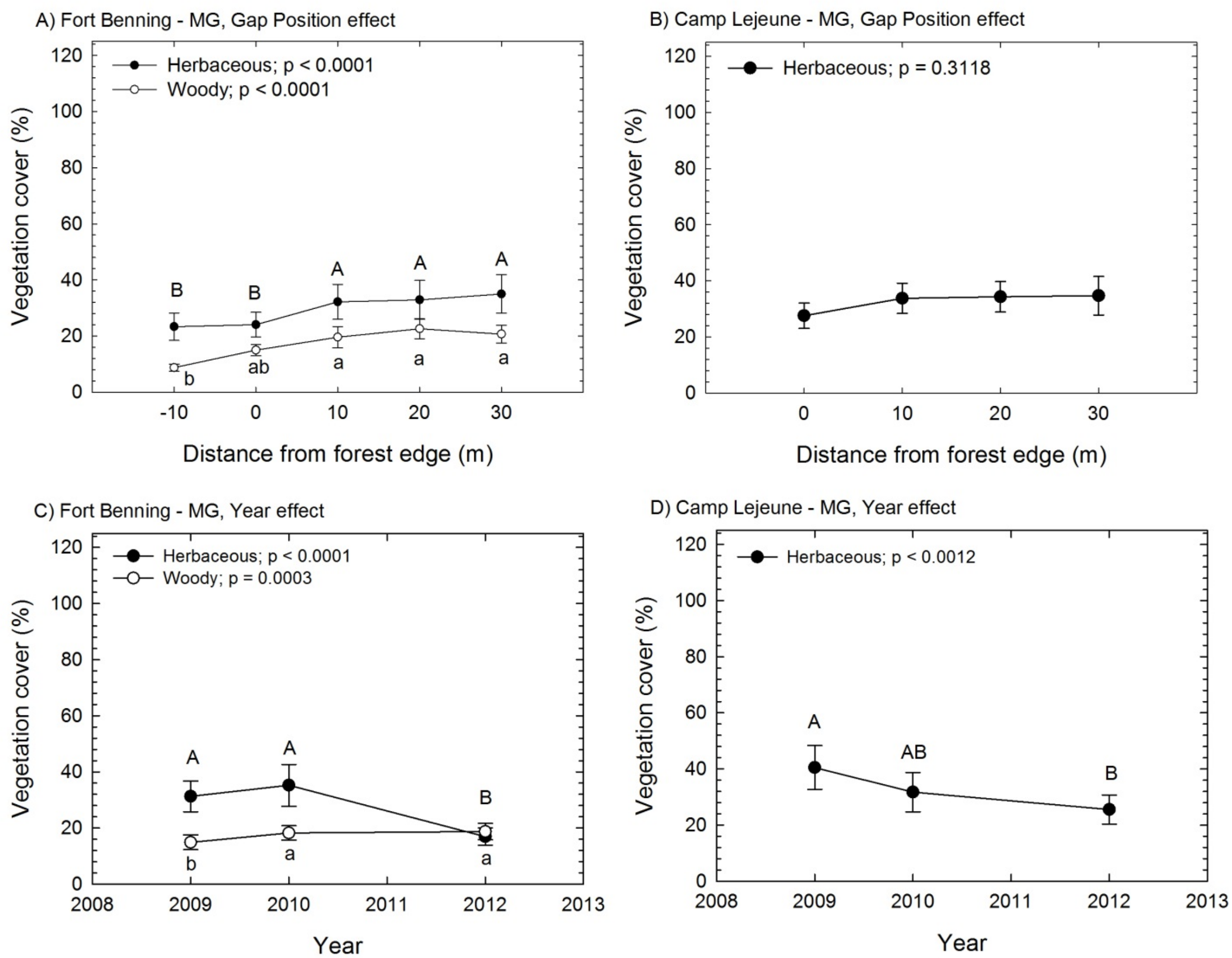

Figure 3.6.7. Cover (mean ± one standard error) of herbaceous vegetation and woody vegetation at Fort Benning and herbaceous vegetation at Camp Lejeune in MG plots by A) canopy gap position at Fort Benning, B) canopy gap position at Camp Lejeune, C) year at Fort Benning, and D) year at Camp Lejeune. The same letter indicates no significant difference within a variable at $\alpha = 0.05$.

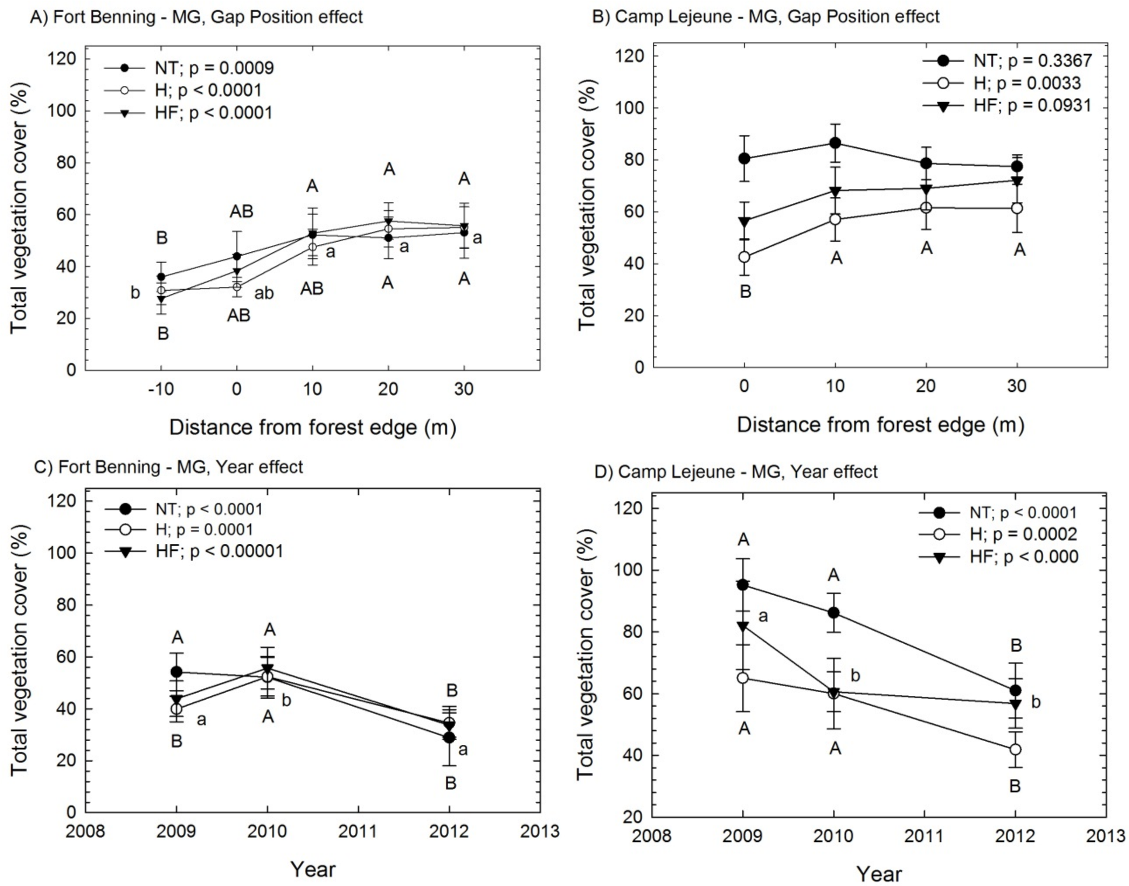

Figure 3.6.8. Cover (mean ± one standard error) of total vegetation by cultural treatment in MG plots for A) canopy gap position at Fort Benning, B) canopy gap position at Camp Lejeune, C) year at Fort Benning, and D) year at Camp Lejeune. The same letter indicates no significant difference within a variable at $\alpha = 0.05$.

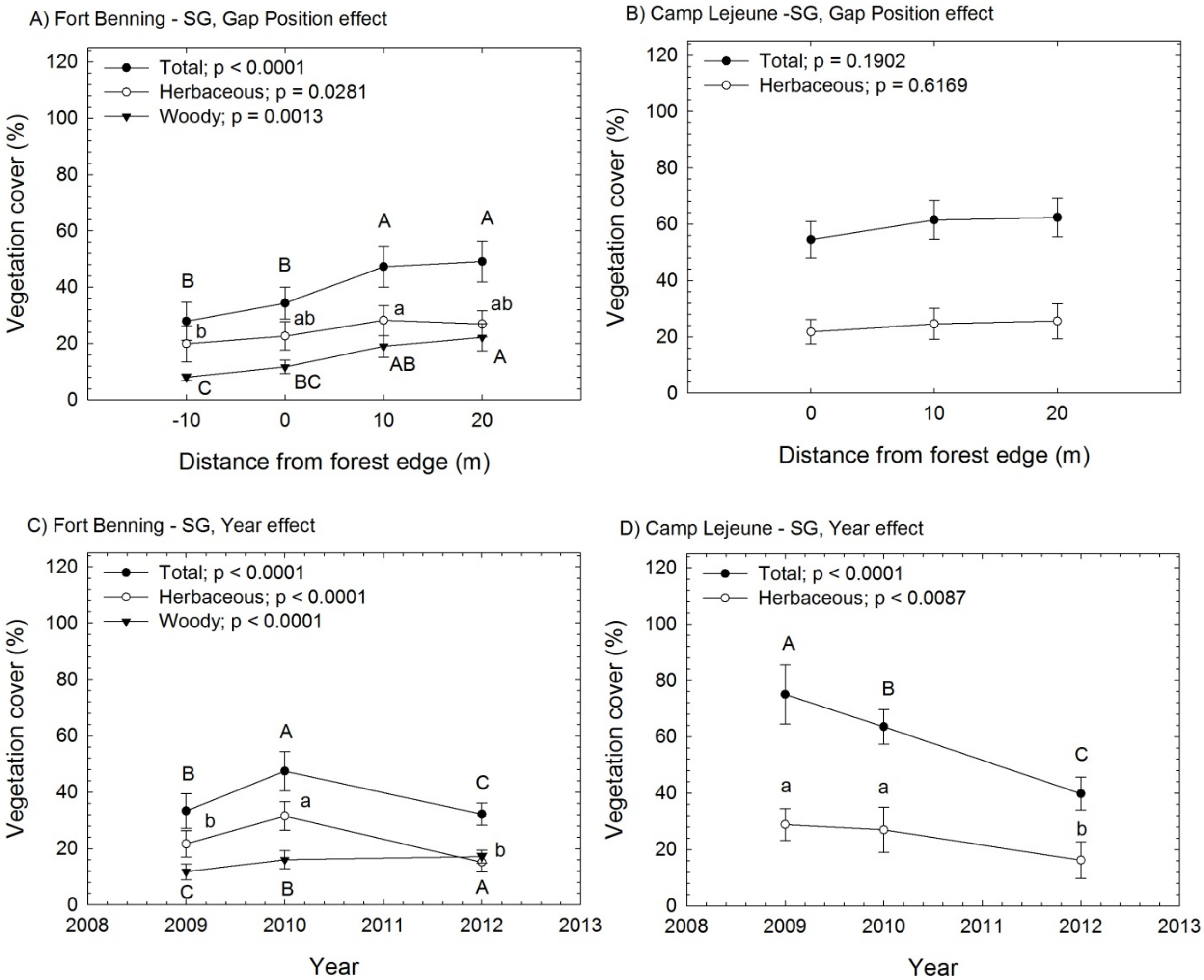

Figure 3.6.9. Cover (mean ± one standard error) of vegetation cover in SG plots by A) canopy gap position at Fort Benning, B) canopy gap position at Camp Lejeune, C) year at Fort Benning, and D) year at Camp Lejeune. The same letter indicates no significant difference within a variable at $\alpha = 0.05$.

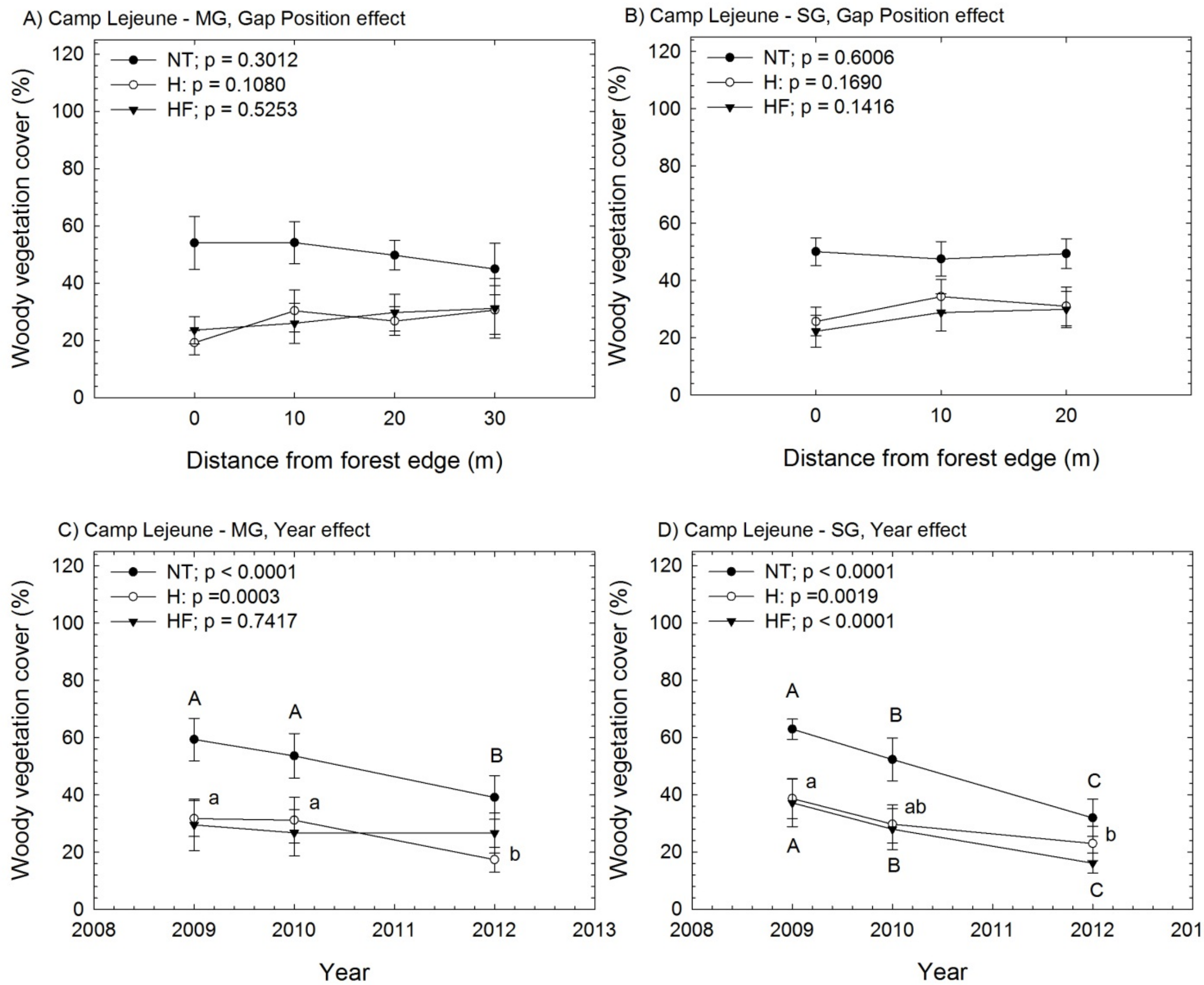

Figure 3.6.10. Cover (mean ± one standard error) of woody vegetation by cultural treatment at Camp Lejeune by A) canopy gap position in MG plots, B) canopy gap position in SG plots, C) year in MG plots, and D) year in SG plots. The same letter indicates no significant difference within a variable at $\alpha = 0.05$.

Camp Lejeune. Total vegetation cover in forest gaps was maximized within 10 m of the forest edge or there was no significant effect of gap position on vegetation cover at Camp Lejeune, but at Fort Benning vegetation cover generally did not reach the maximum until 20 m into the gap interior. It is likely that the overall greater abundance of vegetation at Camp Lejeune and the reduced importance of gap position on vegetation cover resulted in the lack of a gap size effect at Camp Lejeune. In longleaf pine forests of southwestern Georgia, McGuire et al. (2001) reported that mean biomass of understory vegetation increased with increasing gap size (intact canopy, 0.11 ha, 0.41 ha, 1.63 ha gaps), and aboveground biomass of ground layer vegetation reached a maximum 18 m from the forest edge after two growing seasons. Their results are similar to that observed at Fort Benning, which is geographically and ecologically more similar to the sites of McGuire et al. (2001) than are the Camp Lejeune sites.

The morphology and growth habits of herbaceous and woody vegetation are likely to affect their respective response to increases in resource availability. Pecot et al. (2007) used results from a trenching experiment in canopy gaps in longleaf pine forests in southwestern Georgia to suggest that the growth response of woody plants, with deeper roots than the herbaceous layer, is more strongly controlled by competition with canopy pines for below-ground resources than for competition for light. Herbaceous vegetation, on the other hand, was found to respond more strongly to increases in light availability. Similarly, Harrington and Edwards (1999) found that increased abundance of herbaceous vegetation following canopy removal was most strongly controlled by increases in light availability and to a less extent soil moisture. At Camp Lejeune, we observed higher cover of woody vegetation on the south half of gaps than on north half of gaps in 2008 and 2010 despite higher levels of light on the north half of gaps (see Section 3.7), suggesting that below-ground dynamics may be driving the observed differences. The increase in herbaceous cover on the north half of gaps in 2010 and 2012 at Camp Lejeune is not surprising because herbaceous vegetation is expected to respond to increases in light, especially when woody vegetation is not an abundant source of competition.

Control of woody vegetation is often an objective of ground layer restoration in longleaf pine forests, as the reduction of woody vegetation abundance is expected to increase the abundance of herbaceous vegetation (Haywood et al. 2001, Provencher et al. 2001, Freeman and Jose 2009). One concern with the use of patch cutting for longleaf pine restoration is the release and subsequent dominance of woody ground layer species (Jack, et al. 2006, Kirkman et al. 2007), especially if reduced needlefall limits the effective use of prescribed fire as a management tool (Mitchell et al. 2006, Kirkman et al. 2007). Despite a general dominance of woody ground layer vegetation at Camp Lejeune, we did not observe any significant effects of gap position on woody cover. Although woody vegetation cover increased toward gap center at Fort Benning (with the exception of in LG plots), herbaceous vegetation dominated the ground layer in all three years. Woody vegetation encroachment is not increasing at Fort Benning. We think it likely that herbicides used during site preparation killed woody stems and subsequent conditions did not favor new seedling establishment.

Similar to our observations in uniform plots (see Section 3.4), the imazapyr herbicide used in this study was effective at controlling woody vegetation at Camp Lejeune, with reductions in woody vegetation that lasted through 2012. In 2009, the herbicide plus fertilizer treatment resulted in greater herbaceous cover than that in herbicide-only plots, suggesting that herbaceous plants responded to the fertilizer addition with increased growth. However, effects of herbicides on herbaceous vegetation were transient and no longer significant at either site after 2009. At Fort Benning, the sulfometuron methyl treatment was applied to 100% of the sampled area in gaps compared to only around 30% of the sampled area in the uniform plots. Consistent with the difference in area treated, we found a stronger herbicide effect in the gap plots than in the uniform plots (Section 3.4), where the fertilizer treatment increased herbaceous cover to similar levels as the untreated plots. With the complete herbicide coverage in gap sample areas, the response to the fertilizer was limited because there was scant live vegetation present to use the fertilizer and cover was lower than that on untreated plots. The difference in herbaceous cover between the uniform and gap plots represents different methods of application: broadcast, or complete control, in gap plots compared to band-spraying in uniform plots. Managers requiring control of herbaceous vegetation can use band-spray application to reduce competition with planted longleaf pine seedlings at the local seedling level, while maintaining greater abundance of herbaceous vegetation at the stand level.

3.7. Effects of canopy density and distribution on light availability, soil moisture and temperature, and soil nitrogen in pine stands at Fort Benning and Camp Lejeune

Results reported in this section address research objective O-6.

3.7.1. Introduction

Land managers commonly use silvicultural techniques to manipulate growing conditions for target species or individuals, often by removing canopy trees. Canopy removal generally increases the availability of resources (light, nutrients, water) for planted seedlings and other vegetation by eliminating competition from the canopy (e.g. Smith et al. 1997). Light availability at the forest floor is closely related to measures of canopy density because canopy trees are the primary source of light interception within a forest system (Battaglia et al. 2002). However, increases in ground layer or midstory plants following canopy removal may redistribute the level of light interception. Effects of canopy removal on soil nutrients are much more complex; canopy trees provide nutrient inputs through litterfall, uptake nutrients for their own use, and affect microbial activity, litter decomposition, and nutrient release through moderation of soil moisture and temperature (Marshall 2000, Prescott 2002). Nitrogen is the most commonly studied nutrient of forest systems, and previous studies have commonly reported increases in nitrogen following harvesting (Matson and Vitousek 1981, Attiwill and Adams 1993, Titus et al. 2006). Past research has reported varying results of canopy removal on soil moisture, with increases in soil moisture caused by reduced uptake and transpiration by canopy trees (Elliot et al. 1998) and decreases in soil moisture associated with drying effects of increased exposure to solar radiation (Redding et al. 2003). Increased solar radiation also commonly results in increased soil temperatures following timber harvest (Londo et al. 1999, Redding et al. 2003, Moroni et al. 2009).

Natural longleaf pine regeneration is often most successful within canopy gaps, and patch cutting has been proposed as a silvicultural technique for restoring longleaf pine while retaining existing canopy trees for other ecological services. Canopy gaps as small as 0.1 ha have been found to be sufficient for increasing longleaf pine seedling growth (McGuire et al. 2001, also see Section 3.2), suggesting that important changes in resources occur following relatively small-scale canopy removals. Extensive research has been done on the effects of canopy gaps on the micro-environment and site resources in tropical forest systems (e.g. Denslow 1980, Brown 1993, Denslow 1998), where openings in the canopy create very different growing environments than that under the intact canopy. Characteristics of stand structure, including tree height and density, affect the distribution of resources within canopy gaps (Canham et al. 1990), and the relatively open-canopied pine forests of the southeast represent a unique stand structure in which gap dynamics are not fully understood. The smaller spatial extent of canopy gaps as opposed to clear-cut areas allow for evaluation of positional changes in resource distribution following canopy removal, and understanding the dynamics of resource distribution within gaps will inform land managers interested in utilizing patch-cutting as a silvicultural technique for longleaf pine restoration.

The primary objective of this study was to determine the effects of silvicultural treatments that manipulate canopy density and distribution on resources (light, soil moisture, available soil nitrogen) in upland pine stands. Specifically, we were interested in understanding how: 1) canopy density affects available resources; 2) cultural treatments (herbicide and fertilizer) affect available resources; and 3) gap size and position along the north/south axis affect available resources.

3.7.2. Methods

This study was a part of the field experiment replicated at Fort Benning and Camp Lejeune. Study sites, experimental design and treatments are described Section 3.1.

3.7.2.1. Data collection

LIGHT—We used hemispherical photographs to quantify light availability at the main-plot level in July-August, 2008. Hemispherical photographs use geographic information to calculate direct, diffuse, and total light levels that reach a given point throughout the year and have been found to be an accurate assessment of light availability (Canham 1988, Comeau et al. 1998, Battaglia et al. 2003) Within each uniform main plot, we systematically located sampling points at two corners of each split-plot measurement area, with one sampling point at the corner closest to main-plot center and the other located diagonally across each split-plot (n = 8 for each uniform main-plot). In all gap plots, we established sampling points at 10 m intervals along a transect extending north/south across the center of each gap (the number of sampling points varied with gap size). At each sampling point, we mounted a Nikon Coolpix 4500 digital camera that was equipped with a 180° fisheye lens on a self-leveling mount at a height of 1.4 m (DBH). The lens was adjusted to be level with the horizon, and an image of the canopy above each sampling point was captured. To prevent glare and light reflection off foliage, all hemispherical photographs were taken at dawn, dusk, or uniformly cloudy days when the sun was not directly in the image.

To determine effects of ground layer vegetation on light transmittance to longleaf pine seedlings, we quantified photosynthetically active radiation (PAR) at the ground level using an AccuPAR model LP-80 ceptometer (Decagon Devices, Inc.). Measurements of PAR we made only at Fort Benning because we were unable to move the equipment between Fort Benning and Camp Lejeune on a schedule that permitted measuring both locations. All PAR measurements were collected in June-July, 2010. In uniform plots, we selected the longleaf pine seedling that was positioned closest to each split-plot corner and the seedling positioned closest to the split-plot center (target seedlings; n = 5 seedlings per split-plot). We measured PAR 15 cm above the ground directly adjacent to each selected seedling, with care taken to avoid shade from the target seedling. We measured PAR two times at each seedling, with readings taken along perpendicular sides of each seedling. Immediately following seedling-level readings, we repeated PAR measurements at 1.4 m above each target seedling to determine a proportion of light that was penetrating the ground layer vegetation to reach the forest floor. Measurements of PAR were only collected at Fort Benning due to logistics with equipment use, and all PAR measurements were collected in June/July 2010.

SOIL MOISTURE AND TEMPERATURE—In each uniform plot, we measured soil moisture and temperature adjacent to the 5 target seedlings selected for light transmittance estimates. Volumetric soil moisture was measured in the upper 6 cm using a ML2 ThetaProbe moisture meter (Delta-T Devices, Ltd.). The ThetaProbe generates a 100 MHz signal between stainless steel rods extended into the soil, and impedance of the signal between the rods is related to the water content of the soil. We took readings of soil moisture directly east and directly west of each selected seedling. Soil temperature was taken at a depth of 10 cm using a digital thermometer. In each gap plot, we measured soil moisture and temperature at each sampling point established for hemispherical photographs, located at 10 m intervals along a north/south transect through gap center. At Fort Benning, sampling points extended to 20 m into the forest on either end of the transect; at Camp Lejeune, sampling extended to 10 m into the forest on either end. All readings within a block were recorded within two hours to maintain consistent ambient conditions, and no readings were recorded within 24 hours of a precipitation event. Measurements were collected in both May and September in 2009 and in June, July, and August in 2010, and the mean values for each year are reported here.

In each LG plot, we used a PR2 Profile Probe (Delta-T Devices, Ltd.) to measure volumetric soil moisture at depths of 10, 20, 30, 40, 60, and 100 cm. At each 10 m sampling interval we installed a thin-walled fiberglass access tube into which the Profile Probe was inserted for measurement. The Profile Probe generates a 100 MHz signal that is applied to two stainless steel rings at each soil depth, and the stainless steel rings transmit an electromagnetic field that enters the soil around the access tube. The permittivity of the soil is determined by the water content, and an output reading of voltage is converted to volumetric soil moisture through a calibrated equation. Profile moisture was only measured within the large gaps.

AVAILABLE SOIL NITROGEN—We used ion exchange resins (IER) to quantify available nitrogen at different positions within each large gap. The IER technique was developed by Binkley and Matson (1983) and is an effective method for measuring ammonium (NH_4^+) and nitrate (NO_3^-) as it moves through the soil and is thus available to plants (Binkley 1984, 1986). Each IER bag was prepared by mixing 10 g of IONAC C-249 cation (Sybron Chemicals, Inc.) and 10 g IONAC ASB-1P OH anion (Sybron Chemicals, Inc.) in a 5 x 5 cm nylon bag. Nylon bags were created from stocking material, and the edges of the nylon bags were sealed with a heat sealer to prevent stretching and to maintain the size and shape of the bags.

In each large gap, we sampled available soil nitrogen at specific positions on both the north and south half of gaps: gap center (40 meters from forest edge), halfway between gap center and the forest edge (20 m from the forest edge), at the forest edge (0 m from the forest edge) and 10 m into the forest interior (-10 m from the forest edge). At each position, we sub-sampled soil N in three locations: along gap center, halfway between the two longleaf pine seedling rows east of center, and halfway between the two longleaf pine seedling rows west of center. In July 2010, we buried one IER bag 5 cm below the soil surface at each sampling point at Fort Benning. Resin bags were removed in October of 2010 after field incubation for 92 days. In June 2012, we followed the same protocol at each study location, with resin bag removal in October 2012. Care was taken to minimize impacts to the soil surface during installation.

Following removal, IER bags were immediately placed in a cooler for storage for transport to the laboratory and kept in cold storage until extraction. During extraction, each IER bag was placed in 100 ml of 2M KCl and placed on a shaker for 24 hours. The resulting solution was filtered through ashless filter paper and analyzed colorimetrically using a Lachat Auto-Analyzer (Lachat

Instruments) by the USDA Forest Service Rocky Mountain Research Station water lab in Fort Collins, CO.

3.7.2.2. Data analyses

We used HemiView version 2.1 Canopy Analysis Software (Delta-T Devices, Ltd) to calculate light availability for each hemispherical photograph. HemiView uses the longitude and latitude for the study site to determine the diurnal and annual sunpath in each image. A user-defined threshold of light intensity classifies each pixel as open sky or sky obstruction, allowing HemiView to calculate gap fraction and the diffuse and direct solar radiation that reaches the photograph location. For each image, we then calculated the Gap Light Index (GLI) or the percentage of incident PAR transmitted to a point in the understory over the course of a growing season (Canham 1988), using the following equation:

$$GLI = [(T_{diffuse} * P_{diffuse}) + (T_{beam} * P_{beam})] * 100$$

where $P_{diffuse}$ and P_{beam} are proportions of incident seasonal PAR reaching the top of the canopy as diffuse and direct radiation, respectively, and $T_{diffuse}$ and T_{beam} are proportions of diffuse and direct radiation reaching the hemispherical photograph. We assume that $P_{diffuse}$ and P_{beam} are equal to 0.5 (Comeau et al. 1998, Gendron et al. 1998, Battaglia et al. 2002).

We used the PAR values measured with the ceptometer to calculate the percent light transmittance through the ground layer vegetation at each sampling position. Percent light transmittance was calculated as mean PAR at the ground level divided by mean PAR at 1.4 m (above ground layer vegetation) and converted to a percent. To integrate the effects of canopy and sub-canopy vegetation on light transmittance to the forest floor, we multiplied the calculated canopy light transmittance (GLI) by the calculated ground layer light transmittance (sub-canopy transmittance; SCT) as a measure of total light transmittance (TLT) at the seedling level.

We calculated average GLI at the main-plot level and used Analysis of Variance (ANOVA) with a random block effect to determine effects of all seven main-plot canopy treatments on light availability. We determined differences in least square means using post-hoc pairwise comparisons with Tukey's adjustment. We calculated mean percent light transmittance through the ground layer, soil moisture at 6 cm, and soil temperature at the split-plot level for uniform main-plots, and we used split-plot ANOVA with a random block effect to determine main-plot effects, split-plot effects, and main*split-plot interaction effects on response variables.

For gap plots, we used one-way ANOVA with a random block effect to determine the effect of gap position on GLI, light transmittance, surface soil moisture, and soil temperature for each gap. Linear contrasts were used to compare GLI at in the north half of gaps to GLI in the south half of gaps at 10, 20, 30, 40, and 50 m from gap center. We used split-plot ANOVA with gap size as the main-plot treatment and gap direction (north vs. south) as the split-plot treatment to determine such effects on light transmittance, soil surface moisture, and soil temperature. Because only LG plots were used for profile soil moisture and nitrogen availability, we used one-way ANOVA with a random block effect to test effects of gap position and of gap direction (north vs. south) on those variables. We used linear contrasts to determine differences in nitrogen availability (NH_4^+, NO_3^-, and total) between positions within the gap (20 m from the forest edge in either direction and gap center) and positions beneath the intact canopy (in either direction).

3.7.3. Results

3.7.3.1. Light

Light availability at 1.4 m from the ground was significantly affected by the canopy treatments at Fort Benning and at Camp Lejeune (Figure 3.7.1), with the lowest light levels on the uncut Control plots. GLI increased in uniform treatments with decreasing basal area and was near 100% in Clearcut plots. The average GLI in gap plots was highest on LG plots and decreased with gap size, although all canopy gaps had higher light levels than the uncut Control plots. Within gaps, light levels increased from within the forest to gap center at both study sites, with the highest levels of light slightly north of gap center (Figure 3.7.2). Regardless of gap size, the north half of the gaps received higher light levels than the south half of the gaps at both study sites (Figures 3.7.3-3.7.5). The direction effect was strongest (i.e. greatest difference between the north and south sides) at the forest edge for all gap sizes, although we found no effect of direction on GLI at distance from gap center in the SG plots at Camp Lejeune (Figure 3.7.5).

We found a significant main-plot treatment effect on light transmittance through the ground layer vegetation at Fort Benning, where light transmittance was highest on the uncut Control plots and lowest on the Clearcut plots (Figure 3.7.6a). There was no main-plot*split-plot treatment interaction ($F = 0.30$; $p = 0.9327$) and no split-plot treatment effect (Figure 3.7.6b). Despite the higher interception of light by sub-canopy vegetation on Clearcut plots, the Total Light Transmittance was highest on Clearcut and lowest on Control plots, with no significant split-plot effects on total light transmittance (Figure 3.7.6). Among the gap plots, we found no interaction effect between gap size and gap direction ($F = 1.38$; $p = 0.2455$) and there was no effect of gap size ($F = 2.22$; $p = 0.1457$) or direction ($F = 0.01$; $p = 0.9390$) on light transmittance. Although all gaps showed a similar general pattern, with the highest levels of light transmittance within the forest canopy and decreasing transmittance toward gap center, we only found significant position effects in the MG plots (Figure 3.7.7).

3.7.3.2. Soil moisture and temperature

There were no significant interactions between uniform main-plot and split-plot effects on soil moisture at a 6 cm depth in 2009 or 2010 at Fort Benning ($p \geq 0.2908$) or at Camp Lejeune ($p \geq 0.0762$). We observed a general pattern of increasing soil moisture with increasing basal area in both years at Fort Benning, but we found no significant effects of main-plot treatments on soil moisture at either site (Table 3.7.1). There were no significant main-plot by split-plot interaction effects on soil temperature in uniform plots in either year at Fort Benning ($p > 0.0650$) or at Camp Lejeune ($p > 0.8572$). There were no main-plot effects on soil temperature in either year at Camp Lejeune, but we found that uncut Control plots had significantly lower soil temperatures when compared to the LowBA and Clearcut plots at Fort Benning in 2009 (Table 3.7.1). In 2010, the Clearcut plots had higher temperatures than all other treatments at Fort Benning. We found significant split-plot treatment effects on soil temperature in 2009 at Fort Benning and

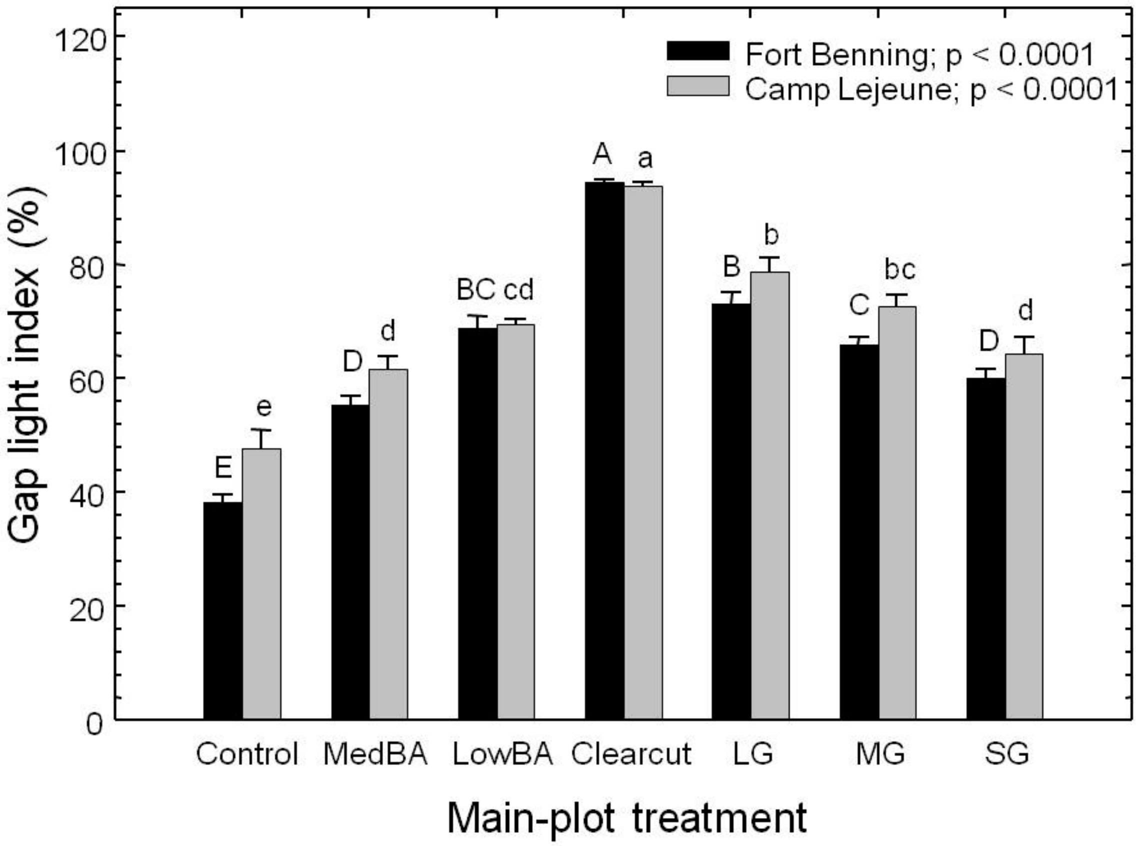

Figure 3.7.1. Gap light index (mean ± one standard error) by main-plot treatment at Fort Benning and Camp Lejeune. Different letters indicate significant treatment differences within a study location.

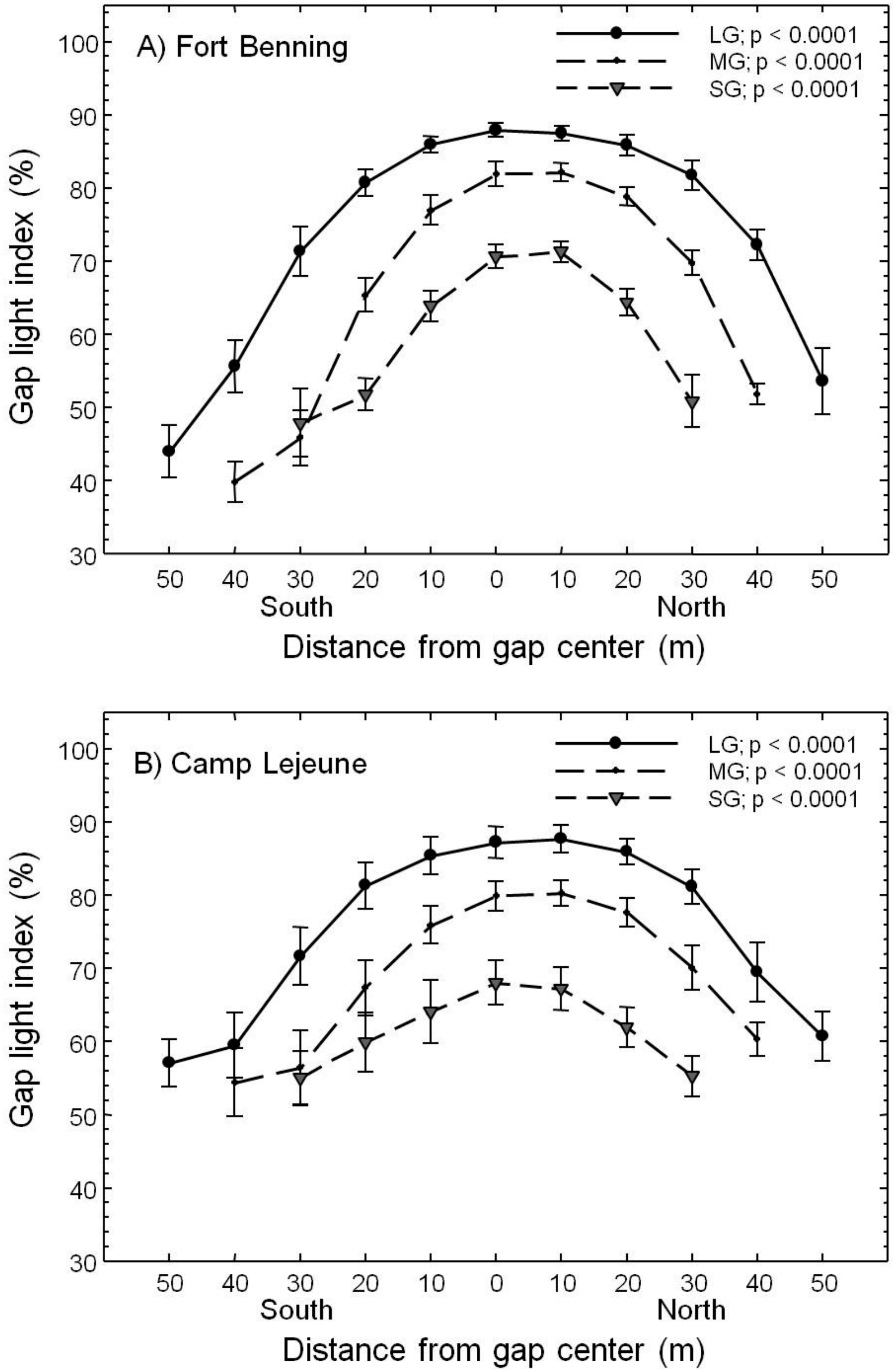

Figure 3.7.2. Gap light index (mean ± one standard error) by distance from gap center for LG, MG, and SG at A) Fort Benning and B) Camp Lejeune. The forest edge locations at each gap are as follows: LG = 40m, MG = 30m, SG = 20m.

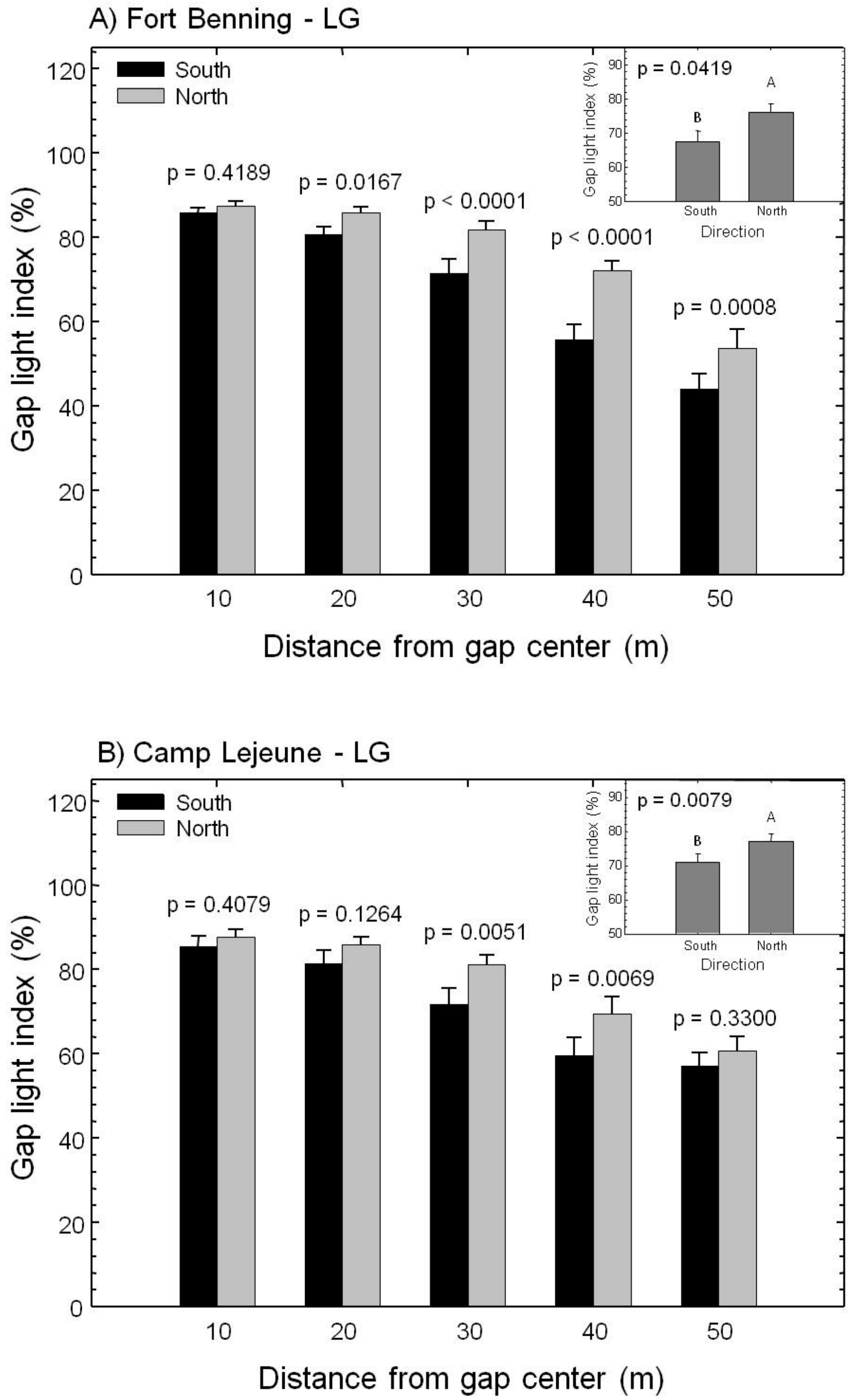

Figure 3.7.3. Gap light index (mean ± one standard error) by distance from center to south and north in LG plots at A) Fort Benning and B) Camp Lejeune. *p*-values are from linear contrasts that compare south and north directions. Insets: gap light index (mean ± one standard error) by direction. Different letters indicate significant differences.

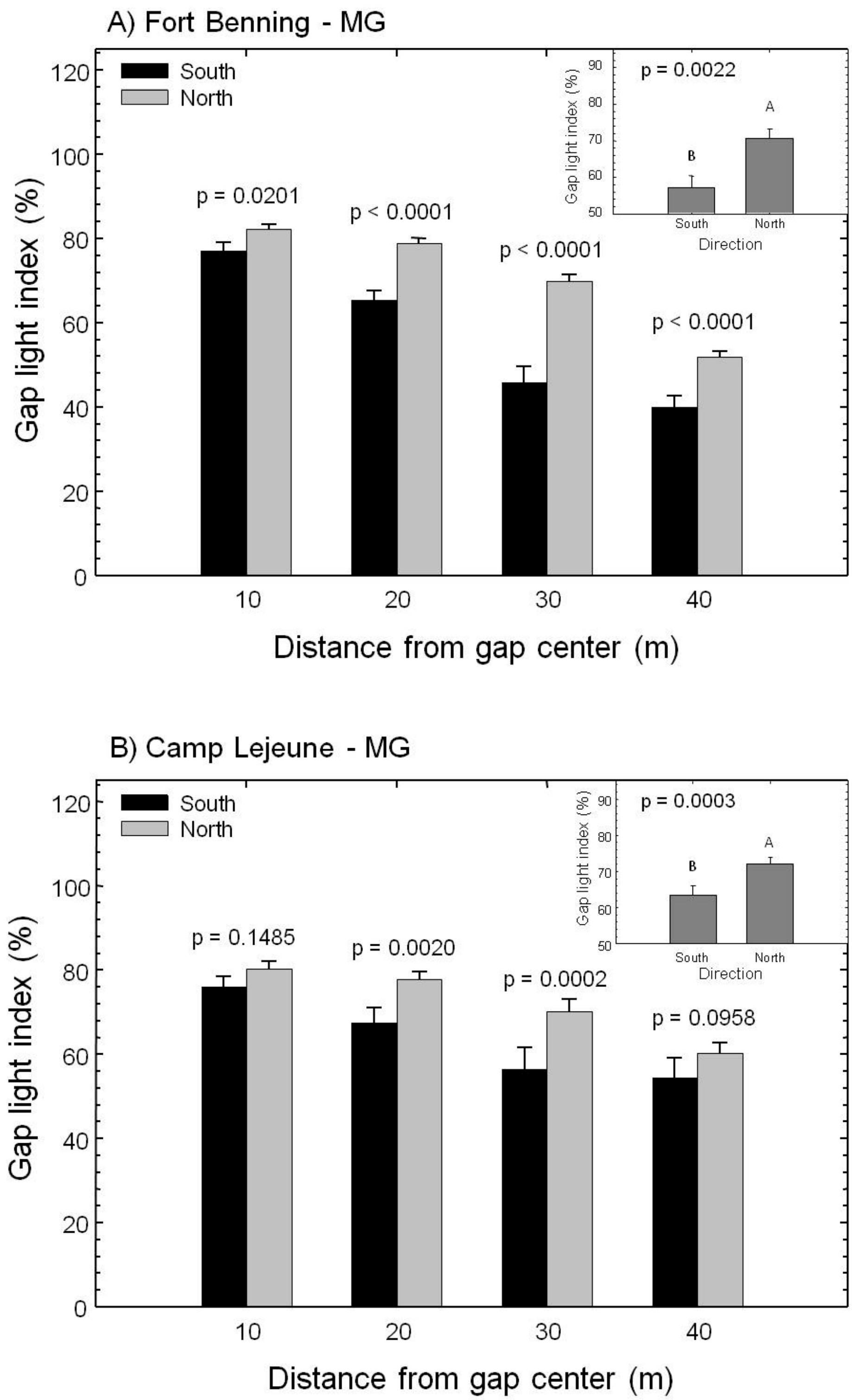

Figure 3.7.4. Gap light index (mean ± one standard error) by distance from center to south and north in MG plots at A) Fort Benning and B) Camp Lejeune. *p*-values are from linear contrasts that compare south and north directions. Insets: gap light index (mean ± one standard error) by direction. Different letters indicate significant differences.

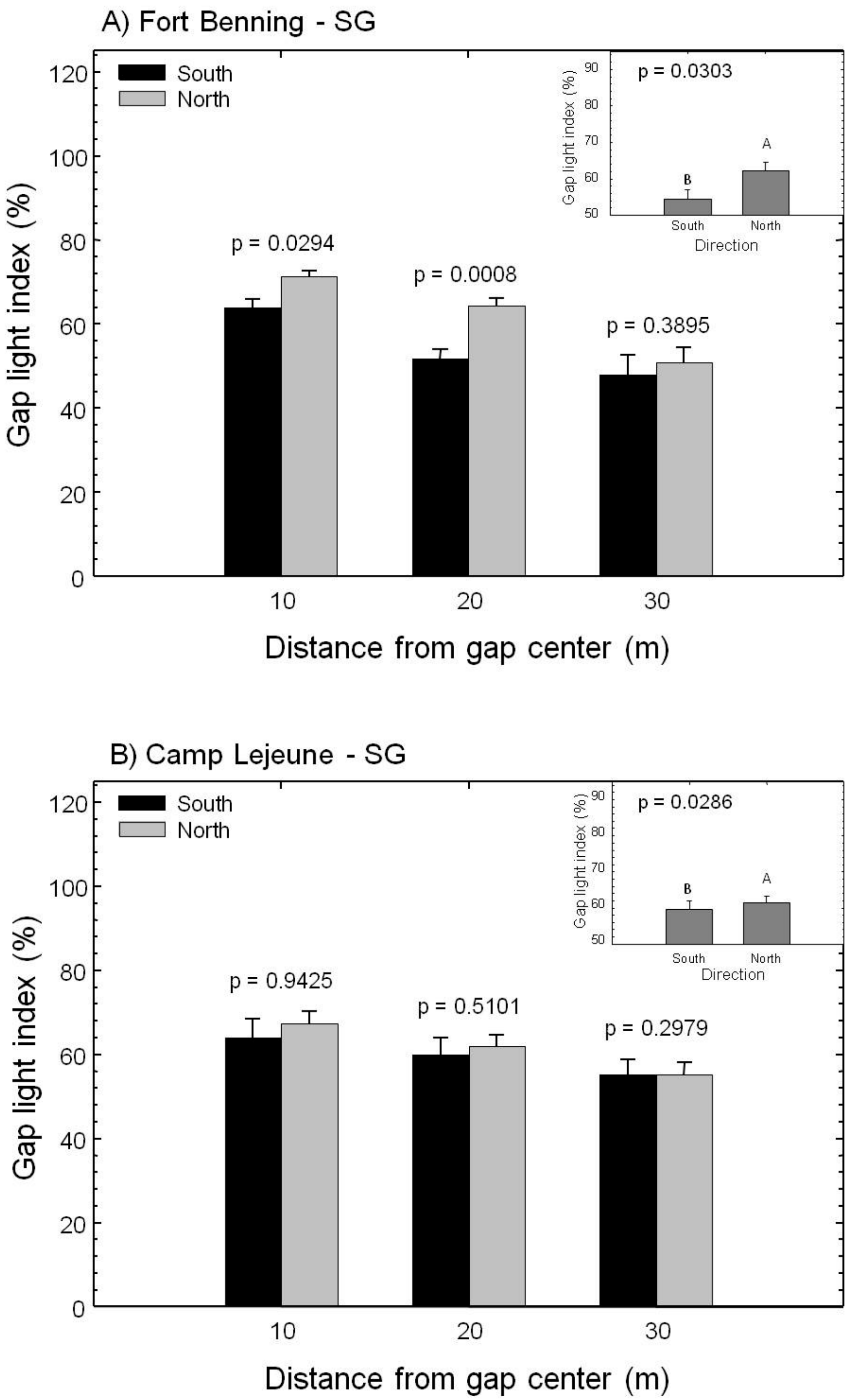

Figure 3.7.5. Gap light index (mean ± one standard error) by distance from center to south and north in SG plots at A) Fort Benning and B) Camp Lejeune. *p*-values are from linear contrasts that compare south and north directions. Insets: gap light index (mean ± one standard error) by direction. Different letters indicate significant differences.

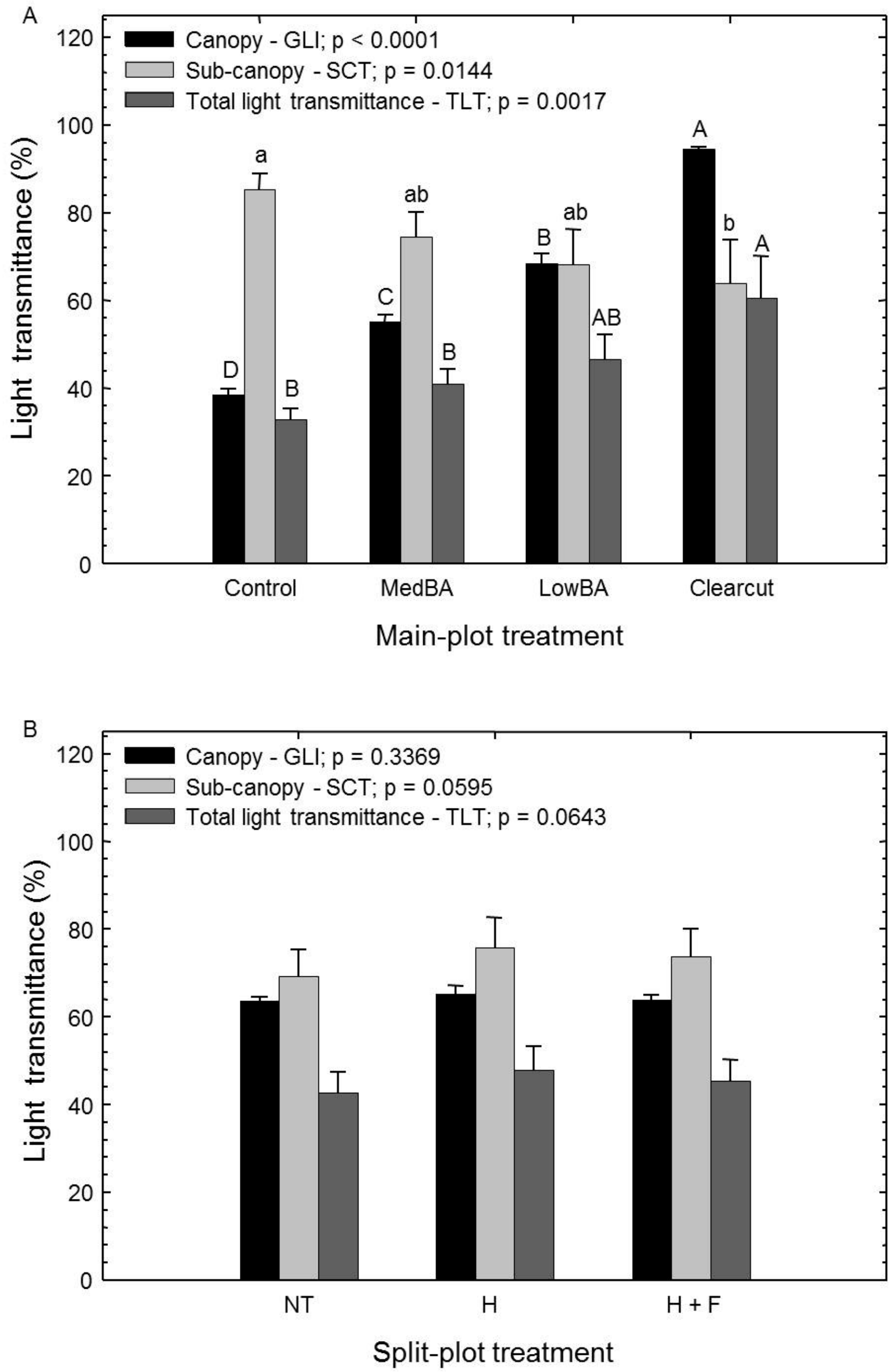

Figure 3.7.6. Transmittance of light (mean + one SE) through the canopy (GLI), the ground layer (SCT), and total light transmittance (TLT) to the forest floor by A) main-plot treatment and B) split-plot treatment. The same letter within a light variable indicates no significant difference at $\alpha = 0.05$.

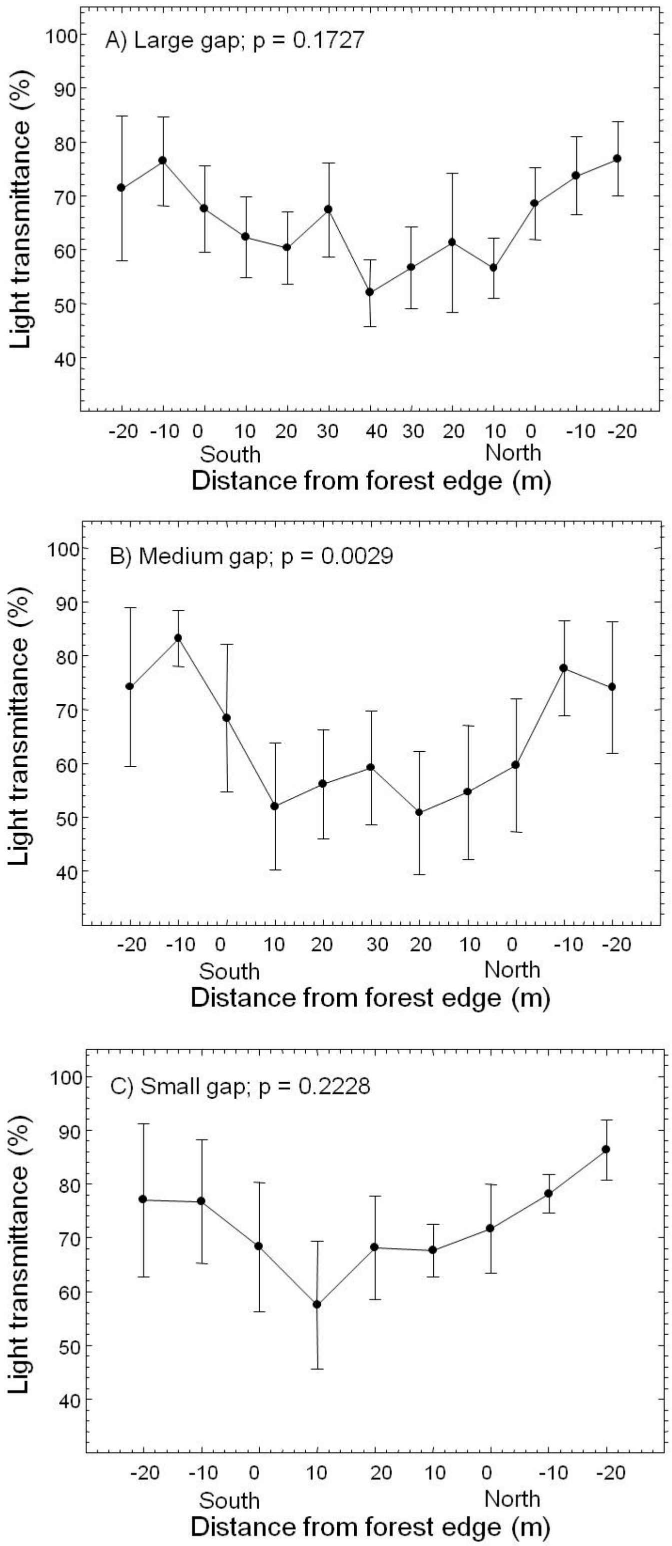

Figure 3.7.7. Percent light transmittance penetrating the ground layer vegetation (PAR; mean ± one standard error) by gap position for A) LG plots, B) MG plots, and C) SG plots at Fort Benning. Scales of the x-axes differ depending on gap size.

Table 3.7.1. Volumetric soil moisture (%) and soil temperature (°C) by main-plot and split-plot treatment at Fort Benning and Camp Lejeune. In 2009, measurements were taken in May, and 2010 values are the average of measurements taken in July and August. Different letters indicate significant differences within a year, variable, and treatment group

		2009				2010			
		Volumetric soil moisture (%)		Soil temperature (°C)		Volumetric soil moisture (%)		Soil temperature (°C)	
Site	Effect	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Fort Benning	Control	17.84	1.84	24.26^{b}	1.55	7.07	1.68	31.16^{b}	0.41
	MedBA	16.47	3.00	24.56^{ab}	1.50	6.89	1.84	31.87^{b}	0.55
	LowBA	14.10	2.85	25.81^{a}	1.69	5.93	1.75	31.85^{b}	0.45
	Clearcut	14.01	2.67	25.62^{a}	1.28	4.66	1.42	33.84^{a}	0.81
	p-value	**0.0810**		**0.0078**		**0.3966**		**0.0056**	
	NT	15.28	2.59	24.76^{b}	1.44	6.20	1.59	31.98	0.33
	H	16.40	2.49	25.28^{a}	1.52	6.01	1.55	32.42	0.49
	H+F	15.14	2.32	25.15^{a}	1.53	5.49	1.35	32.28	0.50
	p-value	**0.2452**		**0.0053**		**0.4891**		**0.1673**	
Camp Lejeune	Control	14.18	1.25	22.53	0.49	7.80	0.75	26.65	0.19
	MedBA	13.01	1.79	22.44	0.89	8.29	1.31	26.37	0.29
	LowBA	16.46	1.73	22.33	0.61	8.16	0.78	26.05	0.42
	Clearcut	15.21	4.05	22.12	0.58	6.52	1.16	26.20	0.46
	p-value	**0.8578**		**0.7486**		**0.3034**		**0.5691**	
	NT	14.74	1.31	22.16^{b}	0.53	8.05^{ab}	0.65	26.21^{bc}	0.23
	H	14.74	2.33	22.66^{a}	0.48	7.12^{b}	0.78	26.66^{a}	0.29
	H+F	15.17	1.54	22.56^{a}	0.52	7.16^{b}	0.48	26.49^{ab}	0.23
	p-value	**0.8271**		**<0.0001**		**0.0064**		**<0.0001**	

Table 3.7.2. Volumetric soil moisture (%) and soil temperature (°C) by gap size and direction at Fort Benning and Camp Lejeune. In 2009, measurements were taken in May, and 2010 values are the average of measurements taken in July and August. No soil temperature measurements were taken in 2009 at Fort Benning due to problems with equipment. Different letters indicate significant differences within a year, variable, and treatment group

		2009				2010			
		Volumetric soil moisture (%)		Soil temperature (°C)		Volumetric soil moisture (%)		Soil temperature (°C)	
Site	Effect	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Fort Benning	LG	15.51	2.06	-	-	6.74	1.80	32.84	0.49
	MG	15.27	2.91	-	-	7.20	2.30	32.66	0.61
	SG	14.02	3.76	-	-	6.31	2.21	32.09	0.67
	p-value	**0.8359**		**-**		**0.8812**		**0.2953**	
	South	16.54^{a}	2.88	-	-	7.94^{a}	2.22	32.01^{b}	0.37
	North	13.50^{b}	2.10	-	-	5.64^{b}	1.43	33.02^{a}	0.67
	p-value	**0.0007**		**-**		**0.0041**		**<0.0001**	
Camp Lejeune	LG	18.35	1.05	22.64^{a}	0.70	10.25	0.79	26.68	0.45
	MG	20.54	2.59	21.37^{b}	0.58	9.31	1.00	26.23	0.47
	SG	16.90	1.89	21.75^{b}	0.53	9.14	1.19	26.01	0.29
	p-value	**0.3426**		**0.0028**		**0.5425**		**0.5028**	
	South	17.93	1.51	21.72^{b}	0.59	9.53	1.07	26.06^{b}	0.27
	North	19.41	2.01	22.20^{a}	0.53	9.34	0.77	26.48^{a}	0.27
	p-value	**0.4215**		**<0.0001**		**0.5821**		**0.0132**	

in both years at Camp Lejeune, with the general pattern of higher temperatures on H and H+F plots when compared to the plots not treated with herbicides.

Among the gap plots, we found no significant interaction effects between gap size and gap direction for soil moisture or soil temperature in either year at Fort Benning ($p = 0.4682$) or at Camp Lejeune ($p = 0.0932$). Gap size had no effect on soil moisture at either site, but we found higher soil temperatures in LG plots than in MG or SG plots in 2009 at Camp Lejeune (Table 3.7.2). At Fort Benning, soil moisture was higher on the south half of gaps than the north half of gaps in both years, and soil temperature was higher in the north half of gaps in 2010. Similarly, soil temperature was higher on the north half of gaps at Camp Lejeune in both years, but we found no effect of direction on soil moisture at Camp Lejeune (Table 3.7.2). Despite the effect of direction on soil moisture at Fort Benning, we found no differences in soil moisture by position in any of the gaps at either site (Figure 3.7.8). Soil temperature in 2010 was strongly affected by gap position at Fort Benning, with a general pattern of increasing temperatures associated with distance from the forest edge. Although there were significant position effects on soil temperature at Camp Lejeune, particularly in 2009, there was no clear pattern of positional effects on soil temperature (Figure 3.7.9).

In the LG plots, we found that soil moisture increased with depth in the soil at Fort Benning, but was similar through the first 40 cm at Camp Lejeune (Figure 3.7.10). At Fort Benning, we found a significant direction effect on soil moisture at 10, 20, and 60 cm in 2009 but only at 10 cm in 2010 (Figure 3.7.11). There were no effects of gap direction on soil moisture at any depth at Camp Lejeune (Figure 3.7.11), and we found no significant effects of gap position at any depth in 2009 or 2010 at Fort Benning or Camp Lejeune (Tables 3.7.3 3.7.4).

3.7.3.3. Soil nitrogen

We found no effects of gap direction on extractable NH_4^+ in 2010 at Fort Benning, but both NO_3^- and total N (NH_4^++NO_3^-) were higher on the north half of gaps than on the south half of gaps (Figure 3.7.12). Generally, levels of NO_3^- were higher than those of NH_4^+. We found a significant effect of gap position on NO_3^- and total N, where the position 20 m north of gap center had significantly higher levels of N than that at the southern forest edge (Figure 3.7.13). There was significant differences between extractable N from positions beneath the forest canopy and positions within the gap interior (Figure 3.7.12). In 2012, there were no significant differences in extractable N between the north and south half of gaps at Fort Benning or at Camp Lejeune (Figure 3.7.14). At Camp Lejeune, both NO_3^- and total extractable N were greater in positions beneath the forest canopy than from positions in the gap interior, but there were no significant effects of forest position on extractable N at Fort Benning (Figure 3.7.15). We found no effect of canopy gap position on NH_4^+, NO_3^-, or total extractable N at either Fort Benning or at Camp Lejeune in 2012 (Figure 3.7.14).

3.7.4. Discussion

The amount of light that penetrates the canopy is invariably related to the density of canopy structures that intercept light. Battaglia et al. (2002) and Palik et al. (1997) reported strong relationships between canopy openness and GLI levels in longleaf pine forests of Georgia.

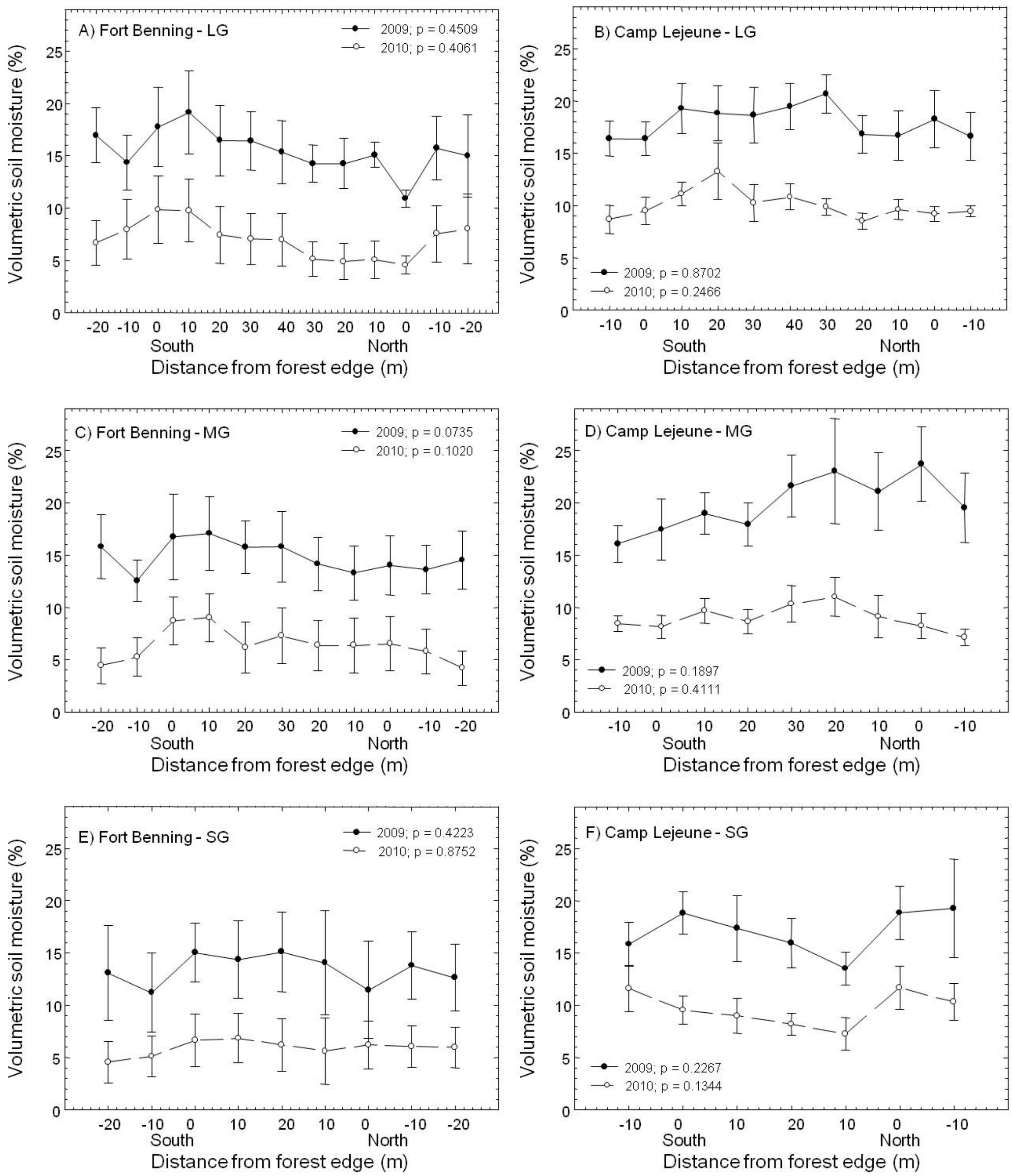

Figure 3.7.8. Volumetric soil moisture (%) (mean ± one standard error) by position along the north/south transect in LG, MG, and SG treatments at Fort Benning (A, C, and E) and Camp Lejeune (B, D, and F).

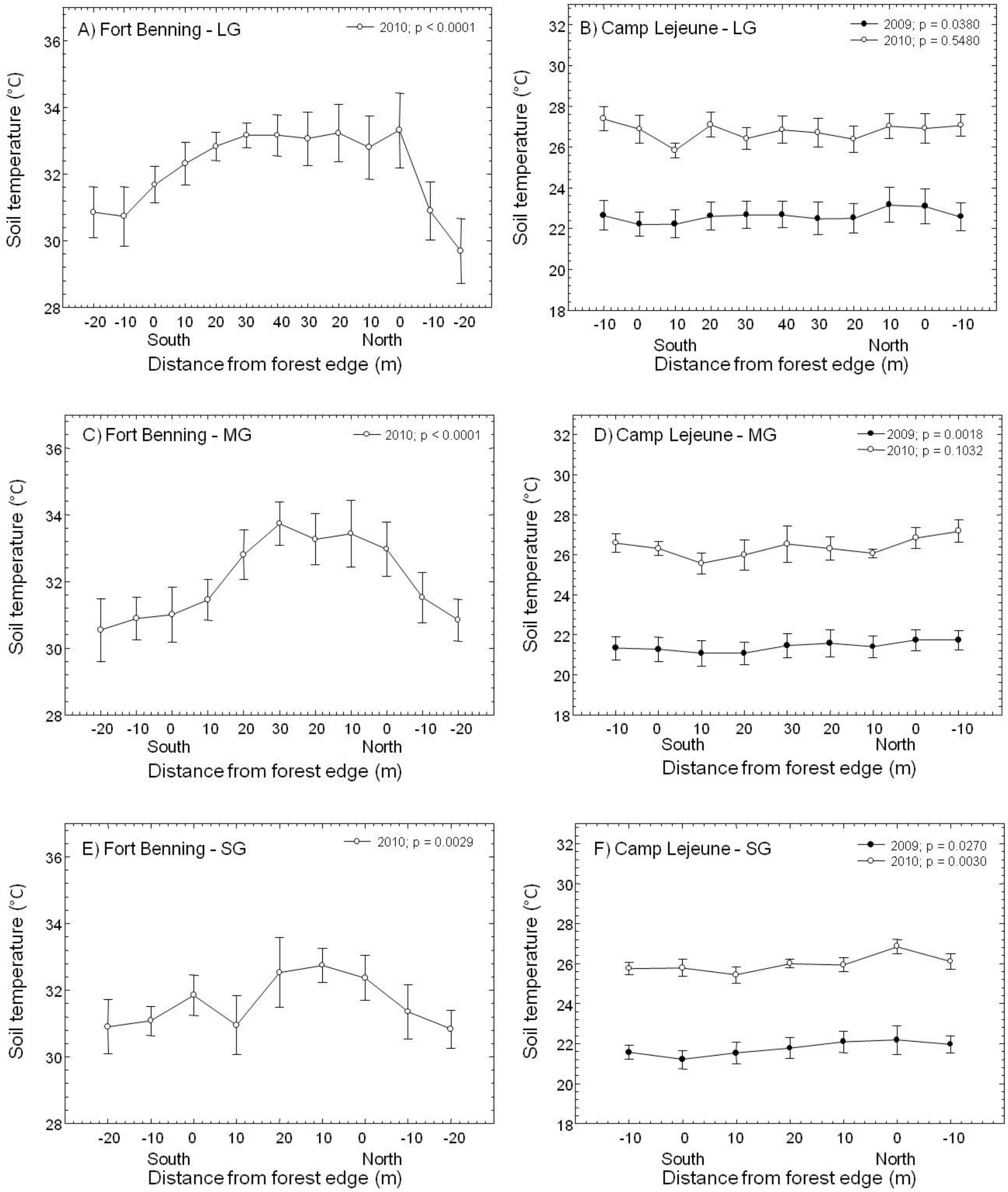

Figure 3.7.9. Soil temperature (°C) (mean ± one standard error) by position along the north/south transect in LG, MG, and SG treatments at Fort Benning (A, C, and E) and Camp Lejeune (B, D, and F).

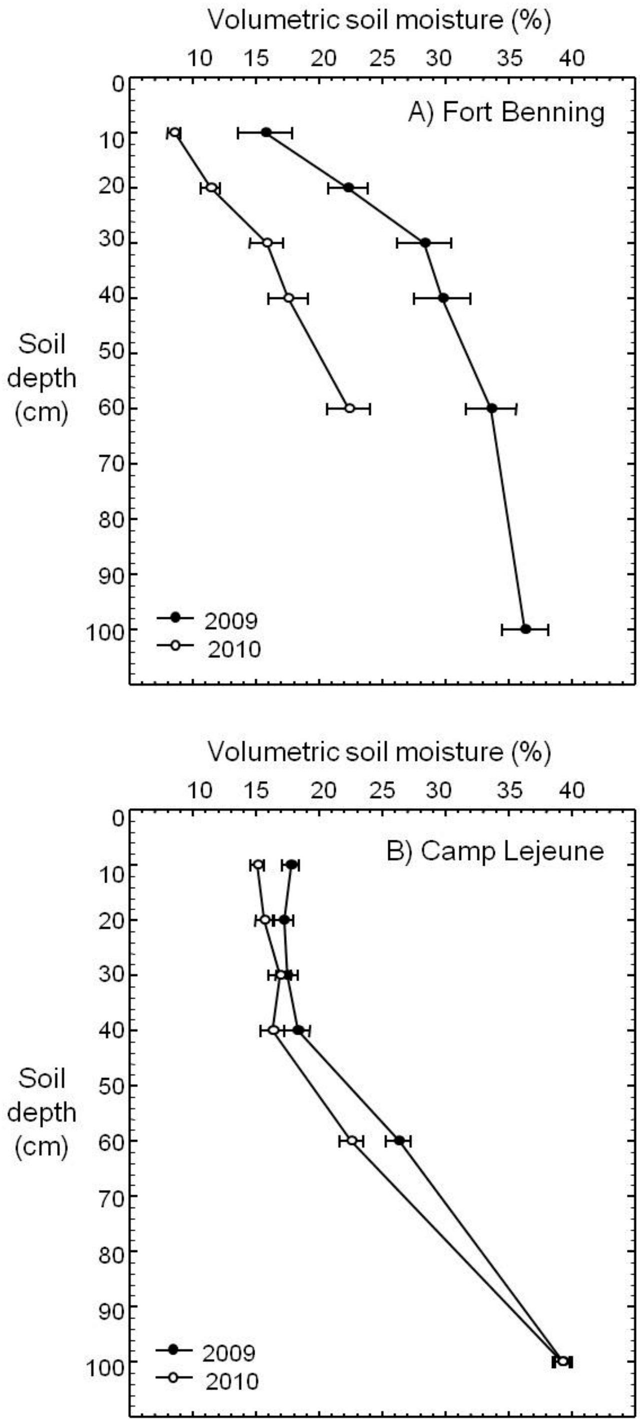

Figure 3.7.10. Volumetric soil moisture (mean ± one standard error) through the soil profile in 2009 and 2010 at A) Fort Benning and B) Camp Lejeune.

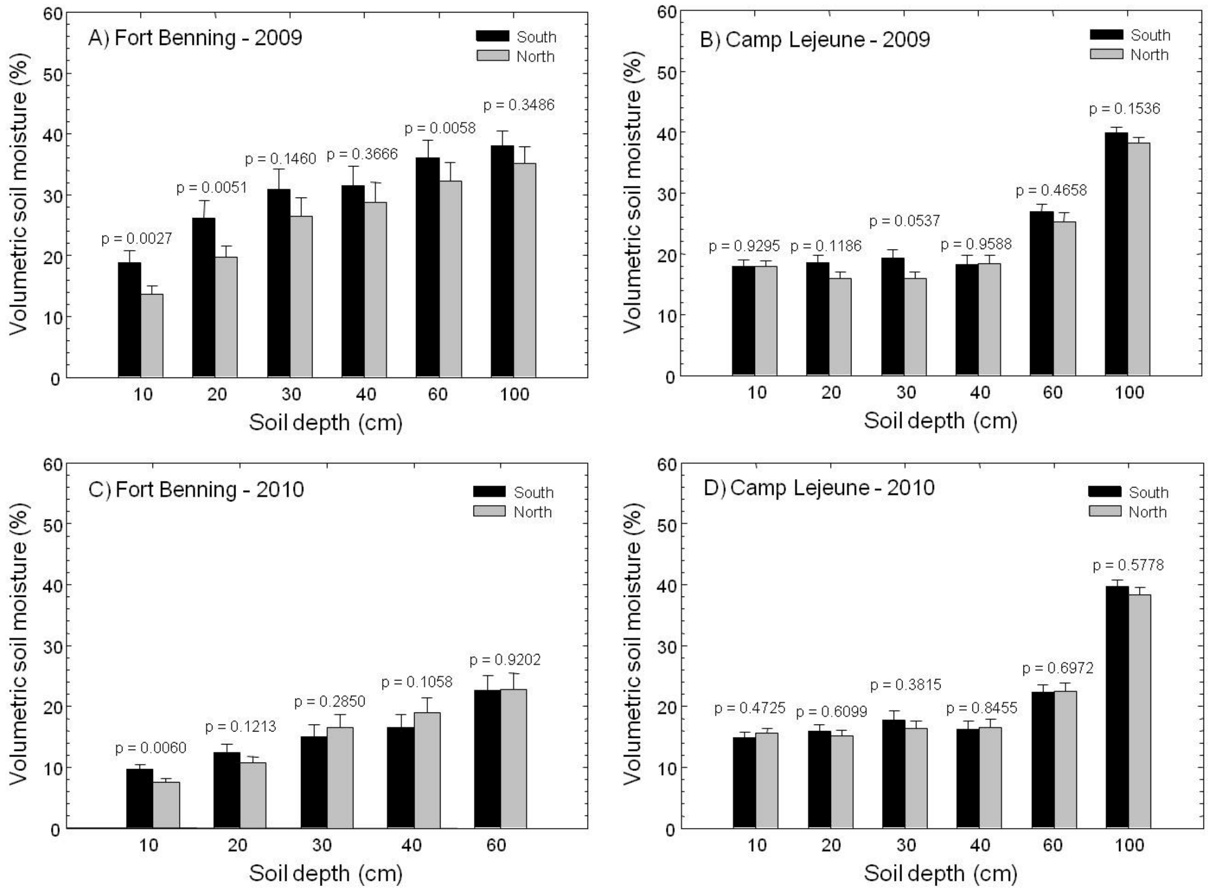

Figure 3.7.11. Volumetric soil moisture (mean ± one standard error) on the south and north half of gaps through the soil depth profile in 2009 and 2010 at Fort Benning (A and C) and Camp Lejeune (B and D).

Table 3.7.3. Volumetric soil moisture by gap position at 10, 20, 30, 40, 60, and 100 cm at Fort Benning, GA

		Distance	Volumetric soil moisture (%)											
		from forest	10 cm		20 cm		30 cm		40 cm		60 cm		100 cm	
Year	Position	edge (m)	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
2009	South	-10	.	.	.	.	.	.	.	.	.	.	.	.
	Forest edge	0	20.21	3.56	26.80	6.60	30.97	7.24	31.19	7.11	35.08	6.09	35.14	4.95
		10	18.23	4.28	24.70	6.31	26.31	7.06	28.05	6.55	37.34	6.40	37.24	6.06
		20	18.33	4.17	25.90	6.23	31.97	6.56	32.58	6.67	34.99	5.78	38.28	5.08
		30	16.48	6.16	27.48	7.51	31.57	10.76	34.43	12.35	37.15	9.32	42.65	5.94
	Gap center	40	14.04	4.58	19.61	4.94	27.90	7.54	28.09	9.08	31.12	6.44	35.54	6.12
		30	13.55	3.18	19.00	3.01	24.61	6.33	25.74	7.75	32.50	7.36	37.98	5.58
		20	14.23	2.13	21.33	5.68	26.88	7.66	29.56	8.44	33.15	8.02	37.86	7.18
		10	15.30	2.42	21.60	4.11	27.22	8.09	29.60	7.67	32.36	7.24	35.63	6.18
	Forest edge	0	10.54	2.29	17.94	3.76	26.71	7.73	30.57	7.35	30.66	6.91	35.06	8.50
	North	-10	14.64	4.72	18.81	4.47	26.85	7.99	28.28	8.43	32.47	7.58	28.87	6.19
		p-value	**0.2754**		**0.3536**		**0.9349**		**0.8910**		**0.0862**		**0.2552**	
2010	South	-10	8.61	2.07	10.32	2.37	16.69	5.15	17.76	5.49	22.69	5.49	.	.
	Forest edge	0	10.18	2.00	12.92	3.67	14.98	4.58	17.95	5.37	23.51	6.32	.	.
		10	9.22	2.33	11.74	2.64	11.34	2.85	13.58	2.86	23.91	6.04	.	.
		20	10.36	1.95	13.62	4.04	17.61	5.25	16.80	4.21	20.67	5.23	.	.
		30	9.00	1.50	13.47	3.06	14.67	4.46	16.80	6.04	22.38	5.89	.	.
	Gap center	40	7.98	1.87	9.16	2.23	15.91	5.07	15.24	5.37	18.81	5.39	.	.
		30	8.15	1.31	10.08	1.95	14.76	4.37	16.58	5.39	21.65	7.37	.	.
		20	7.61	1.35	10.18	1.94	14.66	4.36	16.88	5.30	20.29	4.99	.	.
		10	7.61	1.66	12.41	3.02	18.47	5.24	20.35	6.15	23.49	6.58	.	.
	Forest edge	0	6.47	1.19	10.71	2.07	17.91	5.01	20.83	6.07	22.67	6.40	.	.
	North	-10	7.76	2.11	10.62	2.23	17.16	5.07	20.13	6.81	25.59	6.99	.	.
		p-value	**0.4212**		**0.6144**		**0.5788**		**0.5121**		**0.6032**			

Table 3.7.4. Volumetric soil moisture by gap position at 10, 20, 30, 40, 60, and 100 cm at Camp Lejeune, NC

		Distance	Volumetric soil moisture (%)											
		from forest	10 cm		20 cm		30 cm		40 cm		60 cm		100 cm	
Year	Position	edge (m)	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
2009	South	-10	18.30	3.11	21.65	1.80	20.70	2.81	17.44	4.35	27.05	2.60	40.20	1.01
	Forest edge	0	15.16	2.11	19.27	3.15	14.12	2.89	14.47	2.58	27.59	1.87	38.87	2.79
		10	20.95	2.95	17.14	3.04	19.52	3.06	21.26	2.65	28.13	3.56	41.23	2.23
		20	18.40	2.88	17.82	3.17	22.49	2.29	23.11	3.31	29.59	2.34	39.83	0.93
		30	17.15	2.66	16.38	2.55	23.12	1.71	16.34	3.95	22.16	3.79	39.85	0.89
	Gap center	40	15.83	2.72	17.66	1.39	17.31	2.47	18.23	3.05	28.77	4.51	41.27	1.92
		30	19.27	0.93	18.45	1.29	13.30	2.73	20.08	3.02	28.32	1.46	40.51	1.73
		20	16.37	2.07	12.44	2.86	14.60	3.77	19.92	4.16	26.51	4.46	38.25	2.40
		10	17.25	2.49	12.94	1.84	15.60	2.02	18.77	2.92	22.41	3.43	39.05	2.51
	Forest edge	0	17.44	2.69	17.71	2.43	17.67	1.36	15.02	3.23	24.72	3.09	36.00	1.10
	North	-10	19.38	1.90	18.57	1.93	18.63	3.05	18.02	3.94	24.91	4.09	37.97	1.26
		p-value	**0.9017**		**0.2058**		**0.1653**		**0.8537**		**0.6983**		**0.5612**	
2010	South	-10	13.04	2.23	17.00	1.86	17.83	3.74	15.62	3.72	21.97	2.50	40.67	1.00
	Forest edge	0	13.93	1.55	15.94	2.90	12.78	3.01	12.04	1.79	23.19	1.42	39.50	3.74
		10	17.06	2.12	16.16	2.65	17.68	3.84	18.97	2.78	25.32	3.67	38.77	2.07
		20	17.09	2.16	16.16	3.18	23.26	1.40	20.03	4.03	22.54	2.76	39.89	2.78
		30	13.39	1.78	14.22	1.76	20.71	2.24	15.57	3.58	18.67	2.44	39.82	0.80
	Gap center	40	13.20	1.60	17.16	1.39	15.87	1.55	15.33	2.49	23.74	4.42	41.62	1.67
		30	16.71	1.32	16.87	1.74	14.32	2.24	18.92	2.46	25.82	1.47	44.01	2.74
		20	13.66	0.92	13.60	2.63	16.30	4.49	16.95	3.78	23.53	4.19	38.36	2.95
		10	16.69	2.63	12.48	2.15	15.10	2.53	17.14	2.87	20.50	3.52	38.57	3.14
	Forest edge	0	12.92	1.74	15.15	1.99	17.39	2.69	13.31	3.30	22.13	2.91	33.77	1.84
	North	-10	17.73	0.95	17.81	2.30	18.90	2.21	16.53	3.35	20.46	3.95	38.10	1.33
		p-value	**0.1547**		**0.7638**		**0.4016**		**0.7956**		**0.7672**		**0.2761**	

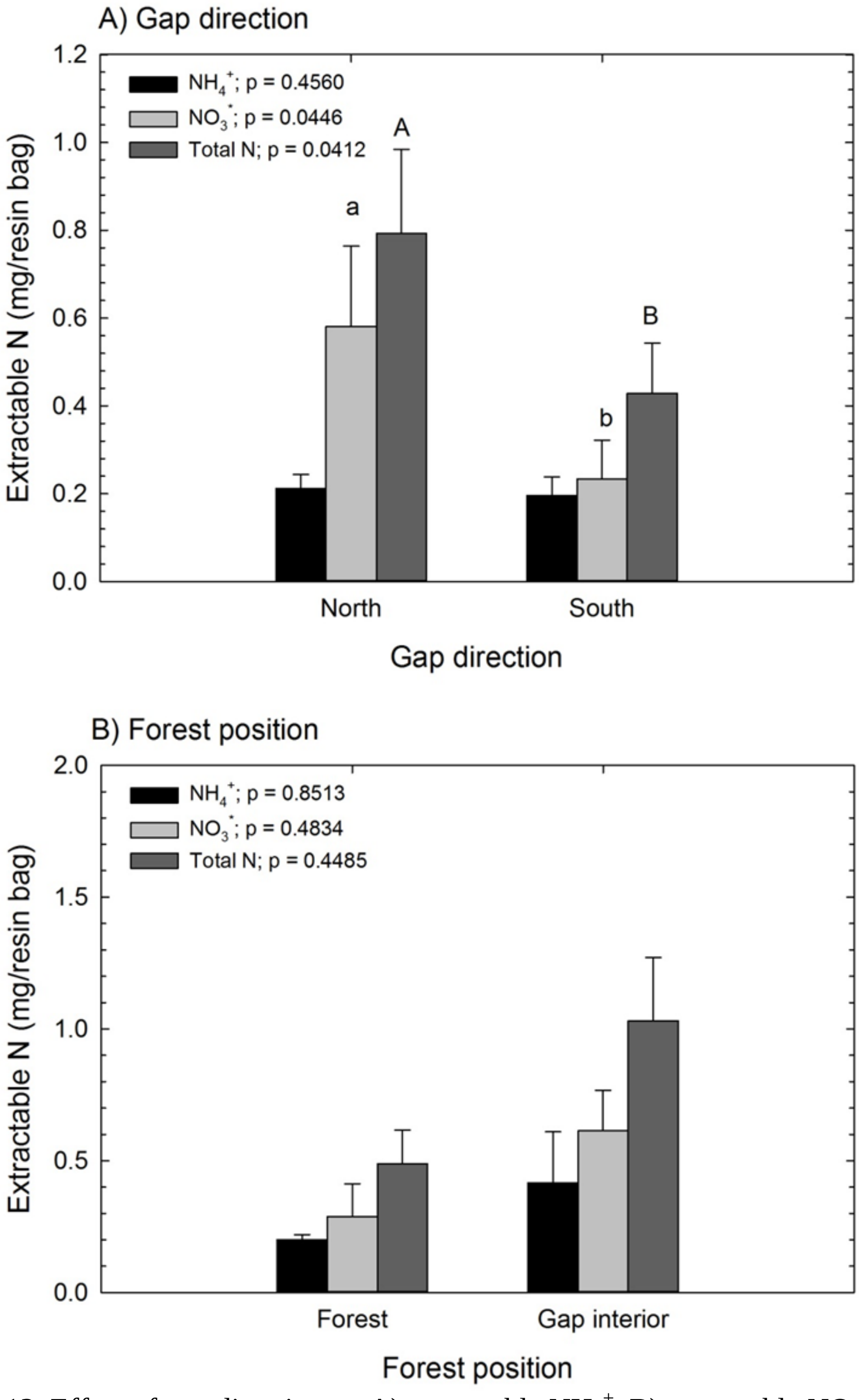

Figure 3.7.12. Effect of gap direction on A) extractable NH_4^+, B) extractable NO_3^-, and C) extractable total N ($NH_4^+ + NO_3^-$) in LG plots at Fort Benning in 2010. Different letters indicate significant treatment differences.

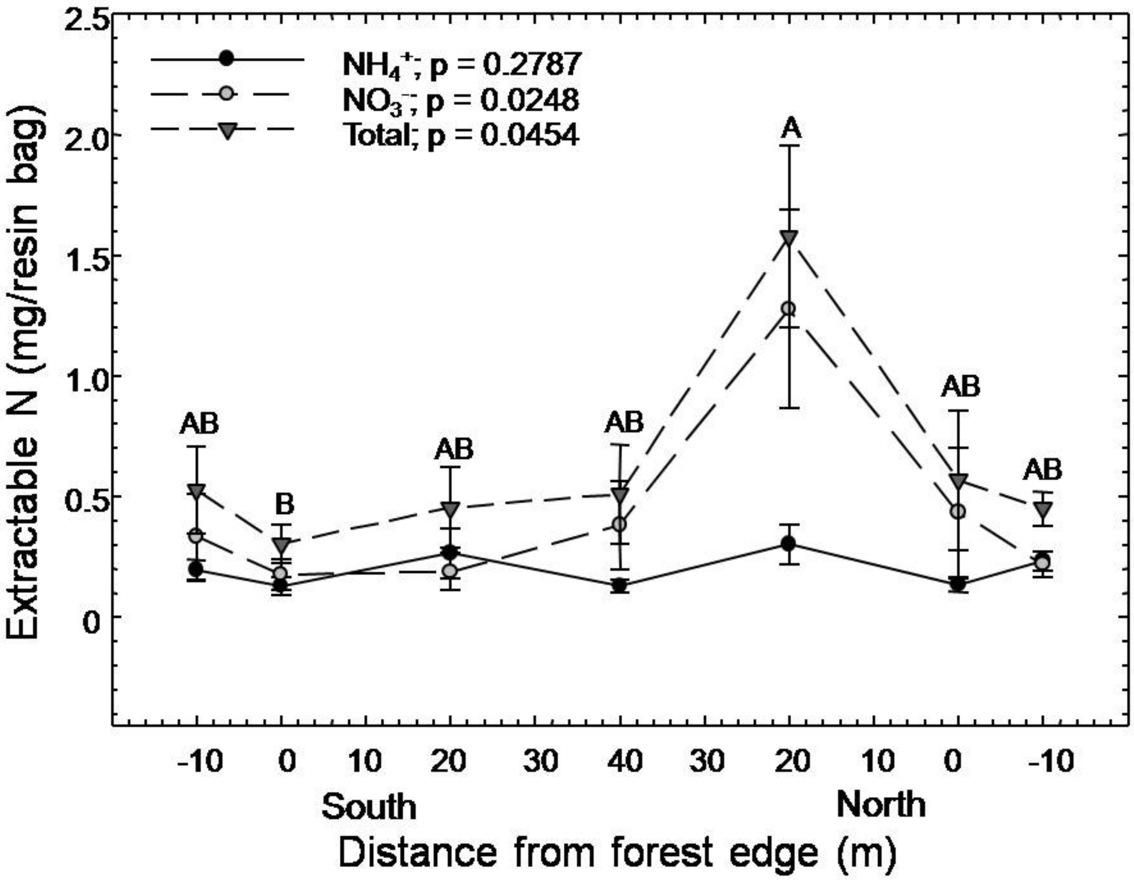

Figure 3.7.13. Extractable N (mean ± one standard error) by position within large gaps at Fort Benning, GA. Different letters indicate significant treatment differences for total N (NH_4^+ + NO_3^-).

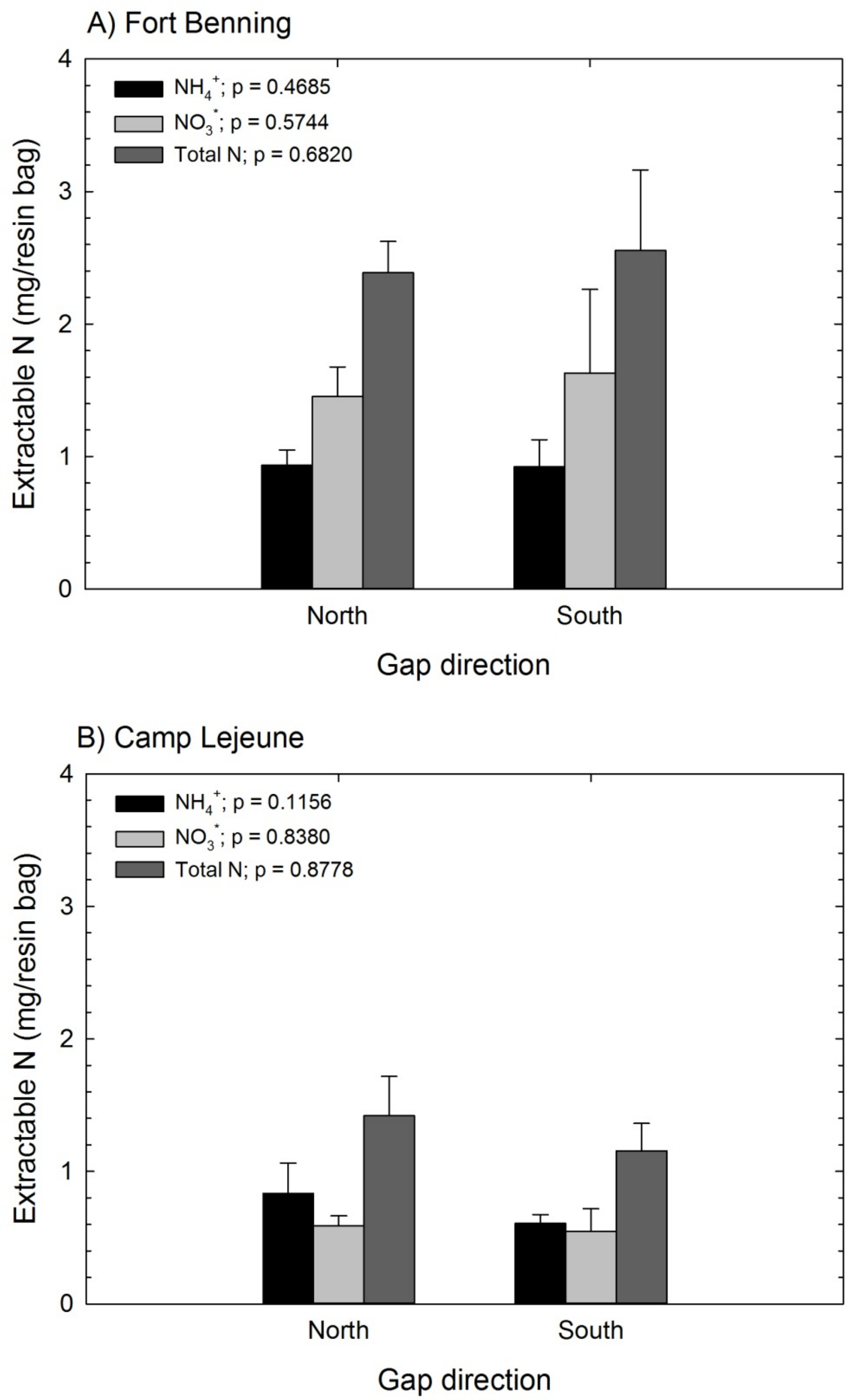

Figure 3.7.14. Extractable N (mean + one standard error) by direction (north vs. south) in large gaps at A) Fort Benning and B) Camp Lejeune in 2012.

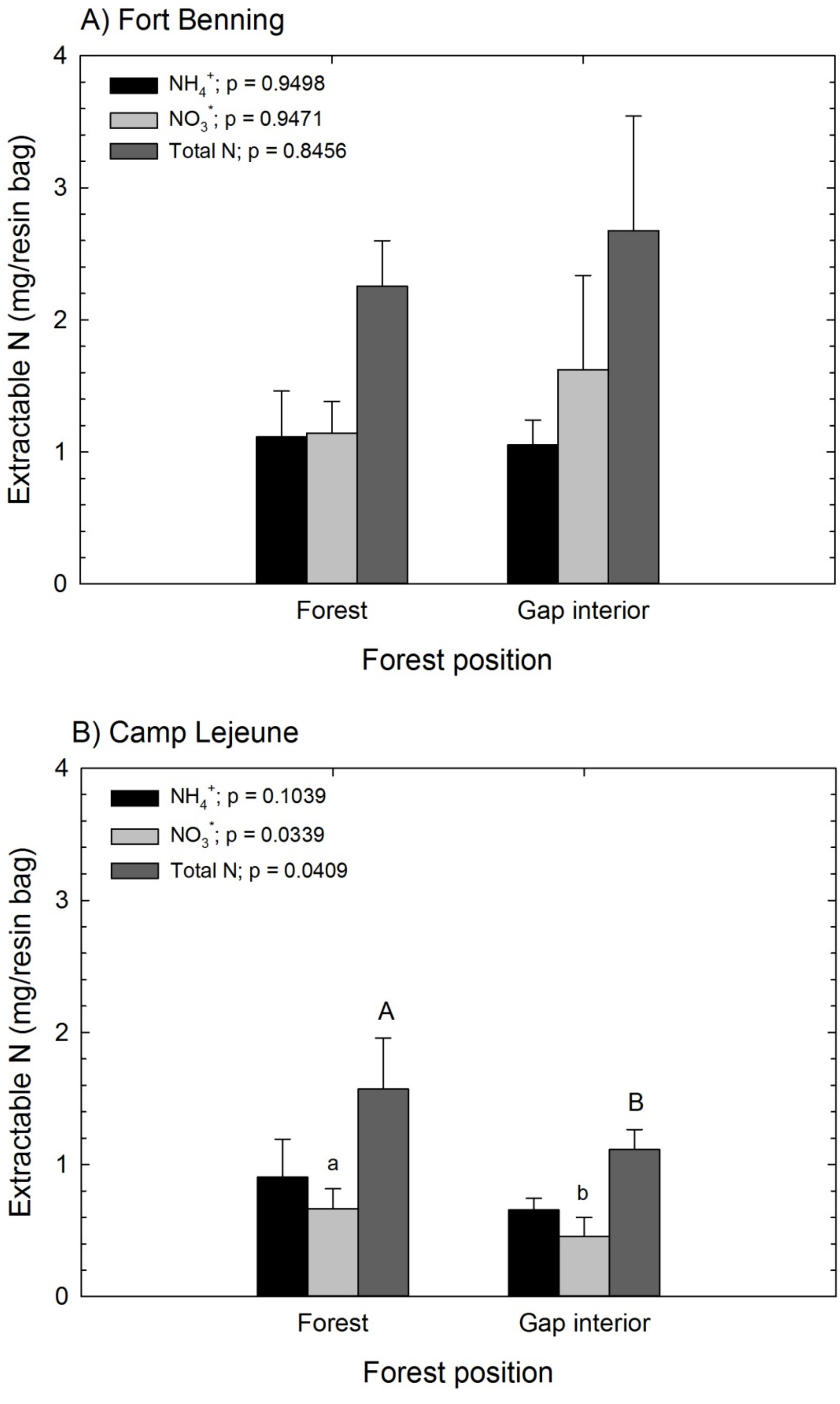

Figure 3.7.15. Extractable N (mean + one standard error) by forest position (comparing 10 m within the forest interior to interior gap positions) at A) Fort Benning and B) Camp Lejeune in 2012. The same letter indicates no significant difference for each type of N.

Our results also demonstrate this relationship; we found very low levels of variability in GLI within each main-plot treatment, resulting in different levels of GLI related to basil area differences with each uniform treatment. A reduction in canopy density increases light availability for target species (e.g., planted longleaf pine seedlings) but also increases light availability for other vegetation and often results in increased abundance of ground layer vegetation (Anderson et al. 1969, Grelen and Enghardt 1973; also see Sections 3.4 and 3.6). The ground layer vegetation provides additional competition for light and can limit longleaf pine seedling growth in the absence of a canopy layer (Knapp et al. 2008). Our results suggest that the greater abundance of ground layer vegetation on Clearcut plots may intercept nearly 40% of the available sunlight before it reaches the forest floor. Similar results were observed in gap plots, where vegetation cover generally increased from the forest edge to gap center (see Section 3.6). Although we found no effect of our split-plot treatments on light transmittance at Fort Benning in 2010, we expect that light transmittance would have been higher on H plots than on NT plots in 2009. By 2010, there were no split-plot effects on total ground layer vegetation cover (Section 3.4), but we found that herbicides (H plot) had reduced vegetation cover the first season after application. The dynamics of light distribution within gaps in the forest canopy have long been of interest to ecologists in many different forest types (e.g. Denslow 1980, Poulson and Platt 1989, Gray et al. 2002). In the northern hemisphere, where the sun moves across the southern portion of the sky, solar radiation is predictably greater on the northern half of gaps than on the southern the southern half of gaps due to shade provided by trees along the southern gap edge (Canham 1988, Gray et al. 2002, Ritter et al. 2005). However, the stand structure of a given forest type can play an important role in light penetration through canopy gaps (Canham et al. 1990). In longleaf pine forests in north central Florida, Brockway and Outcalt (1998) found no significant effects of gap position on the transmittance of solar radiation and postulated that the low density (< 60% canopy cover) of the longleaf pine forest resulted in higher levels of diffuse light penetration regardless of canopy position. However, other studies in similarly open-canopied longleaf pine forests reported significantly higher levels of light in the northern half of gaps than in the southern half of gaps (McGuire et al. 2001, Gagnon et al. 2003). Our results support the findings of differences in light availability along the north/south gradients of canopy gaps, with the highest light levels slightly north of gap center.

Gendreau-Berthiaume and Kneeshaw (2009) discuss the importance of gap size on the position of maximum light within a canopy gap and suggest that discrepancies in the gap position that receives the most light among previous studies can be attributed to the analysis of gaps of different sizes. They report that the highest light levels occur closer to the center of large gaps and closer to the northern gap edge in small gaps. Our results did not support this finding, but the largest gap in their study was slightly smaller (994 m^2) than the smallest gap used in our study (1025 m^2). We did observe clear differences in average light levels among gap sizes, in which gaps ~ 0.1 ha (SG) resulted in average light levels similar to MedBA plots, but gaps ~ 0.5 ha (LG) resulted in average light levels similar to LowBA plots.

Canopy removal affects multiple processes that can influence soil moisture, and previous studies have reported variable responses of soil moisture to harvesting. For example, numerous studies have found increases in soil moisture following canopy removal, and such increases are commonly associated with decreased interception and transpiration by canopy trees (Aussenac and Granier 1988, Elliot et al. 1998, Son et al. 1999). Breda et al. (1995) directly measured soil moisture, interception, and transpiration rates in thinned and unthinned oaks stands and found higher soil moisture levels, lower interception rates, and lower transpiration following thinning. However other studies have reported that raised exposure to solar radiation increases soil temperatures following canopy removal (e.g. Londo et al. 1999, Redding et al. 2003, Moroni et al. 2009), resulting in increased drying of the soil and observed reductions in soil moisture. Our results from Fort Benning support previous findings of increased soil temperatures associated with canopy removal, but the results from Camp Lejeune indicate no canopy effect on soil temperature. It is possible that the greater abundance of ground layer vegetation at Camp Lejeune (Sections 3.4 and 3.6) insulated the soil surface from solar radiation and prevented increased temperatures associated with main-plot treatments. This possibility is supported by the observed split-plot treatment effects, in which treatments with herbicides increased temperatures compared to those without herbicides. Herbicides reduced the abundance of ground layer vegetation and likely increased the exposure of the soil to solar radiation. The increased temperatures may have been associated with reduced soil moisture in herbicide split-plots at Camp Lejeune in 2009, although we observed no other effects of cultural treatments or canopy density on soil moisture in our study.

Previous studies have reported increases in both soil moisture and temperature in canopy gaps when compared to the intact canopy (Mladenoff 1987, Denslow et al. 1998, Gray et al. 2002). In a study in Douglas-fir forests of the Pacific Northwest, Gray et al. (2002) found soil temperatures to be higher on the north edge of canopy gaps than on the south edge and associated increases in temperature with exposure to solar radiation. Despite higher temperatures in the north half compared to the south half of gaps at both sites in our study, we only observed a clear pattern of increased temperatures associated with distance from the forest edge at Fort Benning. Soil surface moisture was highly variable within our canopy gaps, but we did observe higher moisture levels in the south half of gaps compared to the north half of gaps at Fort Benning. In longleaf pine forests of southwestern Georgia, McGuire et al. (2001) found no consistent patterns of soil moisture associated with canopy gap size or position and concluded that variation in soil moisture was more prevalent than clear patterns.

The soils common to our study sites are very sandy and typically have low water holding capacity and it is likely that soil properties affect the response of soil moisture to canopy removal. Additionally, the surface measurement was taken at a depth of 6 cm, allowing the possibility of differential responses at greater soil depths. However, results from the soil profile moisture readings similarly indicate no effect of gap position on soil moisture at depths up to one meter. The directional effect at Fort Benning was observed to a depth of 20 cm in 2009, suggesting that the drying of the surface soil by solar radiation does not occur below this depth.

Nitrogen availability within the soil is strongly controlled by soil moisture, soil temperature, the microbial community, and the quality of the organic substrate within the soil (e.g. Keeney 1980, Myers et al. 1982, Knoepp and Swank 2002), with increases in any of the variables generally resulting in increased mineralization and nitrogen availability. Canopy removal has been shown to increase nitrogen mineralization in the soil following clearcutting (Matson and Vitousek 1981, Kim et al. 1995, Prescott 1997), and Palik et al. (1997) found that decreased overstory basal area resulted in increased nitrogen availability measured with IER bags buried in the mineral soil of longleaf pine forests in southwestern Georgia. The conditions created by patch-cutting are often similar to that created by clearcutting, especially in the LG plots used for N analysis in this study. In a study in a longleaf pine forest in southwestern Georgia, McGuire et al. (2001) reported that nitrification of N generally increased from the forest edge to 10-20 m into canopy gaps of different sizes, although total mineralization was maximized in the smallest gaps of the study (~ 0.1 ha).

The differences in extractable NO_3^- and total extractable N between the north and south half of gaps at Fort Benning in 2010 were primarily driven by the spike in NO_3^- observed 20 m from the north forest edge. Both the mineralization and nitrification of organic N in the mineral soil are positively related to soil temperature (Matson and Vitousek 1981, Knoepp and Swank 2002), and it is possible that increases in soil temperature related to greater exposure to solar radiation resulted in greater nitrification. NO_3^- is more mobile than NH_4^+ and may have transported more readily to the IER bags (Binkley et al. 1986), resulting in the greater contribution of NO_3^- to the total extractable N. However, the patterns in 2012 were different with a non-significant spike in NO_3^- at 20 m south of gap center at Fort Benning but no such pattern at Camp Lejeune (Figure 3.7.16). Our results suggest that NH_4^+ and NO_3^- concentrations are highly variable at small spatial scales, with that variability likely masking possible effects of gap position. At Camp Lejeune, however, we found that NO_3^- and total extractable N were higher beneath the forest canopy than within the gap openings. Following canopy removal, increased growth of ground layer vegetation can quickly fill root space within gap openings and remove available N from the soil (McGuire et al. 2001, Jones et al. 2003). The greater abundance of ground layer and mid-story vegetation at Camp Lejeune than Fort Benning may be the reason that no pattern was observed at Fort Benning.

3.7.5. Conclusions

The silvicultural prescriptions applied by land managers often manipulate stand structure to change the distribution of resource availability on the site. Despite the relatively open canopies of southern pine forests, forest gaps create distinct micro-environments that differ according to position along the north/south axis. Changes in the distribution of resources will directly affect the response of planted longleaf pine seedlings and the ground layer vegetation during longleaf pine restoration. In general, canopy removal results in increased light penetration, although an associated increase in ground layer vegetation may reduce light transmission to the forest floor. In canopy gaps, light levels are highest just north of gap center, and the north half of gaps consistently receives greater light exposure than the south half. Increased solar radiation following canopy removal was associated with increased soil temperatures at Fort Benning, but treatment effects on soil temperature at Camp Lejeune were limited to an increase associated with herbicide cultural treatments. Soil moisture, either at the surface (6 cm) or within the profile, was not strongly affected by canopy removal at either site; however, soil moisture was typically lower in the north half of gaps at Fort Benning. Increased temperatures in the north half of gaps may have resulted in greater nitrogen availability when compared to the south half of gaps at Fort Benning, although variability in N concentrations suggest more research is needed to understand effects of gap position on N dynamics in these nutrient poor soil.

3.8. Effects of resource availability on planted longleaf pine seedlings through three years following silvicultural manipulations

This section links the results of Section 3.7 to seedling responses (research objective o-7).

3.8.1. Introduction

Developing silvicultural protocols for restoring longleaf pine to sites dominated by other species requires an understanding of how management actions affect resource availability and how, in turn, resource availability affects longleaf pine seedling response. Previous research that focused on longleaf pine response to site resources/conditions primarily occurred within existing longleaf pine forests (Palik et al. 1997, McGuire et al. 2001, Pecot et al. 2007), in the absence of canopy trees (Knapp et al. 2008), or in a greenhouse setting (Jose et al. 2003). Loblolly pine trees have shallower root systems than longleaf pine, with the majority of active loblolly pine root concentrated near the soil surface in mature trees (Baker and Langdon 1990, Boyer 1990). It is not clear if morphological and physiological differences between the species will result in different competitive interactions with planted longleaf pine seedlings.

This study relates measures of longleaf pine seedling responses to resource availability in seedling specific microsites. Our specific objectives were to: 1) quantify relationships between canopy density and microsite conditions; 2) quantify relationships between microsite/growing conditions and planted longleaf pine seedling response; 3) determine the effects of management practices (canopy removal, herbicide release, fertilizer) on foliar nutrient concentrations in longleaf pine seedlings; 4) determine the effects of gap position on foliar nutrients of longleaf pine seedlings; and 5) determine the effects of gap position on tissue water potential (a measure of moisture stress) of longleaf pine seedlings.

3.8.2. Methods

This study was a part of the field experiment replicated at Fort Benning, GA and Camp Lejeune, NC. A complete description of study sites, experimental design and treatments is provided in Section 3.1.

3.8.2.1. Data collection

We quantified basal area of the study plots by measuring all trees within main plots immediately following harvest, and we assume that additional tree growth since harvest has been negligible in the context of these analyses. Methods for data collection of soil moisture at 6 cm, soil temperature at 10 cm, and gap light index in uniform plots are described in Sections 3.4 and 3.7. We used an Overstory Abundance Index (OAI) to quantify the competitive effects of overstory pines on longleaf pine seedlings in the uniform plots. OAI is typically expressed as a unitless measure that integrates the distance and size of canopy trees surrounding target individuals and is calculated as:

$$OAI = \sum_{i=0}^{n} A/d$$

where *A* = the bole cross-sectional area of $tree_i$ in cm^2 and *d* = the distance from the target seedling in cm. Trees closer than one m were given a value of *d* = 1 to limit excessive weight placed on close proximity, and we measured all trees within a 15 m radius of each seedling sampled for foliar analysis in uniform plots (Palik et al. 2003, Pecot et al. 2007).

To quantify the concentration of foliar nutrients in longleaf pine seedlings, we collected needles from at least five seedlings per sample unit in 2009 and 2010. Foliar samples were collected between November and February because nutrient levels are the most stable during the dormant season (van den Driessche 1974). We composited needles by split-plot in uniform plots. Our sample included needles from the seedling closest to each corner and the seedling closest to the center of each split-plot. Because we were interested in determining the effect of gap position on foliar nutrients, we established sampling zones across the north/south axis of each LG plot. Sampling zones were positioned at gap center, 20 m north/south of gap center, 40 m north/south of gap center (forest edge) and 50 m north/south of gap center. Seedlings that fell within a four-meter wide belt (two meters north/two meters south) running east/west at each sampling position were sampled for the foliar analyses. All foliar samples were placed into paper bags and stored in a cooler until processing in the lab. Upon return to the laboratory, foliar samples were over dried and analyzed for concentrations of N, P, K, Ca, Mg, S, Zn, Cu, Mn, Fe, and Na by the Agricultural Services Laboratory at Clemson University.

To directly quantify effects of soil moisture on seedling response in different gap positions, we measured foliar water potential of longleaf pine seedlings in LG plots in July and September 2008, May, July, and September 2009, and July and September 2010. In 2008, we tagged six seedlings that fell within four meter wide sampling belts that ran east/west at each 10 m gap position, extending 10 m into the forest on each end. During each sampling period, we removed one current-year fascicle from two randomly selected seedlings at each position. The foliar tissues were cleanly cut with a razor blade and needles were immediately loaded into a pressure chamber to determine xylem water potential (PMS Instruments, Corvallis, OR). All water potential measurements were taken prior to sunrise because tissue moisture is most strongly related to soil moisture conditions before seedlings become photosynthetically active.

3.8.2.2. Data analyses

We used linear and non-linear regression models to determine relationships between canopy density and microsite conditions (light, soil moisture, soil temperature). We determined Pearson's correlations between split-plot level means of longleaf pine seedling responses (growth and mortality) and measures of competition or resource availability, and we evaluated linear and non-linear regression models to describe relationships between variables. A description of variables is provided in Table 3.8.1. At Fort Benning, soil temperature data were collected within a three-hour period for each block, but data were collected over several days during each collection period. To account for daily fluctuations in temperature, we standardized

Table 3.8.1. List of variables and their abbreviations used in correlation analyses of seedling response and environmental conditions

Variable	Type	Description
Mort08	Dependent	Cumulative mortality in October 2008
Mort09	Dependent	Cumulative mortality in October 2009
Mort10	Dependent	Cumulative mortality in October 2010
Mort12	Dependent	Cumulative mortality in October 2012
AnMort09	Dependent	Annual mortality from October 2008 to October 2009
AnMort10	Dependent	Annual mortality from October 2009 to October 2010
AnMort12	Dependent	Incremental mortality from October 2010 to October 2012
RCD08	Dependent	Root collar diameter (mm) in October 2008
RCD09	Dependent	Root collar diameter (mm) in October 2009
RCD10	Dependent	Root collar diameter (mm) in October 2010
RCD12	Dependent	Root collar diameter (mm) in October 2012
RELRCD09	Dependent	Relative change in root collar diameter ((RCD09 - RCD08)/RCD08)
RELRCD10	Dependent	Relative change in root collar diameter ((RCD10 - RCD09)/RCD09)
RELRCD12	Dependent	Relative change in root collar diameter ((RCD12 – RCD10)/RCD10)
OAI	Independent	Overstory abundance index
GLI	Independent	Gap light index (%)
BA	Independent	Basal area (m^2/ha)
Moist09	Independent	Average soil moisture at 6 cm depth in 2009
Moist10	Independent	Average soil moisture at 6 cm depth in 2010
Temp09	Independent	Average soil temperature at 15 cm depth in 2009
Temp10	Independent	Average soil temperature at 15 cm depth in 2010
N09	Independent	Foliar nitrogen concentration (%) in 2009
P09	Independent	Foliar phosphorus concentration (%) in 2009
K09	Independent	Foliar potassium concentration (%) in 2009
N10	Independent	Foliar nitrogen concentration (%) in 2010
P10	Independent	Foliar phosphorus concentration (%) in 2010
K10	Independent	Foliar potassium concentration (%) in 2010
WP08	Independent	Water potential (Mpa) in LG plots in 2008**
WP09	Independent	Water potential (Mpa) in LG plots in 2009**
WP10	Independent	Water potential (Mpa) in LG plots in 2010**

*Data standardized to account for collection on different days; see methods

**Data collected in LG plots only; all correlations determined from dependent variables calculated at each position in LG plots temperature data with the mean daily air temperature (obtained from the Columbus Metro Airport weather station) for each collection day as follows:

$$Temp_S = \left(\frac{Temp_M}{Temp_{BA}}\right) * Temp_{TA}$$

where $Temp_S$ is the standardized temperature, $Temp_M$ is the soil temperature reading from the field, $Temp_{BA}$ is the average air temperature the day the block was measured, and $Temp_{TA}$ is the average air temperature from all study blocks.

Because we had found significant split-plot treatment effects on seedling size (see Section 3.2), we used analysis of covariance (ANCOVA) to account for additional variability in split-plot means of root collar diameter. We used GLM in SAS to test the effects of herbicide split-plot treatments (H and H+F) vs. split-plot treatments without herbicide (NT) on the relationships between dependent variables and gap light index, soil moisture, and soil temperature.

We used repeated measures analysis of variance (ANOVA) to test for effects of year, main-plot treatment, split-plot treatment, and interaction effects on composite samples of foliar nutrients from uniform plots. Because we commonly observed interactions between year and other variables, we used ANOVA tests for each year separately to present our results, and we focus on N, P, and K as those nutrients are often limiting in forest systems and constituted the fertilizer amendment treatment. In gap plots, we tested for effects of gap position on foliar nutrients. We used ANOVA to test the effect of gap position and the effect of gap direction on the xylem water potential of longleaf pine seedlings from LG plots and used linear and non-linear regression to test relationships between xylem water potential and seedling response.

3.8.3. Results

3.8.3.1. Relationships between stand density and site conditions

Gap light index was strongly related to stand basal area and best fit with an exponential decay function at each study location, with 98.1% of the variability explained at Fort Benning and 97.3% of the variability explained at Camp Lejeune (Figure 3.8.1). There were no relationships between soil moisture and basal area at either location in 2009 or 2010 (Figures 3.8.2 and 3.8.3). Soil temperature was significantly, negatively related to stand basal area at Fort Benning in 2009 (Figure 3.8.2), but there were no relationships between soil temperature and stand basal area at Camp Lejeune in either year (Figure 3.8.3).

3.8.3.2. Relationships between growing conditions and longleaf pine seedling response

Although overstory abundance index has been found to be a better measure of competition from overstory trees than basal area in longleaf pine forests with heterogeneous distribution of canopy trees (Palik et al. 2003), the relationship between OAI and basal area was nearly one-to-one at both Fort Benning and Camp Lejeune, with basal area explaining 98% of the variation in OAI at both sites (Figure 3.8.4). Because of the strong relationship and the applicability of basal area to forest managers, we focus on the relationships of basal area on response variables in this report.

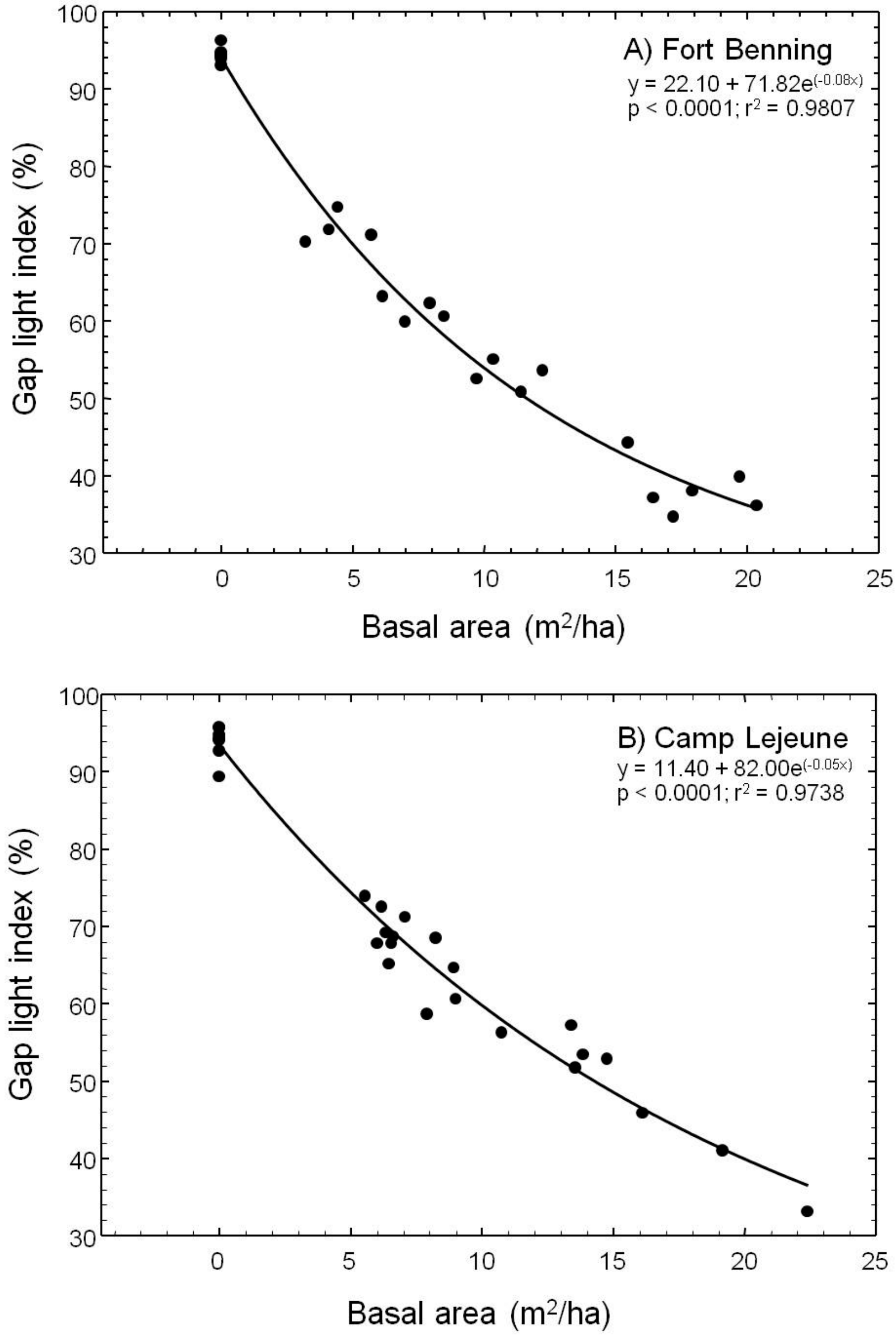

Figure 3.8.1. Relationships between stand basal area and gap light index at 1.4 m from the forest floor in loblolly pine stands at A) Fort Benning and B) Camp Lejeune.

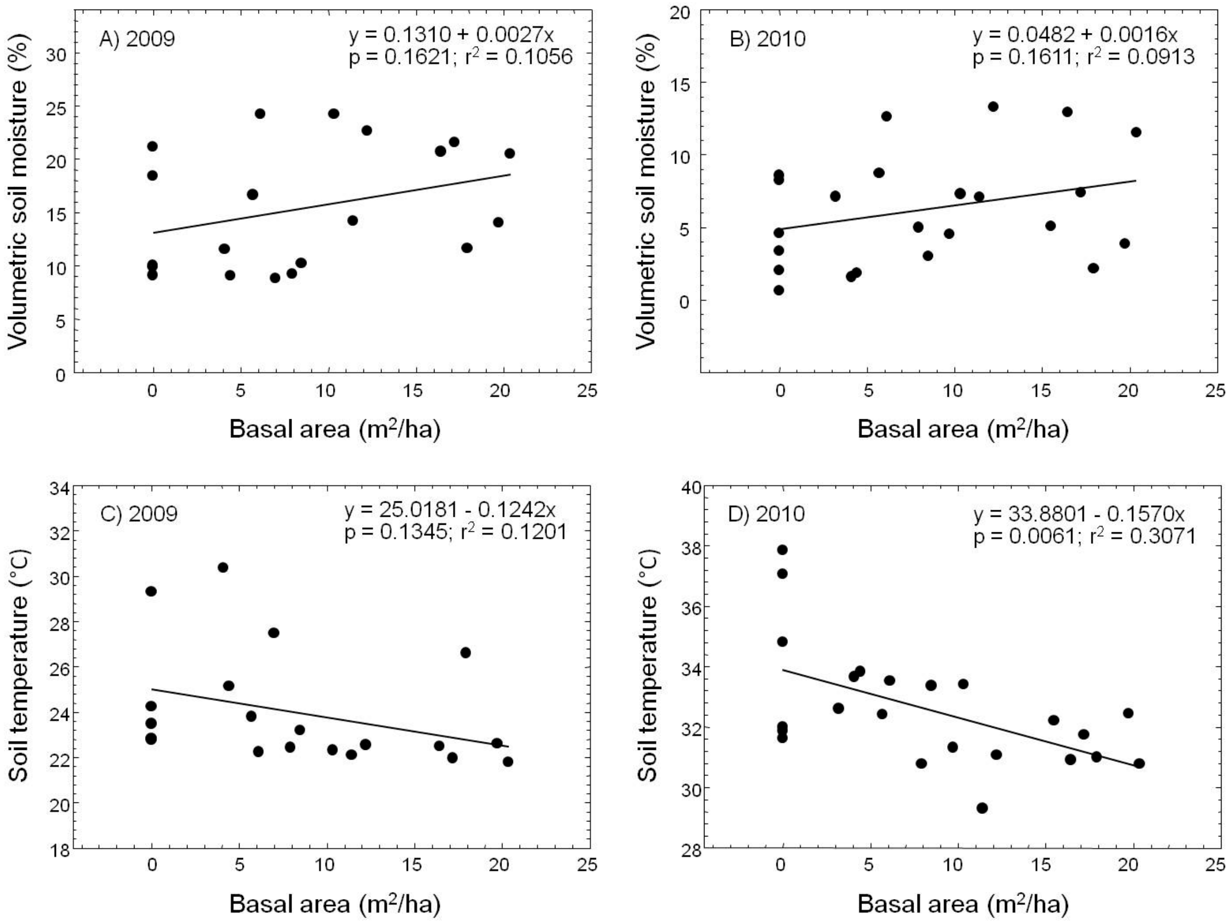

Figure 3.8.2. Relationships between stand basal area and A) 2009 soil moisture, B) 2010 soil moisture, C) 2009 soil temperature, and D) 2010 soil temperature at Fort Benning.

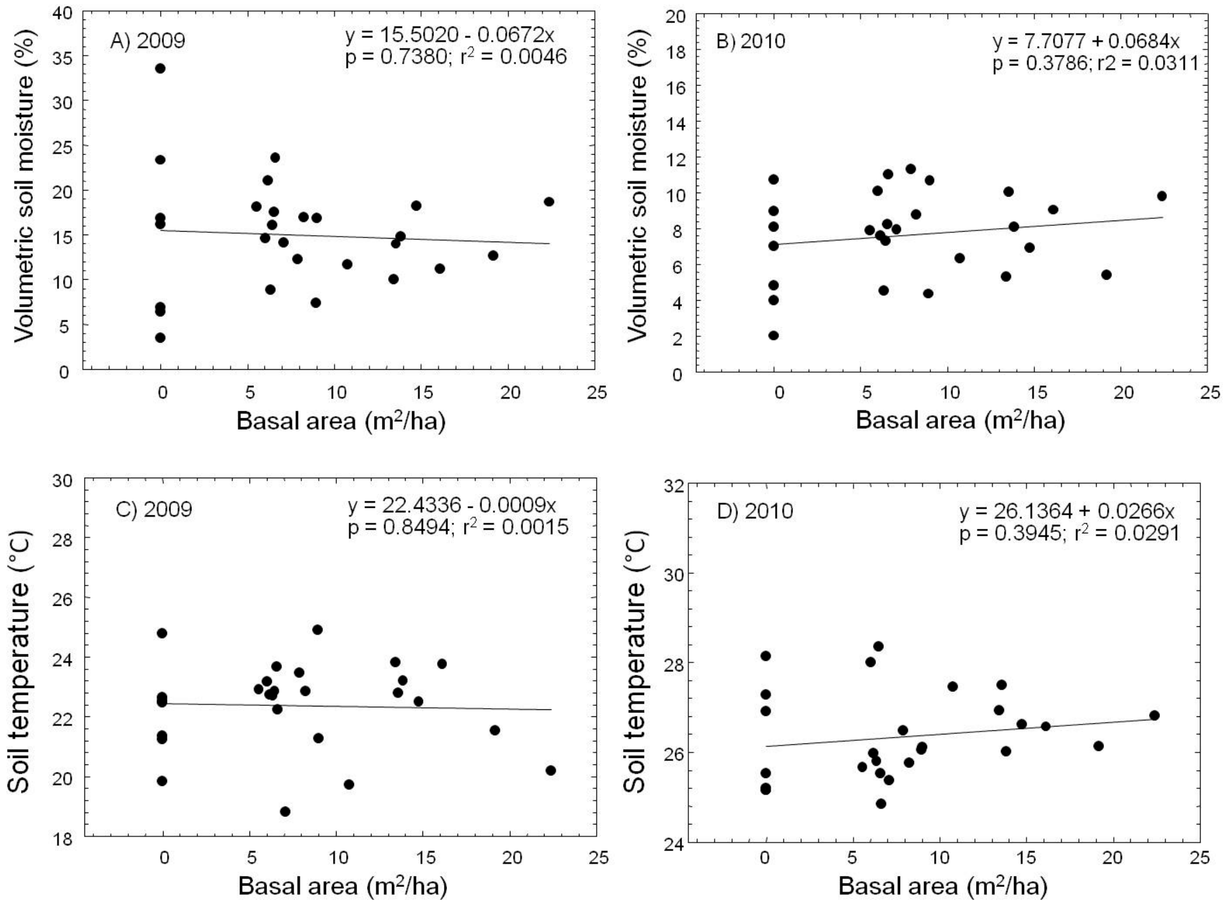

Figure 3.8.3. Relationships between stand basal area and A) 2009 soil moisture, B) 2010 soil moisture, C) 2009 soil temperature, and D) 2010 soil temperature at Camp Lejeune.

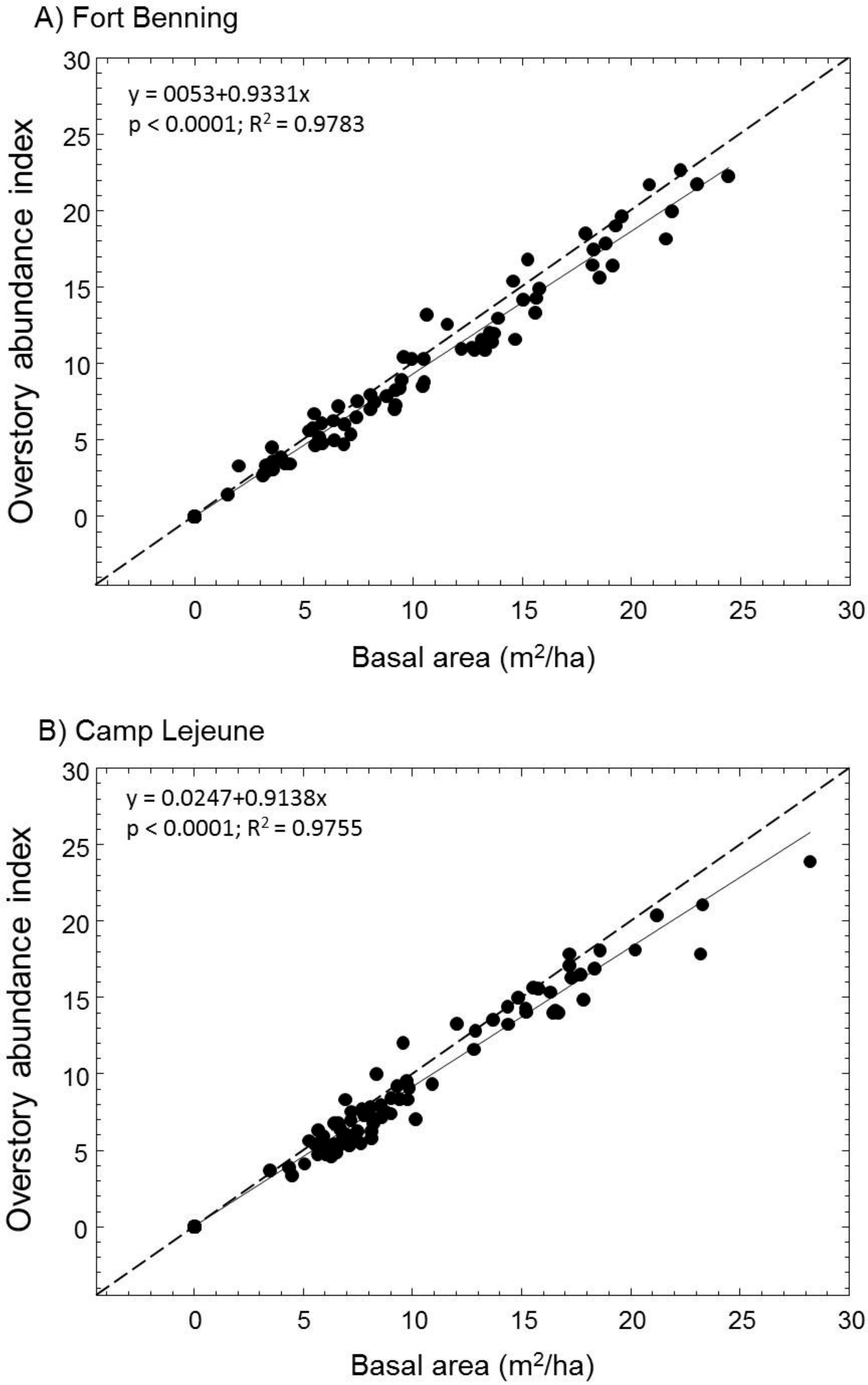

Figure 3.8.4. Relationship between overstory abundance index (OAI) and basal area (m^2/ha) at A) Fort Benning and B) Camp Lejeune.

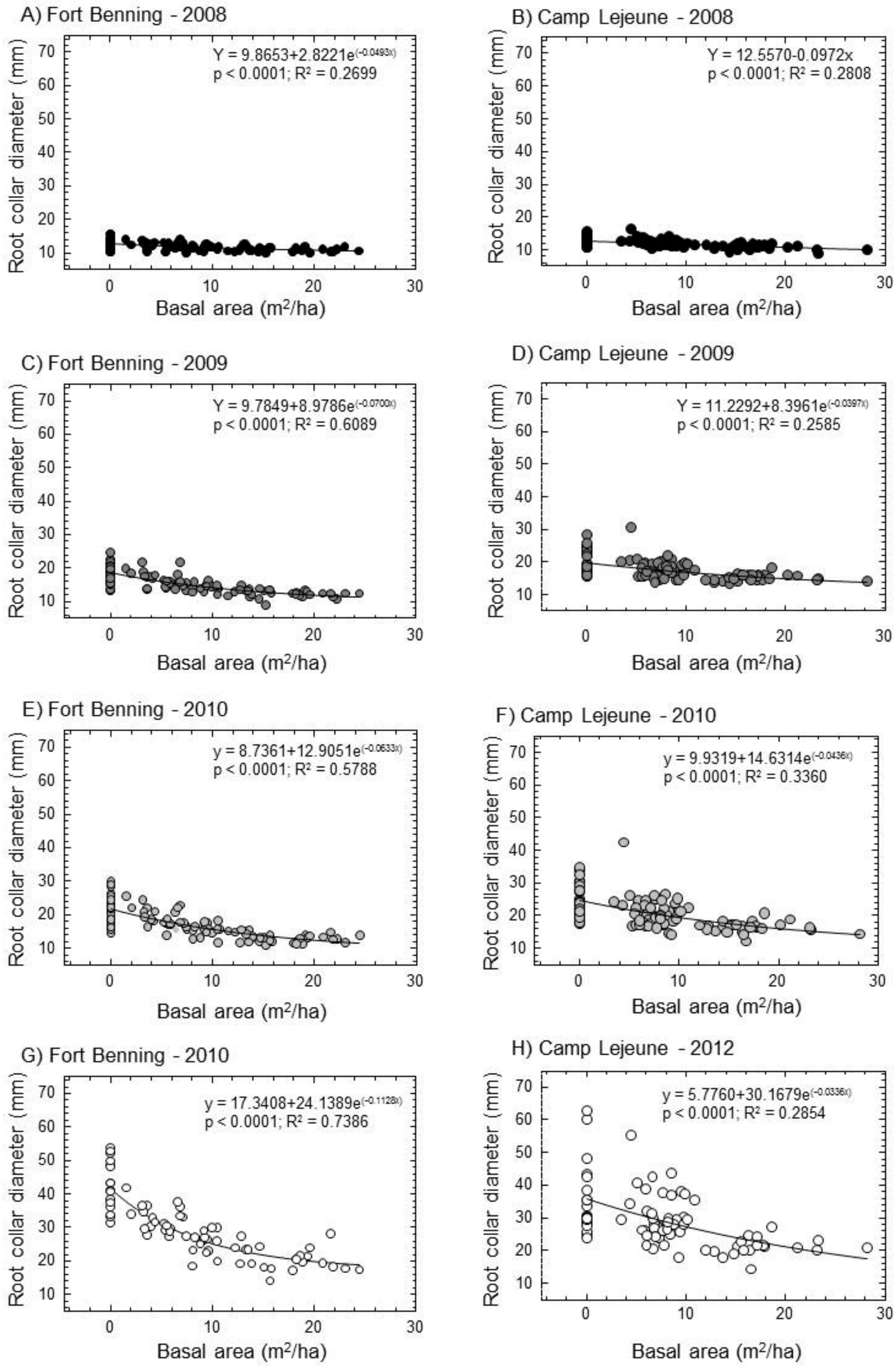

Figure 3.8.5. Relationships between longleaf pine seedling size (root collar diameter) and overstory basal area (m^2/ha) at the split-plot level in 2008, 2009, 2010, 2012 at Fort Benning (A, C, E, and G) and Camp Lejeune (B, D, F, and H).

Basal area was significantly, negatively related to seedling size in each year at both study sites (Figure 3.8.5). The best fit relationship was an exponential decay function for each year's data at Fort Benning. At Camp Lejeune, the best fit relationship was a linear function in 2008 but changed to an exponential decay function for 2009, 2010, and 2012 root collar diameter data. At Fort Benning, the relationship between basal area and root collar diameter increased from the first growing season (R^2 = 0.2699) to the fifth growing season (R^2 = 0.7386), but at Camp Lejeune the strength of the relationship varied little among the years (2008 R^2 = 0.2808; 2012 R^2 = 0.2854). Longleaf pine mortality in 2008 was negatively, exponentially related to basal area at Fort Benning, but the relationship was not significant in 2009 or 2010 (Figure 3.8.6). However, the incremental mortality between 2010 and 2012 at Fort Benning was positively related to basal area. The cumulative mortality in each year was also significantly related to overstory abundance each year (Tables 3.8.2 and 3.8.3), but those patterns were largely driven by the high first year mortality at Fort Benning. At Camp Lejeune, incremental mortality was positively related to basal area in each year other than 2012 (Figure 3.8.6).

Light availability was strongly, positively related to seedling size in each year at both study sites (Figure 3.8.7). After the first growing season, light accounted for 26.3% and 22.9% of the variability in seedling size at Fort Benning and Camp Lejeune, respectively. By the end of the fifth growing season, the strength of the relationship increased at Fort Benning, accounting for 74.6% of the variability in seedling size, but not at Camp Lejeune, accounting for 23.2% of the variability in seedling size. Relationships between seedling mortality and gap light index were similar in magnitude but the inverse of those with overstory abundance (Tables 3.8.2 and 3.8.3).

Analysis of covariance indicated that separate regression lines were appropriate to describe the relationship between root collar diameter and gap light index for herbicide and non-herbicide split-plot treatments (Figure 3.8.8). At Fort Benning, the slopes of the lines were significantly different ($p = 0.0080$), and at Camp Lejeune the slopes were not different ($p = 0.8858$) but the intercepts were significantly different ($p < 0.0001$).

There was a significant negative relationship between soil moisture in 2009 and relative root collar diameter growth during that year at both study sites (Figures 3.8.9 and 3.8.10), but we observed no relationship between soil moisture and relative growth in 2010. Soil temperature was positively related to relative seedling growth in both years at Fort Benning, although no more than 13.8% of the variation was accounted for by soil temperature (Figure 3.8.9), and there was no relationship at Camp Lejeune in either year (Figure 3.8.10). Total root collar diameter size in each year was significantly, negatively correlated with soil moisture and significantly, positively correlated with soil temperature in both years at Fort Benning (Table 3.8.2). At Fort Benning, soil moisture was negatively correlated and soil temperature was positively correlated with annual seedling mortality in 2010, although neither variable accounted for more than 10% of the variability in mortality (Table 3.8.2).

3.8.3.3. Longleaf pine seedling foliar nutrients and water potential

The repeated measures ANOVA indicated significant year effects on foliar concentrations of N, P, and K at Fort Benning and N and K at Camp Lejeune, although there was a significant year*split-plot interaction for N at Fort Benning, year*split-plot interactions for P at Camp

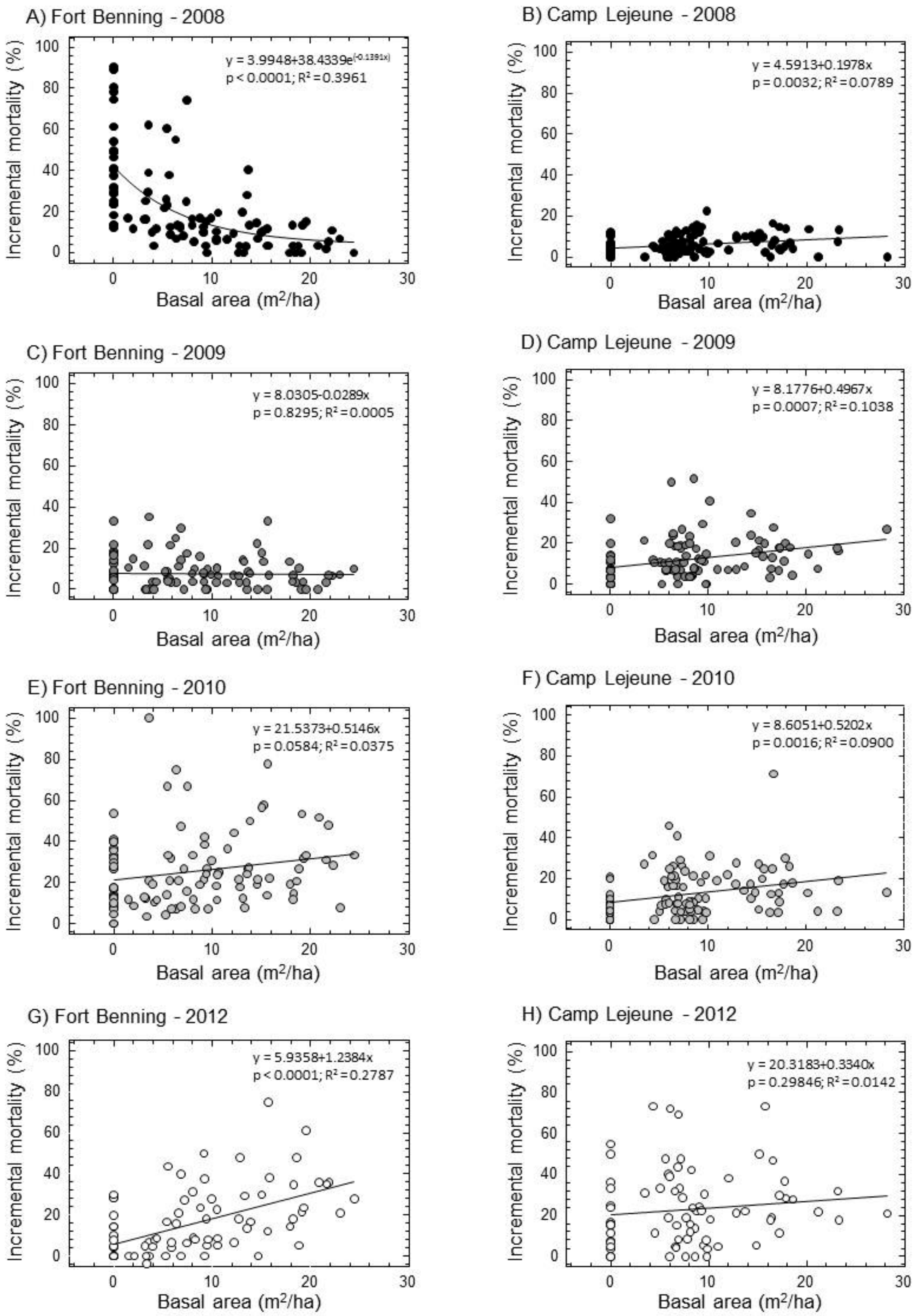

Figure 3.8.6. Relationships between annual longleaf pine seedling mortality and basal area in 2008, 2009, 2010, and 2012 at Fort Benning (A, C, E, and G) and Camp Lejeune (B, D, F, and H).

Table 3.8.2. Results of Pearson correlation analysis (Pearson's r; *p*-values in bold) for longleaf pine dependent variables and growing condition independent variables at Fort Benning. Variables are described in Table 3.8.1

	Independent variables															
Dependent variables	OAI	GLI	BA	Moist09	Moist10	Temp09	Temp10	N09	P09	K09	N10	P10	K10	WP08	WP09	WP10
Mort08	-0.5646	0.6383	-0.5732	.	.	.	.	.	.	.	.	.	.	-0.2685	.	.
	<0.0001	**<0.0001**	**<0.0001**	**.**	**.**	**.**	**.**	**.**	**.**	**.**	**.**	**.**	**.**	**0.0333**	**.**	**.**
Mort09	-0.5466	0.6052	-0.5732	-0.0337	.	0.0687	.	0.4921	0.4332	0.2357	.	.	.	-0.3145	-0.0406	.
	<0.0001	**<0.0001**	**<0.0001**	**0.7669**	**.**	**0.5450**	**.**	**<0.0001**	**0.0001**	**0.0463**	**.**	**.**	**.**	**0.0121**	**0.7503**	**.**
Mort10	-0.2289	0.2806	-0.2552	0.1664	0.2330	-0.0825	0.1183	0.3662	0.3627	0.1783	0.4386	0.5011	0.0272	-0.4150	0.0320	-0.4188
	0.0249	**0.0062**	**0.0121**	**0.1402**	**0.0254**	**0.4667**	**0.2612**	**0.0016**	**0.0017**	**0.1340**	**0.0001**	**<0.0001**	**0.8220**	**0.0007**	**0.8017**	**0.0006**
Mort12	0.1285	-0.0826	0.1271	0.1950	0.2516	-0.2684	-0.3404	0.1096	0.1692	-0.0042	0.1563	0.3784	0.0185	-0.5028	-0.1782	-0.4965
	0.2558	**0.4722**	**0.2614**	**0.1226**	**0.0283**	**0.0320**	**0.0026**	**0.4045**	**0.1962**	**0.9746**	**0.2331**	**0.0029**	**0.8882**	**0.0001**	**0.2018**	**0.0002**
AnMort09	-0.0101	-0.0334	-0.0223	-0.2291	.	0.1102	.	0.0659	0.2256	0.2045	.	.	.	0.0025	-0.1156	.
	0.9222	**0.7492**	**0.8291**	**0.0410**	**.**	**0.3305**	**.**	**0.5824**	**0.0568**	**0.0846**	**.**	**.**	**.**	**0.9845**	**0.3631**	**.**
AnMort10	0.2042	-0.1950	0.1938	0.2598	0.3035	-0.1908	-0.2825	0.0746	0.1637	0.0423	0.0987	0.2289	0.0328	-0.1456	0.0576	-0.0071
	0.0460	**0.0539**	**0.0585**	**0.0200**	**0.0033**	**0.0900**	**0.0064**	**0.5337**	**0.1696**	**0.7241**	**0.4128**	**0.0548**	**0.7858**	**0.2550**	**0.6511**	**0.9559**
AnMort12	0.5135	-0.5182	0.5279	0.2266	0.3662	-0.4652	-0.6221	-0.1462	0.0550	-0.1112	-0.2833	0.1151	-0.2054	-0.1333	-0.0118	0.2945
	<0.0001	**<0.0001**	**<0.0001**	**0.0718**	**0.0011**	**0.0001**	**<0.0001**	**0.2651**	**0.6763**	**0.3946**	**0.0283**	**0.3813**	**0.1154**	**0.3413**	**0.9332**	**0.0323**
RCD08	-0.5215	0.5144	-0.5116	.	.	.	.	.	.	.	.	.	.	0.2416	.	.
	<0.0001	**<0.0001**	**<0.0001**	**.**	**.**	**.**	**.**	**.**	**.**	**.**	**.**	**.**	**.**	**0.0564**	**.**	**.**
RCD09	-0.7612	0.7768	-0.7593	-0.4939	.	0.4982	.	0.3570	0.1221	0.3840	.	.	.	0.3682	-0.2154	.
	<0.0001	**<0.0001**	**<0.0001**	**<0.0001**	**.**	**<0.0001**	**.**	**0.0002**	**0.3070**	**0.0009**	**.**	**.**	**.**	**0.0030**	**0.0874**	**.**
RCD10	-0.7386	0.7559	-0.7423	-0.4990	-0.3273	0.5807	0.6040	0.3916	0.1696	0.3888	0.4667	0.3419	0.4148	0.3267	-0.1556	0.0080
	<0.0001	**<0.0001**	**<0.0001**	**<0.0001**	**0.0015**	**<0.0001**	**<0.0001**	**0.0007**	**0.1573**	**0.0008**	**<0.0001**	**0.0035**	**0.0003**	**0.0102**	**0.2273**	**0.9509**
RCD12	-0.8096	0.8641	-0.8117	-0.3435	-0.2874	0.2923	0.6043	0.6022	0.4275	0.3839	0.5382	0.4870	0.3073	0.2020	-0.0996	0.0471
	<0.0001	**<0.0001**	**<0.0001**	**0.0055**	**0.0118**	**0.0191**	**<0.0001**	**<0.0001**	**0.0007**	**0.0025**	**<0.0001**	**<0.0001**	**0.0169**	**0.1469**	**0.4779**	**0.7376**
RELRCD09	-0.7302	0.7581	-0.7320	-0.3308	.	0.3680	.	0.3779	0.1313	0.3804	.	.	.	0.3757	-0.1617	.
	<0.0001	**<0.0001**	**<0.0001**	**0.0027**	**.**	**0.0004**	**.**	**0.0011**	**0.2716**	**0.0001**	**.**	**.**	**.**	**0.0024**	**0.2017**	**.**
RELRCD10	-0.3240	0.3173	-0.3357	0.1496	0.1897	-0.0682	0.3835	0.2790	0.1171	0.2480	0.0779	0.1396	0.1698	-0.0084	0.0746	0.1044
	0.0012	**0.0020**	**0.0009**	**0.1882**	**0.0718**	**0.5506**	**0.0002**	**0.0185**	**0.3307**	**0.0370**	**0.5185**	**0.2455**	**0.1569**	**0.9490**	**0.5646**	**0.4194**
RELRCD12	-0.4341	0.4963	-0.4181	-0.2784	-0.1950	0.0595	0.2440	0.3242	0.3570	0.0274	0.2239	0.3432	-0.0150	-0.1503	-0.1572	-0.1021
	<0.0001	**<0.0001**	**0.0001**	**0.0259**	**0.0915**	**0.6408**	**0.0337**	**0.0115**	**0.0051**	**0.8354**	**0.0855**	**0.0073**	**0.9094**	**0.2827**	**0.2610**	**0.4670**

Table 3.8.3. Results of Pearson correlation analysis (Pearson's r; *p*-value in bold) for longleaf pine dependent variables and growing condition independent variables at Camp Lejeune. Variables are described in Table 3.8.1

	Independent variables															
Dependent variables	OAI	GLI	BA	Moist09	Moist10	Temp09	Temp10	N09	P09	K09	N10	P10	K10	WP08	WP09	WP10
Mort08	0.2792	-0.3257	0.2809	.	.	.	.	.	.	.	.	.	.	-0.2735	.	.
	0.0034	**0.0006**	**0.0032**	.	.	.	.	.	.	.	.	.	.	**0.0288**	.	.
Mort09	0.3528	-0.4319	0.3855	-0.0214	.	-0.1979	.	0.0578	-0.0585	0.1999	.	.	.	-0.3173	-0.0443	.
	0.0002	**<0.0001**	**<0.0001**	**0.8257**	.	**0.0401**	.	**0.6080**	**0.6041**	**0.0736**	.	.	.	**0.0106**	**0.7259**	.
Mort10	0.3846	-0.4457	0.4130	-0.0129	0.1810	-0.1190	-0.0554	-0.0672	-0.1168	0.0700	0.1891	-0.1381	0.1333	-0.3767	0.0297	-0.4197
	<0.0001	**0.0007**	**<0.0001**	**0.8949**	**0.0608**	**0.2199**	**0.5693**	**0.551**	**0.299**	**0.5347**	**0.091**	**0.2188**	**0.2356**	**0.0022**	**0.8145**	**0.0005**
Mort12	0.2601	-0.2830	0.2833	0.0889	0.2323	-0.1468	-0.2305	-0.0505	-0.0980	0.0815	0.2612	-0.1068	0.0471	-0.0028	-0.8979	0.1114
	0.0215	**0.0121**	**0.0120**	**0.4388**	**0.0407**	**0.1998**	**0.0423**	**0.6606**	**0.3935**	**0.4783**	**0.0209**	**0.3521**	**0.6824**	**0.9823**	**0.4769**	**0.3771**
AnMort09	-0.3526	0.2858	0.3221	0.0337	.	-0.3343	.	0.0984	0.0173	0.1624	.	.	.	-0.1795	-0.0629	.
	0.0002	**0.0027**	**0.0007**	**0.7292**	.	**0.0004**	.	**0.3822**	**0.8782**	**0.1475**	.	.	.	**0.1559**	**0.6185**	.
AnMort10	-0.3070	0.2819	0.2999	0.0038	0.1028	-0.0199	-0.0816	-0.1628	-0.1244	-0.0785	0.1800	-0.0806	0.0568	-0.1532	0.052	-0.0436
	0.0012	**0.0031**	**0.0016**	**0.9688**	**0.2897**	**0.8380**	**0.4011**	**0.1465**	**0.2684**	**0.4864**	**0.1078**	**0.4747**	**0.6148**	**0.2268**	**0.6805**	**0.7299**
AnMort12	0.1156	-0.1070	0.1195	0.1342	0.1344	-0.1894	-0.3124	-0.0341	-0.0286	0.0827	0.2288	-0.0137	-0.0437	**0.0931**	**-0.9719**	**-0.0037**
	0.3135	**0.3510**	**0.2974**	**0.2415**	**0.2406**	**0.0967**	**0.0054**	**0.7667**	**0.8037**	**0.4716**	**0.0439**	**0.9054**	**0.7040**	**0.4608**	**0.4412**	**0.9769**
RCD08	-0.5277	0.47825	-0.53017	.	.	.	.	.	.	.	.	.	.	0.247	.	.
	<0.0001	**<0.0001**	**<0.0001**	.	.	.	.	.	.	.	.	.	.	**0.0491**	.	.
RCD09	-0.5093	0.4414	-0.5017	-0.3004	.	-0.0511	.	0.4338	0.5325	-0.0308	.	.	.	0.3712	-0.2114	.
	<0.0001	**<0.0001**	**<0.0001**	**0.0016**	.	**0.5992**	.	**<0.0001**	**<0.0001**	**0.7849**	.	.	.	**0.0025**	**0.091**	.
RCD10	-0.5752	0.5341	-0.5709	-0.1564	-0.3737	-0.0602	-0.0463	0.4380	0.5041	0.0864	0.0268	0.4779	-0.1546	0.3301	-0.1510	0.0341
	<0.0001	**<0.0001**	**<0.0001**	**0.1059**	**<0.0001**	**0.5362**	**0.6340**	**<0.0001**	**<0.0001**	**0.4429**	**0.8338**	**<0.0001**	**0.1683**	**0.0088**	**0.2376**	**0.7911**
RCD12	-0.5330	0.4888	-0.5282	-0.2998	-0.4676	0.0991	-0.0038	0.3290	0.4918	-0.0185	-0.0995	0.4949	-0.1470	0.3020	-0.0059	-0.1033
	<0.0001	**<0.0001**	**<0.0001**	**0.0073**	**<0.0001**	**0.3851**	**0.9739**	**0.0033**	**<0.0001**	**0.8723**	**0.3859**	**<0.0001**	**0.1991**	**0.0153**	**0.9634**	**0.4165**
RELRCD09	-0.2826	0.2248	-0.2698	-0.3408	-0.3857	-0.1748	0.0612	0.4552	0.6328	-0.0335	.	.	.	0.3778	-0.1619	.
	0.0030	**0.0193**	**0.0047**	**0.0003**	**<0.0001**	**0.0704**	**0.5294**	**<0.0001**	**<0.0001**	**0.7665**	.	.	.	**0.0021**	**0.1975**	.
RELRCD10	-0.4480	0.4722	-0.4529	0.1791	-0.1477	-0.0470	-0.0652	0.2233	0.2280	0.2295	0.0829	0.1253	-0.1885	0.0006	0.0729	0.1319
	<0.0001	**<0.0001**	**<0.0001**	**0.0637**	**0.1272**	**0.6288**	**0.5023**	**0.0451**	**0.0407**	**0.0393**	**0.4618**	**0.2651**	**0.0919**	**0.9965**	**0.5701**	**0.3027**
RELRCD12	-0.2201	0.2188	-0.2234	-0.2658	-0.3199	0.2399	0.1307	0.0484	0.2729	-0.1813	-0.2492	0.3001	-0.1072	0.0605	-0.1271	0.0414
	0.0513	**0.0527**	**0.0478**	**0.0179**	**0.0041**	**0.0332**	**0.2510**	**0.6741**	**0.0156**	**0.1121**	**0.0278**	**0.0076**	**0.3504**	**0.6350**	**0.3171**	**0.7453**

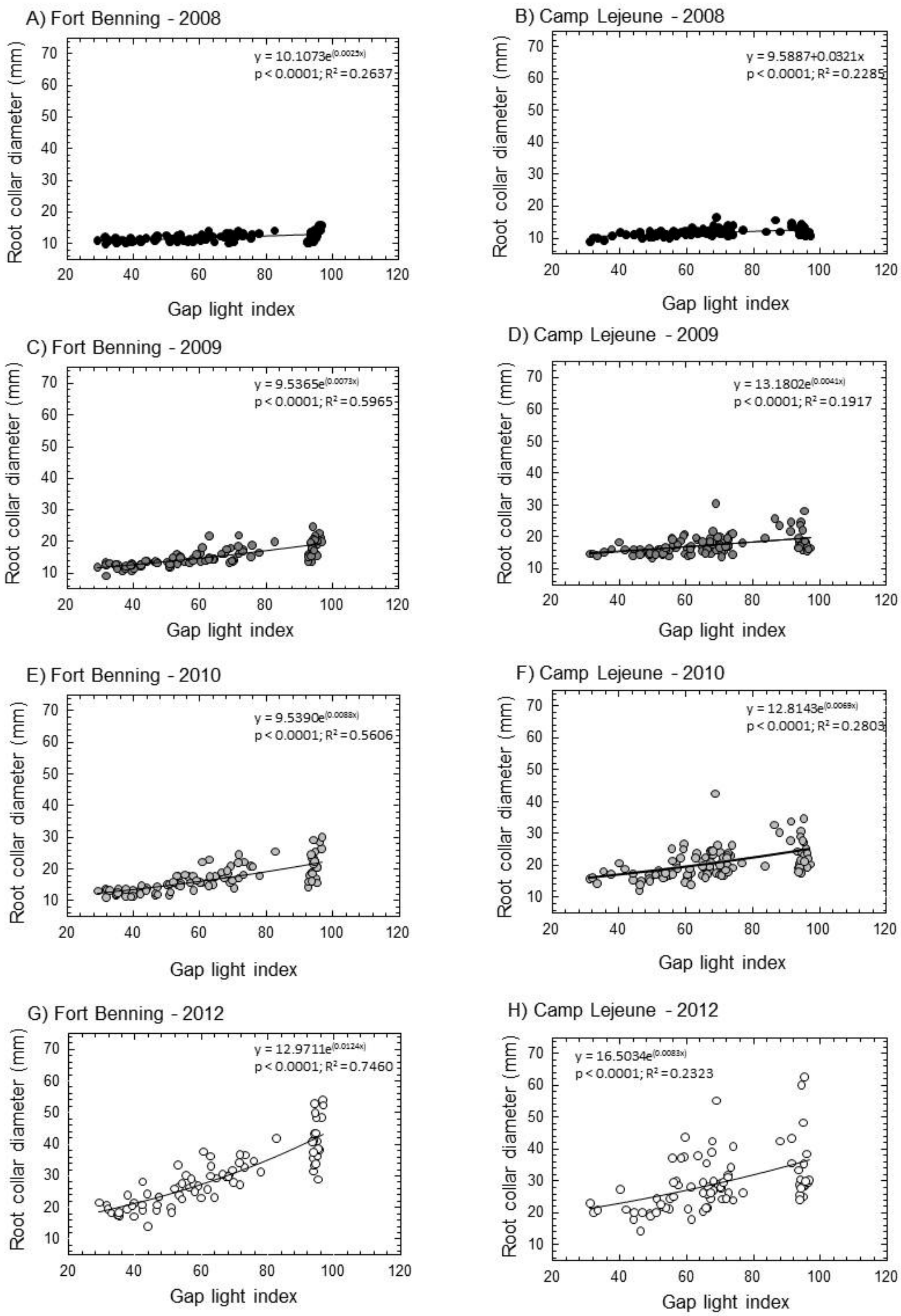

Figure 3.8.7. Relationships between longleaf pine seedling size (root collar diameter) and gap light index in 2008, 2009, 2010, and 2012 at Fort Benning (A, C, E, and G) and Camp Lejeune (B, D, F, and H).

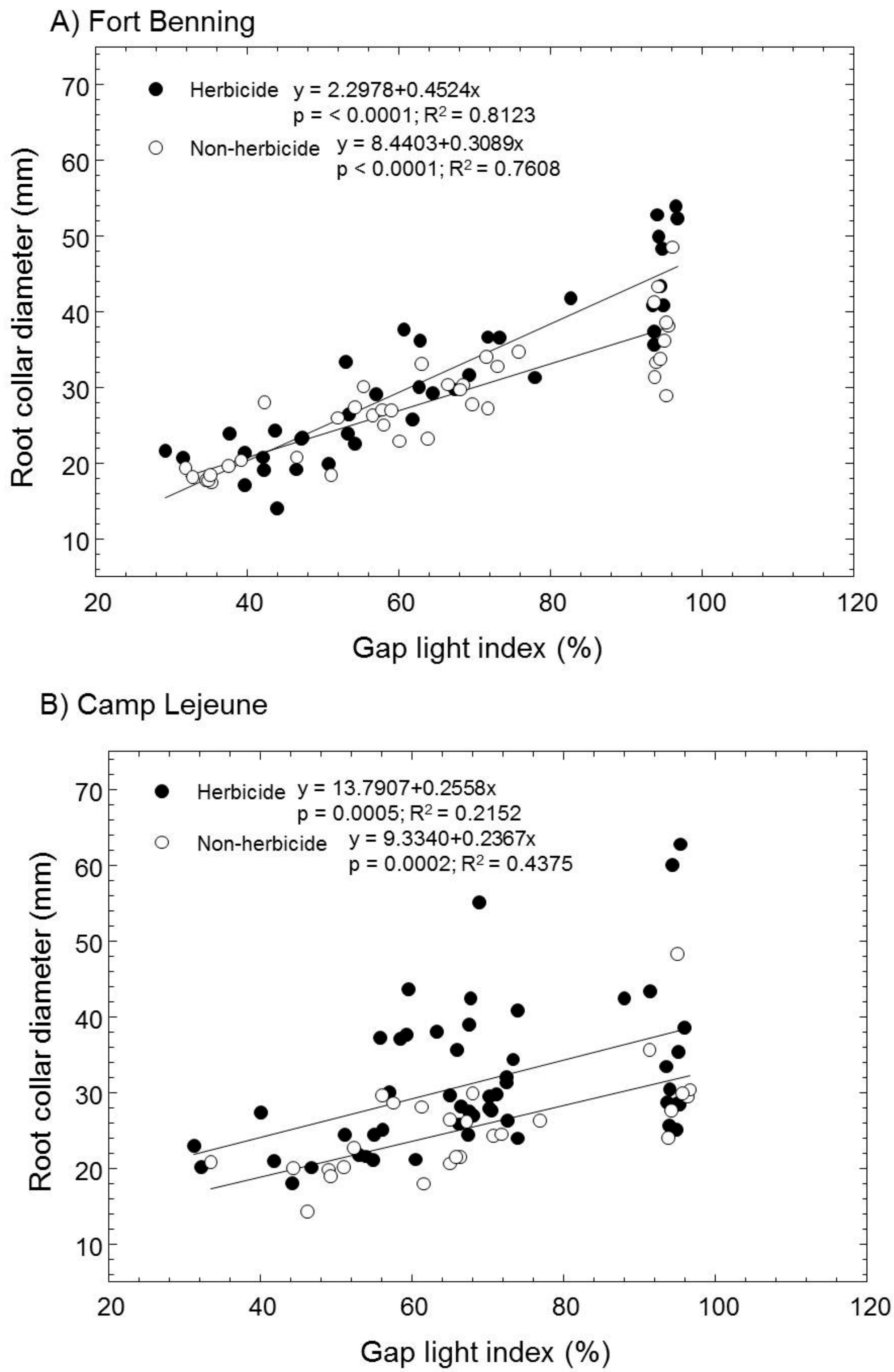

Figure 3.8.8. Relationships between root collar diameter and gap light index by split-plot treatment (herbicide treatments vs. non-herbicide treatments) at A) Fort Benning and B) Camp Lejeune.

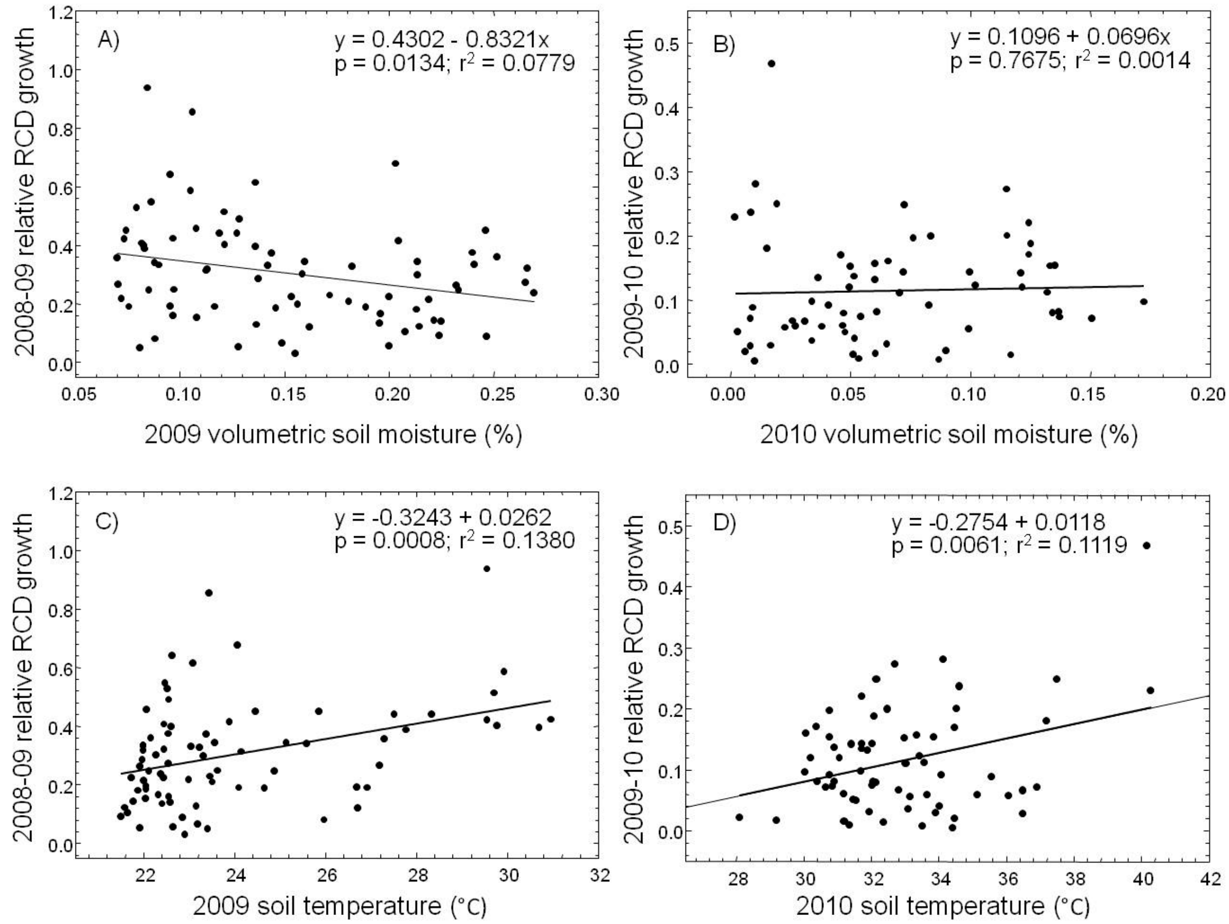

Figure 3.8.9. Relationships between relative annual root collar diameter growth and A) volumetric soil moisture in 2009, B) volumetric soil moisture in 2010, C) soil temperature in 2009, and D) soil temperature in 2010 at Fort Benning.

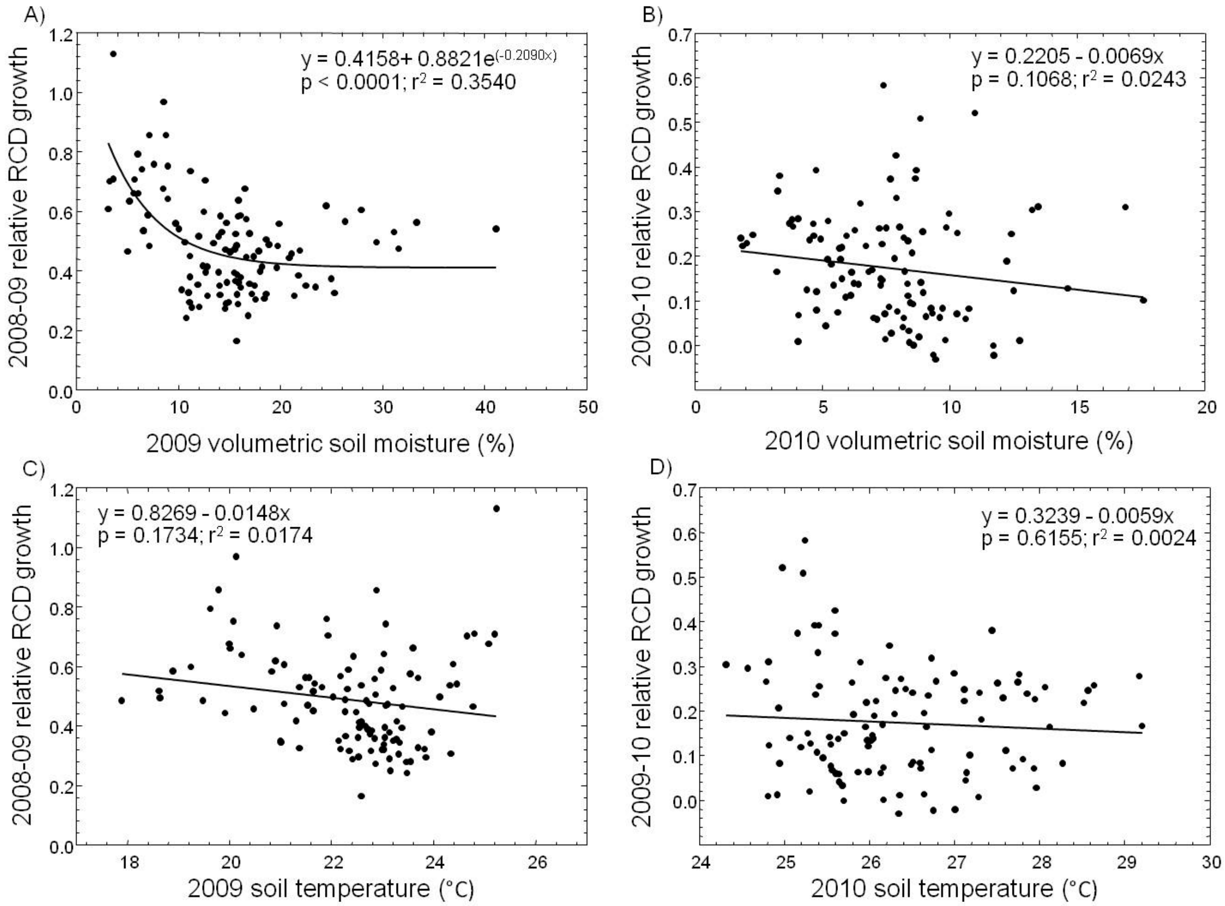

Figure 3.8.10. Relationships between relative annual root collar diameter growth and A) volumetric soil moisture in 2009, B) volumetric soil moisture in 2010, C) soil temperature in 2009, and D) soil temperature in 2010 at Camp Lejeune.

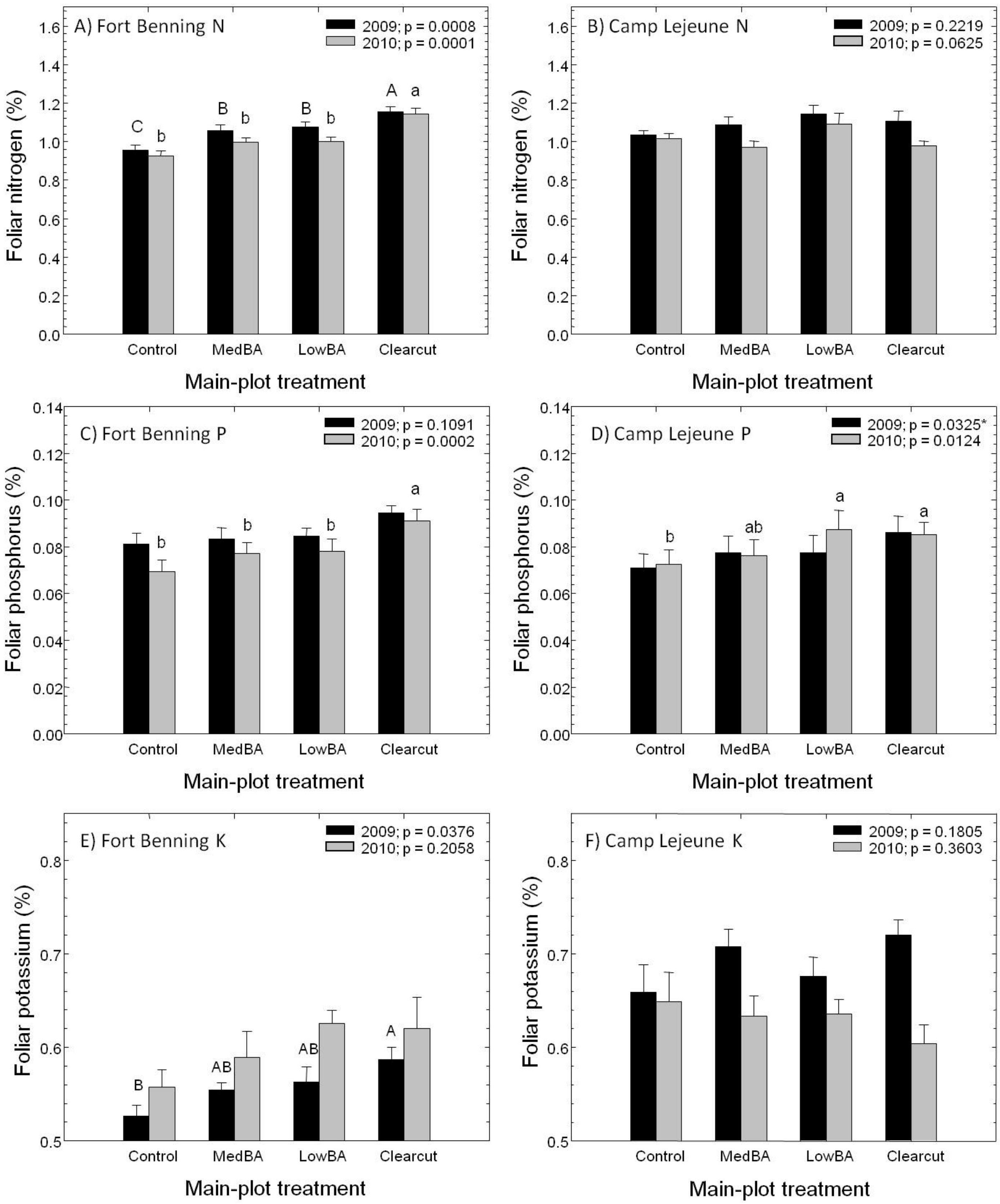

Figure 3.8.11. Foliar nutrient concentrations (mean ± one standard error) of longleaf pine seedlings by main-plot treatment at Fort Benning and Camp Lejeune in 2009 and 2010. Different letters indicate significant treatment differences within each year

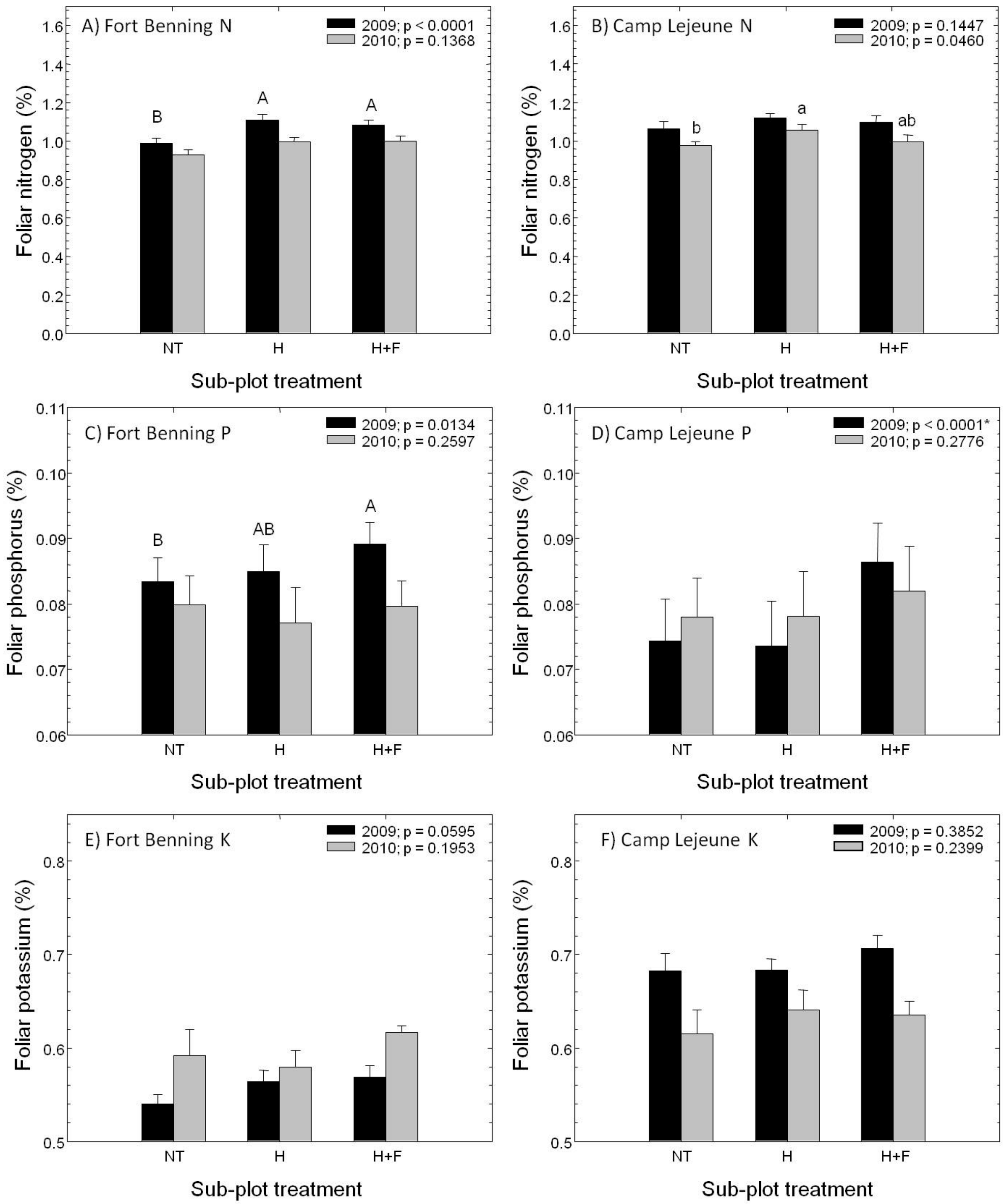

Figure 3.8.12. Foliar nutrient concentrations (mean ± one standard error) of longleaf pine seedlings by split-plot treatment at Fort Benning and Camp Lejeune in 2009 and 2010. Different letters indicate significant treatment differences within each year.

Lejeune, and significant year*main-plot interactions for P and K at Camp Lejeune (Table 3.8.4). When each year was analyzed separately, we generally found that concentrations of N (in both years), P (in 2010), and K (in 2009) were significantly higher in Clearcut plots than Control (Figure 3.8.11). MedBA and LowBA plots had intermediate levels of foliar nutrients, suggesting that the presence of canopy trees reduced foliar nutrient concentrations in longleaf pine seedlings. At Camp Lejeune, the same pattern was observed for P in 2010, but no main-plot effects were seen for N, P, or K in other years.

The split-plot treatments affected foliar N and P concentrations in 2009 at Fort Benning, where both H and HF plots had higher N concentrations than NT plots and HF plots had higher P concentrations than NT plots (Figure 3.8.12). At Camp Lejeune, only foliar N concentrations in 2010 were significantly affected by split-plot treatments, in which H had higher N levels than NT. In gap plots at Fort Benning, there was a slight trend of increases nutrient concentrations associated with distance from the forest edge, but we observed few significant differences (Figure 3.8.13). Potassium levels were higher for seedlings in the north half of gaps than the south half of gaps in 2009 (Figure 3.8.13e). There were no effects of gap direction on foliar nutrients at Camp Lejeune, and significant gap position effects were limited to 2009 phosphorus levels and 2010 potassium levels (Figure 3.8.13). Results for the analysis of the other nutrients (Ca, Mg, S, Zn, Cu, Mn, Fe, and Na) are included as Appendices A-3.8.1—A-3.8.4.

At Fort Benning, we found significant relationships between relative longleaf pine seedling growth from uniform plots in 2009 and foliar concentrations of N and K, where each nutrient variable explained around 15% of the variability in annual seedling growth (Figure 3.8.14). There was no relationship with foliar P or between any foliar nutrient and relative growth in 2010. Similarly, foliar N explained 18.9% of the variability in relative root collar diameter growth in 2009 at Camp Lejeune, while P concentrations explained 37.9% of the variability (Figure 3.8.15). There was no relationship between foliar K and relative growth in 2009 or any nutrient and growth in 2010.

There was no effect of gap position on xylem water potential in 2008 or 2010 at either study location (Figure 3.8.16). Generally, xylem water potential was highly variable within and among positions. However, in 2009 there were significant effects of position at each site; at Fort Benning, water stress increased (i.e. xylem water potential became more negative) at positions beneath the forest canopy as opposed to within gap center, while at Camp Lejeune water stress was higher (more negative xylem water potential) near the northern forest edge than at 20 m from the forest edge on the south half of the gaps. Water stress was significantly higher on the north half of gaps than the south half of gaps in 2009 at Fort Benning (Figure 3.8.16c). Generally, xylem water potential ranged from -0.2 to -0.6 Mpa at the two study sites, but 2010 measurements at Fort Benning indicated higher levels of water stress, with values ranging from -0.8 to -1.2 Mpa. Mortality was significantly, negatively related to water potential (indicating higher mortality with greater water stress) in 2008 at Fort Benning, but the relationship was not strong and explained less than 10% of the variability in mortality (Table 3.8.3).

Table 3.8.4. Results of repeated measures ANOVA for foliar nutrient concentrations measured in 2009 and 2010 at Fort Benning and Camp Lejeune. Only N, P, and K are shown.

Fort Benning						Camp Lejeune					
Nutrient	Effect	NumDF	DenDF	F	p-value	Nutrient	Effect	NumDF	DenDF	F	p-value
N	year	1	60.2	8.21	0.0057	N	year	1	69.5	28.75	<0.0001
	trt	3	15.0	15.52	<0.0001		trt	3	18.0	2.24	0.1185
	year*trt	3	60.2	0.88	0.4555		year*trt	3	69.3	2.24	0.0909
	split	2	40.2	11.93	<0.0001		split	2	47.1	3.12	0.0535
	year*split	2	60.2	7.27	0.0015		year*split	2	69.7	0.06	0.9450
	trt*split	6	40.1	1.94	0.0983		trt*split	6	47.0	0.33	0.9159
	year*trt*split	6	60.2	0.72	0.6388		year*trt*split	6	69.5	1.11	0.3680
P	year	1	60.3	19.77	<0.0001	P	year	1	70.3	2.40	0.1261
	trt	3	15.0	8.33	0.0017		trt	3	18.1	4.60	0.0146
	year*trt	3	60.2	1.36	0.2645		year*trt	3	70.3	3.64	0.0167
	split	2	40.1	2.54	0.0917		split	2	48.5	9.16	0.0004
	year*split	2	60.2	1.86	0.1652		year*split	2	70.9	8.14	0.0007
	trt*split	6	40.1	0.48	0.8161		trt*split	6	48.5	2.13	0.0665
	year*trt*split	6	60.2	1.41	0.2256		year*trt*split	6	70.8	1.26	0.2864
K	year	1	59.7	15.08	0.0003	K	year	1	72.2	28.75	<0.0001
	trt	3	15.0	3.23	0.0524		trt	3	18.2	0.28	0.8357
	year*trt	3	59.7	0.60	0.6173		year*trt	3	72.1	4.13	0.0092
	sub	2	40.0	1.90	0.1622		split	2	48.4	1.55	0.2232
	year*split	2	59.7	1.59	0.2123		year*split	2	72.4	0.70	0.4978
	trt*split	6	40.0	1.19	0.3297		trt*split	6	48.4	1.03	0.4183
	year*trt*split	6	59.7	1.36	0.2468		year*trt*split	6	72.3	0.75	0.6139

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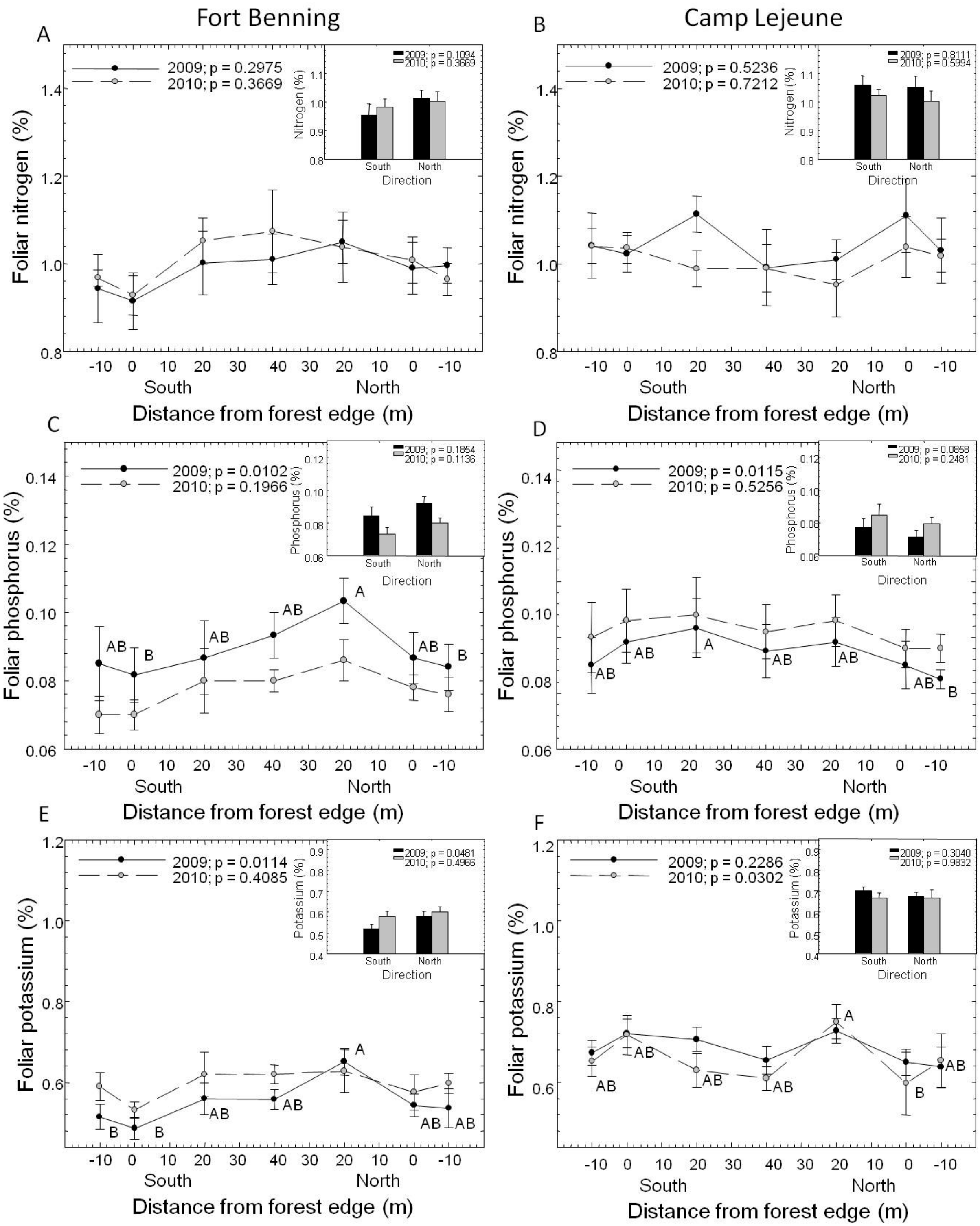

Figure 3.8.13. Foliar nutrient concentrations (mean ± one standard error) of longleaf pine seedlings by gap position and direction (insets) in 2009 and 2010 at Fort Benning (A, C, E) and Camp Lejeune (B, D, F). Different letters indicate significant differences with each year.

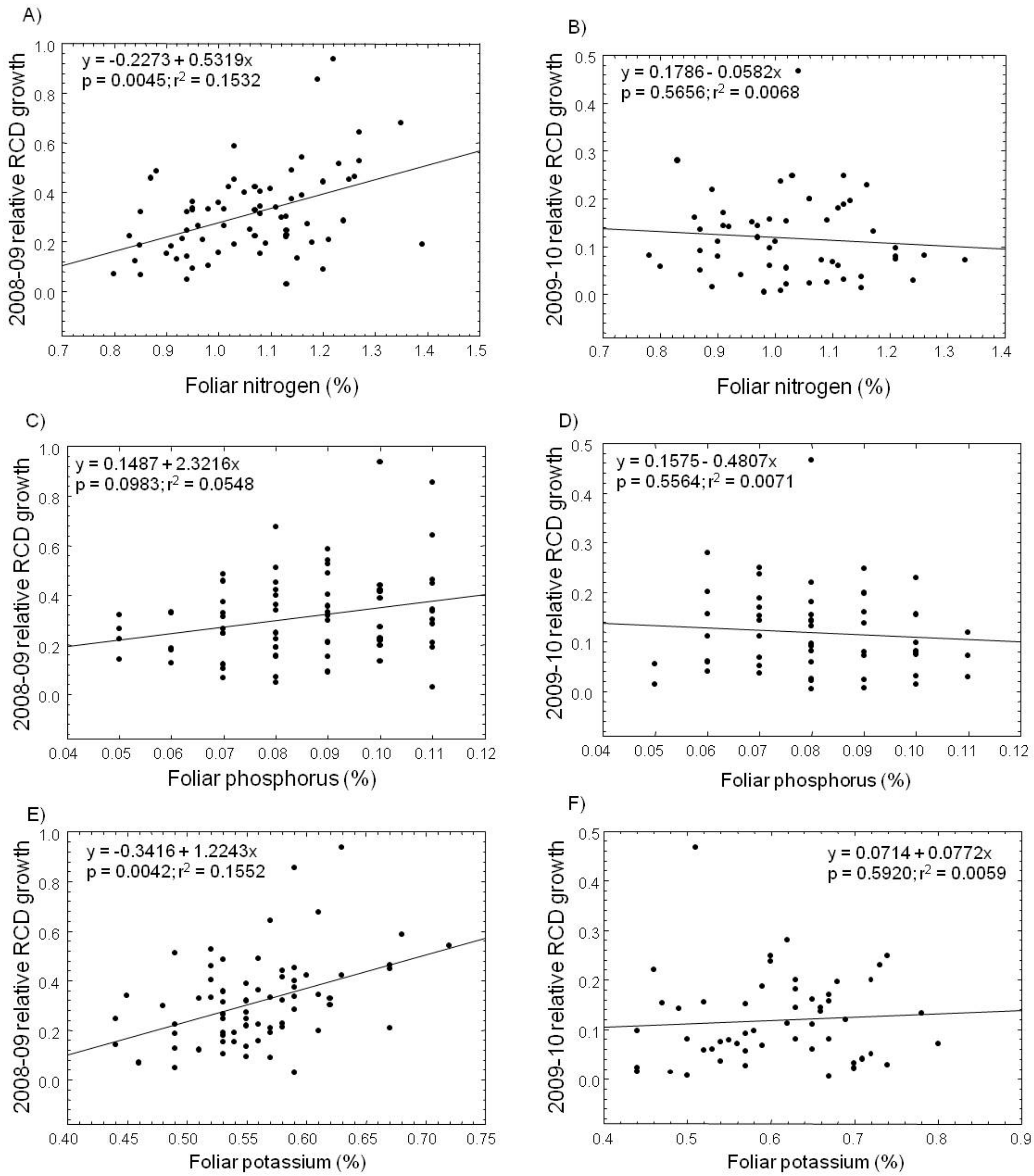

Figure 3.8.14. Linear regression relationships between foliar nutrients (N, P, and K) in 2009 (panels A, C, and E) and 2010 (panels B, D, and F) and the relative longleaf pine root collar diameter growth for each respective year at Fort Benning.

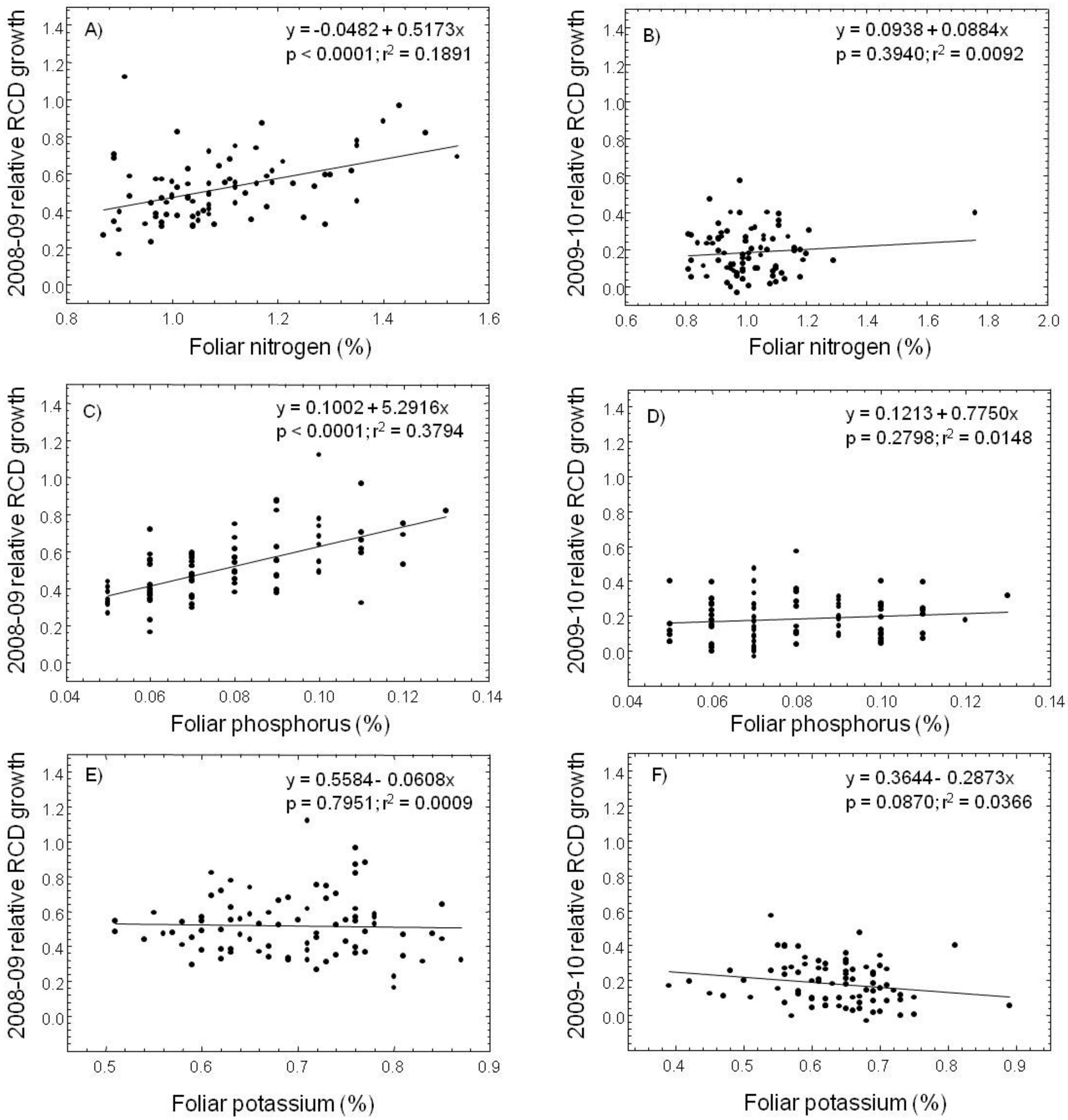

Figure 3.8.15. Linear regression relationships between foliar nutrients (N, P, and K) in 2009 (panels A, C, and E) and 2010 (panels B, D, and F) and the relative longleaf pine root collar diameter growth for each respective year at Camp Lejeune.

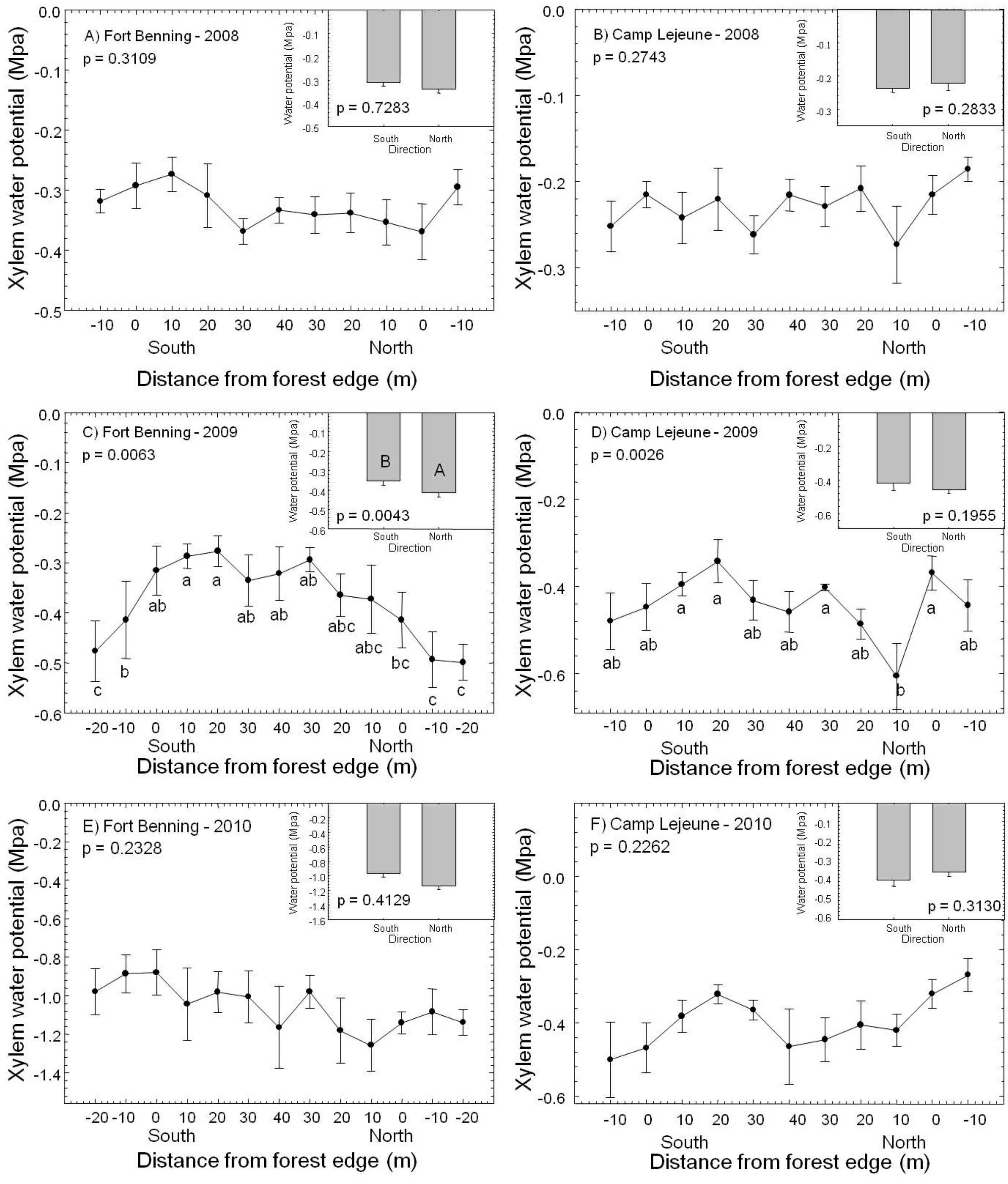

Figure 3.8.16. Xylem water potential (mean ± one standard error) of longleaf pine seedlings by gap position and direction (insets) in 2008, 2009, and 2010 at Fort Benning (A, C, E) and Camp Lejeune (B, D, F). Different letters indicate significant differences.

3.8.4. Discussion

The canopy treatments used in this study created very different light conditions at the ground layer (see Section 3.7) because light is primarily controlled by canopy density. Previous studies in longleaf pine forests have also found strong relationships between light availability and various measures of canopy abundance, including gap fraction (Battaglia et al. 2002), overstory abundance index (Palik et al. 2003), and basal area (Palik et al. 1997). Our results indicate that the light conditions at 1.4 m above the ground in upland loblolly pine forests similar to those in this study can be accurately predicted from measures of overstory basal area. However, despite a significant effect of canopy density treatments on soil temperature at Fort Benning (Section 3.7), the negative relationship between basal area and soil temperature was significant only in 2010 at Fort Benning. Moreover, we did not observe any relationships between soil moisture and basal area at either study location. Because our soil moisture measurements were limited to the top 6 cm of the soil, it is possible that effects of canopy removal on soil moisture occurred at greater soil depths and were not observed in our study. However, we measured soil moisture to a depth of 1 m in gap plots and found no effect of distance from forest edge (Section 3.7), suggesting that soil moisture levels were not strongly affected by canopy density in the dry, sandy soils of our study sites.

Previous studies have found that overstory competition strongly limits longleaf pine seedling growth following a curvilinear function (Palik et al. 1997, Palik et al. 2003). Our results demonstrate a similar growth response by seedlings at Fort Benning, and a slightly weaker linear pattern at Camp Lejeune. Separating competitive effects of canopy trees into competition for above-ground resources (light) or below-ground resources (water, nutrients) is often difficult because of the complex interactions between competing organisms and resource availability in field studies. Canopy removal directly results in increased light availability and reduced competition for water and nutrients from canopy pines; however, ground layer vegetation quickly responds to available resources and provides additional competition for longleaf pine seedlings. McGuire et al. (2001) found that rapid growth of understory plants following canopy gap creation in longleaf pine woodlands filled root gaps following canopy removal, and Pecot et al. (2007) concluded that understory plants limited nitrogen availability to longleaf pine seedlings regardless of longleaf pine overstory density.

Our results show that competition for light is a major limiting factor for longleaf pine seedlings but that competition from ground layer vegetation additionally reduces seedling growth. Increased light availability resulted in the same growth increase in plots with ground layer vegetation intact and in plots with complete woody vegetation control at Camp Lejeune, and root collar diameters were several millimeters larger on herbicide plots regardless of gap light index (Figure 3.8.8). The response at Fort Benning, where differences in seedling growth between herbicide and non-herbicide treatments were evident when light levels were high, suggests that the competitive effects of ground layer plants became most important when ground layer abundance increased following canopy removal. There results support findings of McGuire et al. (2001) and Pecot et al. (2007) that ground layer plants provides important competition with longleaf pine seedlings for available resources following canopy removal.

The interactions between plants within an ecosystem can vary from competition to facilitation, depending on the site conditions and response variable being measured (Holmgren et al. 1997). The relationships between overstory competition and seedling mortality in 2008 at Fort Benning and Camp Lejeune indicate that different processes are occurring at the two study sites: at Fort Benning, we observed a facilitation effect of the canopy trees on seedling survival, but at Camp Lejeune there was a competition effect. First year mortality was very different between the two study locations (Section 3.2), and it is likely that site conditions interacted with a summer drought to cause the observed mortality patterns. High levels of longleaf pine seedling mortality have been observed in dry years, and facilitation from canopy trees increases seedling survival in such conditions (McGuire et al. 2001, Gagnon et al. 2003, Rodriguez-Trejo et al. 2003). Interestingly, the facilitation effect at Fort Benning was not observed in subsequent years, and the incremental mortality between the third and fifth growing seasons was positively related to canopy density. These results suggest that canopy retention can increase first year survival of planted seedlings, but high levels of canopy density will result in increased mortality over time (see Section 3.2 for repeated measures analyses of seedling survival).

Longleaf pine seedlings are well-adapted to dry, sandy environments (Sword Sayer et al. 2005), and competition for soil moisture is generally not considered to be a limiting factor for seedling establishment. In fact, in poorly drained sites on the coastal plain of North Carolina, Knapp et al. 2008 found that soil moisture was negatively related to longleaf pine seedlings size and that site preparation treatments that improved soil drainage resulted in increased growth. Similarly, we observed negative relationships between soil moisture and incremental growth in 2009 and total seedling size in both years. However, in a greenhouse study using one-year-old seedlings, Jose et al. (2003) found that seedlings watered 5 days a week grew better than those only watered once a week, suggesting the importance of water limitation for seedling growth. It is often difficult to compare greenhouse studies to field studies because the complex interactions of factors in field studies; for instance, soil moisture levels may not have varied enough *in situ* to strongly affect seedling growth, and micro-sites with increased soil moisture levels are likely to support greater ground layer vegetation abundance (that is, greater competition).

Measures of xylem water potential in LG plots indicate that longleaf pine seedlings generally did not experience high levels of water stress throughout this study. Sword Sayer et al. (2005) reported xylem water potential measurements of around -0.5 Mpa for longleaf pine seedlings in a no stress treatment, and water potential readings in our LG plots were generally greater than -0.6 Mpa in all years except 2010 at Fort Benning. Interestingly, results from 2009 at Fort Benning showed greater water stress beneath the intact canopy than within canopy gaps, suggesting that canopy trees can affect the ability of longleaf pine seedlings to access soil moisture and that increased ground layer cover within canopy gaps does not necessarily have the same effect. However, because these results were not consistent every year or at both study sites, it is difficult to discern the role of canopy competition for soil moisture on seedling growth or survival response.

Foliar nutrients provide direct information about the nutrient availability for plants (van den Driessche 1974), and we generally found that the study treatments affected the levels of N, P, and K in longleaf pine seedlings at Fort Benning but had fewer effects at Camp Lejeune. At Fort Benning, competition from overstory trees and ground layer plants reduced seedling foliar N, and the fertilizer treatment increased seedling P in 2009. Few previous studies have used foliar nutrient analysis to determine competition effects of surrounding vegetation on longleaf pines. In a study in Louisiana, Haywood (2005) found no effects of herbaceous or woody plant control on the foliar nutrients of six year old seedlings, despite significant differences in seedling size caused by the study treatments. Our results from 2009 suggest that higher levels of foliar nutrients, especially nitrogen, result in increased relative seedling growth. Because relative growth rates were generally smaller in 2010 than 2009 but foliar nutrient levels were similar, we believe that growth was limited by factors other than nutrient availability. Blevins et al. (1996) list sufficiently levels for longleaf pine foliar N, P, and K at 0.95, 0.08, and 0.30%, respectively, suggesting that retaining high levels of overstory density in loblolly pine stands will likely result in nutrient deficiencies of N and P for planted longleaf pine seedlings.

3.8.5. Conclusions

Restoring longleaf pine to loblolly pine stands will require some degree of canopy removal in order to change micro-site conditions and favor longleaf pine seedlings. We found light levels to be strongly related to longleaf pine seedling growth and that overstory structure directly controlled light levels at the ground layer. Decoupling the competitive influences of surrounding vegetation on longleaf pine seedlings is difficult, but our results suggest that soil moisture is not a limiting factor for seedling growth under conditions similar to those in our study. Light availability exhibited considerable influence on seedling growth, both in the presence and absence of competition from ground layer vegetation; however, at Fort Benning we found that herbicide control of ground layer plants resulted in increased seedling response only when canopy density was low and light was abundant. Although foliar nutrients were generally above sufficiency levels, surrounding vegetation (both canopy and in some cases ground layer plants) reduced nutrient levels in longleaf pine seedlings, particularly at Fort Benning. Managers interested in increasing longleaf pine seedling growth must reduce competition from canopy trees to levels below approximately 7 m^2/ha basal area (found to be similar to OAI in this study) to elicit seedling growth response. Because canopy pines may facilitate early seedling survival, depending on site and weather conditions, retaining some canopy trees may increase seedling establishment at the stand level.

3.9. Effects of canopy and cultural treatments on fine fuel production, fire behavior, and fire effects

This section addresses research objective O-8.

3.9.1. Introduction

A disturbance regime of frequent surface fires maintains the characteristic structure of longleaf pine communities. In longleaf pine stands, the ground layer contains pyrogenic fine fuels such as live and standing dead warm season grasses and pine needle litter (Gilliam et al. 2006). These fine fuels play a crucial role in the longleaf system by providing a continuous fuel bed to carry and maintain a frequent surface fire regime (Mitchell et al. 2006, Kirkman et al. 2007). Benefits of recurrent surface fires include maintaining high floristic diversity by controlling competition from other non-fire-adapted species, preparing a seedbed for longleaf seedling regeneration, and reducing pathogens and harmful insects (Brockway and Lewis 1997, Thaxton and Platt 2006, Mitchell et al. 2006).

The need for frequent fire application in the management of longleaf pine systems has been widely documented (Glitzenstein et al. 2003, Gilliam et al. 2006, Mitchell et al. 2006, Kirkman et al. 2007). Several authors have discussed the importance of pine needles for maintaining fuel bed continuity and the subsequent spread of fire (Kirkman et al. 2007, O'Brien et al. 2008, Hiers et al. 2009). Less is known, however, about fuel accumulation/composition and fire behavior in areas that are being converted from loblolly pine to longleaf pine. Longleaf pine can be successfully established by clearcutting and planting seedlings (Brockway et al. 2006). However, that approach would remove an important fuel source, that is, the needlefall from existing adult loblolly pines. In addition, clearcutting often releases shrubs and woody species in the ground layer and midstory that must be controlled (often mechanically and/or chemically). Both approaches can complicate ground cover restoration and reduce needle input. Without these fuel sources, restoration of frequent surface fire regime is impeded by lack of fine fuels (Glitzenstein et al. 2003, Kirkman et al. 2007). Therefore, when restoring longleaf pine, variable, partial, and/or complete canopy removal could substantially influence the amount and type of fine fuel as well as subsequent fire behavior and effects.

Fire behavior is affected by variables besides fuel, including weather and topography (Iverson et al. 2004). Furthermore, fires burn heterogeneously at spatial and temporal scales, making accurate measurement of fire behavior difficult. Field observations of fire intensity are often based on flame length and rate of spread; however, these are highly subjective measurements that can vary considerably across a study area and are difficult to obtain in the interior of fires (Wally et al. 2006). Therefore, time-temperature measurement devices such as electronic thermocouple probes and data loggers (logger-probes) have been employed to measure temperatures in many ecological studies of fire behavior and fire effects (Iverson et al. 2004, Kennard et al. 2005). Logger-probes are a useful method of collecting quantitative and spatially explicit measures of fire behavior, like temperature and time data that are linked to spatial locations (Bova and Dickson 2008, Kennard et al. 2005, Iverson et al. 2004).

As part of a larger study to evaluate various silvicultural techniques for restoring longleaf pine to sites currently occupied by longleaf pine, this study focused on fire behavior and fuels. Our specific objectives were to: 1) determine the effects of harvesting treatments that vary the density and distribution of canopy trees on fine fuel loads, fire behavior, and fire effects; 2) determine the effects of cultural treatments designed to improve longleaf pine restoration on fine fuel loads, fire behavior and fire effects; and 3) determine the effects of gap direction and position on fine fuel loads, fire behavior, and fire effects.

3.9.2. Methods

This study was a part of the field experiment replicated at Fort Benning and Camp Lejeune. Study sites, experimental design and treatments are detailed in Section 3.1.

3.9.2.1. Data collection

DOWNED WOODY FUEL (1-, 10-, 100-HOUR FUELS, TOTAL FINE WOODY DEBRIS, 1000-HOUR FUELS)—We measured downed woody fuels using the planar intercept method described by Brown (1974). In the uniform canopy plots (Control, MedBA, LowBA, and Clearcut), one 15 m transect was established from the split-plot center to each split-plot corner (Figure 3.9.1). Three split-plots in each main plot (NT, H, and H+F) were sampled, yielding a total of 12 sample points in each main plot. Fuels were classified by diameter size class: 1-hour fuels (0-0.6 cm), 10-hour fuels (0.6-2.5 cm), 100-hour fuels (2.5-7.6 cm), and 1000-hour fuels (7.6+ cm). Downed woody fuel intercepts were counted in the middle of each 15 m transect (as opposed to the transect origins or ends) to avoid concentrating sample points at the center of the split-plot and to avoid possible edge effects from the boundaries of the split-plots. The midpoint of each 15-m transect was used as the midpoint for each size class count: 1- and 10-hour fuels were tallied from 6.6 – 8.4 m (1.8 m) along the 15 m transect, 100-hour fuels were counted from 5.7 – 9.3 m (3.6 m), and 1000-hour fuels were counted along the entire 15 m transect. 1000-hr fuels were recorded by species (pine or hardwood) and decay class, and we measured the diameter of each log. Fuel quantities were converted to weights using equations given by Brown (1974).

In the gaps, we established four transects, each originating at the gap center and extending to the north, south, east, and west directions (Figure 3.9.1). Transects extended 10 m beyond each gap's radius to capture edge effects (LG - 50 m radius; MG - 40 m radius; SG - 30 m radius). In the LG plots, the north and south transects were moved 2 m to the east to minimize effects from human disturbance caused by repeated measurement along the center north/south row. Along each transect, sampling points were established at 10 m intervals, yielding 12, 16, and 20 points for SG, MG, and LG, respectively. Using each sampling point as the transect center, a 1.8 m transect was used to inventory 1- and 10-hour fuels, and a 3.6 m transect was used to inventory 100-hour fuels. One thousand-hour fuels were counted along the entire length of each transect and recorded by species (pine or hardwood), diameter, decay class, and sound or rotten condition. Fuel quantities were converted to weights using equations given by Brown (1974).

FOREST FLOOR FUEL DEPTH AND FUEL COVER—In the uniform canopy, we measured depth of the litter and duff layers and depth of the total fuel bed at 4, 8, and 12 m on each 15 m transect (Figure 3.9.1). Fuel bed depth was measured from the bottom of the litter layer to the highest intersected dead, downed woody material along 60 cm sections (30 cm on each side of the 4, 8, and 12 m mark). Live and standing dead fuel cover was measured in three 1 m^2 quadrats

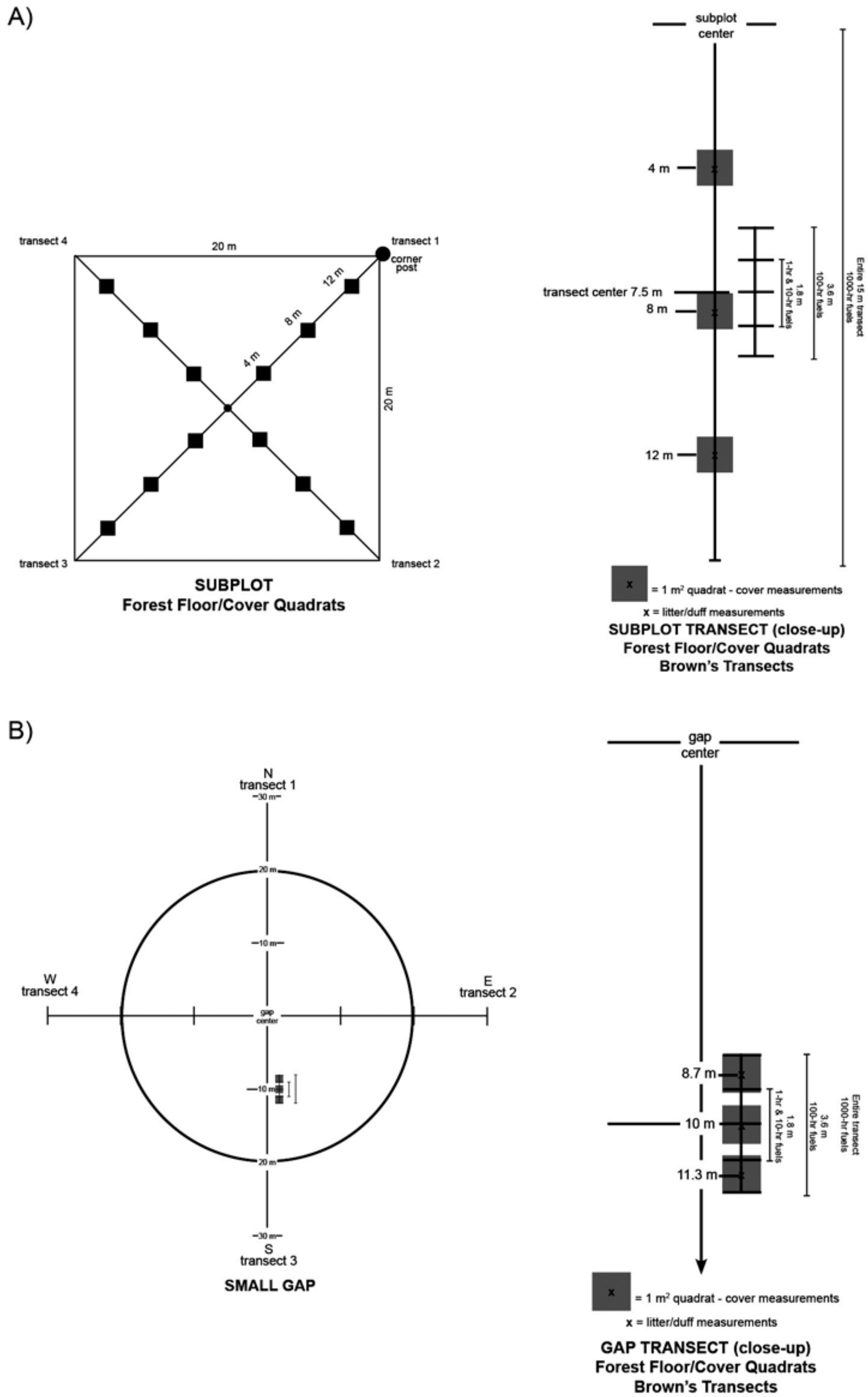

Figure 3.9.1. Layout of A) split-plots with transects and transect close-ups for uniform main plots and B) transects and transect close-ups for gaps (note: small gap shown here for illustration).

centered on 4, 8, and 12 m along each 15 m transect. We used cover classes from the Carolina Vegetation Survey methods (1 = trace, 2 = 0-1%, 3 = 1-2%, 4 = 2-5%, 5 = 5-10%, 6 = 10-25%, 7 = 25-50%, 8 = 50-75%, 9 = 75-95%, 10 = 95-100%) to visually estimate cover of live and standing dead vegetation less than 1 m in height (Peet et al. 1998). Cover was recorded in the following categories: graminoids, forbs, woody plants, broadleaf litter, pine needle litter, woody litter (pine cones/pieces of bark), and bare ground. The midpoint of each cover class was used as percent cover for statistical analyses.

In the gaps, we established three sampling points at every 10 m interval along each of the four transects (Figure 3.9.1). At each 10 m position (i.e. 10 m, 20 m, 30 m, etc.), we measured litter, duff, and total fuel bed depth at the 10 m interval position and at 1.3 m on each side of the mark along the transect. For example, at the 20 m mark, measurements were taken at the 18.7 m, 20 m, and 21.3 m points. For live and standing dead fuel, we established three 1 m^2 quadrats at each 10 m interval along each of the four transects with the quadrats centered directly on the mark and at 1.3 m on each side of the mark.

Following the prescribed burns, downed woody fuel, litter depth, duff depth, fuel bed depth, and cover class were measured using the same methods and locations that were used for pre-fire fuel measurements. Fuel consumption was calculated as pre-fire minus post-fire fuel measurements. A "burned" category was added to cover class to estimate the cover of burned areas in each 1 m^2 quadrat used for cover measurements.

LOGGER-PROBE INSTALLATION—Hobo® data loggers (Onset Computer Corporation) connected to type-K thermocouple probes (accuracy +/- 4 ºC; dimension 0.5 cm in diameter and 30 cm long) were employed to record temperatures during the prescribed burns. The data loggers were programmed to record temperature at 1.5 second intervals for a period of 12 hours. We placed each data logger in an anti-static bag with a desiccant pack for transportation and burial. The anti-static bags containing the data loggers were then placed in plastic Whirl-Pak bags and sealed tightly before installation. Holes for the data loggers were dug very carefully to keep from disturbing the litter. The thermocouples were buried at the base so that the probe tips were 25 cm above the soil (Iverson et al. 2004).

We installed five logger-probes per split-plot in the uniform canopy plots, with one logger-probe directly on the split-plot center point and four other logger-probes 7.5 m away from the split-plot center point on the midpoint of each 15 m transect (Figure 3.9.2). Logger-probes were installed in NT, H, and H+F split-plots, for a total of 60 logger-probes installed in uniform plots of each selected block. In the gaps, one logger-probe was placed at each 10 m interval along each of the four transects (Figure 3.9.2). We installed logger-probes in the LG and SG plots only, for a total of 32 logger-probes in a block (20 in the large gap and 12 in the small gap). Due to the intense time requirements of data logger preparation and installation, we deployed logger-probes in only two experimental blocks at Fort Benning (5 and 6) and in one block at Camp Lejeune (2). In the Camp Lejeune block, logger-probes were not installed in the SG plot due to lack of access prior to the prescribed burns.

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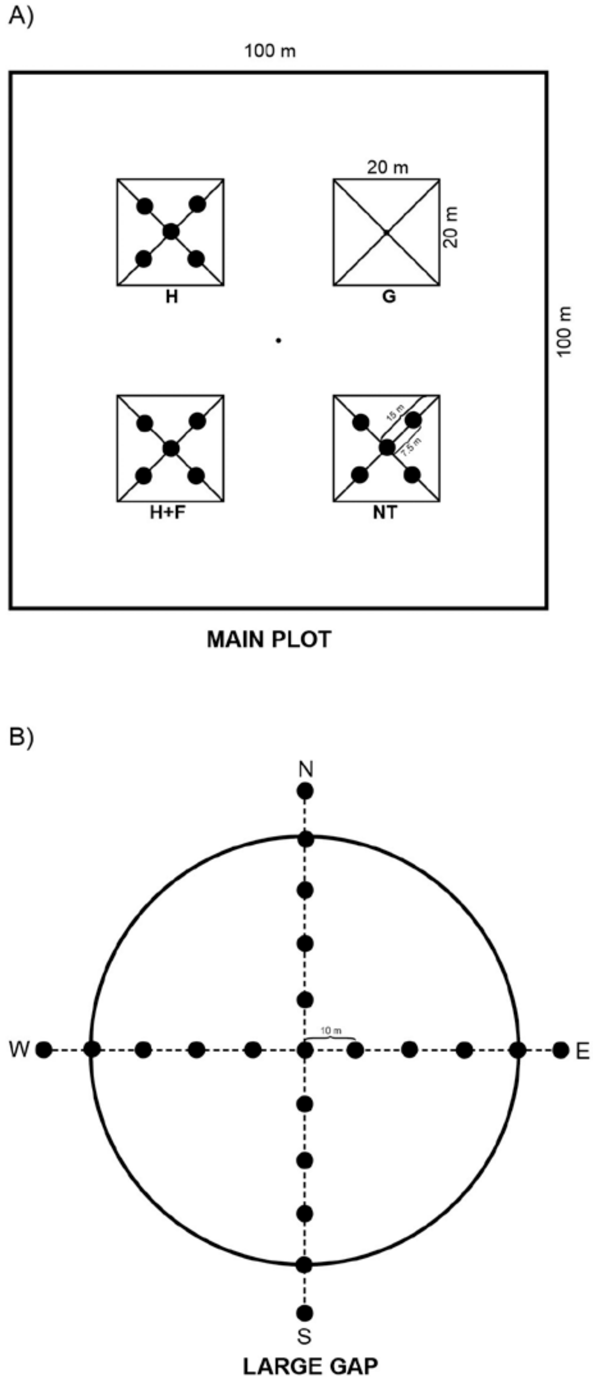


Figure 3.9.2. Layout of HOBO® data logger-probe installation in A) split-plots within each uniform main plot and B) within each gap (note: large gap shown here for illustration).

3.9.2.2. Data analyses

We calculated fuel consumption as the difference between pre-fire fuel measurements and post-fire fuel measurements. Equations provided by Brown (1974) were used to calculate plot means for downed woody debris, and we analyzed fine woody debris (FWD) data by size class (1-, 10-, and 100-hour fuels) and total FWD (1-, 10-, and 100-hour fuels weights combined). Data from uniform plots were averaged at the split-plot level, and we used split-plot analysis of variance (ANOVA) with a random block effect to determine main-plot effects, split-plot effects, and main*split-plot interaction effects for each response variable. Data from gaps were analyzed with split-plot ANOVA to determine significant effects of gap direction (main-plot effect), gap position at 10 m intervals (split-plot effect), and direction*position interactions. Each gap size was analyzed separately because the number of positions differed according to gap size. Differences in least square means were determined with pair-wise comparisons and Tukey's adjustment, and degrees of freedom were calculated using the Satterthwaite approximation. Transformations were used when needed to meet assumptions of normality and constant variance. All means are reported in the original (non-transformed) units.

The time - temperature data captured by the logger-probes were processed to yield six variables that described fire behavior and intensity:

1. duration of temperature above ambient temperature (DURAMB);
2. duration of temperature above 60° C (DUR60);
3. duration at maximum temperature (DURMAX);
4. maximum temperature (MAXT);
5. integrated area under the temperature curve above ambient temperature (AREAAMB);
6. integrated area under the temperature curve above 60° C (AREA60)

Maximum temperature was defined as the highest temperature the logger-probe recorded. Beginning time for DURAMB was defined as the last time that ambient temperature was recorded by the logger-probe prior to the peak temperature increase, and end time for DURAMB was defined as the first time temperature returned to ambient after the peak temperature increase. DUR60 was calculated from the first and last times that the recorded temperature was above 60° C. The area under the temperature curves was determined by summing all temperatures greater than or equal to ambient or 60° C multiplied by the time-step (1.5 s) (Bova and Dickinson 2008, Kennard et al. 2005). The duration of increased temperature, maximum temperature, and the 60° C threshold (the temperature at which plant cell death occurs) have been utilized in many fire ecology studies (e.g. Iverson et al. 2004, Kennard et al. 2005, Wally et al. 2006).

Pearson's correlation was used to test the significance of several pre-fire independent variables (PRE1HR, PRE10HR, PRE100HR, PRELITT, PREGR, PREPNDL, PREBARE) and fuel consumption independent variables (D1HR, D10HR, D100HR, DLITT, DGR, DPNDL, DBARE) on the fire behavior dependent variables (DURAMB, DUR60, DURMAX, AREAMB, AREA60, and MAXT) and on the dependent variable, BURNED.

We evaluated which combinations of pre-fire fuel load variables could predict fire behavior measures by running multiple regressions with forward stepwise selection using each of the logger-probe metrics (and burned cover class) in separate analyses.

For correlation and regression analyses, logger-probe locations coincided spatially with fuel measurements. For example, cover class and litter depth from the 8 m mark only (not the entire transect) were compared with the logger-probe installation (at 7.5 m) in uniform plots. In gaps, the mean of the three fuel measurements taken at each 10 m interval (for cover and litter) was compared with each logger-probe installation, which was at every 10 m increment. Fine woody debris measurements were centered on each 10 m mark in the gaps and on each transect in the uniform split-plots and thus were co-located with each logger-probe. Logger-probe measurements from the split-plot/gap centers were excluded from the analyses since we did not take fuel measurements at the split-plot/gap centers. In addition, any logger-probes that failed were excluded from analyses.

3.9.3. Results

3.9.3.1. Uniform treatment effects

At Camp Lejeune, main plot treatments significantly affected the total fine woody fuel load, with the lowest amount on the Control plots (Figure 3.9.3; Appendix A-3.9.6). Split-plot treatments significantly affected the pre-fire 1-hour fuel load which was lowest on the no treatment (NT) split-plots (Appendix A-3.9.6). No other plot or split-plot treatments significantly affected downed woody fuel loads at Camp Lejeune (Appendix A-3.9.6). At Fort Benning, there were no significant split-plot, main plot, or main*split-plot effects for any pre-fire downed woody fuels (Appendix A-3.9.1).

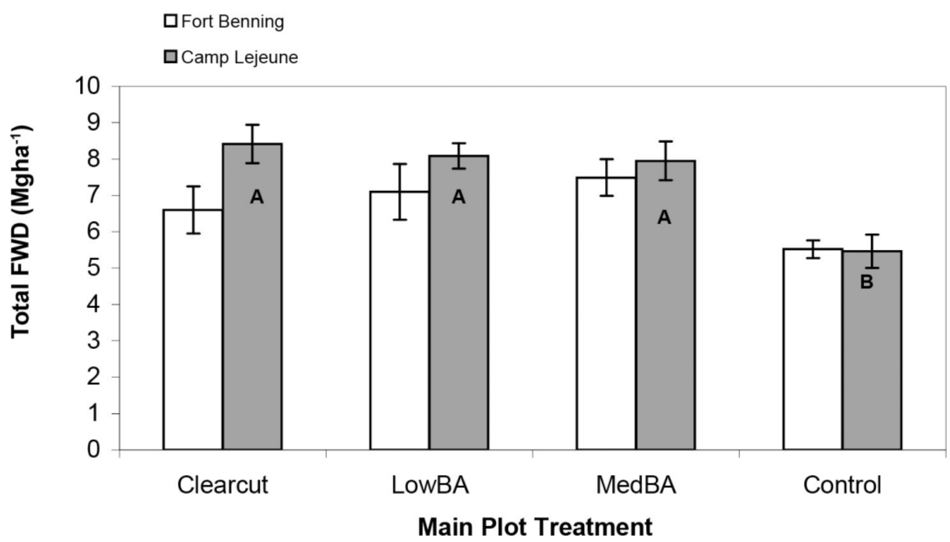
Fort Benning and Camp Lejeune had similar total fine woody fuel loading with mean total FWD fuel loads ranging from 5.51 Mg ha^{-1} in the Control treatments to 7.49 Mg ha^{-1} in the MedBA treatments at Fort Benning and from 5.46 Mg ha^{-1} in the Control treatments to 8.42 Mg ha^{-1} in the Clearcut treatments (Figure 3.9.3). We generally found that 1-hour fuel loads were greater at Camp Lejeune (means range from 0.387 to 0.437 Mg ha^{-1}) that at Fort Benning (means range from 0.090 to 0.234 Mg ha^{-1}) (Figure 3.9.3; Appendix A-3.9.1).

Fuel consumption of 1-, 10-,100-hour fuels, total fine woody debris, and 1000-hr fuels were not significantly affected by main- or split-plot treatments at either Fort Benning or Camp Lejeune (Appendices A-3.9.1 and A-3.9.6).

There was a significant effect of canopy treatment on litter depth at Fort Benning (Figure 3.9.4; Appendix A-3.9.1), where the Control plots had the greatest litter depth (mean of 3.3 cm). Litter depth tended to increase with increasing canopy cover, and we observed the lowest litter depth in the Clearcut treatments (mean 2.05 cm). Split-plot treatments did not significantly affect litter depth at Fort Benning (Figure 3.9.4; Appendix A-3.9.1). There were significant effects of main and split-plot treatments on litter depth at Camp Lejeune (Figure 3.9.4; Appendix A-3.9.6). The Control plots had the greatest litter depth (mean 3.12 cm) while the Clearcut had a mean litter depth of 2.00 cm. The NT split-plots had the greatest litter depth (3.17 cm).

At Fort Benning, there was a significant main-plot*split-plot interaction on duff depth ($F = 3.59$, $p = .0084$) (Figure 3.9.5; Appendix A-3.9.1). In the MedBA main-plots, there was significantly greater duff depth in the herbicide split-plots than in the untreated or herbicide + fertilizer split-

A)



B)

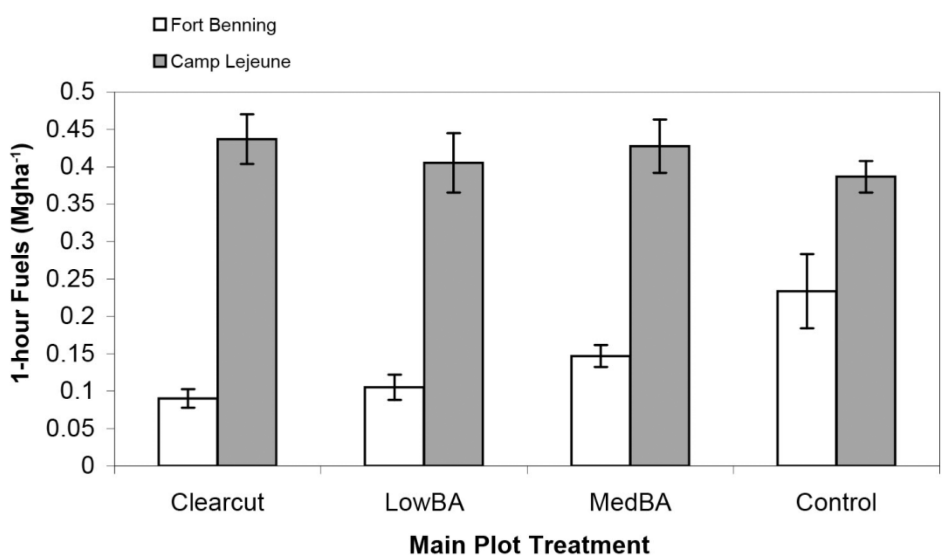
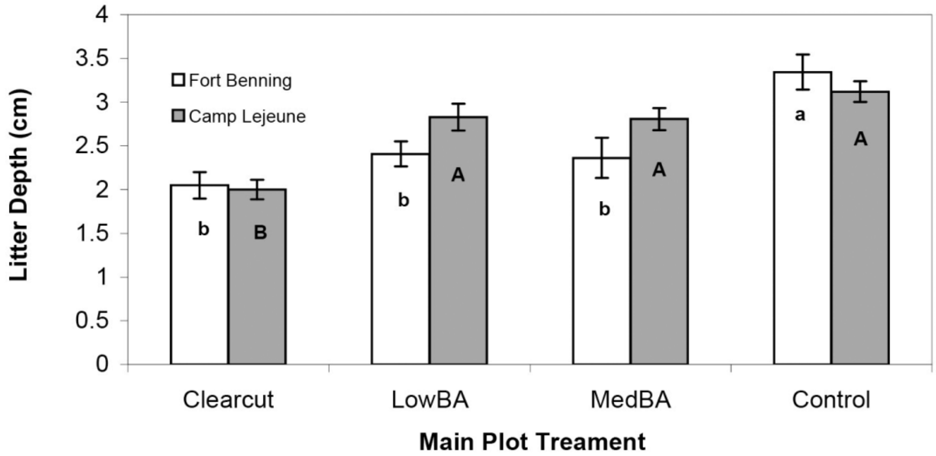


Figure 3.9.3. Pre-fire downed woody debris loading (mean ± SE) for A) total fine woody debris (1-, 10-, and 100-hour fuels summed) and B) 1-hour fuels for Fort Benning and Camp Lejeune. Different letters within a study location indicate significant differences at the $\alpha = 0.05$ level.

A)



B)

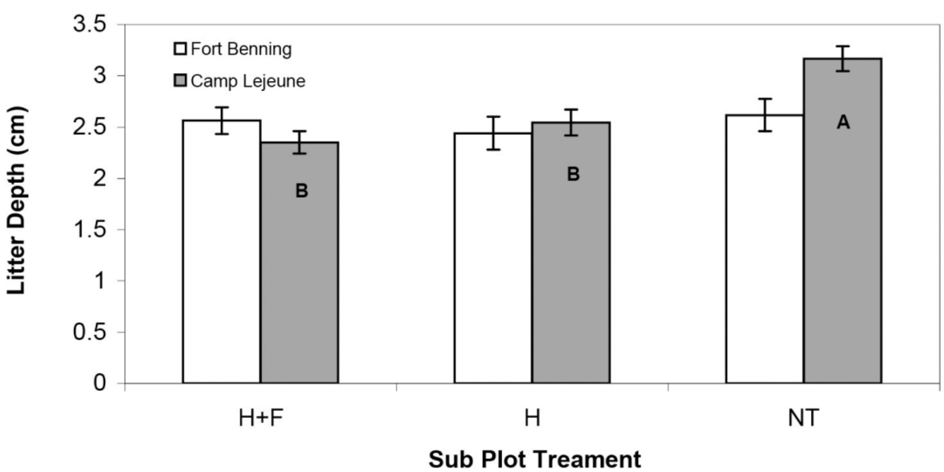


Figure 3.9.4. Pre-fire litter depth (mean ± SE) for A) main plot treatments and B) split-plot treatments at Fort Benning and Camp Lejeune. Different letters within a study location indicate significant differences at the $\alpha = 0.05$ level.

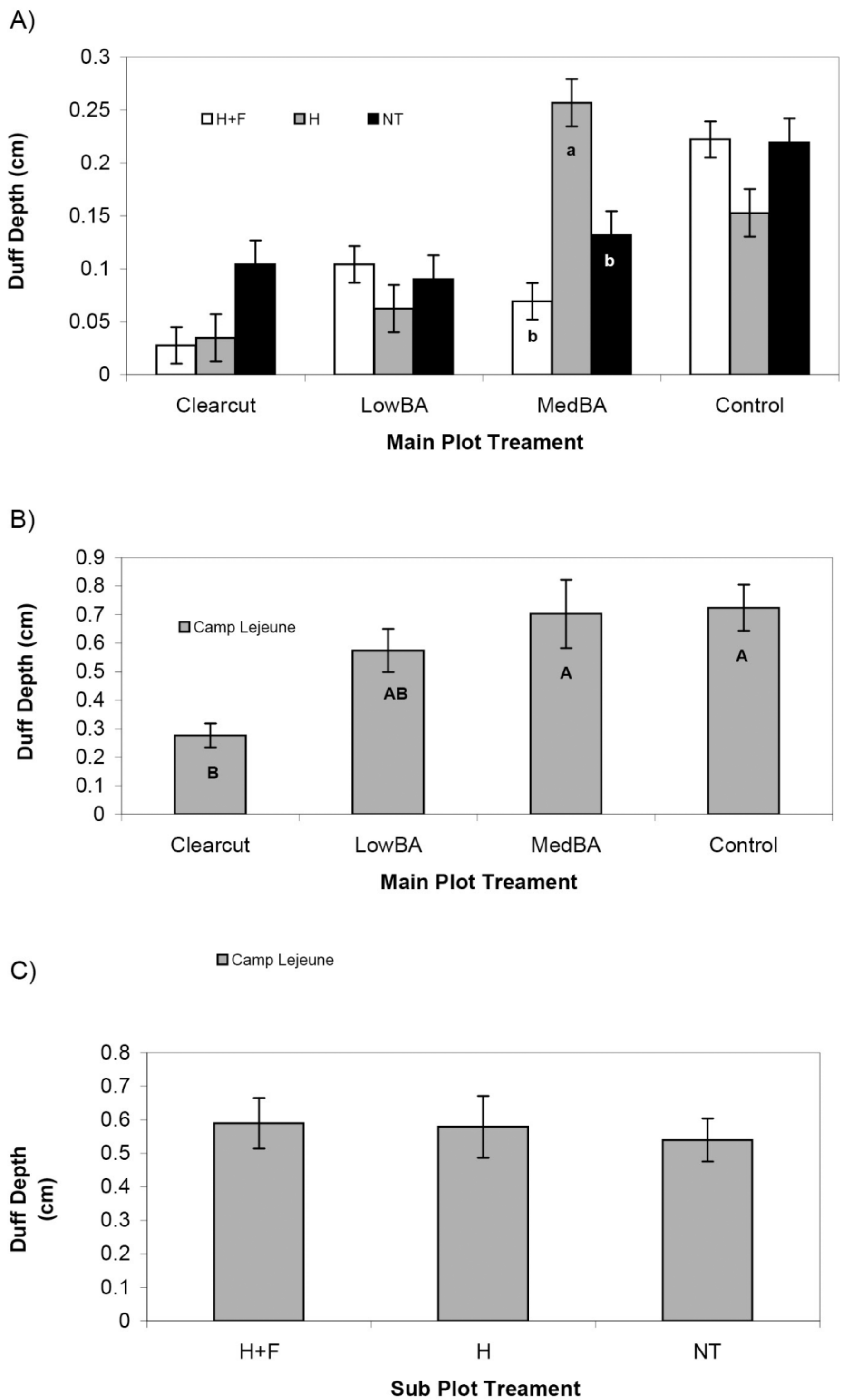


Figure 3.9.5. Pre-fire duff depth (mean ± SE) for A) main*split-plot treatments at Fort Benning, B) main plot treatments at Camp Lejeune, and C) split-plot treatments at Camp Lejeune. Different letters within a study location indicate significant differences at the $\alpha = 0.05$ level.

plots (Figure 3.9.5). Duff depth was significantly affected by main-plot treatments at Camp Lejeune with the greatest duff depths in the Control plots (mean 0.72 cm) and the least on the Clearcut plots (mean 0.28 cm; Figure 3.9.5; Appendix A-3.9.6). Duff depth was not significantly affected by split-plot treatments at Camp Lejeune (Figure 3.9.5; Appendix.A-3.9.6). Duff depth was generally greater at Camp Lejeune than at Fort Benning (average of 0.5 cm compared to 0.15 cm, respectively).

We found no significant effects of treatments on pre-fire fuel bed depth (Appendices A-3.9.1 and A-3.9.6).

Litter consumption was not significantly affected by main or split-plot treatments at Fort Benning (Figure 3.9.6; Appendix A-3.9.1). However, there was a significant main-plot effect on litter consumption at Camp Lejeune; mean litter consumption ranged from 1.8 cm in the Control treatments to 0.7 cm in the Clearcut treatments (Figure 3.9.6; Appendix A-3.9.6). Litter consumption was also significantly affected by split-plot treatments at Camp Lejeune; the NT split-plots had greater litter consumption than the H or the H+F treatments (Figure 3.9.6; Appendix A-3.9.6). In general, litter consumption tended to increase with increasing canopy density at both study locations.

Duff consumption was not significantly affected by main or split-plot treatments at either Fort Benning or at Camp Lejeune (Figure 3.9.7; Appendices A-3.9.1 and A3.9.6). Although there were no significant treatment effects, duff consumption had a tendency to increase with increasing canopy cover in the main plots.

Fuel bed consumption was not significantly affected by main- or split-plot treatments at Fort Benning (Appendix A-3.9.1). At Camp Lejeune, there were no significant split-plot effects on fuel bed consumption. However, Control plots had the greatest reduction in fuel bed depth among the main plot treatments (mean 2.1 cm) (Appendix A-3.9.6).

At both Fort Benning and Camp Lejeune, abundance (cover) of graminoids, pine needles, bare ground, and area burned were significantly affected by main plot treatments (Figure 3.9.8; Appendices A-3.9.1 and A3.9.6). Patterns and responses were similar at both locations. Graminoid cover and bare ground cover tended to decrease as canopy density increased while pine needle cover and percent area burned tended to increase as canopy density increased. Percent area burned ranged from 59.1% (Fort Benning) and 55.8% (Camp Lejeune) on the Clearcut treatments to 82.8% (Fort Benning) and 78.3% (Camp Lejeune) on the Control treatments. Split-plot treatment effects were significant for the percent area burned at Fort Benning, with the greatest area burned in the NT split-plots with a mean of 79.3% compared to 73.3% in the H+F split-plots and 68.6% in the H split-plots (Appendix A-3.9.1). There was no split-plot treatment effect on percent area burned at Camp Lejeune (Appendix A-3.9.6), and there were no split-plot treatment effects on graminoids, pine needle, or bare ground cover at either site (Appendices A-3.9.1 and A-3.9.6).

At Fort Benning, forb cover and woody cover were significantly affected by main plot treatments. The Clearcut treatments had the highest forb cover (mean 12.1%) while the Control treatments had the lowest (mean 4.6%). Woody cover was highest on the LowBA treatments

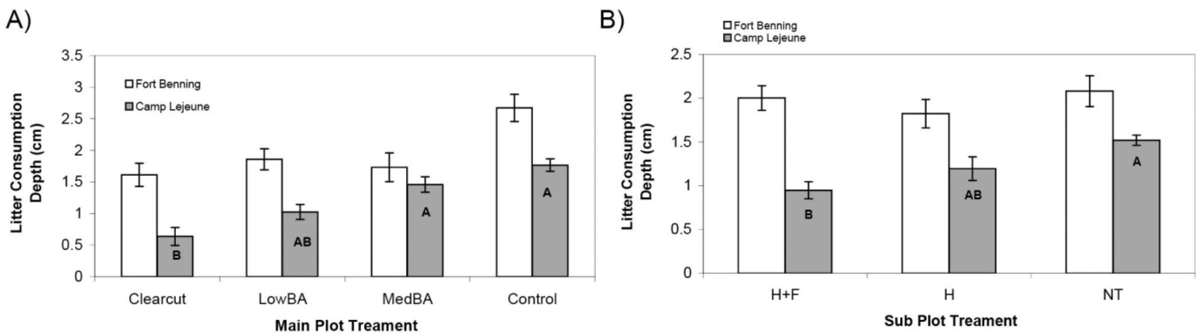


Figure 3.9.6. Litter consumption (mean ± SE) for A) main plot treatments and B) split-plot treatments at Fort Benning and Camp Lejeune. Different letters within a study location indicate significant differences at the α = 0.05 level.

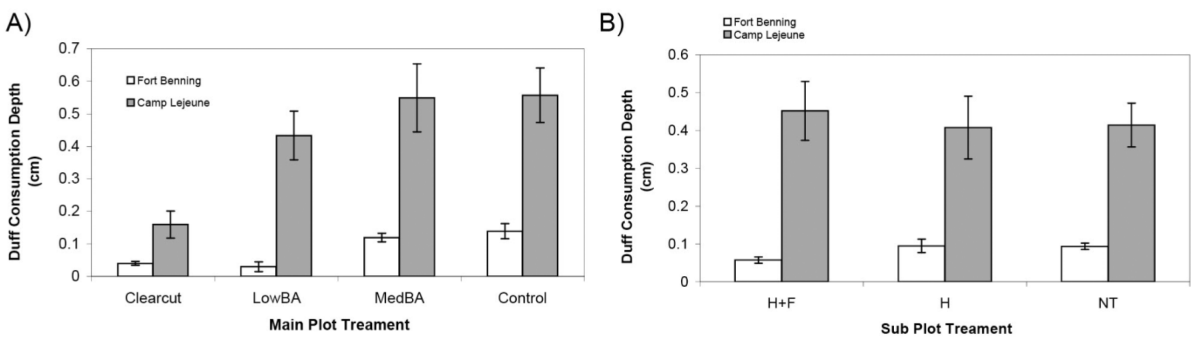


Figure 3.9.7. Duff consumption (mean ± SE) for A) main plot treatments and B) split-plot treatments at Fort Benning and Camp Lejeune. Different letters within a study location indicate significant differences at the α = 0.05 level.

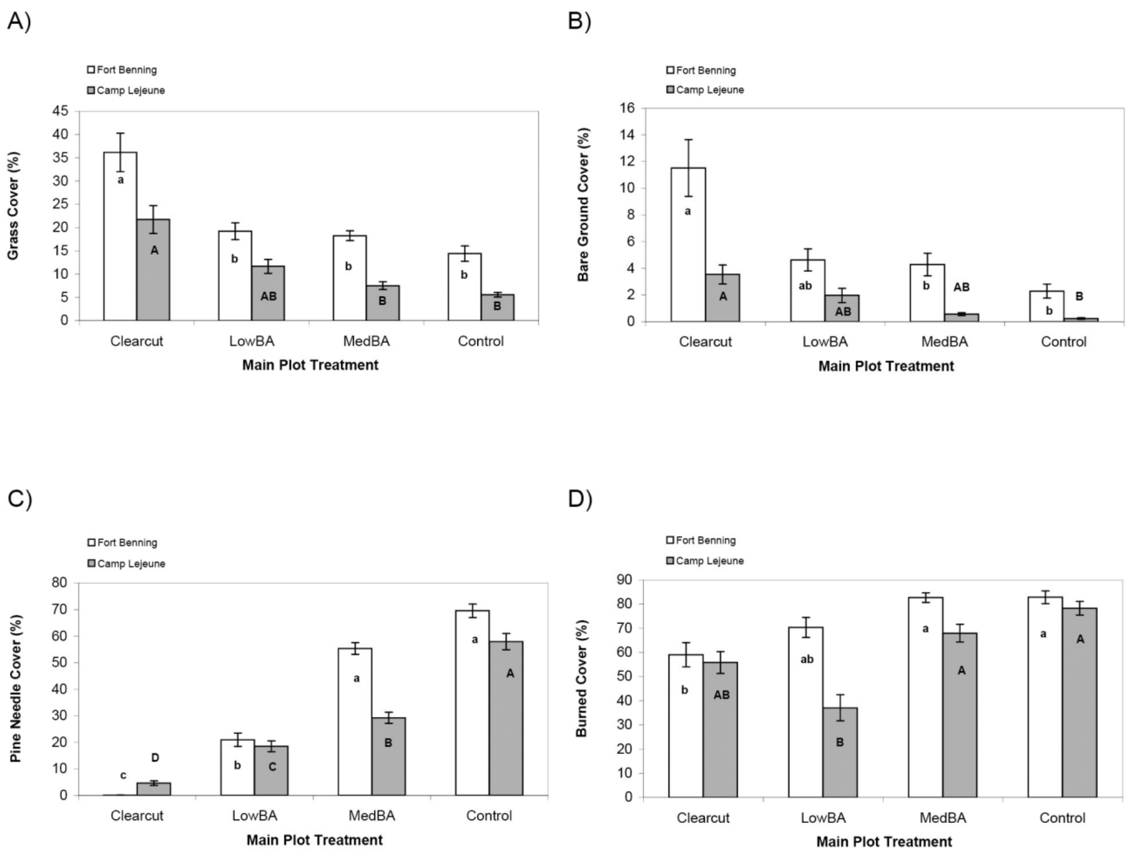


Figure 3.9.8. Pre-fire A) grass, B) pine needle, C) bare ground, and D) burned cover (mean ± SE) by main plot treatment at Fort Benning and Camp Lejeune. Different letters within a study location indicate significant differences at the $\alpha = 0.05$ level.

(mean 14.6%) and lowest on the Control treatments (mean 3.3%). Split-plot treatment effects were significant for forb cover; the H split-plots had the lowest forb cover (mean 7.7%) while the H+F and NT split-plots had similar, higher forb cover (mean 10.5% and 10.6%, respectively) (Appendix A-3.9.1). At Camp Lejeune, woody cover and hardwood litter cover were significantly affected by main plot treatments. Woody cover ranged from 8.3% on the Control treatments to 21.8% on the Clearcut treatments. Hardwood litter cover ranged from 2.7% on the Control treatments to 10.6% on the LowBA treatments. Split-plot treatments significantly affected forb cover, hardwood litter cover, and woody litter cover (Appendix A-3.9.6). Woody litter cover and forb cover were lowest on the NT split-plots (mean 2.4% and 1.0%, respectively) while hardwood litter cover was highest on the NT split-plots (mean 14.4%) (Appendix A-3.9.6).

Consumption of graminoid and pine needle cover were significantly affected by main-plot treatments at Fort Benning (Appendix A-3.9.1). Graminoid fuel consumption was greater in the Clearcut treatments compared to the Control treatments. Pine needle consumption was lowest in the Clearcut treatments and highest in the Control treatments. There was a significant split-plot effect on forb consumption at Fort Benning. The H split-plot treatments had the lowest forb consumption compared to the H+F and NT split-plot treatments (Appendix A-3.9.1). At Camp Lejeune, there was a split-plot treatment effect on hardwood litter consumption. The NT treatments had the greatest consumption while the H+F and H treatments gained hardwood litter (Appendices A-3.9.6). Fuel consumption of all other cover categories was not significantly affected by either main-or split-plot treatments at Camp Lejeune (Appendix A-3.9.6).

3.9.3.2. Effects of gap direction and position

At Fort Benning, pre-fire 10-hour fuels and pre-fire total FWD were significantly affected by gap direction in the large gap only; the eastern transects had higher fuel loads compared to the other transects (Appendix A-3.9.2). Pre-fire 1-hour fuels were significantly affected by gap position in the large gap, with fuel loads gradually increasing from the gap center to the forest edge (Appendix A-3.9.2). There was a significant direction*position effect on pre-fire 100-hour fuels in the medium gap at Fort Benning. The pre-fire 100-hour fuel load at the 40 m gap position on the east transect was significantly less than the 100-hour fuel load from the 10 m gap position on the north transect. Pre 100-hour fuel load means by position showed a similar trend and gradually increased from the gap edge to the gap center (Appendix A-3.9.3). No direction or position effects were significant for any of the pre-fire fuel load categories in the small gap (Appendix A-3.9.3). At Camp Lejeune, no pre-fire fuel categories were significantly affected by direction. Gap position significantly affected pre-fire 100-hour and total FWD fuel loads in the medium gap (Appendix A-3.9.8) and pre-fire 1-hour fuel loads in the small gap (Appendix A-3.9.9). In fuel load categories with significant position effects, there was no detectable pattern to explain the observed fuel load patterns at Camp Lejeune.

There was a significant effect of direction on fuel consumption of 10-hour fuels in the large gaps at Fort Benning. The eastern and western transects had the highest 10-hour fuel consumption (mean 0.576 Mg ha^{-1} and 0.384 Mg ha^{-1}, respectively) while the northern and southern transects gained 10-hour fuels (northern mean: -0.384 Mg ha^{-1}; southern mean: -0.730 Mg ha^{-1}) (Appendix A-3.9.2). There was a direction*position interaction for consumption of 1-hour fuels in the large gaps (Appendix A-3.9.2). In the medium gaps, there was a direction*position interaction for consumption of 1-hour fuels (Appendix A-3.9.3). There were no significant direction or position effects in the small gap for fuel consumption of any of the downed woody fuel categories (Appendix A-3.9.4). At Camp Lejeune, there were no significant direction or direction*position effects for any of the downed woody fuel consumption categories in any of the gap sizes (Appendices A-3.9.7, A-3.9.8, A-3.9.9, and A-3.9.10). There were significant position effects on total FWD consumption in the large gaps (Appendix A-3.9.7) and on 1-hour, 100-hour, and total FWD consumption in the medium gaps (Appendix A-3.9.8). There were no position effects on fuel consumption of any of the downed woody fuel categories in the small gap (Appendix A-3.9.9).

There were no gap size, direction, or gap size*direction effects on pre-fire or consumption of 1000-hour fuels in any of the gap sizes (Appendices A-3.9.5 and A-3.9.10

There were no significant direction effects in any of the gap sizes for any of the pre-fire forest floor categories at Fort Benning (Appendices A-3.9.2, A-3.9.3, and A-3.9.4). Position effects were significant for pre-fire fuel bed depth in the large gap fuel bed depths at the 30, 40, and 50 m positions were significantly greater than fuel bed depths at the 10 and 20 m positions (Appendix A-3.9.2). Pre-fire litter depth in the medium gap treatments was also significantly affected by gap position with the greatest litter depths (mean 3.42 cm) within in the forest (Figure 3.9.9; Appendix A-3.9.3). Position effects were not significant in the large or small gaps for any other pre-fire forest floor fuel category at Fort Benning (Appendices A-3.9.2 and A-3.9.4). At Camp Lejeune, there was a significant direction effect on pre-fire litter depth in the small gap treatments with the greatest litter depth on the western transects (mean 4.3 cm) (Appendix A-3.9.9). Pre-fire litter depth in the large gap treatments was significantly affected by gap position with the greatest litter depth within the forest (mean 3.1 cm; Figure 3.9.9; Appendix A-3.9.7). There were no other significant direction, position, or direction*position effects on pre-fire forest floor fuel categories in any of the gap sizes at Camp Lejeune (Appendix A-3.9.7, A-3.9.8, and A-3.9.9).

Although duff depth was not significantly affected by direction or position in any of the gap sizes at either study location, duff depth was greater at Camp Lejeune (average of approximately 0.8 across gap direction and position) than at Fort Benning where it averaged around 0.05 cm across gap direction and position (Figure 3.9.10).

Litter consumption was significantly affected by position in the medium gaps at Fort Benning. The 40 m position (within the forest) had the largest litter consumption (mean 2.89 cm) compared to the other gap positions (Appendix A-3.9.3). Direction and position

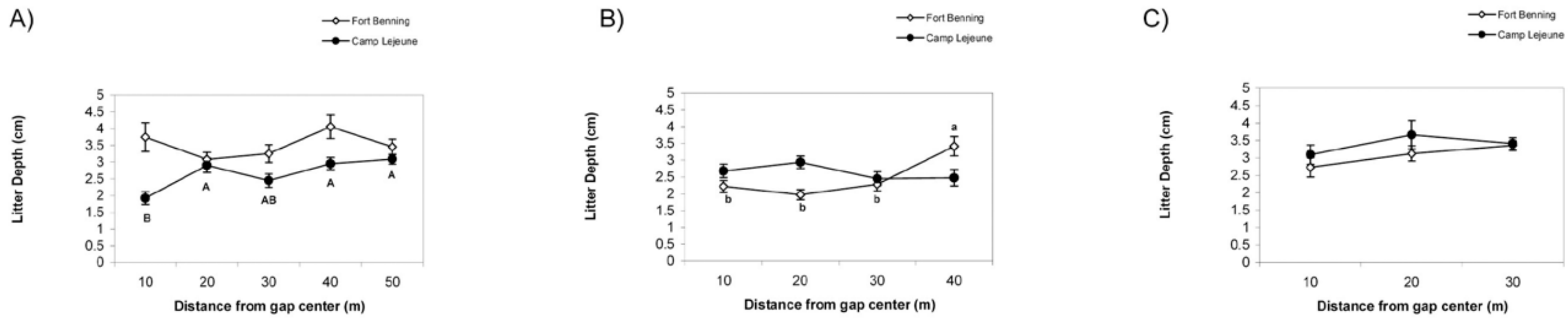


Figure 3.9.9. Pre-fire litter depth (mean ± SE) by gap position for A) large gap B) medium gap and C) small gap treatments at Fort Benning and Camp Lejeune. Different letters within a study location indicate significant differences at the α = 0.05 level.

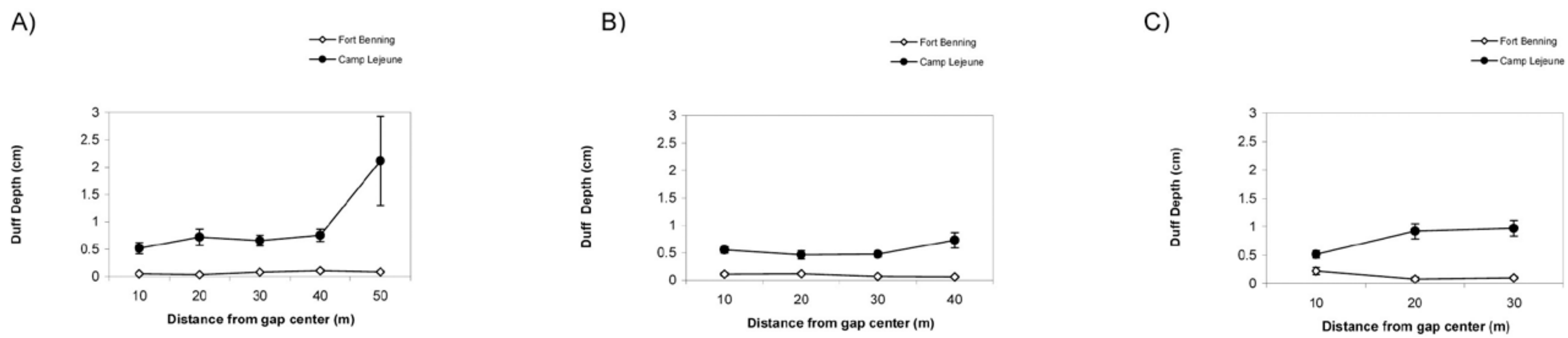


Figure 3.9.10. Pre-fire duff depth (mean ± SE) by gap position for A) large gap B) medium gap and C) small gap treatments at Fort Benning and Camp Lejeune. Different letters within a study location indicate significant differences at the α = 0.05 level.

significantly affected fuel bed depth consumption in the medium gaps at Fort Benning (Appendix A-3.9.3). The western transect had the greatest fuel bed depth consumption (mean 3.9 cm) compared to the other transects. The 40 and 20 m gap positions had the greatest fuel bed depth consumption (mean 2.9 cm and 2.1 cm, respectively) compared to the 10 and 30 m gap positions (Appendix A-3.9.3). Fuel consumption of litter, duff, and fuel bed depth were not significantly affected by direction in any of the gap treatments at Camp Lejeune (Appendices A-3.9.7, A-3.9.8, and A-3.9.9). Of the three forest floor fuel categories, only litter consumption in the large gap treatments exhibited a position effect with the greatest fuel consumption at the 50 m from gap center position (mean 1.8 cm) (Appendix A-3.9.7).

At Fort Benning, cover of graminoid, pine needles, bare ground, and percent area burned were significantly affected by gap position in all three gap sizes (Figure 3.9.11; Appendices A-3.9.2, A-3.9.3, and A-3.9.4). At Camp Lejeune, the same cover categories were significantly affected by gap position except for graminoids, bare ground, and percent area burned in the medium gaps and bare ground in the small gaps (Figure 3.9.11; Appendices A-3.9.7, A-3.9.8, and A-3.9.9). Cover of these categories exhibited a similar pattern at both locations. Graminoid cover and bare ground cover tended to decrease as canopy density increased while pine needle cover and percent area burned tended to increase as canopy density increased. In general, cover of each category was higher at Fort Benning than at Camp Lejeune (Figure 3.9.11).

3.9.3.3. Fire behavior

The earliest fires occurred at Camp Lejeune on June 5th and latest applied at Fort Benning on April 5th (Table 3.9.1). Weather conditions on the day of the burn varied among the burned areas. For instance, the ambient temperature for the blocks that received logger-probe installation ranged from 2.2° C to 24° C. Relative humidity also varied considerably between Block 2 in Camp Lejeune (45%) and Blocks 5 and 6 at Fort Benning (26%).

Metrics calculated from the logger-probes reveal a wide range of fire durations and temperatures (Table 3.9.2). The Clearcut plot in Block 5 at Fort Benning, for example, had a maximum temperature of 259.30°C while the Clearcut plot in Block 6 had a maximum temperature of 53.92°C. Overall, Block 2 at Camp Lejeune had the lowest maximum temperatures and heat index values (AREAAMB and AREA60) while Block 5 at Fort Benning had the highest heat index values, duration at 60°C (DUR60), and maximum temperatures.

The time-temperature curves captured by logger-probes at single points in the H+F, H, and NT split-plots within each of the main-plots of Block 6 at Fort Benning show wide variation in recorded temperatures (Figure 3.9.12). Among the NT split-plots, for example, the Control plot had the highest recorded temperature (150.5°C) compared to the LowBA plot (61.5°C). Generally, the recorded temperature seemed to decrease as canopy density decreases (apart from the NT subplots where the LowBA had a lower recorded temperature than the Clearcut).

The north, south, and west transects show the highest temperatures at the 40 and 50 m gap position, locations closest to the forest (Figure 3.9.13). However, the east transect exhibited the opposite trend with the highest temperature at the 10 m position (closest to the gap center)

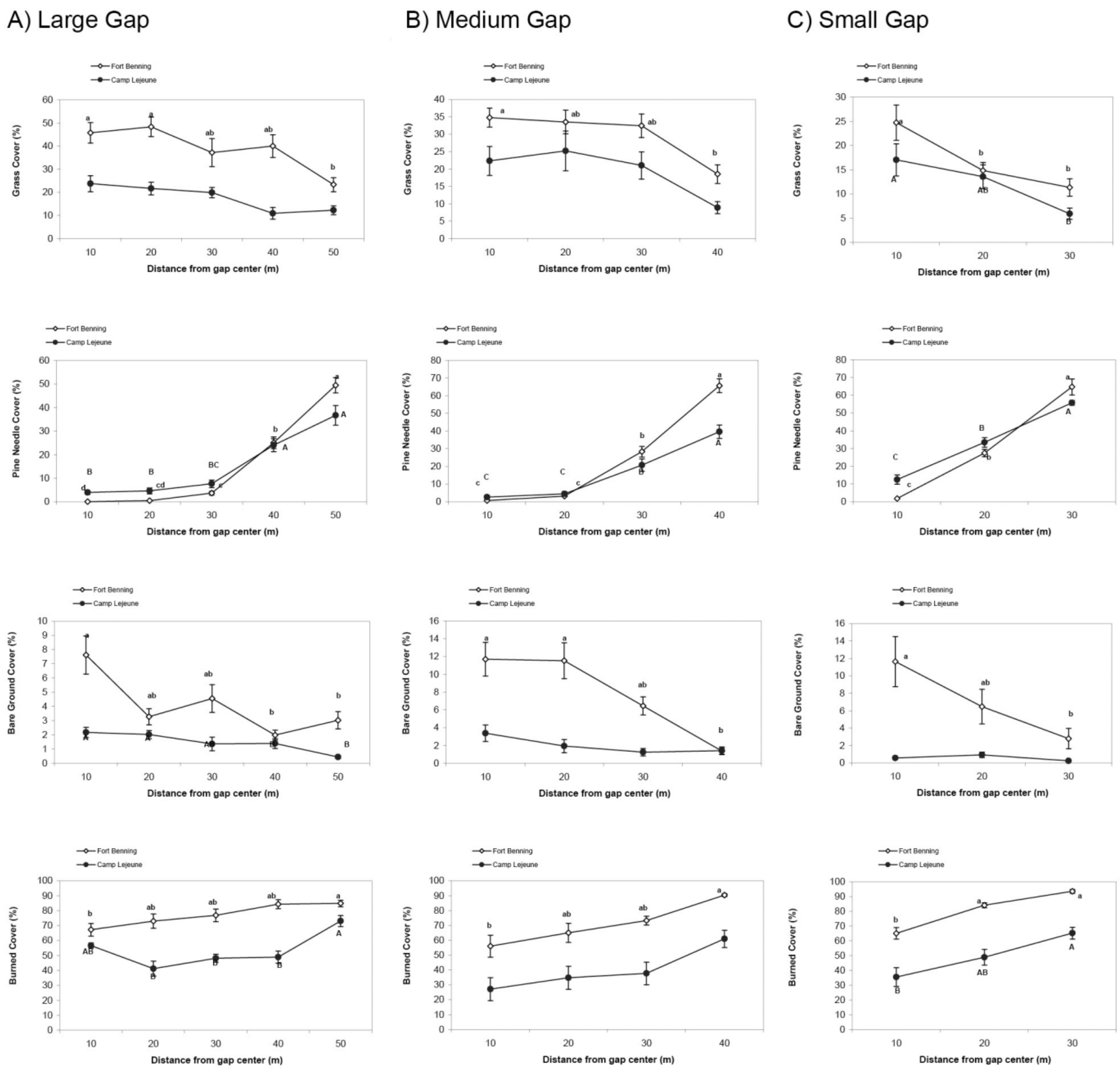


Figure 3.9.11. Pre-fire grass, pine needle, bare ground, and burned cover (mean ± SE) by gap position in the A) large gap B) medium gap and C) small gap treatments at Fort Benning and Camp Lejeune. Different letters within a study location indicate significant differences at the $\alpha = 0.05$ level.

Table 3.9.1. Weather conditions from the 2010 dormant season prescribed fires at Fort Benning and Camp Lejeune. Data at Fort Benning were collected with a Kestrel 3000 Pocket Weather Meter at the time of ignition; data from Camp Lejeune were acquired from the North Carolina Division of Forest Resources, Remote Automated Weather Station at the Sandy Run station (34.61° N, 77.49° W).

Site	Block	Treatment	Burn date	Temp. °C	Relative Humidity (%)	Average wind speed (km/hr)	Max gust wind speed (km/hr)	Wind direction
Fort Benning	1; Z4	All	7-Mar-10	16.7	15	7.9	17.6	West
	2; Q1	All	5-Apr-10	26.9	44	3.2	4.7	Southwest
	3; U3	Clearcut	17-Feb-10	7.8	49	14.4	28.8	West
	3; M7/M8	LowBA, MedBA, Control, Gap	25-Feb-10	7.2	26	4.7	10.1	Northwest
	4; O7	Clearcut, LowBA, Gap	18-Feb-10	12	28	4.7	11.2	West
	4; O7	MedBA, Control	25-Feb-10	6.1	27	17.6	30.6	Northwest
	5; Z3	All	8-Mar-10	24	26	2.9	4.7	North
	6; K5	All	18-Feb-10	14.4	26	6.5	13	Northwest
Camp Lejeune	1; HH	All	5-Jan-10	2.2	45	14.4	27.7	Northwest
	2; HH	All	5-Jan-10	2.2	45	14.4	27.7	Northwest
	3; HH	All	5-Jan-10	2.2	45	14.4	27.7	Northwest
	4; HH	All	27-Feb-10	11.1	31	9.6	24.1	Southwest
	5; KD	All	10-Mar-10	22.7	39	11.2	25.8	Southwest
	7; KB	All	15-Mar-10	16.7	47	14.4	32	Northwest
	8; MA	All	26-Feb-10	7.7	33	14.4	32.2	Northwest

Table 3.9.2. Descriptive statistics of logger-probe metrics (mean|*SD*) by main plot and gap treatment at Fort Benning and Camp Lejeune.

Site	Block	Treatment	N	MINT (°C)	MAXT (°C)		DURAMB (h:mm:ss)		DUR60 (h:mm:ss)		DURMAX (h:mm:ss)		AREAAMB (sec°C)		AREA60 (sec°C)	
Fort Benning	6; K5	Clearcut	5	27	53.92	*19.21*	0:03:42.1	*0:00:09.4*	0:00:28.9	*0:00:40.9*	0:00:37.5	*0:00:22.3*	10362.38	*2580.06*	2783.70	*3936.75*
	6; K5	LowBA	11	27	47.27	*3.53*	0:02:35.9	*0:01:08.2*	0:00:08.1	*0:00:09.4*	0:00:25.7	*0:00:35.0*	7469.53	*1904.21*	1530.74	*427.71*
	6; K5	MedBA	13	27	100.93	*22.63*	0:04:27.7	*0:01:08.9*	0:01:31.7	*0:00:04.4*	0:00:18.6	*0:00:08.8*	16179.59	*2090.72*	9888.03	*1663.87*
	6; K5	Control	15	27	118.20	*13.86*	0:06:21.3	*0:01:45.1*	0:02:08.2	*0:00:20.6*	0:00:09.4	*0:00:01.5*	22226.65	*3257.96*	12056.20	*1480.16*
	6; K5	LG	18	27	110.67	*45.49*	0:04:00.2	*0:00:41.6*	0:01:29.0	*0:00:46.8*	0:00:22.2	*0:00:40.2*	14863.42	*4033.76*	8680.63	*5689.97*
	6; K5	SG	11	27	93.50	*56.92*	0:03:52.2	*0:01:02.0*	0:01:10.4	*0:01:04.5*	0:00:18.4	*0:00:20.2*	13558.23	*7334.25*	7008.41	*7804.47*
	5; Z3	Clearcut	13	27	259.30	*28.83*	0:06:14.7	*0:00:31.8*	0:02:48.7	*0:00:14.5*	0:00:04.2	*0:00:01.1*	31898.97	*3464.23*	23826.32	*3085.01*
	5; Z3	LowBA	5	27	191.50	*73.47*	0:10:51.7	*0:03:29.9*	0:03:05.8	*0:01:05.5*	0:00:17.5	*0:00:10.1*	41263.75	*7126.09*	23817.63	*11232.40*
	5; Z3	MedBA	14	27	140.17	*4.14*	0:08:11.5	*0:00:23.8*	0:02:40.8	*0:00:34.6*	0:00:12.4	*0:00:04.6*	29471.36	*2491.20*	16445.74	*2951.34*
	5; Z3	Control	4	27	145.50	*17.32*	0:07:47.3	*0:01:13.2*	0:02:54.4	*0:00:00.5*	0:00:03.4	*0:00:01.6*	28710.19	*1061.99*	17326.31	*1643.23*
	5; Z3	LG	15	27	197.33	*69.96*	0:10:17.4	*0:06:41.8*	0:03:14.5	*0:01:38.9*	0:00:06.8	*0:00:04.0*	40915.80	*22488.27*	24890.20	*17618.12*
	5; Z3	SG	11	27	204.18	*133.86*	0:09:16.9	*0:02:58.1*	0:04:04.0	*0:01:57.3*	0:00:10.4	*0:00:09.5*	44075.73	*27909.88*	31751.05	*26995.50*
Camp Lejeune	2; HH	Clearcut	10	7.5	56.76	*8.45*	0:08:08.6	*0:01:05.6*	0:00:28.6	*0:00:24.8*	0:00:33.8	*0:00:14.3*	12457.58	*794.83*	2701.02	*2346.10*
	2; HH	LowBA	12	7.5	88.42	*37.71*	0:08:29.7	*0:01:59.3*	0:01:01.6	*0:00:38.5*	0:00:12.6	*0:00:07.1*	16847.20	*6532.16*	6559.15	*5594.53*
	2; HH	MedBA	6	7.5	75.63	*36.67*	0:09:02.0	*0:01:46.2*	0:01:01.5	*0:01:03.9*	0:00:20.8	*0:00:11.5*	15944.06	*4912.03*	5131.75	*5950.79*
	2; HH	Control	12	7.5	62.63	*22.39*	0:08:13.2	*0:01:43.2*	0:00:33.8	*0:00:29.5*	0:00:24.9	*0:00:24.8*	15288.25	*2945.67*	2911.20	*2521.32*
	2; HH	LG	14	7.5	64.43	*36.68*	0:07:31.7	*0:02:28.3*	0:00:42.4	*0:00:52.5*	0:00:25.9	*0:00:25.2*	12378.11	*5188.63*	3563.79	*4466.43*

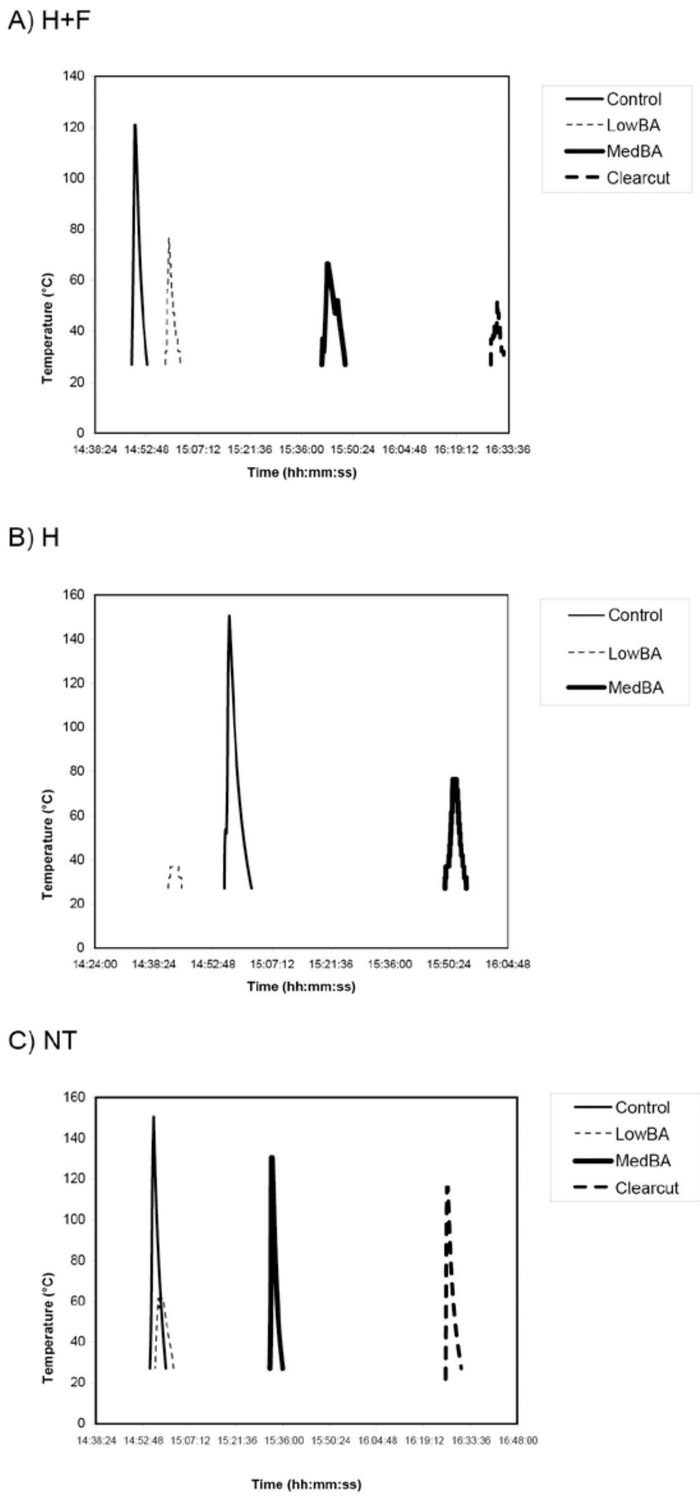


Figure 3.9.12. Time x temperature curves for logger-probes installed at single points in the A) H+F split-plot, B) H split-plot, and C) NT split-plot within the main-plots of Block 6 (K5) at Fort Benning during the February 18, 2010 prescribed burn. Note: Logger probes that failed not shown.

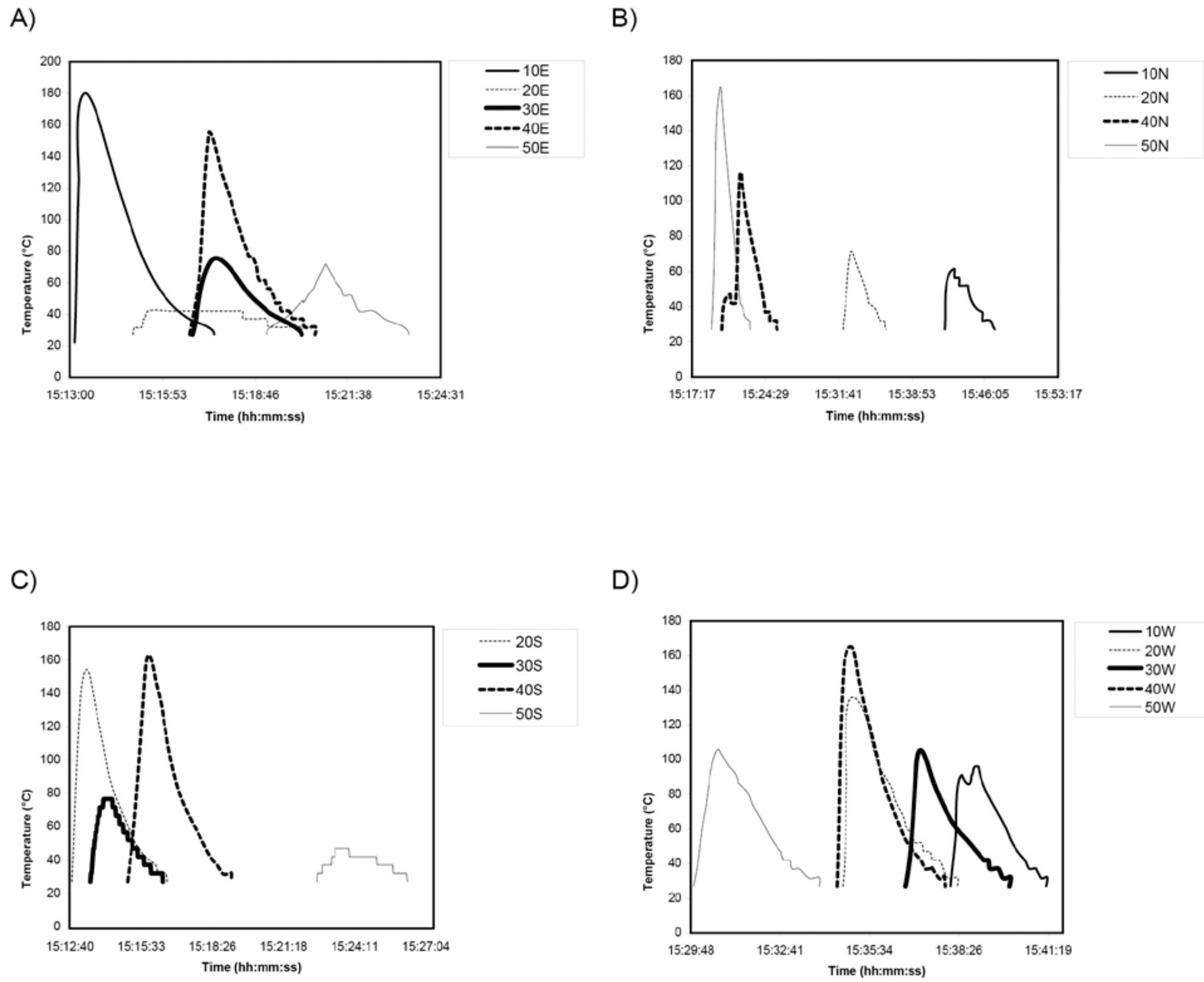


Figure 3.9.13. Time x temperature curves for logger-probes installed at single gap positions on the A) east transect, B) north transect, C) south transect, and D) west transect within the large gap of Block 6 (K5) at Fort Benning during the February 18, 2010 prescribed burn. Note: Logger probes that failed not shown.

Table 3.9.3. Pearson's correlation coefficient (r) matrices with probability of r values for fuel and fire behavior/effects variables in the uniform treatments for A) pre-fire fuels, Fort Benning, B) fuel consumption, Fort Benning, C) pre-fire fuels, Camp Lejeune, and D) fuel consumption, Camp Lejeune.

A) Fort Benning - Uniform pre-fire

	DURAMB	DUR60	DURMAX	AREAAMB	AREA60	MAXT	BURNED
PRE1HR	0.24191	0.23360	0.16376	0.24530	0.19480	-0.02417	-0.08641
	0.0603	0.0700	0.2073	0.0567	0.1325	0.8533	0.4025
PRE1HR	61	61	61	61	61	61	96
PRE10HR	0.13880	0.14370	0.04080	0.16285	0.13746	-0.06625	0.07003
	0.2861	0.2692	0.7549	0.2099	0.2908	0.6120	0.4978
PRE10HR	61	61	61	61	61	61	96
PRE100HR	-0.26460	-0.44043	0.15282	-0.41777	-0.42538	-0.41350	-0.36702
	0.0393	0.0004	0.2397	0.0008	0.0006	0.0009	0.0002
PRE100HR	61	61	61	61	61	61	96
PRELITT	0.20400	0.33784	-0.18151	0.35743	0.38491	0.37773	0.26210
	0.1148	0.0077	0.1615	0.0047	0.0022	0.0027	0.0099
PRELITT	61	61	61	61	61	61	96
PREGR	-0.00292	0.18931	-0.21634	0.22951	0.32104	0.52754	0.26219
	0.9822	0.1440	0.0940	0.0752	0.0116	<.0001	0.0099
PREGR	61	61	61	61	61	61	96
PREPNDL	0.08749	0.20492	-0.14395	0.01081	0.00370	-0.13341	0.29185
	0.5026	0.1131	0.2684	0.9341	0.9774	0.3054	0.0039
PREPNDL	61	61	61	61	61	61	96
PREBARE	-0.26151	-0.20411	-0.03426	-0.25638	-0.17432	-0.10859	-0.15746
	0.0418	0.1146	0.7932	0.0461	0.1791	0.4048	0.1255
PREBARE	61	61	61	61	61	61	96

B) Fort Benning - Uniform consumption

	DURAMB	DUR60	DURMAX	AREAAMB	AREA60	MAXT	BURNED
	0.13980	0.13074	-0.04928	0.07631	0.03128	-0.02398	0.09203
	0.2826	0.3152	0.7061	0.5589	0.8109	0.8545	0.3725
D1HR	61	61	61	61	61	61	96
	0.20448	0.22024	-0.02451	0.25032	0.22245	0.02518	0.09259
	0.1139	0.0881	0.8513	0.0517	0.0849	0.8473	0.3696
D10HR	61	61	61	61	61	61	96
	0.22682	-0.06241	0.10755	0.06375	-0.10181	-0.10779	-0.10368
	0.0788	0.6328	0.4094	0.6255	0.4350	0.4083	0.3148
D100HR	61	61	61	61	61	61	96
	0.05124	0.10444	-0.15963	0.16823	0.17764	0.29585	0.29959
	0.6949	0.4231	0.2191	0.1950	0.1708	0.0206	0.0030
DLitt	61	61	61	61	61	61	96
	0.01838	0.21955	-0.21688	0.25559	0.34577	0.54364	0.33908
	0.8882	0.0891	0.0932	0.0468	0.0063	<.0001	0.0007
DGR	61	61	61	61	61	61	96
	0.09065	0.20495	-0.15213	0.01403	0.00468	-0.12893	0.30576
	0.4872	0.1131	0.2418	0.9146	0.9715	0.3220	0.0024
DPNDL	61	61	61	61	61	61	96
	-0.10628	-0.15668	0.11392	-0.15078	-0.14268	-0.08429	-0.19162
	0.4149	0.2279	0.3820	0.2461	0.2727	0.5184	0.0614
DBARE	61	61	61	61	61	61	96

C) Camp Lejeune - Uniform pre-fire

	DURAMB	DUR60	DURMAX	AREAAMB	AREA60	MAXT	BURNED
PRE1HR	-0.18574	0.34140	0.10652	0.15727	0.30089	0.29364	0.05732
	0.3088	0.0558	0.5617	0.3982	0.1062	0.1089	0.6988
PRE1HR	32	32	32	31	30	31	48
PRE10HR	-0.27933	-0.18204	0.10490	-0.13031	-0.14698	-0.18669	-0.26842
	0.1216	0.3187	0.5678	0.4847	0.4383	0.3146	0.0651
PRE10HR	32	32	32	31	30	31	48
PRE100HR	-0.08760	-0.32727	-0.10575	-0.32817	-0.32600	-0.34257	0.02831
	0.6335	0.0675	0.5646	0.0715	0.0787	0.0592	0.8485
PRE100HR	32	32	32	31	30	31	48
PRELITT	0.03427	-0.02521	-0.09627	0.15584	0.05663	0.03480	0.06576
	0.8523	0.8911	0.6002	0.4025	0.7663	0.8526	0.6570
PRELITT	32	32	32	31	30	31	48
PREGR	-0.10696	0.06095	0.00842	-0.10961	0.05019	0.01154	0.15683
	0.5601	0.7403	0.9635	0.5572	0.7923	0.9509	0.2871
PREGR	32	32	32	31	30	31	48
PREPNDL	0.03035	-0.03637	-0.18315	0.09650	-0.05419	-0.01900	0.24398
	0.8690	0.8433	0.3157	0.6056	0.7761	0.9192	0.0947
PREPNDL	32	32	32	31	30	31	48
PREBARE	0.34007	0.15585	-0.07190	0.14198	0.07270	0.08259	-0.07638
	0.0569	0.3943	0.6958	0.4461	0.7026	0.6587	0.6059
PREBARE	32	32	32	31	30	31	48

D) Camp Lejeune - Uniform consumption

	DURAMB	DUR60	DURMAX	AREAAMB	AREA60	MAXT	BURNED
	-0.34633	0.22335	0.13525	0.09900	0.22074	0.24031	-0.10174
	0.0522	0.2191	0.4605	0.5962	0.2411	0.1929	0.4914
D1HR	32	32	32	31	30	31	48
	-0.36505	-0.19345	0.11779	-0.20480	-0.15283	-0.20499	-0.26907
	0.0399	0.2888	0.5208	0.2691	0.4201	0.2686	0.0644
D10HR	32	32	32	31	30	31	48
	0.10350	-0.40803	0.00220	-0.17847	-0.30443	-0.32582	0.25646
	0.5729	0.0204	0.9905	0.3368	0.1019	0.0737	0.0785
D100HR	32	32	32	31	30	31	48
	0.16571	0.07419	-0.08258	0.28037	0.15610	0.14534	0.36903
	0.3730	0.6916	0.6588	0.1334	0.4187	0.4435	0.0107
DLitt	31	31	31	30	29	30	47
	-0.14368	0.14637	-0.01810	-0.07354	0.06675	0.05841	0.17722
	0.4327	0.4241	0.9217	0.6942	0.7260	0.7550	0.2282
DGR	32	32	32	31	30	31	48
	0.19381	0.01808	-0.28781	0.15858	0.00595	0.07105	0.64168
	0.2879	0.9217	0.1102	0.3942	0.9751	0.7041	<.0001
DPNDL	32	32	32	31	30	31	48
	0.17564	0.12802	0.03169	0.07572	0.07096	0.05817	-0.46888
	0.3363	0.4850	0.8633	0.6856	0.7094	0.7559	0.0008
DBARE	32	32	32	31	30	31	48

PRE1HR, pre-fire 1hr fuel; PRE10HR, pre-fire 10hr fuel; PRE100HR, pre-fire 100hr fuel; PRELITT, pre-fire litter depth; PREGR, pre-fire grass cover; PREPNDL, pre-fire pine needle cover; PREBARE, pre-fire bare ground cover, D1HR, difference of pre-post 1hr fuel; D10HR, difference of pre-post 10hr fuel; D100HR, difference of pre-post 100hr fuel; DLITT, difference of pre-post litter depth; DGR, difference of pre-post grass cover; DPNDL, difference of pre-post pine needle cover; DBARE, difference of pre-post bare ground cover DURAMB, duration of burn above ambient temperature; DUR60, duration of burn above 60 °C; DURMAX, duration of burn at maximum temperature; AREAAMB, area under time-temperature curve above ambient temperature; AREA60, area under time-temperature curve above 60 °C; MAXT, maximum temperature; BURNED, burned cover.

Table 3.9.4. Pearson's correlation coefficient (r) matrices with probability of r values for fuel and fire behavior/effects variables in the gap treatments for A) pre-fire fuels, Fort Benning, B) fuel consumption, Fort Benning, C) pre-fire fuels, Camp Lejeune, and D) fuel consumption, Camp Lejeune.

A) Fort Benning - gap pre-fire

	DURAMB	DUR60	DURMAX	AREAAMB	AREA60	MAXT	BURNED
PRE1HR	0.26640	0.52717	-0.12483	0.51971	0.58157	0.59852	0.17869
	0.0493	<.0001	0.3638	<.0001	<.0001	<.0001	0.1577
PRE1HR	55	55	55	55	55	55	64
PRE10HR	0.12391	0.30219	0.06138	0.31427	0.36819	0.25059	-0.04672
	0.3674	0.0249	0.6562	0.0195	0.0057	0.0650	0.7139
PRE10HR	55	55	55	55	55	55	64
PRE100HR	0.33914	0.04950	0.21045	0.18161	0.02052	-0.03300	-0.21210
	0.0113	0.7197	0.1230	0.1845	0.8818	0.8109	0.0925
PRE100HR	55	55	55	55	55	55	64
PRELITT	0.12879	0.48779	-0.10789	0.46154	0.58162	0.57177	0.41705
	0.3487	0.0002	0.4330	0.0004	<.0001	<.0001	0.0006
PRELITT	55	55	55	55	55	55	64
PREGR	0.02114	-0.16916	-0.08383	-0.11551	-0.17955	-0.04131	0.08111
	0.8783	0.2170	0.5429	0.4010	0.1896	0.7646	0.5240
PREGR	55	55	55	55	55	55	64
PREPNDL	-0.10028	0.15341	-0.10192	0.04902	0.14369	0.09354	0.35793
	0.4664	0.2635	0.4590	0.7223	0.2953	0.4970	0.0037
PREPNDL	55	55	55	55	55	55	64
PREBARE	-0.35508	-0.45158	-0.00448	-0.40322	-0.37500	-0.39107	-0.57685
	0.0078	0.0005	0.9741	0.0023	0.0048	0.0032	<.0001
PREBARE	55	55	55	55	55	55	64

B) Fort Benning - gap consumption

	DURAMB	DUR60	DURMAX	AREAAMB	AREA60	MAXT	BURNED
	-0.04277	0.05475	0.01664	0.09206	0.14669	0.15551	0.02835
	0.7566	0.6913	0.9040	0.5038	0.2852	0.2569	0.8241
D1HR	55	55	55	55	55	55	64
	0.03613	0.28377	0.08372	0.28530	0.37248	0.31218	-0.01665
	0.7934	0.0358	0.5434	0.0347	0.0051	0.0203	0.8961
D10HR	55	55	55	55	55	55	64
	-0.01753	-0.07028	0.16013	-0.08400	-0.09587	-0.10100	-0.15945
	0.8989	0.6101	0.2429	0.5420	0.4862	0.4631	0.2082
D100HR	55	55	55	55	55	55	64
	0.05738	0.39812	-0.15216	0.36599	0.49072	0.48962	0.50937
	0.6773	0.0026	0.2674	0.0060	0.0001	0.0001	<.0001
DLitt	55	55	55	55	55	55	64
	-0.07028	-0.20296	-0.07642	-0.17477	-0.20360	-0.05297	0.14008
	0.6101	0.1373	0.5792	0.2019	0.1360	0.7009	0.2696
DGR	55	55	55	55	55	55	64
	-0.16142	0.01048	-0.05682	-0.05033	0.02802	-0.04107	0.29572
	0.2391	0.9395	0.6803	0.7152	0.8391	0.7659	0.0177
DPNDL	55	55	55	55	55	55	64
	0.15180	0.17944	0.05452	0.16720	0.15356	0.13355	-0.36233
	0.2686	0.1899	0.6926	0.2224	0.2630	0.3310	0.0033
DBARE	55	55	55	55	55	55	64

C) Camp Lejeune - gap pre-fire

	DURAMB	DUR60	DURMAX	AREAAMB	AREA60	MAXT	BURNED
PRE1HR	0.05673	-0.36007	0.28287	-0.27058	-0.36443	-0.34083	-0.00124
	0.8473	0.2060	0.3271	0.3495	0.2002	0.2331	0.9959
PRE1HR	14	14	14	14	14	14	20
PRE10HR	0.15165	-0.31314	0.14106	-0.21476	-0.33711	-0.36744	-0.20182
	0.6048	0.2756	0.6305	0.4609	0.2385	0.1962	0.3935
PRE10HR	14	14	14	14	14	14	20
PRE100HR	-0.04317	-0.23727	0.12932	-0.11280	-0.25656	-0.18197	-0.40917
	0.8835	0.4141	0.6595	0.7010	0.3759	0.5335	0.0732
PRE100HR	14	14	14	14	14	14	20
PRELITT	-0.13837	0.18502	-0.35306	0.29474	0.23578	0.41224	-0.01227
	0.6371	0.5266	0.2156	0.3063	0.4171	0.1430	0.9590
PRELITT	14	14	14	14	14	14	20
PREGR	-0.37927	0.05328	0.14881	-0.16800	0.08092	0.12690	0.60705
	0.1811	0.8565	0.6117	0.5659	0.7833	0.6655	0.0045
PREGR	14	14	14	14	14	14	20
PREPNDL	0.58459	0.26675	-0.40813	0.58470	0.24426	0.20002	0.12109
	0.0281	0.3566	0.1474	0.0281	0.4000	0.4930	0.6111
PREPNDL	14	14	14	14	14	14	20
PREBARE	0.16624	-0.39615	0.50635	-0.36551	-0.39122	-0.48468	-0.17356
	0.5700	0.1608	0.0647	0.1987	0.1666	0.0790	0.4643
PREBARE	14	14	14	14	14	14	20

D) Camp Lejeune - gap consumption

	DURAMB	DUR60	DURMAX	AREAAMB	AREA60	MAXT	BURNED
	0.07213	-0.34635	0.19976	-0.20138	-0.34923	-0.28821	0.16093
	0.8064	0.2251	0.4935	0.4900	0.2210	0.3177	0.4979
D1HR	14	14	14	14	14	14	20
	-0.28891	-0.35592	0.21809	-0.40228	-0.37053	-0.36898	-0.40397
	0.3164	0.2117	0.4538	0.1539	0.1922	0.1942	0.0773
D10HR	14	14	14	14	14	14	20
	-0.49452	0.39265	-0.12459	-0.02351	0.39339	0.26834	-0.36622
	0.0722	0.1649	0.6713	0.9364	0.1641	0.3536	0.1123
D100HR	14	14	14	14	14	14	20
	-0.10301	-0.03266	-0.34146	0.10118	0.02935	0.20639	0.66524
	0.7260	0.9118	0.2321	0.7307	0.9207	0.4790	0.0014
DLitt	14	14	14	14	14	14	20
	-0.05987	-0.09034	0.20688	-0.07351	-0.08667	-0.01090	0.73916
	0.8389	0.7587	0.4779	0.8028	0.7683	0.9705	0.0002
DGR	14	14	14	14	14	14	20
	0.57401	-0.07164	-0.27090	0.31841	-0.08261	-0.03973	0.28695
	0.0318	0.8077	0.3489	0.2672	0.7789	0.8927	0.2200
DPNDL	14	14	14	14	14	14	20
	-0.02241	-0.68262	0.72473	-0.64754	-0.66765	-0.68137	-0.39061
	0.9394	0.0071	0.0034	0.0123	0.0091	0.0073	0.0886
DBARE	14	14	14	14	14	14	20

PRE1HR, pre-fire 1hr fuel; PRE10HR, pre-fire 10hr fuel; PRE100HR, pre-fire 100hr fuel; PRELITT, pre-fire litter depth; PREGR, pre-fire grass cover; PREPNDL, pre-fire pine needle cover; PREBARE, pre-fire bare ground cover, D1HR, difference of pre-post 1hr fuel; D10HR, difference of pre-post 10hr fuel; D100HR, difference of pre-post 100hr fuel; DLITT, difference of pre-post litter depth; DGR, difference of pre-post grass cover; DPNDL, difference of pre-post pine needle cover; DBARE, difference of pre-post bare ground cover DURAMB, duration of burn above ambient temperature; DUR60, duration of burn above 60 °C; DURMAX, duration of burn at maximum temperature; AREAAMB, area under time-temperature curve above ambient temperature; AREA60, area under time-temperature curve above 60 °C; MAXT, maximum temperature; BURNED, burned cover.

and the lowest temperature was at the 50 m gap position (closest to the forest).

Pearson's correlation coefficients and their associated probabilities for the uniform and gap treatments are presented in Tables 3.9.3 and 3.9.4, respectively. These figures show that various fuel measurement variables are significantly correlated to various fire behavior metrics. For example, both pre-fire (PREPNDL) and consumed pine needle cover (DPNDL) were significantly correlated with BURNED in the uniform and gap plots at Fort Benning. Pre-fire litter cover (PRELITT) was significantly correlated with AREAAMB, AREA60, MAXT and BURNED in both the uniform (r ranged from 0.26 to 0.38) and gap plots (r^2 ranged from 0.42 to 0.58) at Fort Benning. DLITT (litter depth consumption) was significantly correlated with BURNED and MAXT in the uniform and gap treatments at Fort Benning.

In the uniform plots at Camp Lejeune, no pre-fire variables were significantly correlated with any of the fire behavior metrics (Table 3.9.3). Among the fuel consumption variables in the uniform treatments, DLITT, DPNDL and DBARE were significantly correlated with BURNED (with r^2 = 0.37, 0.64, and -0.47, respectively) (Figure 3.9.14). DLITT was significantly correlated with BURNED in the gap treatments at Camp Lejeune (Table 3.9.4).

In the correlation matrices, BURNED was the most frequently significant fire behavior measure followed by MAXT, AREA60 and AREAAMB. DURAMB and DUR60 were the next most frequently significant fire behavior measures. DURMAX was the least frequently significant fire behavior measure (Tables 3.9.3 and 3.9.4).

Regression models showed that, in general, most pre-fire fuel load variables and fuel consumption variables were weak predictors of fire behavior metrics (Tables 3.9.5 and 3.9.6) in both uniform and gap treatments at both study locations. Although many fuel combinations were significant, r values were typically low (many less than 0.5). Among the pre-fire fuel load variables, the combination of PRE100HR, PRELITT, PREGR, and PREPNDL was a reasonably good predictor of MAXT on the uniform plots at Fort Benning (r^2 = 0.5134; Table 3.9.5). In the gaps at Fort Benning, the combination of PRE1HR, PRE10HR, and PRELITT variables predicted AREA60 (r^2 = 0.5361; Table 3.9.5). In the uniform plots at Camp Lejeune, AREA60 was predicted fairly well by a combination of PRE10HR, PRELITT, and PREPNDL (r^2 = 0 .5461; Table 3.9.5). The combination of PRE1HR, PRE100HR, PRELITT, PREGR, and PREPNDL was a strong predictor of BURNED in the gaps at Camp Lejeune (r^2 = 0.7809) (Table 3.9.5). Fire behavior metrics that were associated with temperature (MAXT) or that integrated time and temperature (AREA60) were generally more strongly associated with various combinations of pre-fire fuel variables. The single variable PRELITT appeared in all the above mentioned models.

Among the fuel consumption variables, the combination of D1HR, D100HR, DLITT, DGR, DPNDL, and DBARE was a good predictor of BURNED in the uniform plots at Camp Lejeune (r^2 = 0.6716; Table 3.9.6). Relationships between any fuel consumption variables or combinations and fire behavior metrics were weak in both the Fort Benning uniform and gap plots; no r^2 values were above 0.3341 (Table 3.9.6). However, the highest r^2 values were associated with BURNED (Table 3.9.6). All of the fuel consumption variable

Table 3.9.5. Regression models for pre-fire fuel and fire behavior variables and with associated model-based r^2 and p value for A) Fort Benning uniform plots, B) Camp Lejeune uniform plots, C) Fort Benning gap plots, and D) Camp Lejeune gap plots.

A) Fort Benning - uniform pre-fire

Dependent	Intercept	Variable1	Variable2	Variable3	Variable4	Variable5	Variable6	r^2	p value
DURAMB (SQRT)	20.852	- 0.725 PRE100HR	- 0.112 PREBARE					0.2290	0.0005
DUR60	108.375	- 10.914 PRE100HR	- 14.046 PREBARE					0.2608	0.0002
DURMAX (LOG10)	1.000	+ 2.157 PRE1HR	- 0.006 PREGR					0.1992	0.0016
AREAAMB	18716.000	+ 2352.412 PRE10HR	- 1524.192 PRE100HR	+ 2561.840 PRELITT				0.3074	<0.0001
AREA60	7382.241	+ 2235.393 PRE10HR	- 1292.491 PRE100HR	+ 1999.840 PRELITT	+ 113.970 PREGR			0.3848	<0.0001
MAXT (LOG10)	1.866	- 0.038 PRE100HR	+ 0.036 PRELITT	+ 0.006 PREGR	+ 0.002 PREPNDL			0.5134	<0.0001
BURNED (SQRT)	7.126	- 0.238 PRE100HR	+ 0.039 PREGR	+ 0.030 PREPNDL				0.3016	<0.0001

B) Camp Lejeune - uniform pre-fire

Dependent	Intercept	Variable1	Variable2	Variable3	Variable4	Variable5	Variable6	r^2	p value
DURAMB	493.002	+ 15.952 PREBARE						0.1156	0.0569
DUR60 (LOG10)	1.913	+ 2.096 PRE1HR						0.3371	0.0295
DURMAX		No relationship						n/a	n/a
AREAAMB (SQRT)	129.089	- 4.839 PRE100HR						0.1104	0.0678
AREA60 (LOG10)	4.259	- 0.084 PRE10HR	- 0.192 PRELITT	- 0.014 PREPNDL				0.5461	0.0411
MAXT (LOG10)	1.879	- 0.049 PRE100HR						0.1157	0.0612
BURNED (SQRT)	1.570	- 0.473 PRE10HR	+ 0.466 PRE100HR	+ 0.058 PREGR	+ 0.079 PREPNDL			0.2812	0.0058

C) Fort Benning - gap pre-fire

Dependent	Intercept	Variable1	Variable2	Variable3	Variable4	Variable5	Variable6	r^2	p value
DURAMB (LOG10)	2.521	+ 0.655 PRE1HR	+ 0.022 PRE100HR	- 0.014 PREBARE				0.3679	<0.0001
DUR60 (SQRT)	10.937	+ 20.711 PRE1HR	- 0.294PREBARE					0.3920	<0.0001
DURMAX (LOG10)	0.917	- 1.275 PRE1HR	+ 0.054 PRE100HR					0.1558	0.0122
AREAAMB (LOG10)	4.345	+ 1.271 PRE1HR	- 0.021 PREBARE					0.4744	<0.0001
AREA60	-12702.000	+ 72608 PRE1HR	+ 8626.763 PRE10HR	+ 6422.689 PRELITT				0.5361	<0.0001
MAXT	20.816	+ 416.766 PRE1HR	+ 31.379 PRELITT					0.4875	<0.0001
BURNED (LOG10)	1.934	+ 0.168 PRE1HR	- 0.046 PRE10HR	- 0.007 PRE100HR	+ 0.001 PREGR	+ 0.001 PREPNDL	- 0.004 PREBARE	0.4820	<0.0001

D) Camp Lejeune - gap pre-fire

Dependent	Intercept	Variable1	Variable2	Variable3	Variable4	Variable5	Variable6	r^2	p value
DURAMB	0.006	- 0.001 PRELITT	+ 0.00006 PREPNDL					0.5029	0.0214
DUR60 (SQRT)		No relationship						n/a	n/a
DURMAX (LOG10)	-3.517	- 0.012 PREPNDL						0.2263	0.0856
AREAAMB	9537.816	+ 154.824 PREPNDL						0.3419	0.0281
AREA60		No relationship						n/a	n/a
MAXT (LOG10)	1.909	- 0.080 PREBARE						0.3197	0.0351
BURNED	-55.498	+ 108.352 PRE1HR	- 6.334 PRE100HR	+ 12.630 PRELITT	+ 1.606 PREGR	+ 1.257 PREPNDL		0.7809	0.0003

PRE1HR, pre-fire 1hr fuel; PRE10HR, pre-fire 10hr fuel; PRE100HR, pre-fire 100hr fuel; PRELITT, pre-fire litter depth; PREGR, pre-fire grass cover; PREPNDL, pre-fire pine needle cover; PREBARE, pre-fire bare ground cover, DURAMB, duration of burn above ambient temperature; DUR60, duration of burn above 60 °C; DURMAX, duration of burn at maximum temperature; AREAAMB, area under time-temperature curve above ambient temperature; AREA60, area under time-temperature curve above 60 °C; MAXT, maximum temperature; BURNED, burned cover.

Table 3.9.6. Regression models for fuel consumption and fire behavior variables and with associated model-based r^2 and p value for A) Fort Benning uniform plots, B) Camp Lejeune uniform plots, C) Fort Benning gap plots, and D) Camp Lejeune gap plots.

A) Fort Benning - uniform consumption

Dependent	Intercept	Variable1	Variable2	Variable3	Variable4	Variable5	Variable6	r^2	p value
DURAMB		No realtionship						n/a	n/a
DUR60	54.058	+ 15.848 D10HR	+ 1.528 DGR	+ 0.916 DPNDL				0.2320	0.0017
DURMAX (LOG10)	1.118	- 0.007 DGR						0.1071	0.0101
AREAAMB	19726.000	+ 2808.237 D10HR	+ 150.828 DGR					0.1483	0.0095
AREA60 (SQRT)	50.696	+ 1.329 DGR	+ 0.716 DPNDL					0.2423	0.0003
MAXT	99.448	+ 1.882 DGR						0.2955	<0.0001
BURNED	51.691	+ 0.609 DGR	+ 0.412 DPNDL	- 0.482 DBARE				0.3188	<0.0001

B) Camp Lejeune - uniform consumption

Dependent	Intercept	Variable1	Variable2	Variable3	Variable4	Variable5	Variable6	r^2	p value
DURAMB	454.525	- 556.375 D1HR	- 25.349 D10HR					0.2476	0.0161
DUR60 (SQRT)	4.353	- 0.862 D100HR						0.2111	0.0065
DURMAX (LOG10)		No relationship						n/a	n/a
AREAAMB (LOG10)	4.090	+ 0.051 DLITT						0.1868	0.0376
AREA60 (SQRT)	44.635	- 8.026 D100HR						0.0946	0.0171
MAXT (LOG10)	1.859	- 0.057 D10HR	- 0.041 D100HR					0.2631	0.0139
BURNED	19.304	- 63.576 D1HR	+ 2.412 D100HR	+ 5.084 DLITT	+ 0.408 DGR	+ 0.645 DPNDL	- 1.573 DBARE	0.6716	<0.0001

C) Fort Benning - gap consumption

Dependent	Intercept	Variable1	Variable2	Variable3	Variable4	Variable5	Variable6	r^2	p value
DURAMB (SQRT)		No relationship						n/a	n/a
DUR60 (LOG10)	1.926	+ 0.092 DLITT	+ 0.009 DBARE					0.2805	0.0004
DURMAX (SQRT)		No relationship						n/a	n/a
AREAAMB (LOG10)	4.161	+ 0.065 DLITT						0.0748	0.0433
AREA60 (LOG10)	3.830	+ 0.161 DLITT	- 0.003 DPNDL	+ 0.011 DBARE				0.3511	0.0002
MAXT (LOG10)	1.903	+ 0.075 DLITT						0.1418	0.0046
BURNED	64.831	+ 7.396 DLITT	- 0.392 DBARE					0.3341	<0.0001

D) Camp Lejeune - consumption

Dependent	Intercept	Variable1	Variable2	Variable3	Variable4	Variable5	Variable6	r^2	p value
DURAMB (LOG10)	-2.375	- 0.025 D100HR	+ 0.004 DLITT					0.5340	0.0150
DUR60	0.001	+ 0.001 D1HR	- 0.0004 D10HR	+ 0.0001 D100HR	- 0.0004 DLITT	- 0.00001 DPNDL	- 0.00027 DBARE	0.9204	0.0016
DURMAX	0.0004	- 0.00001 DPNDL	+ 0.00012 DBARE					0.6606	0.0026
AREAAMB (LOG10)	4.017	+ 0.286 D1HR	- 0.078 D10HR	- 0.118 DLITT	+ 0.006 DPNDL	- 0.094 DBARE		0.8044	0.0102
AREA60	7315.976	+ 10028 D1HR	- 3306.444 D10HR	+ 878.156 D100HR	- 2428.470 DLITT	- 87.877 DGR	- 1835.323 DBARE	0.8684	0.0082
MAXT	65.393	- 10.381 D10HR	- 13.013 DBARE					0.5871	0.0077
BURNED	40.385	+ 16.578 DLITT	+ 0.895 DGR					0.6986	<0.0001

D1HR, difference of pre-post 1hr fuel; D10HR, difference of pre-post 10hr fuel; D100HR, difference of pre-post 100hr fuel; DLITT, difference of pre-post litter depth; DGR, difference of pre-post grass cover; DPNDL, difference of pre-post pine needle cover; DBARE, difference of pre-post bare ground cover DURAMB, duration of burn above ambient temperature; DUR60, duration of burn above 60 °C; DURMAX, duration of burn at maximum temperature; AREAAMB, area under time-temperature curve above ambient temperature; AREA60, area under time-temperature curve above 60 °C; MAXT, maximum temperature; BURNED, burned cove combinations and fire behavior metric models in the Camp Lejeune gap plots had high r^2 values (all above 0.5; Table 3.9.6). For example, the combination of D1HR, D10HR, D100HR, DLITT, DPNDL, and DBARE was a strong predictor of DUR60 (r^2 = 0.9204; Table 3.9.5). DLITT was in virtually all of the fuel consumption variable combinations that were strong predictors of various fire behavior metrics (Table 3.9.6).

3.9.4. Discussion

In general Camp Lejeune had a greater pre-fire 1-hour fuel load than at Fort Benning. We hypothesize that this difference resulted from contrasting management and burn histories, and most directly from the prescribed fires applied as part of the site preparation for the study. Fort Benning blocks had a history of frequent fire, and thus had a component of fine fuels derived from small woody and herbaceous vegetation. Further, the sites had been treated with herbicide, producing a well aerated woody fuel component. The mix of aerated woody fuels and abundant fine fuels facilitated fuel consumption during site preparation. In contrast, half of the Camp Lejeune blocks (Blocks 5-8) had not been burned recently, because they were not high priority burn areas during the years preceding the study and Blocks 1-4 had burned infrequently (Daniel Becker, personal communication). The absence of burning resulted in a component of larger hardwoods unevenly distributed in the sites, and a lack of uniformly distributed finer shrubby and herbaceous components typically found in more frequently burned areas. The mulching site preparation effectively reduced the larger woody fuels to a layer of mulch on all of the study blocks, producing a fuel that is comparatively compressed but not spatially uniformly distributed. Although a mix of such compressed fuels without homogenously distributed 1-hour fuels may have been consumed during the site preparation burns if burned under ideal conditions, the fire staff was forced to burn the sites under less than ideal conditions. They used all the available windows of acceptable fire weather in the midst of a general ban on burning to burn all but Block 8 before planting. Consequently, the burns were patchy, and even the available fine fuels were not fully consumed throughout much of the area during the site preparation for this study. Additionally, the mulching site preparation stimulated basal sprouting of hardwoods and shrubs, contributing a new source of abundant fine fuels. Thus, the abundance of pre-fire 1-hour fuels at Camp Lejeune resulted from the failure to consume fuels in the site preparation burns, and the continued accumulation of fuels from re-sprouting hardwoods and shrubs after mulching. According to Mitchell et al. (2009), postponing the reintroduction of fire for just 2 -3 years after a disturbance (such as harvesting) can result in increased available fuel as small stems decay and other fine fuels continue to accumulate, as observed at Camp Lejeune.

Greater duff depths at Camp Lejeune were likely related to burn history. Since frequently burned ecosystems have little to no forest floor accumulation and low fuel loads (Varner et al. 2005), lack of frequent fires and/or fires of low intensity would allow duff to accumulate. An accumulation of duff may have important implications for mortality of overstory pines and for understory diversity. When a forest floor develops in fire-adapted ecosystems, it forms an uncharacteristic fuel source that fine roots can colonize (Varner et al. 2005). When fire is reintroduced, the forest floor is typically consumed which often results in significant delayed overstory mortality (Sullivan et al. 2003, O'Brien et al. 2010). O'Brien et al. (2010) further hypothesized that root loss from forest floor consumption hinders water conduction and initiates a decline in health that ultimately results in tree mortality. Reduced understory diversity associated with the development of a woody midstory are other consequences of reduced fire frequency (Glitzenstein et al. 2003). Although such changes in ground layer vegetation are often attributed to light interception by the midstory (Provencher et al. 2001), Hiers et al. (2007) reported that a loss of understory diversity was associated with forest floor accumulation, which can create physical and chemical barriers to understory plant growth.

At Fort Benning and at Camp Lejeune, percent cover of graminoids, pine needles, bare ground, and area burned displayed similar trends that appear to be associated with canopy cover. Graminoid cover and bare ground cover increased with increasing canopy removal in the uniform treatments and increased from within the forest to the gap center in the gaps. Previous studies have noted that canopy gaps increase resource and light availability to understory plants (McGuire et al. 2001, Battaglia et al. 2003) simultaneously reducing fine fuel loads and leading to decreased fire intensity and frequency (O'Brien et al. 2008). O'Brien et al. (2008) suggest that even though grasses increase in the ground layer with increased resource availability, they are often insufficient (especially in the absence of pine needle input) to carry fire across areas when mixed with less flammable vegetation. We generally observed a decrease in percent area burned with greater canopy removal in the uniform treatments; in the gap treatments percent area burned was greatest within the forest and gradually decreased toward the gap centers. The graminoid communities in our study plots were largely dominated by bluestems and rosette grasses (*Dichanthelium* spp.). Wiregrass, the characteristic species of longleaf pine ecosystems, does not naturally occur at Fort Benning and was not present on the Camp Lejeune sites. Therefore, the species composition of the ground layer, particularly regarding graminoids, may be important to fuel bed continuity, fire behavior, and fire effects and should be further investigated.

In contrast to graminoid cover, pine needle cover tended to increase with decreasing canopy removal in the uniform treatments and with proximity to the forest edge. Pine litter plays a critical role in fire-dependent ecosystems by carrying fire especially across areas without vegetation (such as rock or bare ground) and across areas with less flammable vegetation (O'Brien et al. 2008). This role may be even more vital in areas that are in the process of being restored to a fire adapted community where the pyrogenic graminoids typically found in longleaf systems are not yet substantially present in the ground layer. Results from both study locations and from both uniform and gap treatments suggest that pine needle cover influences percent area burned. In general, we observed an increase in percent area burned as pine needle cover increased and canopy cover increased. Previous studies have reported that fire intensity increases with increased pine fuel loads (Grace and Platt 1995, Gilliam et al. 2006, Thaxton and Platt 2006). Grace and Platt (1995) found that fire temperature was strongly related to needle density; hotter fire temperatures occurred in areas with high pine needle accumulation. Thaxton and Platt (2006) reported that addition of longleaf needles in their experimental plots increased consumption by >100% and mean maximum temperature by 300-400°C.

The interaction of canopy density, ground cover vegetation, and pine needle cover could have implications for longleaf seedling survival. Gilliam et al. (2006) noted that fire intensity increases in areas with high densities of needles (such as areas with greater canopy density), which can cause seedling mortality and lower seedling recruitment. Conversely, open areas with increased ground layer growth and lower densities of pine needles may improve natural seedling recruitment. Gap size is also an important determinant of fine fuel continuity. Gaps must be small enough to ensure that there is sufficient fine fuel to carry low intensity fire through the area. However, they need to be large enough to allow light and nutrients to reach developing longleaf seedlings allowing the seedlings to attain a fire-tolerant height more quickly (O'Brien et al. 2008).

The prescribed fires measured with logger-probes in this study were heterogeneous, but generally low-intensity. As a comparison, Kennard et al. (2005) reported a mean maximum temperature of 166°C (SD 93.3°C) from thermocouple logger-probes deployed in a longleaf pine forest in the southeastern US. Grace and Platt (1995) reported maximum fire temperatures of > 342°C in over 50% of their longleaf plots in southern Georgia. The mean maximum temperature for both of our study locations combined was 118.6°C (SD 62.6°C). The time-temperature curves recorded by logger-probes in our study plots reflect this variability. The north, south, and west transects of the large gap in block 6 at Fort Benning, for instance, showed the highest temperatures in locations closest to the forest, supporting the idea that, in areas where canopy density is greater (and presumably needle fall higher), fires burn hotter. However, the east transect exhibited the opposite trend with the highest temperature closest to the gap centers and the lowest closest to the forest. Several factors could contribute to this variability. Fuels and fire behavior are highly variable at fine and large scales. Hiers et al. (2009) used a novel approach with ground-based LIDAR and digital infrared thermography to characterize small-scale variation in fuels and fire in longleaf systems. They found that fuels and fire behavior showed considerable heterogeneity at scales < 1 m. Even at these small scales, a wide variety of fuel types ranging from pine litter, grasses, and shrubs to bare ground and coarse woody debris was present. Not only are fuels highly variable, but environmental conditions such as wind patterns, moisture levels, and topography also vary considerably at both temporal and spatial scales. These factors illustrate the difficulty of capturing fuels and fire behavior data at the multitude of scales needed to guide conservation and prescribed fire management programs.

3.9.5. Restoration implications

Understanding the implications of restoration on fuels and fire behavior requires consideration of all levels of stand structure: the overstory, midstory, and understory, as well as the ecological process that drive the development of each. Overstory structure impacts fine fuel amounts and distribution, as well as subsequent fire effects (Gilliam et al. 2006, Mitchell et al. 2006, O'Brien et al. 2008). Results from our study support the idea that pine needles are an important fuel source for fire continuity in southern pine forests. Therefore, harvesting treatments that allow for the retention of some canopy pines will be necessary to provide a continuous source of fine fuels. Canopy gaps facilitate increased resource availability to longleaf pine seedlings, and fuel dynamics in gaps mediate fire intensity through ground cover development and lowered pine needle density. Although similarities in the pattern of fuel loading and fire effects exist at both study locations (burned area increased with pine needle cover, for example), each location has different site legacies that impact management decisions and silvicultural recommendations. At Camp Lejeune, for instance, it may be important to ensure that prescribed fire is applied regularly and uniformly to areas that are in the process of being restored to longleaf pine as well as to areas that are being considered for restoration. Woody vegetation control will be necessary in both locations to remove competition from longleaf pine seedlings and from the herbaceous ground layer. However, the method of shrub control must also be considered carefully as mechanical and chemical methods may hinder ecological goals of restoring the floral diversity of areas targeted for restoration (Kirkman et al. 2007). Prescribed fire applied as frequently as the fuels will allow has been proposed as a strategy for maintaining a diverse understory and controlling midstory woody encroachment (Brockway and Lewis 1997, Glitzenstein et al. 2003, Hiers et al. 2007). Prescribed fire, midstory control, and variable canopy removal will all contribute to the complex interactions of light and resource availability, fine fuel accumulation, and species richness and composition necessary to restore longleaf pine ecosystems.

3.10. Contrasting longleaf pine restoration outcomes at ecologically distinct study locations

This section focuses on a comparison between forest responses at Fort Benning and Camp Lejeune. It identifies factors related to locational differences, as well as results that were similar between sites.

3.10.1 Introduction

Given the ecological, cultural, and economic value of longleaf pine in the southeastern United States, the widespread loss of high-quality longleaf pine ecosystems in the time since European settlement has resulted in current interest in longleaf pine restoration and conservation management. Management objectives for longleaf pine restoration often include increasing or conserving floristic diversity, creating high-quality wildlife habitat for species such as the red-cockaded woodpecker, gopher tortoise, or other longleaf pine associates, creating recreational opportunities such as quail hunting, and managing timber. As a result, restoration targets generally include establishing the characteristic two-layer structure of longleaf pine stands, shifting composition to diverse, herbaceous vegetation in the ground-layer, and perpetuating the ecosystem through fire management, each of which contributes to restoring ecosystem structure and function (Brockway et al. 2005).

A recent survey of landowners disseminated by The Longleaf Alliance indicates that longleaf pine restoration is occurring throughout the extensive longleaf pine range (Lavoie et al. 2011), which historically occupied approximately 37 million hectares within nine states in the southeastern United States (Frost 2006). In addition to occurring over an extensive geographical area, longleaf pine was also a dominant species across a wide range of site types, from hydric flatwoods of the Atlantic coastal plain to xeric sandhills. There are six ecoregions commonly used to describe the longleaf pine range, and Peet (2006) describes 135 vegetation associations of longleaf pine ecosystems. The wide ecological amplitude of longleaf pine suggests that current restoration efforts are likely occurring across a range of ecological conditions.

Management prescriptions for longleaf pine restoration have been informed and refined by extensive research on longleaf pine ecosystem dynamics and operational practices used to elicit specific responses, as well as extensive experience of forest management professionals. However, the majority of past studies, especially those of an experimental nature, were conducted at single study locations, and it is not clear if the results from these individual studies are transferrable to other site types or stand conditions. Because the vegetation associations, ecological conditions, and legacies of past land use vary across the longleaf pine range, it is likely that ecosystem responses to restoration treatments would likewise vary. For example, Glitzenstein et al. (2003) found that the response of the vegetation community to fire frequency treatments differed between South Carolina and Florida flatwoods sites. Moreover, their findings contrasted those of Beckage and Stout (2000), who suggested that sandhill communities may be less sensitive to changes in fire frequency than flatwoods. In another example, Haywood (2005) found that the growth response of planted longleaf pine seedlings differently following release on two sites that differed in vegetation communities at the study initiation. Such examples suggest that more information is required to understand which ecological responses to longleaf pine restoration may be generalized across site types and which responses may be more localized. This study was designed to compare the responses of different ecosystem components to similar longleaf pine restoration treatments applied at two ecologically distinct study sites within the longleaf pine range. Specifically, our objectives were to: 1) determine if canopy treatments and cultural treatments affected longleaf pine seedling mortality and growth similarly between sites; 2) determine if patterns of longleaf pine seedlings mortality and growth across canopy gaps differed between study sites; 3) determine if canopy treatments and cultural treatments affected ground layer vegetation cover and mid-story stem density similarly between sites; and 4) determine if canopy treatments and cultural treatments affected light and soil moisture similarly between sites.

3.10.2. Methods

See Section 3.1 for details on study sites, experimental design, and treatment installation.

3.10.2.1. Data collection

The data collection methods for this study have been described in previous chapters and more detail can be found in those respective sections.

In June 2008, we selected a sub-sample of longleaf pine seedlings in each split-plot, and we permanently marked each seedling with an aluminum tag for repeated measurements. In uniform canopy plots (Control, MedBA, LowBA, and Clearcut), we randomly selected a sample of 30 seedlings (approximately half of the seedlings planted in each 20 x 20 m measurement area), and in gap plots we tagged every seedling that occurred on each split-plot measurement row, extending 20 m into the forest on either end. Therefore, the total number of seedlings marked in each gap varied with gap size.

We monitored seedling survival at the end of the first, second, third, and fifth growing seasons after planting (October 2008, 2009, 2010, and 2012). Root collar diameter (RCD) of each seedling was measured at two perpendicular axes with digital calipers, and the average of the two measurements was calculated to account for irregularity in RCD shape. Seedling height was measured as the distance from the root collar to the tip of the terminal bud. Because all seedlings were in the grass stage in 2008, seedling heights were measured only in 2009, 2010, and 2012. We determined seedlings to be in height growth if seedling height was ≥ 15 cm. In addition, five seedlings were systematically selected from each split-plot for measurements of resource availability and overstory competition (see Section 3.8). We determined the overstory basal area surrounding each seedling by measuring the diameter at breast height of each tree within a 15 m radius of the selected seedlings.

The abundance of ground layer vegetation was described by recording cover values of all vegetation < 1 m tall. Only uniform main-plot treatments were included in these analyses because the application of split-plot treatments differed between uniform and gap plots. In each split-plot experimental unit, we established two parallel 20 m transects, and the percent cover of ground layer vegetation was recorded in ten 1 m^2 quadrats located randomly along each transect.

We estimated cover by functional group (graminoids, ferns, forbs, woody shrubs/trees, and woody vines), and cover was recorded using the following cover classes: 1 = trace, 2 = 0-1%, 3 = 1-2%, 4 = 2-5%, 5 = 5-10%, 6 = 10-25%, 7 = 25-50%, 8 = 50-75%, 9 = 75-95%, and 10 = 95-100%.

The number of woody stems in the mid-story (> 1 m tall but < 10 cm DBH) was counted within a 2 m belt transect centered on each vegetation transect. All woody stems were tallied by species. More information on the data collection methods can be found in Section 3.4.

We used the five seedlings selected in each uniform split-plot as locations to quantify light and soil moisture levels. Two of the five seedlings were selected for measuring the light environment, and we took one hemispherical photograph 1.4 m directly above each selected seedling, using a Nikon Coolpix 4500 digital camera equipped with a 180° fish-eye lens and mounted on a self-leveling tripod. The lens was adjusted to be parallel to the horizon and oriented such that north was marked on the photograph. To prevent glare and the reflection of light off the foliage, all hemispherical photographs were taken at dawn, dusk, or uniformly cloudy days when the sun was not directly in the image. Adjacent to each of the five selected seedlings in each split-plot, volumetric soil moisture was measured in the upper 6 cm using a ML2 ThetaProbe moisture meter (Delta-T Devices, Ltd.). We took readings of soil moisture directly east and directly west of each selected seedling. All readings within a block were recorded within two hours to maintain consistent ambient conditions, and no readings were recorded within 24 hours of a precipitation event.

3.10.2.2. Data analyses

Split-plot means were calculated for seedling variables (longleaf pine seedling mortality, root collar diameter, seedling height, the percentage of seedlings in height growth, the number of seedlings in height growth per hectare), ground layer vegetation cover (total vegetation cover, herbaceous vegetation cover, woody vegetation cover), mid-story stem density (total mid-story stems, loblolly pine stems, and hardwood stems including shrubs > 1 m tall), and resource availability (gap light index (see Section 3.7) and volumetric soil moisture). The number of seedlings in height growth per hectare was calculated as the product of the number of seedlings planted per hectare, percent survival, and percentage of remaining seedlings in height growth. We used Mixed Model ANOVA in a split-plot randomized block design to test the effects of site, main-plot treatment, split-plot treatment, and all interactions on each dependent variable.

For the gap plots, we calculated mean values by gap position on 10 m intervals along the N/S axis of each gap size, extending 10 m into the forest on either end for seedling morality (2008 and 2012) and seedling root collar diameter (2012). We used Mixed Model ANOVA in a split-plot randomized block design to test the effects of site and gap position for each gap size separately. For each model, block was a random effect that was nested within site. We used the Satterthwaite approximation to calculate degrees of freedom, and pairwise comparisons were determined using Tukey’s honestly significant test.

The five target seedlings identified in each split-plot were used to determine the probability of longleaf pine seedlings being in height growth after five growing seasons. We used logistic regression to model the probability of beginning height growth in 2012 based on canopy basal area within a 15 m radius (BA), site, split-plot treatment, and the interaction of site and split-plot treatment.

3.10.3. Results

3.10.3.1. Longleaf pine seedling mortality

First-year seedling mortality was significantly different between Fort Benning (29.3% mortality) and Camp Lejeune (9.3% mortality), and there was a significant interaction between site and main-plot treatment effects (Table 3.10.1). In the first year after planting, longleaf pine seedling mortality was significantly greater at Fort Benning than at Camp Lejeune on Clearcut, LowBA, LG, SG, and MG plots but was not different on Control or MedBA plots (Figure 3.10.1). At Fort Benning, first-year mortality increased with canopy removal, but there was no treatment effect at Camp Lejeune. There was no effect of the split-plot treatment (not applied in 2008) or any other interaction effects on mortality in 2008. After five growing seasons, the only significant effect in the model was a site*main-plot interaction (Table 3.10.1), with no significant treatment effect at Fort Benning but lower mortality in Clearcut plots than in MG plots at Camp Lejeune. In 2012, mortality was significantly higher at Fort Benning than at Camp Lejeune in Clearcut plots only (Figure 3.10.1).

There was a significant interaction between site and gap position for 2008 mortality in LG plots ($p < 0.0001$) and MG plots ($p = 0.0011$) but not in SG plots ($p = 0.0756$). At Fort Benning, first-year mortality increased from the forest edge to gap center in LG and SG plots, but the opposite trend was observed in LG plots at Camp Lejeune (Figure 3.10.2). As a result, mortality was significantly higher in gap interiors of LG and MG plots at Fort Benning compared to Camp Lejeune. There was no effect of gap position on mortality in SG plots. After five growing seasons, there was a significant interaction effect between site and gap position on seedling mortality, with mortality remaining higher in the gap interior at Fort Benning but no effect of position at Camp Lejeune (Figure 3.10.2). There was no interaction in MG or SG plots; in MG plots, mortality did not differ by gap position but there was a slight increase in mortality in the gap interior in SG plots.

3.10.3.2. Longleaf pine seedling growth

After five growing seasons, root collar diameter was not significantly affected by site, but there were significant interactions between site and main-plot treatment and site and split-plot treatment (Table 3.10.1). Root collar diameter was larger at Fort Benning than at Camp Lejeune on Clearcut plots only (Figure 3.10.3). At both sites, Clearcut plots had significantly larger root collar diameters than Control plots, and at Camp Lejeune there were no other treatment differences. At Fort Benning, Clearcut plots had larger root collar diameters than all other treatments other than SG, and Control plots had smaller root collar diameters than all treatments other than MedBA and LG plots. Among the split-plot treatments, there were no significant differences in seedling sizes between Fort Benning and Camp Lejeune (Figure 3.10.3b). At both sites, root collar diameter was larger on H plots than on NT plots, and at Camp Lejeune root collar diameter was also larger on H+F plots than on NT plots.

Table 3.10.1. Results from ANOVA testing the effect of study site, main-plot treatment (canopy manipulation), split-plot treatment (cultural treatment), and interactions on seedling mortality, root collar diameter, and mean height.

Variable	Year	Effect	Num DF	Den DF	F-value	p-value
Mortality	2008	site	1	11	22.8	0.0006
		main	6	65.1	10.44	<.0001
		site*main	6	65.1	10.43	<.0001
		split	2	152	0.43	0.6520
		site*split	2	152	0.55	0.5782
		main*split	12	152	1.17	0.3120
		site*main*split	12	152	1.09	0.3712
	2012	site	1	9.95	1.62	0.2318
		main	6	58.3	1.07	0.3885
		site*main	6	58.3	2.55	0.0292
		split	2	134	2.56	0.0814
		site*split	2	134	1.24	0.2933
		main*split	12	134	0.87	0.5776
		site*main*split	12	134	0.93	0.5240
Root collar Diameter	2012	site	1	9.78	0.7	0.4231
		main	6	57.6	15.64	<0.0001
		site*main	6	57.6	2.47	0.0343
		split	2	132	30.37	<0.0001
		site*split	2	132	4.6	0.0117
		main*split	12	132	1.39	0.1775
		site*main*split	12	132	1.1	0.3623
Total height	2012	site	1	9.91	0.37	0.5567
		main	6	57.2	25.54	<.0001
		site*main	6	57.2	3.87	0.0026
		split	2	132	23.66	<.0001
		site*split	2	132	4.8	0.0097
		main*split	12	132	0.81	0.6399
		site*main*split	12	132	0.98	0.4714

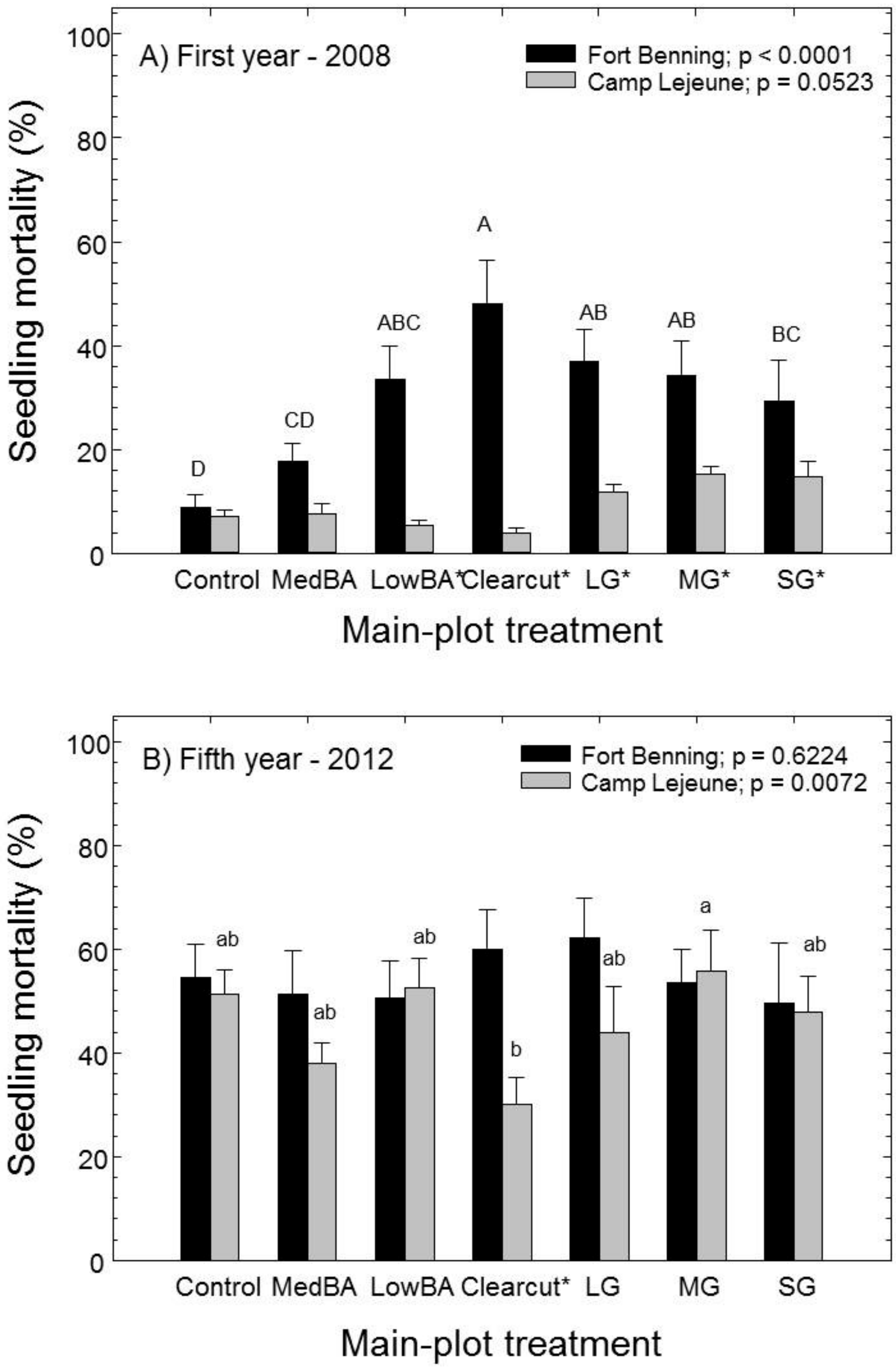


Figure 3.10.1. Mortality (mean + one standard error) at Fort Benning and Camp Lejeune after the A) first and B) fifth growing seasons, with an interaction in site*main-plot treatment. The same letter indicates within a site indicates no difference among main-plot treatments and '*' indicates a significant difference between sites within a treatment at $p = 0.05$.

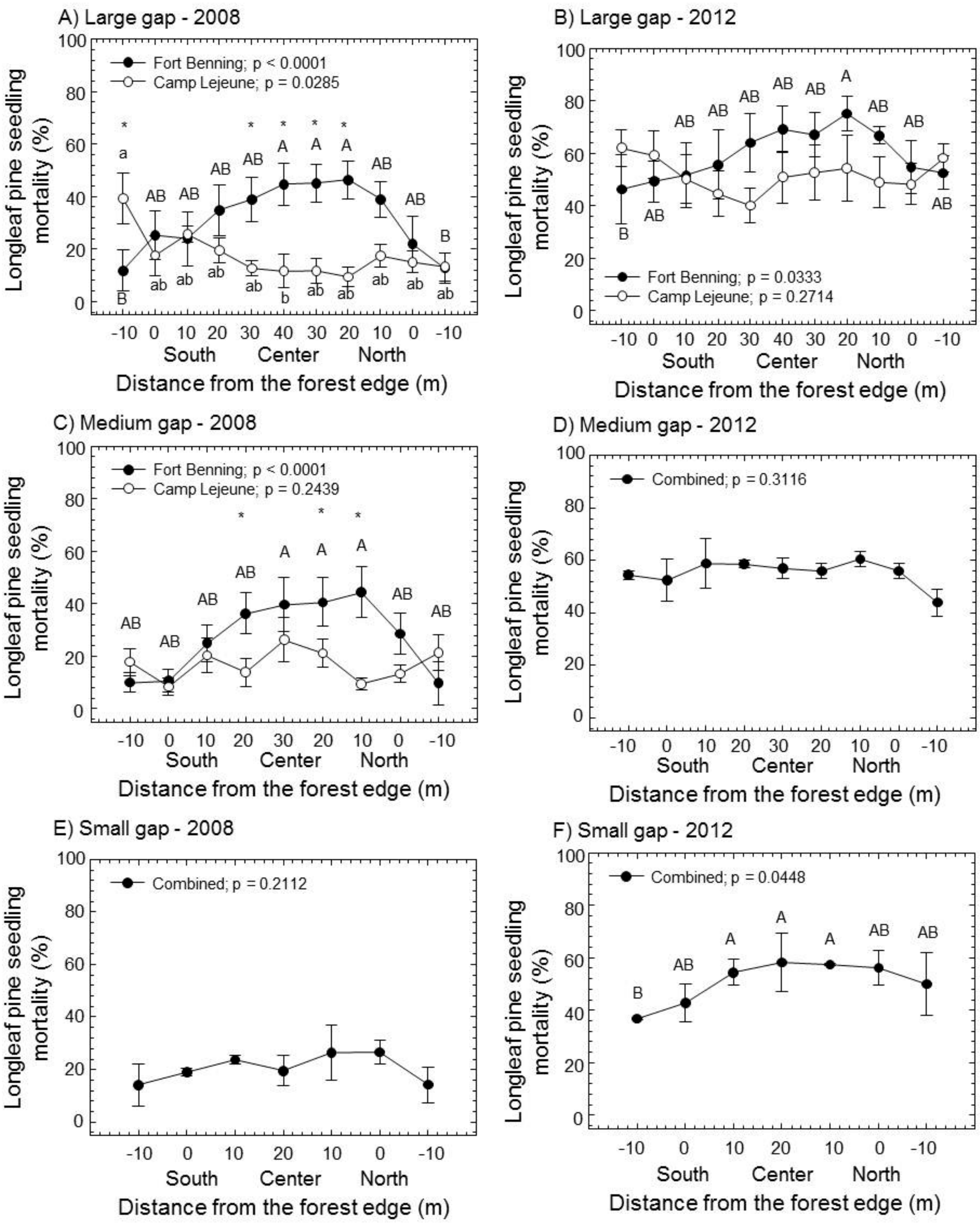


Figure 3.10.2. Longleaf pine seedling mortality by canopy gap position in 2008 (A, C, and E) and 2012 (B, D, and F). When interactions between site and position were present (A, B, and C) both sites are shown. The same letter indicates no significant difference within a site, and an '*' indicates significant differences between sites for a gap position.

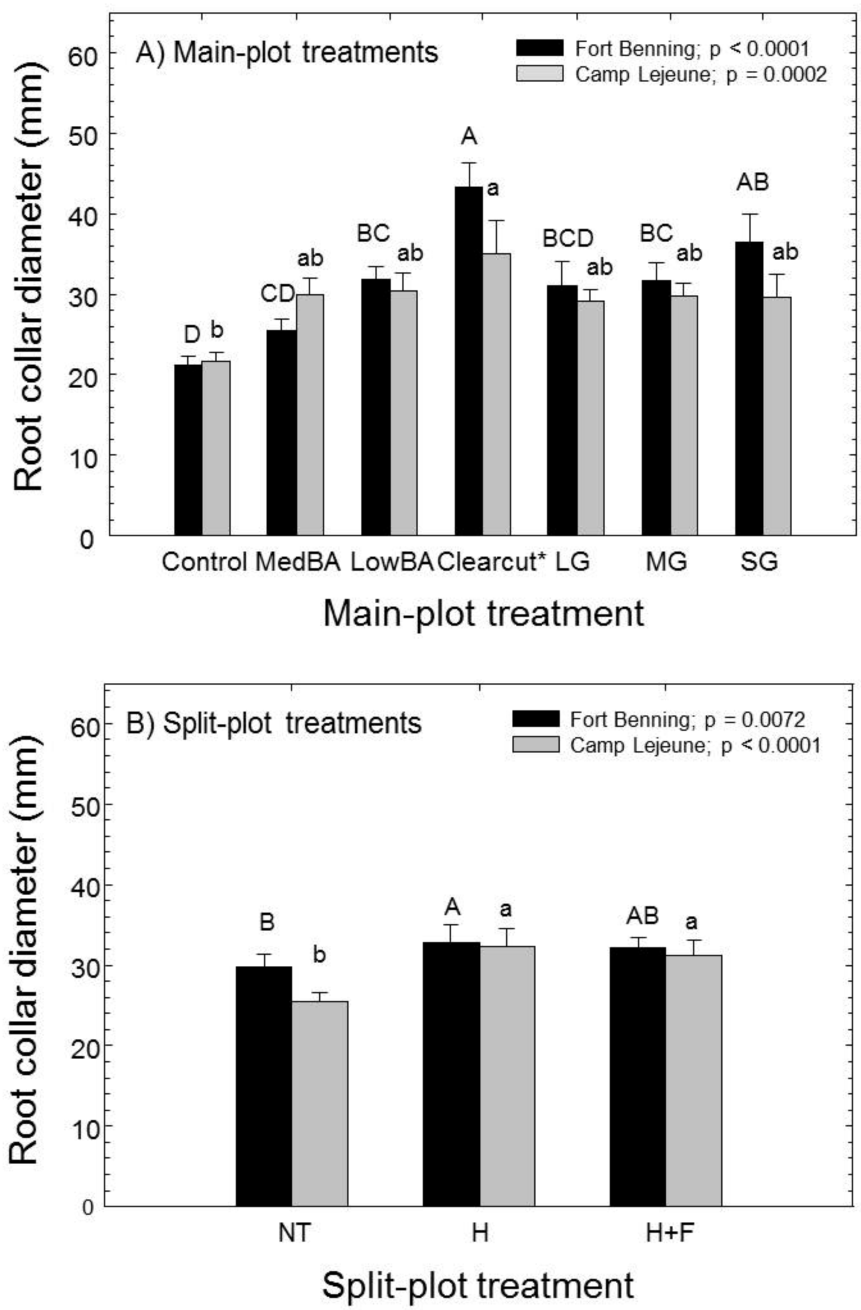


Figure 3.10.3. Root collar diameter (mean + one standard error) by A) main-plot treatment and B) split-plot treatment in 2012, with an interaction in site*main-plot treatment. The same letter indicates within a site indicates no difference among main-plot treatments and '*' indicates a significant difference between sites within a treatment at $p = 0.05$.

There were significant interactions between study site and gap position for LG plots (p = 0.0027), MG plots (p = 0.0460), and SG plots (p = 0.0107). At Camp Lejeune, root collar diameter was not affected by gap position in any of the gaps, but at Fort Benning root collar diameter was largest in the gap interior positions and significantly smaller beneath the intact canopy (Figure 3.10.4). However, root collar diameter did not differ among any interior gap position for any gap size at Fort Benning.

Results for mean seedling height were similar to that for root collar diameter, with significant interactions between site and main-plot treatments and between site and split-plot treatments. Seedlings at Fort Benning were larger on Clearcut plots than seedlings on Clearcut plots at Camp Lejeune (Figure 3.10.5). Seedlings were taller on split-plot treatments with herbicide (H and H+F) than on NT plots at Camp Lejeune, but only H and NT were significantly different at Fort Benning.

For both the percentage of living seedlings in height growth and the total number of seedlings in height growth in 2012, there were significant site*main-plot treatment effects and site*split-plot treatment effects (Table 3.10.2). At Fort Benning, 86% of the remaining seedlings were in height growth on Clearcut plots in 2012, compared to only 3% on Control plots. At Camp Lejeune, the percentage of seedlings in height growth on Clearcut plots (57%) was significantly lower than at Fort Benning (Table 3.10.3). The density of seedlings in height growth followed similar patterns, but incorporated survival and planting density into the final numbers of seedlings present. At both sites, Clearcut plots had significantly higher seedling densities than Control plots. At both sites, the NT split-plot treatment had significantly lower percentage of seedlings in height growth than the H and H+F plots. However, at Fort Benning, there was no effect of the split-plot treatment on the density of seedlings in height growth after five growing seasons (Table 3.10.4).

The logistic model determined that site and the site*split-plot treatment effects did not significantly affect the probability of seedlings in height growth after five growing seasons (p = 0.1766 and p = 0.8814, respectively). The probability of seedlings in height growth was around 0.2 with 12 m^2/ha and increased rapidly with a reduction in basal area (Figure 3.10.6). There was greater than 0.5 probability that seedlings would be in height growth after five growing seasons at basal areas below 5 m^2/ha. The split-plot treatments used in the study significantly affected the probability of seedlings in height growth after five growing seasons (p = 0.0457). At all levels of basal area, the probability was lower on NT treatment than on the H and H+F treatments. The highest probability of seedlings in height growth was in clearcut plots with the H split-plot treatment (Figure 3.10.6).

3.10.3.3. Cover of ground layer vegetation and mid-story stem density

There was no interaction between site and main-plot treatment effects on total vegetation cover after five growing seasons (Table 3.10.5). Total ground layer vegetation cover did not significantly differ between Fort Benning (36% cover) and Camp Lejeune (42%), but cover on Control plots was significantly lower than that on LowBA and Clearcut plots (Figure 3.10.7). There was a significant site*split-plot treatment effect, in which there was no effect of split-plot treatments at Fort Benning but higher total vegetation cover on NT plots than on H+F plots at Camp Lejeune (Figure 3.10.7). Herbaceous ground layer vegetation was not significantly

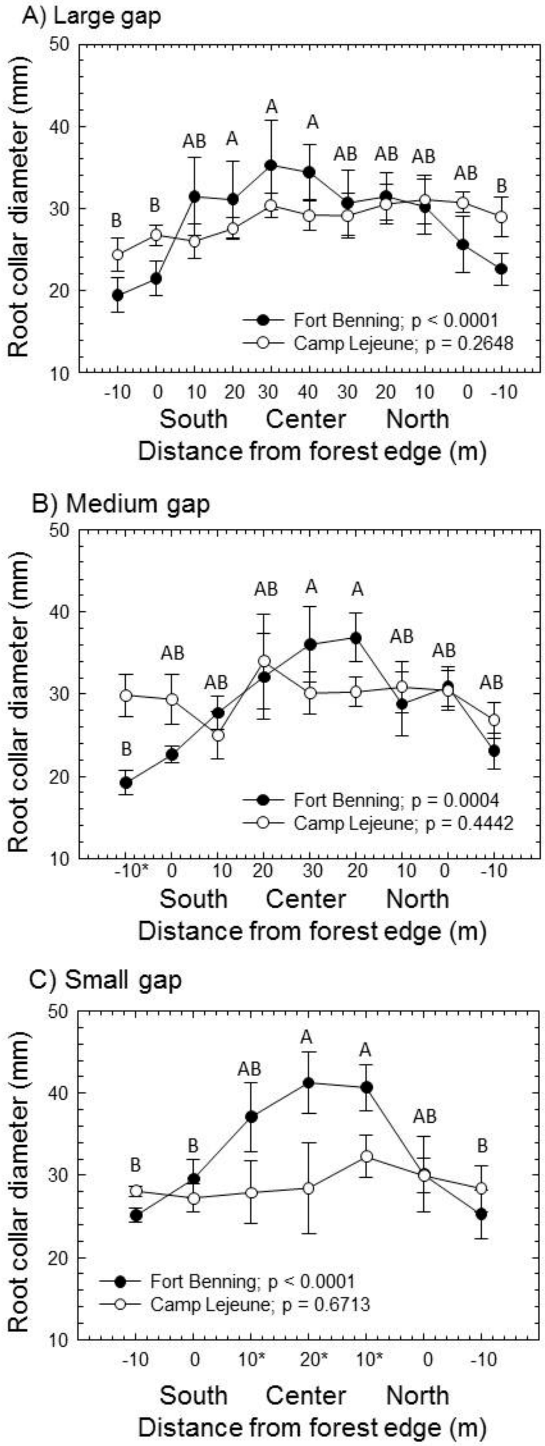


Figure 3.10.4. Longleaf pine seedling root collar diameter by canopy gap position in 2010 for A) LG plots, B) MG plots, and C) SG plots. Both sites are shown with interactions present. The same letter indicates no significant difference within a site, and an ‘*’ indicates significant differences between sites for a gap position.

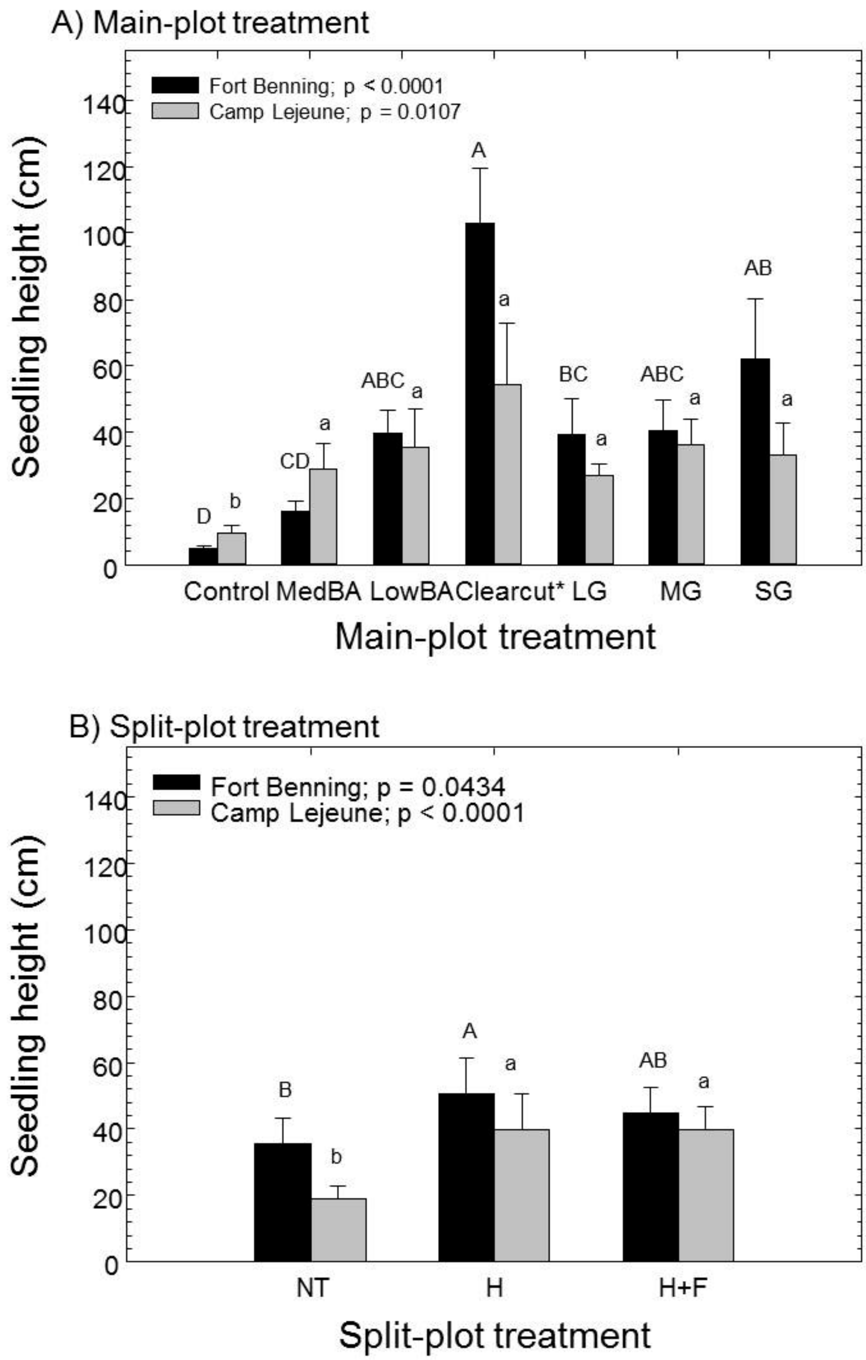


Figure 3.10.5. Seedling height (mean + one standard error) by A) main-plot treatment and B) split-plot treatment in 2012, with an interaction of each with site. The same letter indicates within a site indicates no difference among main-plot treatments and ‘*’ indicates a significant difference between sites within a treatment at $p = 0.05$.

Table 3.10.2. Results from ANOVA testing the effect of study site, main-plot treatment (canopy manipulation), split-plot treatment (cultural treatment), and interactions on the percentage of live seedlings in height growth and the total number of seedlings in height growth per hectare.

Variable	Year	Effect	Num DF	Den DF	F-value	p-value
Percentage of living seedlings in height growth	2012	site	1	9.89	0.77	0.4021
		main	6	57.5	21.35	<.0001
		site*main	6	57.5	4.57	0.0007
		split	2	134	22.7	<.0001
		site*split	2	134	4.36	0.0147
		main*split	12	134	0.41	0.9592
		site*main*split	12	134	0.48	0.9238
Seedlings in height growth (trees per acre)	2012	site	1	9.9	0.77	0.4023
		main	6	58	14.88	<.0001
		site*main	6	58	2.81	0.0179
		split	2	134	22.98	<.0001
		site*split	2	134	6.32	0.0024
		main*split	12	134	0.52	0.8990
		site*main*split	12	134	1.09	0.3762

Table 3.10.3. Means and standard errors of percentage of live seedlings in height growth in 2012 for the interaction of site and main-plot treatment. The same superscript letter indicates no significant difference within an effect at p = 0.05.

Percentage of living seedlings in height growth

		Site				
		Fort Benning		Camp Lejeune		
Effect	Level	Mean	*SE*	Mean	*SE*	**p-value**
Main-plot	Control	3.0^{d}	*2.0*	13.3^{b}	*5.1*	**0.3887**
	MedBA	23.0^{cd}	*5.9*	45.5^{a}	*9.7*	**0.0550**
	LowBA	61.7^{ab}	*7.2*	46.4^{a}	*9.8*	**0.1860**
	Clearcut	86.6^{a}	*4.9*	56.9^{a}	*8.8*	**0.0164**
	LG	50.8^{bc}	*14.2*	43.1^{a}	*2.5*	**0.7122**
	MG	54.8^{abc}	*5.5*	45.6^{a}	*6.3*	**0.4228**
	SG	65.4^{ab}	*11.1*	40.9^{ab}	*8.3*	**0.0384**
	p-value	**< 0.0001**		**< 0.0001**		
Split-plot	NT	43.4^{b}	*6.4*	28.5^{b}	*4.8*	**0.0955**
	H	51.9^{a}	*6.9*	47.2^{a}	*7.6*	**0.5439**
	H+F	52.6^{a}	*4.4*	52.1^{a}	*5.2*	**0.9721**
	p-value	**0.0412**		**< 0.0001**		

Table 3.10.4. Means and standard errors of total number of seedlings in height growth (per hectare) in 2012 for the interaction of site and main-plot treatment. The same superscript letter indicates no significant difference within an effect at p = 0.05.

Seedlings in height growth (tpa)

		Site				
		Fort Benning		Camp Lejeune		
Effect	Level	Mean	*SE*	Mean	*SE*	**p-value**
Main-plot	Control	26^{b}	*17*	130^{b}	*55*	**0.1688**
	MedBA	157^{ab}	*48*	543^{a}	*141*	**0.0215**
	LowBA	448^{a}	*93*	402^{a}	*100*	**0.6624**
	Clearcut	529^{a}	*113*	755^{a}	*151*	**0.3451**
	LG	329^{a}	*131*	451^{a}	*86*	**0.1724**
	MG	399^{a}	*88*	387^{ab}	*99*	**0.7064**
	SG	567^{a}	*179*	423^{a}	*111*	**0.4004**
	p-value	**< 0.0001**		**< 0.0001**		
Split-plot	NT	302	*84*	290^{b}	*62*	**0.8301**
	H	375	*94*	531^{a}	*101*	**0.2071**
	H+F	374	*80*	550^{a}	*78*	**0.1895**
	p-value	**0.0965**		**< 0.0001**		

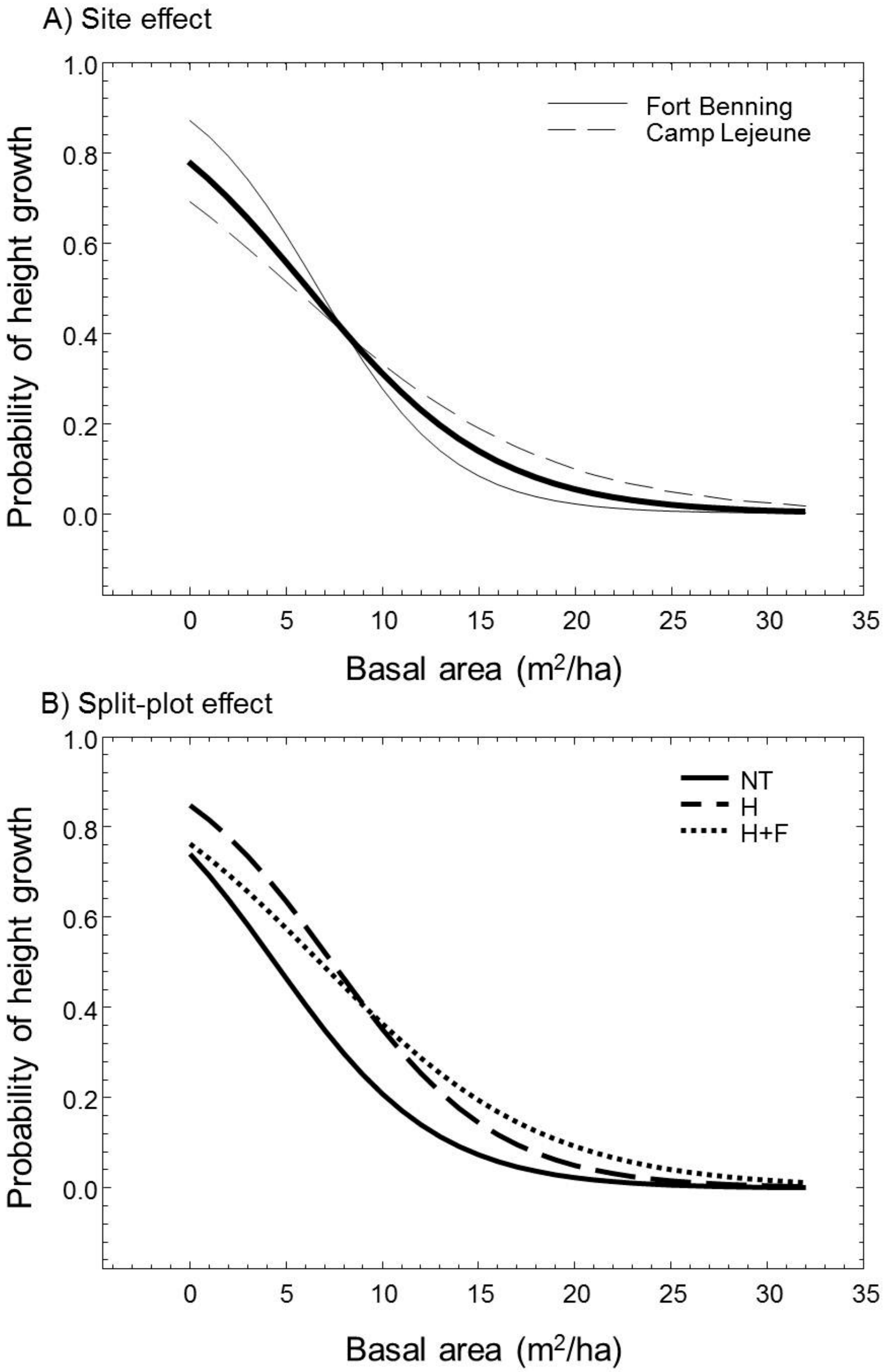


Figure 3.10.6. Probability of longleaf pine seedlings being in height growth in relation to basal area after five growing seasons as influenced by A) site and B) split-plot treatment.

Table 3.10.5. Results from ANOVA testing the effect of study site, main-plot treatment (canopy manipulation), split-plot treatment (cultural treatment), and interactions on total, herbaceous, and woody vegetation cover in the ground layer at Fort Benning and Camp Lejeune.

Variable	Year	Effect	Num DF	Den DF	F-value	p-value
Total vegetation	2012	site	1	10	0.66	0.4355
		main	3	29.2	5.37	0.0046
		site*main	3	29.2	2.28	0.1004
		split	2	78	2.78	0.0685
		site*split	2	78	5.88	0.0042
		main*split	6	78	2.20	0.0528
		site*main*split	6	78	1.21	0.3082
Herbaceous Vegetation	2012	site	1	10.1	3.42	0.0939
		main	3	29.2	2.79	0.0582
		site*main	3	29.2	2.83	0.0557
		split	2	78	3.57	0.0329
		site*split	2	78	3.33	0.0409
		main*split	6	78	0.83	0.5498
		site*main*split	6	78	2.00	0.0757
Woody Vegetation	2012	site	1	10	8.34	0.0379
		main	3	29.2	4.26	0.013
		site*main	3	29.2	1.83	0.1638
		split	2	78	10.34	0.0001
		site*split	2	78	19.15	<.0001
		main*split	6	78	1.95	0.0831
		site*main*split	6	78	0.91	0.4956

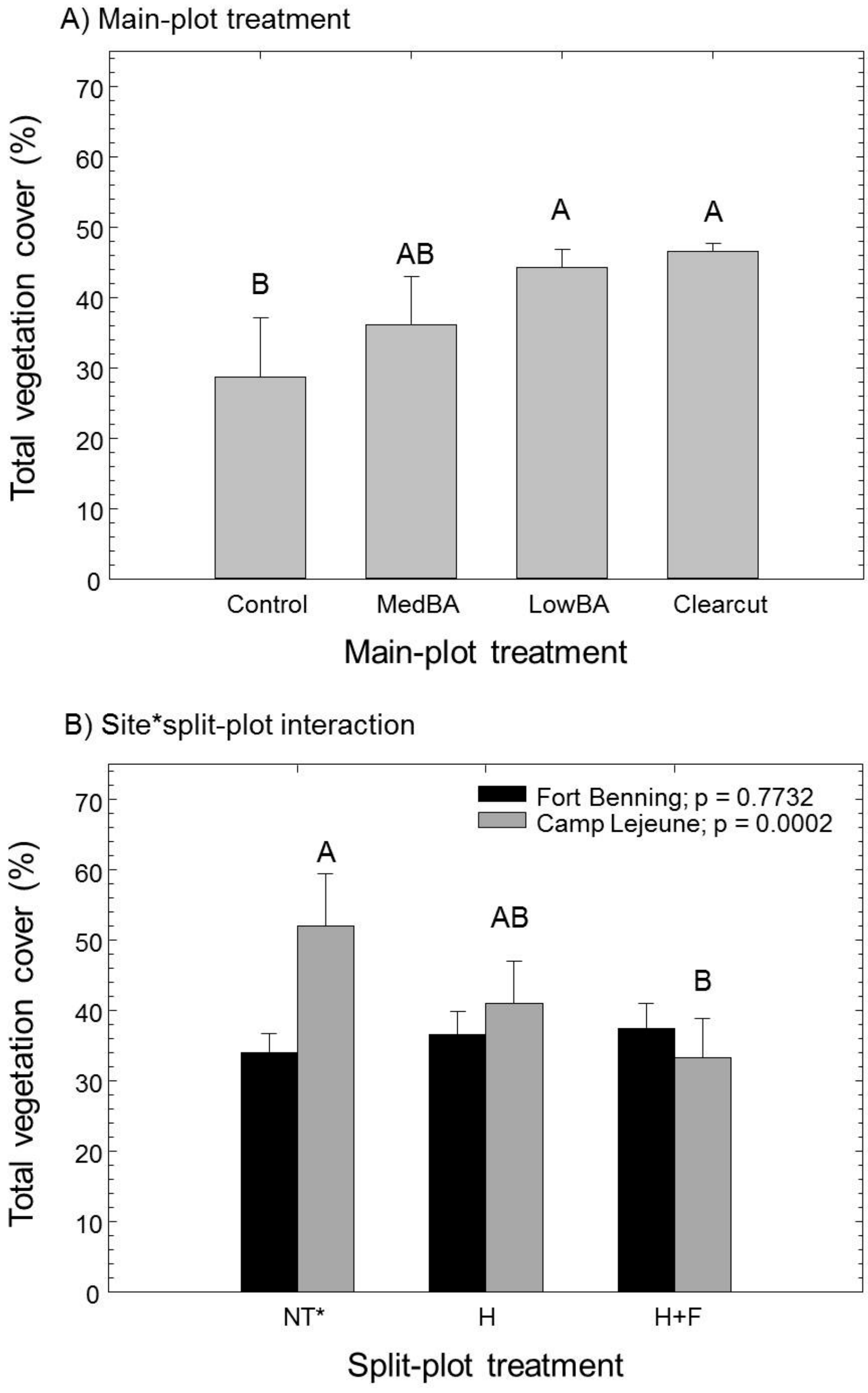


Figure 3.10.7. Total ground-layer vegetation cover (mean + one standard error) by A) main-plot treatment and B) split-plot treatment in 2012, with an interaction of site*split-plot treatment. The same letter indicates no difference among treatments, and '*' indicates a significant difference between sites within a split-plot treatment at $p = 0.05$.

affected by site or by main-plot treatment (Table 3.10.5). A significant site*split-plot treatment effect indicated that the split-plot treatments did not affect herbaceous cover at Fort Benning but resulted in significantly higher herbaceous vegetation cover on H plots than on NT plots at Camp Lejeune (Figure 3.10.8). Woody vegetation cover in the ground layer was higher at Camp Lejeune (26%) than at Fort Benning (14%) and was significantly affected by the main-plot treatments, with higher woody vegetation cover on Clearcut and LowBA plots than on Control plots (Figure 3.10.9). There was a significant site*split-plot treatment interaction (Table 3.10.5) in which split-plot treatments did not affect woody vegetation cover at Fort Benning, but at Camp Lejeune the NT plots had significantly greater woody cover than the H and H+F plots (Figure 3.10.9). On the NT split-plots, total vegetation cover and woody vegetation cover was greater at Camp Lejeune than at Fort Benning, but herbaceous cover on NT plots was greater at Fort Benning than at Camp Lejeune.

Total mid-story stem density was higher at Camp Lejeune (6,910 stems per hectare) than at Fort Benning (2,377 stems per hectare) after five growing seasons. There was no interaction between site and main-plot treatment (Table 3.10.6), with stem density on Clearcut plots higher than stem density on Control plots (Figure 3.10.10). There was no significant split-plot treatment effect on total mid-story stems at Fort Benning, but at Camp Lejeune the stem densities were higher on NT split-plots than on H or H+F split-plots (Figure 3.10.11). Patterns in hardwood stem densities were very similar to those for total stems, with higher density at Camp Lejeune (4,386 stems per hectare) than at Fort Benning (1,594 stems per hectare), increasing hardwood density with decreased canopy removal, and significantly higher stem densities on NT plots than H and H+F plots at Camp Lejeune (Figure 3.10.12). There were no interactions among any of the effects on pine stem density, which was also higher at Camp Lejeune (4,418 stems per hectare) than at Fort Benning (767 stems per hectare). At both sites, loblolly pine stem densities were higher on H and H+F plots than on NT plots.

3.10.3.4. Light and soil moisture

Gap light index was significantly different between Fort Benning (68.9%) and Camp Lejeune (64.1%), but there was a significant site*main-plot treatment interaction (Table 3.10.7). At both study sites, the gap light index at each treatment level was significantly different from that at all other treatment levels (Figure 3.10.13), but on Control and MedBA plots the light levels at Camp Lejeune exceeded those at Fort Benning, despite no difference in basal area between the study sites on Control plots ($p = 0.7550$; Fort Benning = 17.5 and Camp Lejeune = 17.2 m^2/ha) or on MedBA plots ($p = 0.0857$; Fort Benning = 10.1 and Camp Lejeune = 8.3 m^2/ha). There were no significant effects of any variable or interactions on soil moisture in 2008 or soil moisture in 2009 (Table 3.10.7).

3.10.4. Discussion

Forest vegetation dynamics are controlled by multiple interacting factors that include physical, biological, and anthropogenic drivers. The extensive range of longleaf pine occurs across a variety of site types within the southeastern region of the United States, and the physical and climatic characteristics of any given site greatly influence the vegetation communities that occur within (Peet 2006). Our study sites differ in ecoregion, with Fort Benning located within both the Fall-line Sandhills and the Eastern Gulf Coastal Plain and Camp Lejeune located within the

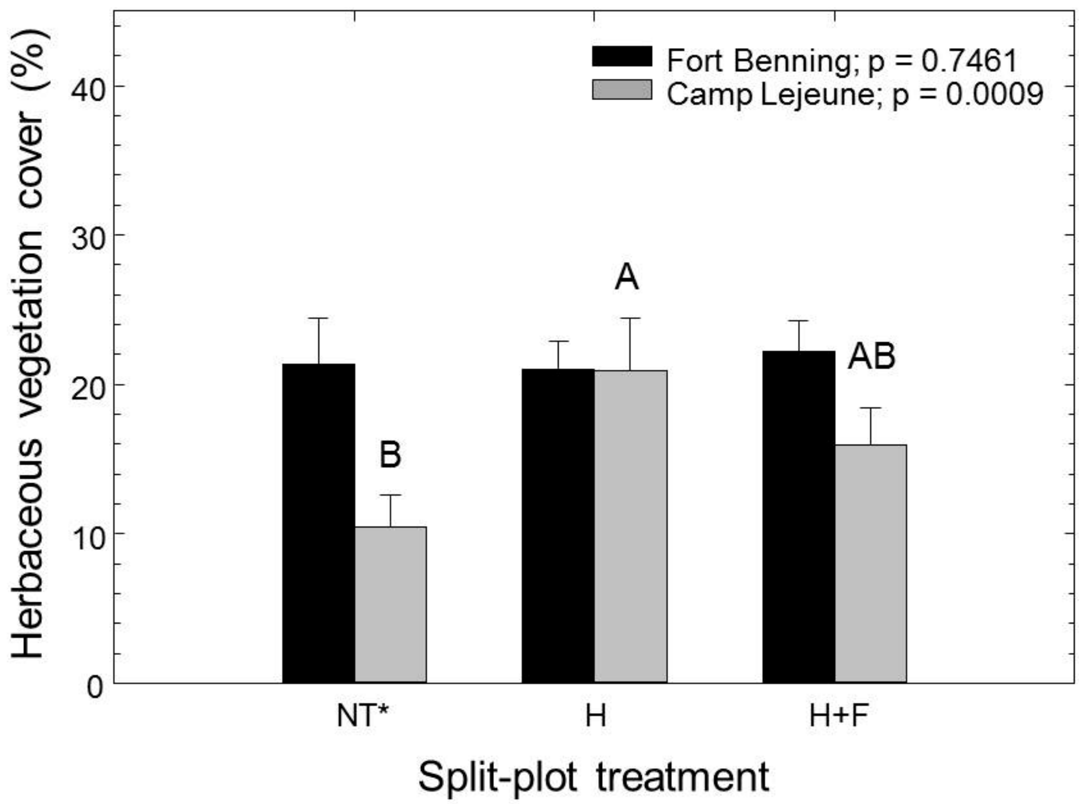


Figure 3.10.8. Herbaceous ground-layer vegetation cover (mean + one standard error) by split-plot treatment in 2012, with an interaction of site*split-plot treatment. The same letter indicates no difference among treatments, and ‘*’ indicates a significant difference between sites within a split-plot treatment at $p = 0.05$.

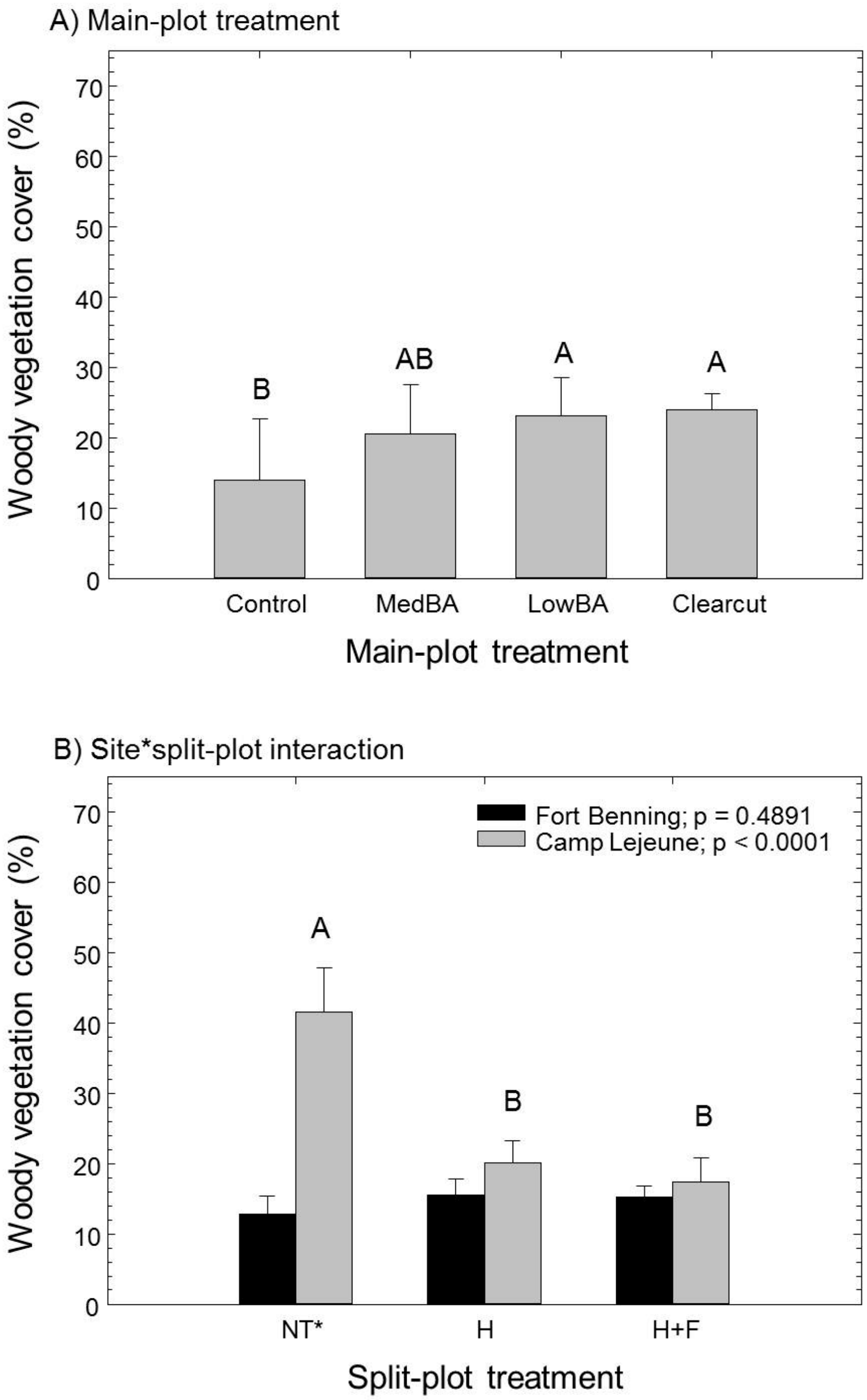


Figure 3.10.9. Woody ground-layer vegetation cover (mean + one standard error) by A) main-plot treatment and B) split-plot treatment in 2012, with an interaction of site*split-plot treatment. The same letter indicates no difference among treatments, and ‘*’ indicates a significant difference between sites within a split-plot treatment at $p = 0.05$.

Table 3.10.6. Results from ANOVA testing the effect of study site, main-plot treatment (canopy manipulation), split-plot treatment (cultural treatment), and interactions on total stem density, loblolly pine stem density, and hardwood stem density in the midstory at Fort Benning and Camp Lejeune

Variable	Year	Effect	Num DF	Den DF	F-value	p-value
Total stem density	2012	site	1	9.58	7.2	0.0238
		main	3	27.1	6.66	0.0016
		site*main	3	27.1	0.57	0.6425
		split	2	72.7	2.91	0.0608
		site*split	2	72.7	7.95	0.0008
		main*split	6	71.6	0.74	0.6198
		site*main*split	6	71.6	0.88	0.511
Loblolly pine stem density	2012	site	1	28	13.23	0.0011
		main	3	28	2.35	0.0936
		site*main	3	28	1.35	0.2796
		split	2	56	4.8	0.0119
		site*split	2	56	1.41	0.2534
		main*split	6	56	0.59	0.7348
		site*main*split	6	56	1.55	0.1797
Hardwood stem density	2012	site	1	9.94	13.63	0.0042
		main	3	29.2	5.19	0.0054
		site*main	3	29.2	1.08	0.3739
		split	2	78	36.41	<.0001
		site*split	2	78	11.68	<.0001
		main*split	6	78	1.05	0.3991
		site*main*split	6	78	0.83	0.5519

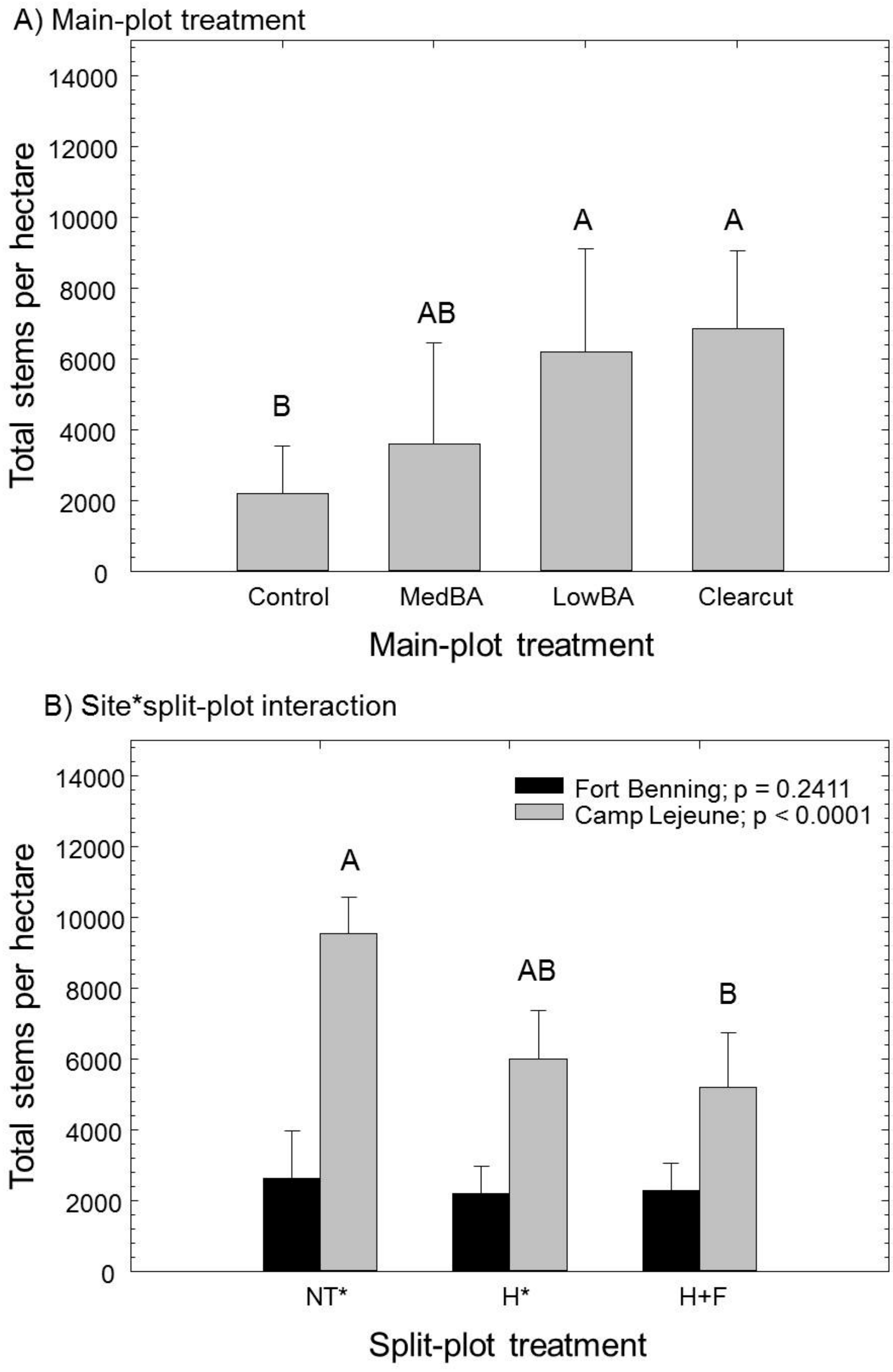


Figure 3.10.10. Total stem density in the mid-story (mean + one standard error) by A) main-plot treatment and B) split-plot treatment in 2012, with an interaction of site*split-plot treatment. The same letter indicates no difference among treatments, and '*' indicates a significant difference between sites within a split-plot treatment at $p = 0.05$.

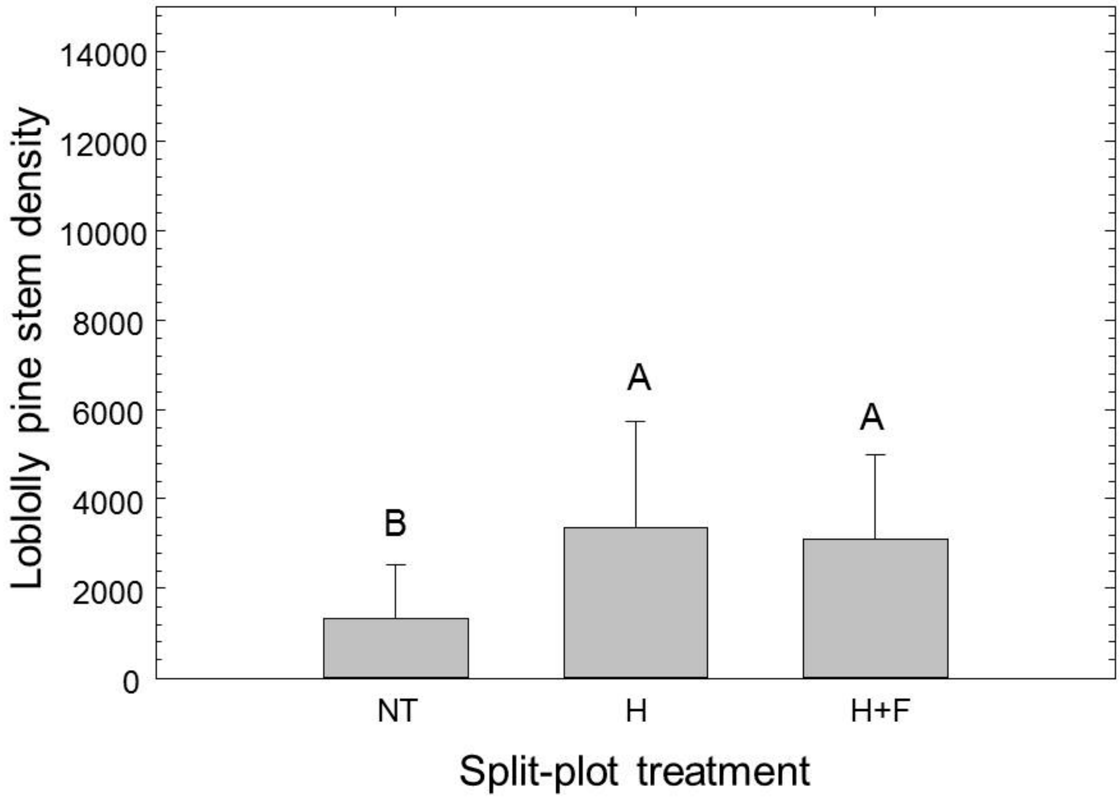


Figure 3.10.11. Loblolly pine stem density in the midstory (mean + one standard error) split-plot treatment in 2012. The same letter indicates no difference among treatments at $p = 0.05$.

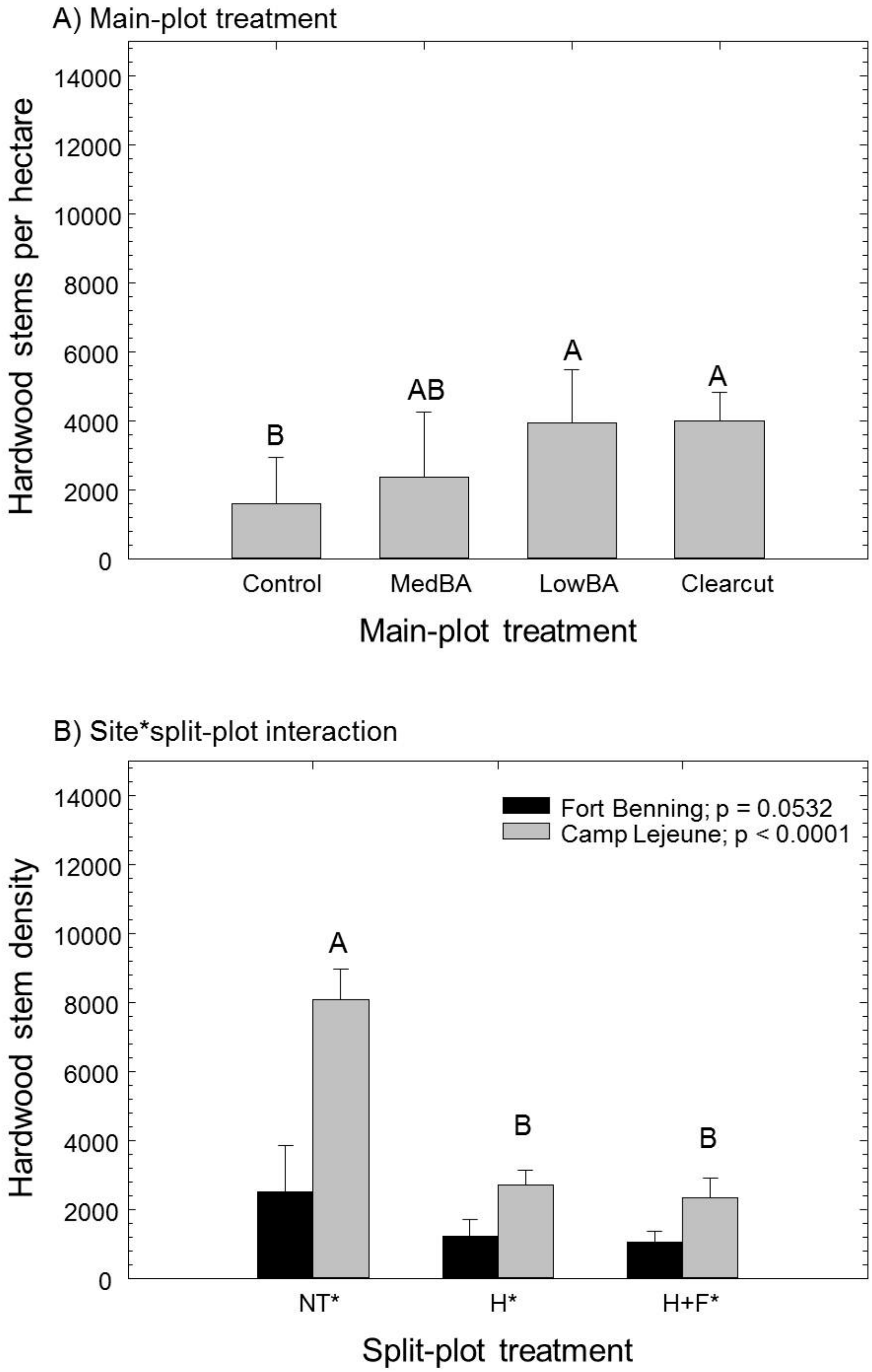


Figure 3.10.12. Hardwood stem density in the midstory (mean + one standard error) by A) main-plot treatment and B) split-plot treatment in 2012, with an interaction of site*split-plot treatment. The same letter indicates no difference among treatments, and ‘*’ indicates a significant difference between sites within a split-plot treatment at $p = 0.05$.

Table 3.10.7. Results from ANOVA testing the effect of study site, main-plot treatment (canopy manipulation), split-plot treatment (cultural treatment), and interactions on gap light index and volumetric soil moisture in 2008 and 2009 at Fort Benning and Camp Lejeune

Variable	Year	Effect	Num DF	Den DF	F-value	p-value
Gap light index (%)	2008	site	1	11	6.58	0.0263
		main	3	32.2	463.34	<.0001
		site*main	3	32.2	5.21	0.0048
		split	2	85.3	1.73	0.1843
		site*split	2	85.3	0.63	0.5339
		main*split	6	85.3	1.18	0.3227
		site*main*split	6	85.3	0.65	0.6869
Volumetric soil moisture (m m^{-1})	2008	site	1	9.91	0.06	0.8116
		main	3	29	0.15	0.9311
		site*main	3	29	1.09	0.3677
		split	2	78	0.34	0.7105
		site*split	2	78	1.25	0.2928
		main*split	6	78	1.22	0.3064
		site*main*split	6	78	0.79	0.5785
Volumetric soil moisture (m m^{-1})	2009	site	1	10.8	1.05	0.3273
		main	3	31	1.58	0.2141
		site*main	3	31	0.15	0.9302
		split	2	84	1.86	0.1624
		site*split	2	84	0.57	0.5689
		main*split	6	84	0.65	0.6873
		site*main*split	6	84	0.85	0.5365

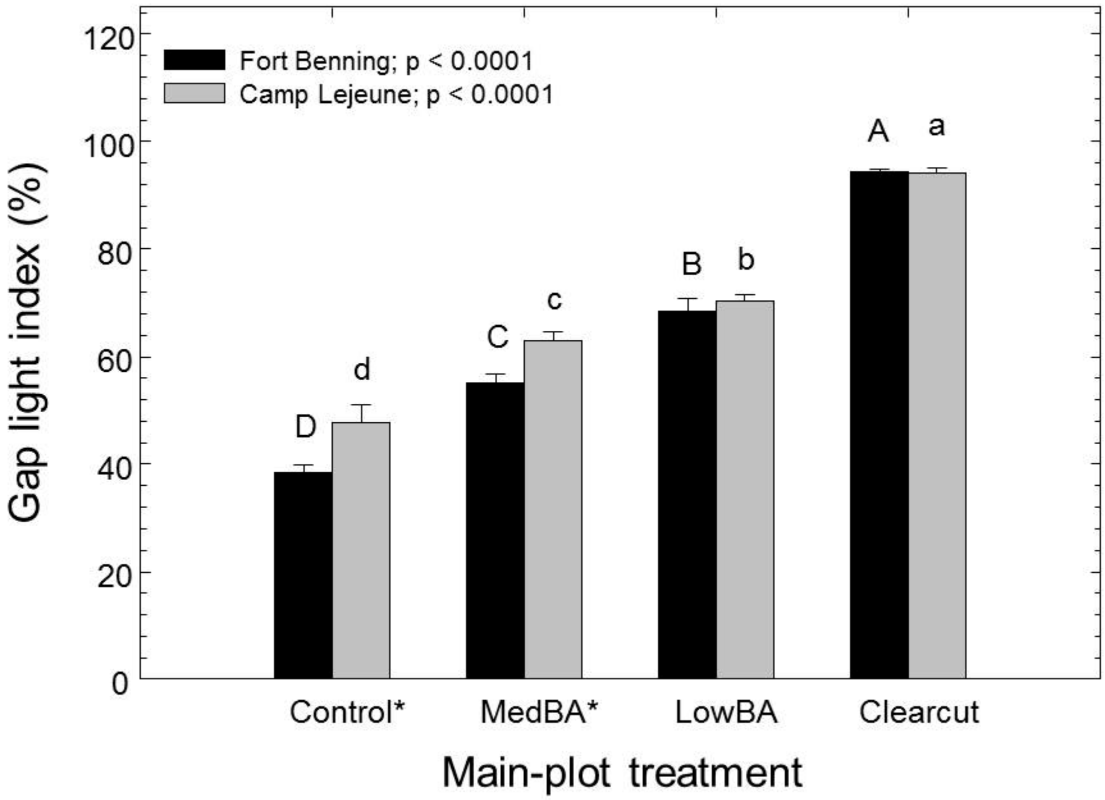


Figure 3.10.13. Gap light index (mean + one standard error) by main-plot treatment. The same letter indicates no difference within each site, and ‘*’ indicates a significant difference between sites within a main-plot treatment at $p = 0.05$.

Atlantic Coastal Plain (Peet 2006). Fort Benning generally experiences hotter and dryer conditions than does Camp Lejeune. Over the period of the study, Fort Benning experienced a wider range in precipitation relative to the 50-year mean when compared to Camp Lejeune, with temperatures that were generally hotter than the 50-year mean (see Figure 3.1.4 in Section 3.1). Generally, the early growing season of 2008 was dry at Fort Benning but less so at Camp Lejeune, and much of the growing season of 2010 was dry at both sites. The effects of climatic patterns can be accentuated by differences in physical site conditions, and we found that bulk density and clay content differed between the study sites, with higher bulk density and more clay in Fort Benning soils (see Table 3.1.1 in Section 3.1). It is widely accepted that soil texture and soil moisture availability are important drivers of vegetation composition and species richness within longleaf pine ecosystems (Kirkman et al. 2001, Kirkman et al. 2004); they are likely to be important for driving the responses to management treatments in this study.

Legacies of past land-use and management practices also control contemporary forest structure, composition, and restoration potential of longleaf pine forests (Hedman et al. 2000, Smith et al. 2002, Brudvig and Damschen 2011). Although past legacies are often not known or easily accounted for, differences in recent management practices certainly influenced the condition of the vegetation at each study site. Most notably, the site preparation methods used at each site differed according to the standard practices at each installation, with the objective of making our study results directly applicable to each respective installation. At Fort Benning, herbicides were used as a site preparation treatment to control mid-story hardwood development, and at Camp Lejeune mulching was used to reduce mid-story hardwood density. However, the differential effects of these practices are likely related to the subsequent vegetation response. As another example, Blocks 5-8 at Camp Lejeune had not been burned with prescribed fire in the past few decades, but all study areas at Fort Benning had been managed with a frequent fire regime. This study was not designed to determine the effects of past fire management or site preparation on response variables, but their impacts undoubtedly contribute to the observed response patterns.

Our results suggest that several generalizations can be made across our study sites regarding vegetation response to restoration treatments. Similar to previous studies, we found that harvesting to reduce canopy density resulted in an increase in ground layer vegetation (Anderson et al. 1969, Ares et al. 2010). However, in contrast to Grelen and Enghardt (1973), we found no effect of canopy removal on herbaceous vegetation across study sites after five growing seasons. It is likely that any initial responses of herbaceous vegetation to canopy removal (see Section 3.4) may have been transient or lost due to the development of woody stems in the mid-story. After five growing seasons, the density of woody stems in the mid-story was strongly moderated by canopy density across sites, but this was true for hardwoods and not loblolly pines. Previous studies have also reported greater abundances of hardwoods within gap openings in longleaf pine forests (Jack et al. 2006, Mitchell et al. 2006, Pecot et al. 2007), and Kirkman et al. (2007) discussed canopy retention to suppress hardwood development during longleaf pine restoration in slash pine stands. Our results support this previous finding, suggesting that canopy retention can be expected to suppress hardwood development across site types. In contrast, we found no effect of canopy density on the density of loblolly pines in the mid-story, suggesting that other practices, principally fire, must be used to control loblolly pine regeneration (see Section 3.3).

Despite some similarities, the vegetation structure and response to study treatments differed in many respects between Fort Benning and Camp Lejeune. Generally, the ground layer at Fort Benning was dominated by herbaceous vegetation and that at Camp Lejeune was dominated by woody vegetation, although total vegetation cover was similar across sites (see Sections 3.4 and 3.6). Likewise, we found the densities of hardwoods, loblolly pine, and total stems to be greater at Camp Lejeune than at Fort Benning. We expect that the site preparation treatments contributed to the development of the hardwood mid-story at Camp Lejeune, where the mulching treatment initiated re-sprouting of the existing hardwood stems; in contrast, the herbicide site preparation at Fort Benning was more likely to kill the hardwoods prior to application of the study treatments. However, land use legacies and site/climatic characteristics also likely contributed to differences in the initial composition and suitability of the sites for mid-story development. For example, loblolly pine regeneration may vary regionally with differences in seed production and site suitability, with more consistent seed production occurring along the Atlantic Coastal Plain than further inland (Schultz 1997).

The herbicide split-plot treatments used in this study had different effects on the 2012 vegetation response between the two study sites. The pattern in total ground layer vegetation cover at Camp Lejeune, with higher cover on the untreated plots than those treated with herbicide, was driven by a reduction in woody vegetation cover on the herbicide plots. In contrast, there was no effect of the herbicide treatment on ground layer vegetation cover at Fort Benning, where woody cover was much lower. Likewise, the densities of total woody stems and hardwoods in the mid-story were reduced by the herbicide treatments at Camp Lejeune, which had more hardwoods in the mid-story than Fort Benning. It is likely that the reduction in woody vegetation in both the ground layer and the mid-story at Camp Lejeune resulted in the increase in herbaceous cover in the ground layer, a result that corresponds to objectives of longleaf pine restoration. However, the herbicide treatments resulted in higher densities of loblolly pines in the mid-stories of both study sites. Several past studies have discussed the potential for using herbicides to reduce the development of a woody mid-story during longleaf pine restoration (e.g., Freeman and Jose 2009, Martin and Kirkman 2009, Jose et al. 2010, Addington et al. 2012). Our results demonstrate that outcomes of herbicide application may depend on the vegetation community, with the potential for releasing natural loblolly pine regeneration during stand conversation.

The successful establishment of longleaf pine seedlings is critical to restoring longleaf pine in loblolly pine stands, and the first year after planting is common when the risk of mortality is highest. Our results indicate that first-year mortality of longleaf pine seedlings can be variable across sites, with higher mortality rates at Fort Benning than at Camp Lejeune on plots with high levels of canopy removal and in the interior of canopy gaps. Previous studies have reported reduced early mortality of longleaf pine seedlings beneath canopy trees, especially in harsh conditions such as drought years (e.g., McGuire et al. 2001, Gagnon et al. 2003, Rodriguez-Trejo et al. 2003), suggesting that canopy trees can facilitate survival by alleviating stress associated with exposure. The different patterns of first-year mortality may be related to interactions of soil conditions and climatic patterns of 2008. Soils at Fort Benning have higher clay content than those at Camp Lejeune, and the dry conditions during the early growing season in 2008 likely resulted in poor initial root development and low water availability at Fort Benning. The lack of a difference in volumetric soil moisture between the two sites in 2009 and 2010 suggests that water availability may not have been the driver; however, no data on volumetric soil water content were collected in 2008. By the end of the fifth growing season, mortality on only the Clearcut plots differed between sites, indicating that reducing the risk of initial mortality through some level of canopy retention can result in persistent differences in seedling density.

Measures of seedling growth showed mostly similar patterns in response to the canopy treatments at both sites, with increasing growth (root collar diameter and height) associated with canopy removal. Generally, seedling growth was higher at Fort Benning than at Camp Lejeune with complete canopy removal, with significant differences between the sites in Clearcut plots and within the center of SG plots. Likewise, seedling growth was greater on plots treated with herbicides at both sites, with the site and split-plot treatment interaction likely associated with the greater magnitude of difference between NT and H/H+F plots at Camp Lejeune. Seedling emergence from the grass stage into height growth is a critical stage of stand development that is required for seedling recruitment. Barnett et al. (1990) recommend the initial survival of at least 740 seedlings per hectare of planted longleaf pine but do not provide recommendations for the number of seedlings in height growth at any point in time. The density of seedlings in height growth after five years in our study was dependent on initial planting density, mortality, and grass stage emergence, and it varied by canopy density and cultural treatment. The minimum number of longleaf pine seedlings required for stand conversion in a restoration context is not known, but treatments that maintain high canopy cover (Control and MedBA at Fort Benning and Control at Camp Lejeune) are not likely to result in adequate longleaf pine stocking.

Although general patterns in longleaf pine seedling growth were evident from our results, specific responses are dependent on the interactions of multiple factors occurring simultaneously. A major difference between the study locations was in the dominance and development of the ground layer and mid-story vegetation. We were unable to directly separate the influence of canopy and sub-canopy vegetation on longleaf pine response in this study, but our results suggest that the greater abundance of mid-story vegetation at Camp Lejeune limited seedling growth rates. For example, we observed consistently smaller seedlings in clearcuts and gap openings at Camp Lejeune, where stem densities were highest. Likewise, the relationship between overstory basal area and seedling growth response was stronger at Fort Benning than at Camp Lejeune (see Figure 3.8.5, section 3.8), suggesting other factors were exerting strong control on seedling growth at Camp Lejeune. Therefore, although herbicides resulted in increased seedling growth at both sites, the need for herbicide release is dependent on the existing vegetation and factors such as site preparation.

3.10.5. Conclusions

The interacting factors affecting ecological responses to restoration treatments include physical factors associated with the sites, anthropogenic effects and legacies, and biological interactions of the species present. Although it is difficult to elucidate the specific influence of each of these factors, our study demonstrates that some responses to our study treatments may be generalized across sites and other responses may be more site-specific. Notably, longleaf pine seedling survival during the first year after planting differed between study sites, with evidence of facilitation by canopy trees at Fort Benning but evidence of competition at Camp Lejeune. It is likely that climate and site conditions will strongly affect seedling survival, but retaining some level of canopy retention will reduce the risk of mortality. Longleaf pine seedling growth can be expected to increase with canopy removal, although the abundance of mid-story vegetation can reduce growth. In situations with abundant hardwoods in the mid-story, control with herbicides may be a necessary treatment for increasing seedling size and reaching the objectives for restoring the vegetation structure of longleaf pine ecosystems.

4. Which stands on the landscape are most susceptible to decline? (Question 2)

Section 4 considers environmental factors and stand characteristics that are associated with loblolly pine canopy health at Fort Benning.

4.1. Loblolly pine health on Fort Benning: site characteristics associated with declining health

This section has been adapted from a manuscript published online in *Forest Science and Technology* (Ryu et al. 2013). It addresses research objective O-9, to quantify loblolly pine canopy health status relative to stand and site conditions and recent stand management.

4.1.1. Introduction

Loblolly pine is the most widely planted pine species in the southeastern USA because of its relatively fast growth, wide geographical habitat range, and high commercial value (Schultz 1997). However, several studies reported decline of loblolly pine trees over the last 50 years (Sheffield et al. 1985; Sheffield and Cost 1987; Hess et al. 1999). The suspected decline was a primary motivation for the current project (Section 2).

Tree mortality is a vital process in forest dynamics (Das et al. 2008) and tree vigor is often closely related to tree mortality, because trees with low vigor are more susceptible to environmental stresses (Manion 1991; Pedersen 1998). Various methods have been developed to assess tree health in the field, each focused on a single metric including crown transparency (Eichhorn et al. 2004), needle size or shape (Kozlov and Niemela 1999), crown morphology (Roloff 1987), crown ratio (Burkhart et al. 2001), and foliar and sapwood nutrient analyses (Stefan et al. 1997). Most of these approaches consider the crown condition, because photosynthesis is the energy source and trees allocate energy to canopy development as a priority (Ryu et al. 2006). Because it is difficult to clearly assess tree vigor using a single measure, the USDA Forest Service (1999) developed a canopy assessment system that can be used to readily evaluate tree health in the field based on canopy conditions, and it was found to be well related to tree growth for many species (e.g., Manion 1991, Kramer 1996, Dobbertin 2005). Crown vigor classes (CVCs) consider live crown ratio, crown dieback, and crown density to classify trees into good (CVC1), fair (CVC2), and poor (CVC3) vigor conditions (USDA Forest Service 1999). We used this system to generate the canopy health metrics used in our study.

The goal of this part of the project was to identify factors that may be negatively influencing loblolly pine health. We evaluated the relationships between stand health and several factors that had previously been reported to be associated with declining health including slope and aspect (Eckhardt and Menard 2008); nutrient and/or water stress; and management practices (specifically harvesting and burning history).

4.1.2. Methods

4.1.2.1. Study area

Fort Benning is located on the southern edge of the fall line, which borders the Piedmont and Coastal Plain physiographic provinces. The study landscape covers two major physiographic subsections, the Sand Hills and the Upper Loam Hills (McNabb and Avers 1994). The Sand Hills are part of the Lower Coastal Plains and Flatwoods section and cover approximately the northeast two thirds of the installation (Figure 4.1.1). The Upper Loam Hills are part of the Middle Coastal Plains and are more mesic, with higher organic matter content than soils of the Sand Hills. The predominantly rolling terrain is highest (225 m above sea level) in the east and lowest (58 m above sea level) in the southwest along the Chattahoochee River. The climate is characterized by hot and humid summers and mild winters (National Data Center, Asheville, NC). Mean annual precipitation is 1240 mm and is evenly distributed throughout the year (Columbus, GA, Airport weather station). During the last 10 years (1997 – 2006), March had the highest mean precipitation (135 mm) followed by June (119 mm) and July (114 mm), while October was the driest (50 mm). Prior to establishment as a military installation in 1918, the Fort Benning landscape was heavily farmed, primarily for cotton, resulting in widespread erosion and depletion of organic matter in the soil (USAIC 2006).

4.1.2.2. Stand selection and data collection

Plot sampling was designed to include the spatial extent of Fort Benning and to cover a range of stand age and stand health conditions. We first located all mature (> 35 years old) loblolly pine stands on the stand map derived from Fort Benning's forest inventory and then overlaid each stand with 2003 aerial photographs (50 cm resolution) to determine species composition and stand size. We then visited each candidate stand to visually confirm whether the stands were dominated by loblolly pine. Among the stands satisfying these criteria, we selected study plots systematically using the management compartments designated for army training purposes. When a compartment had more than two qualifying stands, we selected two stands representing the healthiest and unhealthiest condition based on visual inspection. This approach resulted in 28 compartments with one suitable loblolly stand and 25 compartments with two sample stands. Four additional compartments had relatively large and heterogeneous (e.g., age structure) loblolly stands, so we selected three plots from each to capture the variation. We installed one 30 m x 30 m plot in each selected stand for a total of 90 plots (36 in 2006 and 54 in 2007). Field survey and data collection were conducted over two growing seasons: during July-September 2006 and June – August 2007. During that interval, one plot was lost to logging, and was dropped from analyses in this section, so data analyses are based on a maximum of 89 plots.

We measured the diameter at breast height (DBH; 1.3 m height) and recorded the species of each tree > 5 cm dbh in each plot. We evaluated crown condition of each loblolly pine tree using the protocol established by the USDA Forest Service Health Monitoring program (USDA Forest Service 1999). Each tree was assigned to a crown vigor class (CVC; CVC1 = good, CVC2 = fair, and CVC3 = poor) as an indicator of tree health. CVC was determined by live crown ratio,

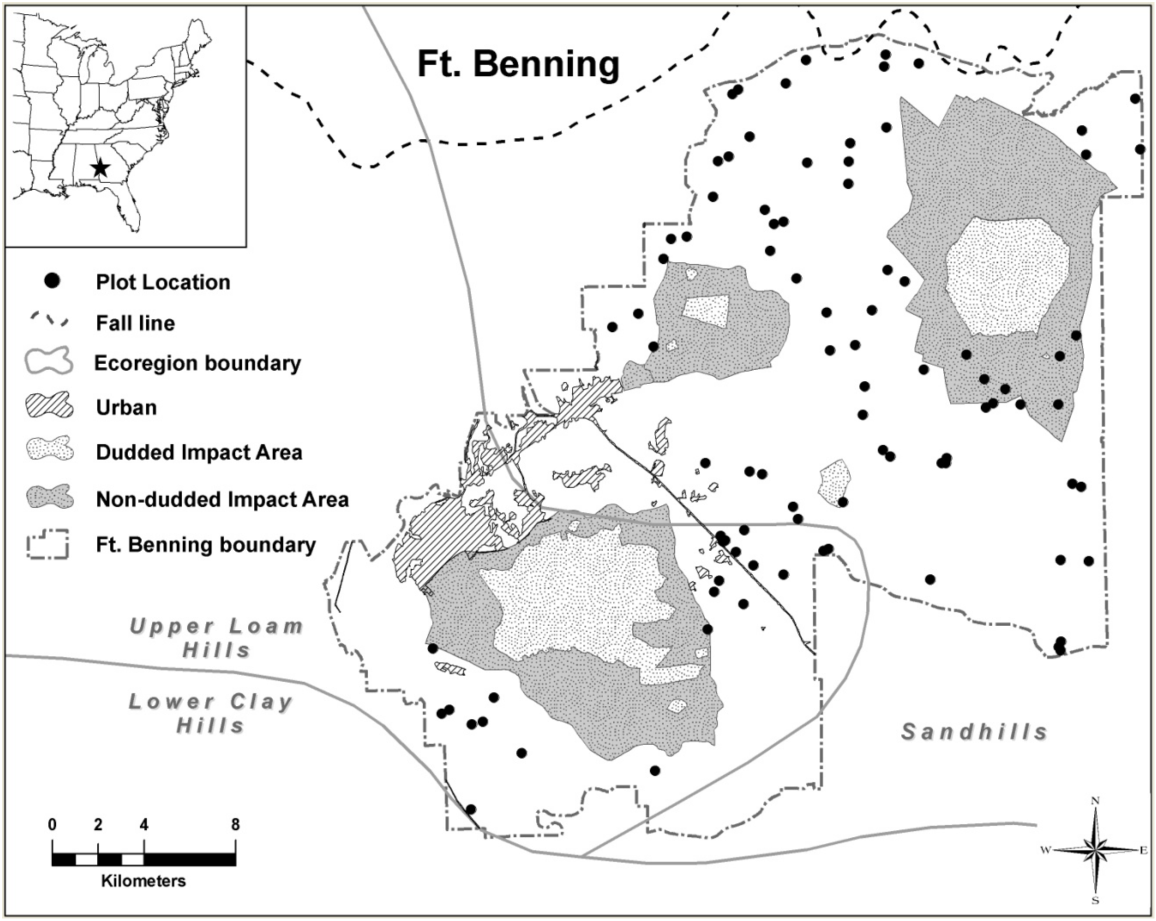


Figure 4.1.1. Geographic location of Fort Benning (inset), and the locations of study plots (total 89 plots) in the base.

crown dieback (% crown), and crown density (%; relative to the surrounding healthy trees) as follows: CVC1 = crown ratio > 35 percent, crown dieback < 5 percent, and crown density > 80 percent; CVC3 = crown density < 35 percent, crown dieback > 50 percent, and crown density < 20; and all other trees were classified as CVC2. We also measured crown light exposure (range 0 to 5; 0 is the lowest light exposure and 5 is full exposure; a point is given to a quarter of crown exposed to direct sunlight and top of the tree exposed to direct sunlight) and crown position in the canopy (dominant/codominant, and intermediate/overtopped). Any visible symptoms of poor health or damage (e.g., fusiform rust, physical scar, stem canker, and excessive cone production) were also noted.

Samples for soil chemical analysis were collected during the dormant season (February 2007 for 2006 plots and March 2008 for 2007 plots). We collected five samples (plot center and the points midway between the center and each corner) per plot using a 2.5 cm diameter Oakfield soil corer (0 – 20 cm depth), and samples were composited for analysis. Soil samples were air-dried and then sent to Spectrum Analytic Inc. (Ohio, USA) to analyze soil pH (water), organic matter (%), exchangeable phosphorus, potassium, magnesium, and calcium (ppm; extracted by Mehlich-3), and CEC (cmol kg^{-1}). We analyzed soil texture of each plot using the hydrometer method (Milford 1997) and classified soil texture following the USDA soil classification system.

Foliar samples were collected in August 2006 and July 2007 to evaluate the nitrogen (N) and phosphorus (P) status of canopy pines in each plot. We randomly selected five super-dominant or dominant loblolly trees per plot, and three samples from each tree were collected from between the top 1/4 and the bottom 1/3 of the crown using a shotgun during the growing season. The three samples were composited and immediately stored in a cooler after collection, followed by freezer storage until analysis. Foliar N and P were analyzed at the Clemson University Agricultural Service Laboratory (Clemson, SC, USA). The sampling period was August for 2006 plots and July for 2007 plots. We sampled 20 plots in 2006 and 50 plots in 2007 but failed to sample 20 plots because access to the plots could not be gained before natural senescence occurred. We averaged the foliar N and P of trees in a plot to be related to other plot level variables.

The center of each plot was mapped using global positioning systems (GPS) unit, and slope and aspect of each plot were recorded. We estimated stand age, site index (SI), and management history (e.g. years since the last burn and thinning; number of burns since 1985) from Fort Benning forestry inventory data. Stand density index (SDI; Equation 1) was calculated to standardize tree competition (Reineke 1933), where TPH and DBHq stand for number of trees per hectare and quadratic mean diameter (cm), respectively.

$$\text{(Equation 1)} \quad SDI = TPH\left(\frac{DBHq}{25}\right)^{1.6}$$

4.1.2.3. Statistical analyses

To quantify stand health, we calculated %CVC1, %CVC3, and %Dead as the percentage of all loblolly trees (both live and dead) classified as crown vigor class 1or 3 respectively. High %CVC1 and high %CVC3 indicates healthy and poor-health loblolly pine stands, respectively.

We compared the plot characteristics of healthiest (top 10%; 9 plots of highest %CVC1) and poorest (bottom 10%; 9 plots of highest %CVC3) stands using t-tests.

Because data did not satisfy normality assumptions, we conducted a Spearman correlation test to evaluate the correlations among crown health metrics (%CVC1 and %CVC3) and stand characteristics (stand age (year), site index (m at age 50), slope (degree), stem density (SD; live stems only; number of stems ha^{-1}), basal area (BA; m^2 ha^{-1}), soil chemistry (soil pH, organic matter (%), exchangeable soil P, K, Mg, and Ca (ppm), cation exchange capacity (cmol kg^{-1})), foliar nutrients of canopy trees (N and P), and management history (time since last thinning (years), time since burning (years), and number of burns since 1985). The Kruskal-Wallis test was used to determine effects of soil texture on %CVC1 and %CVC3. Effects of fusiform rust, stem canker, physical damage, and abundant cone presence on the CVC of individual trees were tested using Chi-square and Kendall's Tau-b. We tested if there was an effect of CVC class on dbh at the individual tree level using ANOVA followed by post-hoc Tukey tests. We also compared the light exposure among different CVC trees using Kruskal-Wallis tests and evaluated the relationship between them using Kendall's Tau-b test. All statistical analyses were performed using SAS (SAS version 9.1, SAS institute, Inc., Cary, NC, USA) and significant differences were based on an alpha of 0.05 unless stated otherwise.

4.1.3. Results

4.1.3.1. Characteristics of loblolly pine stands at Fort Benning

Selected plots covered a wide range of age (38 – 98 years), SI (19.5 – 36.3 m at age 50), slope (0 – 10 degree), SDI (108.8 – 541.0), SD (55.6 – 577.8 stems ha^{-1}), loblolly pine SD (55.6 – 566.7 stems ha^{-1}), and BA (8.1 – 28.4 m^2 ha^{-1}) (Table 4.1.1). Mean stand age was 62 years, and most stands had open canopies (mean SD of 195.8 stems ha^{-1} and loblolly pine BA of 13.7 m^2 ha^{-1}) in compliance with RCW habitat management guidelines, which recommend maintaining basal areas between 9 and 14 m^2 ha^{-1} (USFWS 2003). The plots had been rigorously managed, with a mean fire return interval of three years and average of 8.5 years since thinning. More than half the plots (60 plots) had over 50% of their pines classified as CVC1, and only 21 plots had any loblolly tree classified in CVC3. Of those plots with trees in poor health, 11 had more than 10% of their trees classified as CVC3 and only 3 plots had more than 20% of their trees in CVC3. Overall, we found that 8.2% of all trees were dead, with 7.9% and 4.5% of trees dead in plots with > 10 and > 20% of trees classified in CVC3, respectively.

When we compared the top 10% stands and the bottom 10% stands, we found significant (p < 0.10) differences in slope, SDI, and SD (both total and loblolly trees) between the two groups (Table 4.1.1). The percentage of trees in CVC1 was significantly (p<0.01) higher in the top 10% stands, and %CVC2, %CVC3, and %Dead were significantly (p<0.05) higher in bottom 10% stands. The poorest stands had 63% higher SD than the healthiest stands, but BA was only 22% larger in the poorest stands, suggesting that loblolly pines had smaller DBH in bottom 10% than top 10% stands. The BA of the bottom 10% stands (17.4 m^2 ha^{-1}) slightly exceeded the RCW habitat guideline (Table 4.1.1).

Table 4.1.1. Summary on the characteristics of loblolly pine study plots. Data are presented as mean values (one standard error; SE). SDI = stand density index, SD = stem density, and CVC = crown vigor class, where 1, 2, and 3 are healthy, intermediate, and poor, respectively, and the percentage was calculated only among loblolly pine trees. *, **, and *** within a row indicate a significant difference ($p < 0.10$, 0.05, and 0.01, respectively) between healthy (top 10%) and poor-health (bottom 10%) stands.

		Mean (SE)	Sample Size	Min	Max	Top 10 %	Bottom 10 %
Age (yr)		62.1 (1.7)	86	38.0	98.0	59.0 (5.0)	61.3 (6.0)
Site Index		26.5 (0.4)	86	19.5	36.3	28.0 (1.6)	24.8 (1.2)
Slope (degree)		3.4 (0.3)	89	0.0	10.0	2.6 (2.6)*	4.4 (0.8)*
SDI		280.6 (8.6)	90	108.8	541.0	262.1 (19.2)*	341.9 (38.4)*
SD (stems ha^{-1})		195.8 (10.9)	90	55.6	577.8	155.6 (14.4)*	248.1 (48.1)*
Basal Area (m^2 ha^{-1})		15.2 (0.5)	90	8.1	28.4	13.5 (0.9)	17.4 (1.9)
Time since last thinning (yr)		8.5 (0.8)	87	0.0	30.0	9.0 (3.0)	12.3 (3.9)
Time since last burn (yr)		1.1 (0.1)	87	0.0	3.0	0.9 (0.3)	0.9 (0.4)
Number burn since 1985 (times)		6.7 (0.2)	87	2.0	12.0	6.7 (0.8)	7.4 (0.5)
Loblolly Pine	Live SD	153.4 (8.3)	89	55.6	566.7	128.4 (11.5)*	209.9 (39.4)*
Loblolly Pine	Live Basal Area	13.7 (0.4)	89	4.5	25.8	13.2 (0.9)	16.1 (1.7)
Loblolly Pine	%CVC1	54.1 (2.6)	89	0.0	100.0	91.7 (1.3)***	37.4 (8.0)***
Loblolly Pine	%CVC2	34.8 (2.4)	89	0.0	100.0	6.2 (1.7)***	36.0 (7.7)***
Loblolly Pine	%CVC3	2.9 (0.7)	89	0.0	31.0	0.0 (0.0)**	19.1 (2.4)**
Loblolly Pine	%Dead	8.2 (0.9)	89	0.0	33.3	2.1 (1.5)**	7.5 (1.9)**

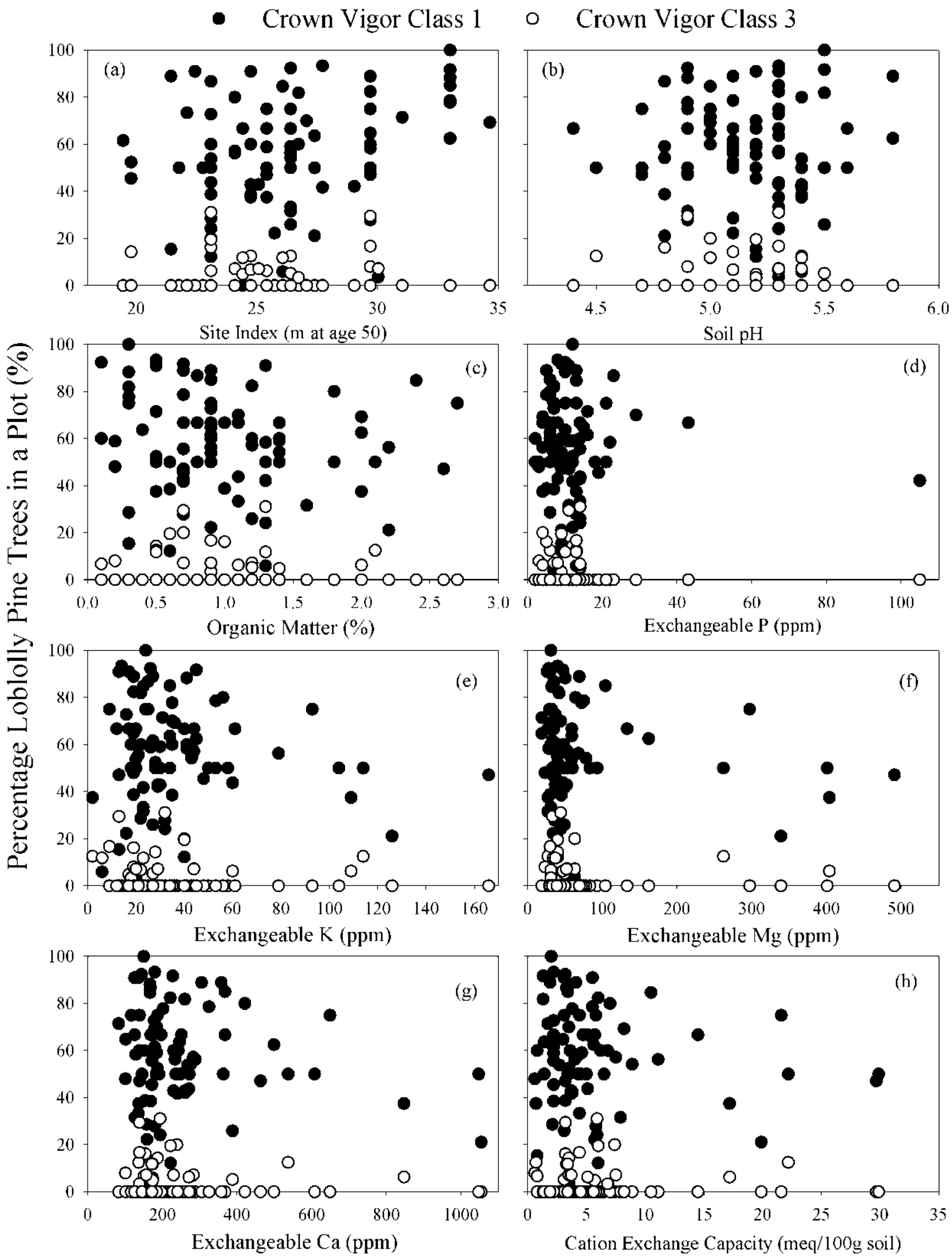


Figure 4.1.2. The relationship between loblolly pine trees classified as Crown Vigor Class 1 (%; closed circle) and Crown Vigor Class 3 (%; empty circle) with (a) site index, (b) soil pH, (c) organic matter, (d) exchangeable phosphorus (P), (e) exchangeable potassium (K), (f) exchangeable magnesium (Mg), (g) exchangeable calcium (Ca), and (h) cation exchange capacity.

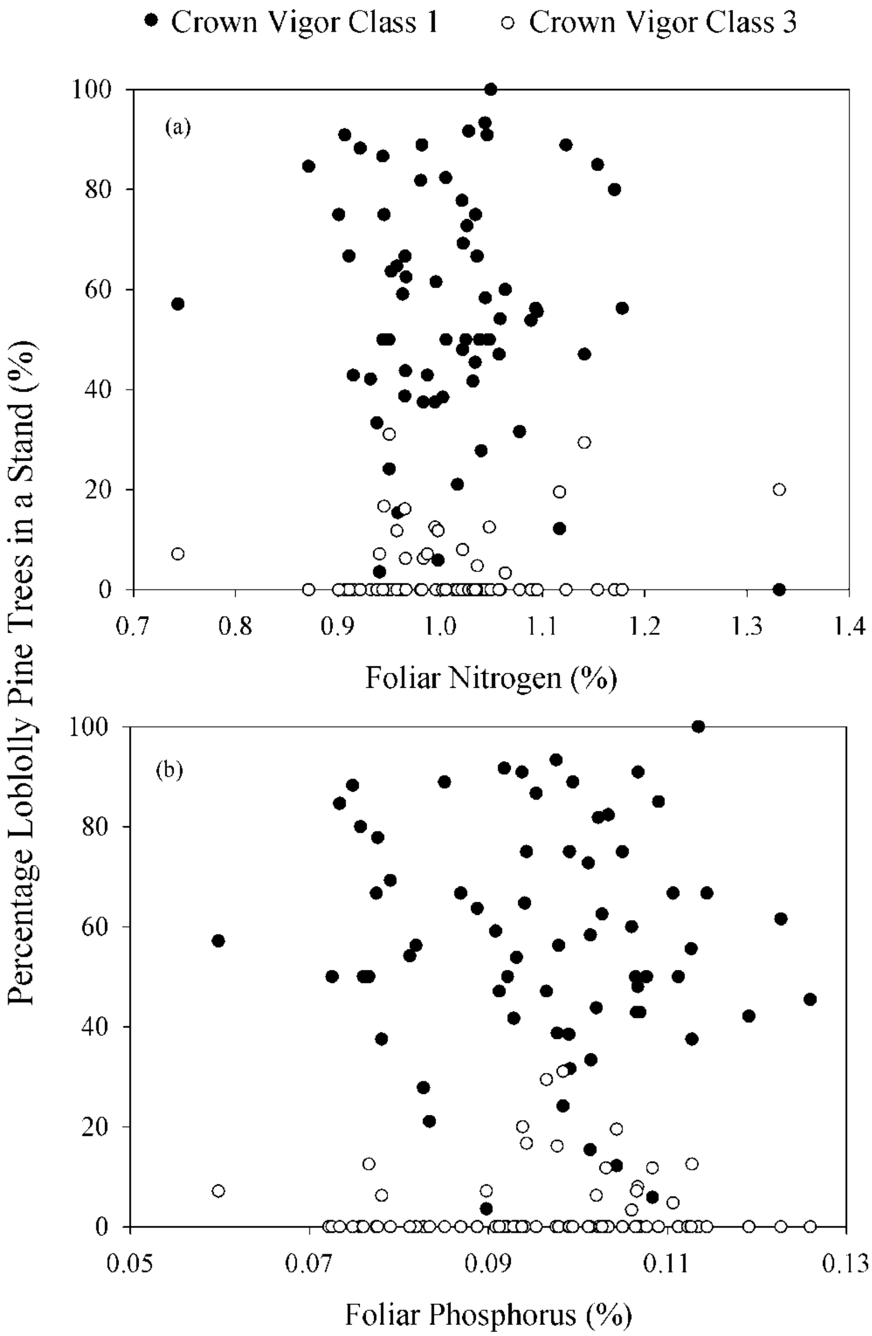


Figure 4.1.3. The relationship between loblolly pine trees classified as Crown Vigor Class 1 (%; closed circle) and Crown Vigor Class 3 (%; empty circle) with (a) foliar nitrogen and (b) foliar phosphorus concentration.

Soil pH ranged between 4.4 and 5.8 (Figure 4.1.2b). Mean organic matter content was 1.0% (median 0.9) with standard deviation of 0.6% and ranged between 0.1 and 2.7% (Figure 4.1.2c). Mean (±standard deviation) values of exchangeable P, K, Mg, and Ca were 11.5 (±11.7), 35.7 (±26.9), 67.8 (±85.9), and 250.2 (±174.7) ppm, respectively (Figures 4.1.2defg). Mean CEC was 5.4 cmol kg^{-1}; median and standard deviation were 3.7 and 5.6 cmol kg^{-1}, respectively (Figure 4.1.2h). Among 89 plots, 32, 42, 11, 3, and 1 plots were classified as sand, loamy sand, sandy loam, sandy clay loam, and clay loam, respectively. Mean foliar N content was 1.01% with standard deviation of 0.08% (Figure 4.1.3a). Foliar N content ranged between 0.74 and 1.33% (Figure 4.1.3a). Mean foliar P content was 0.10% with standard deviation of 0.01% (Figure 4.1.3b). Foliar P content ranged between 0.06 and 0.13% (Figure 4.1.3b).

4.1.3.2. Factors related to crown health

Slope showed no significant relationship (Figure 4.1.4c) with either %CVC1 (r= -0.04, p=0.74) or %CVC3 (r=0.13, p=0.21). The highest %CVC3 was observed at slope 8 degree, but it was not significantly different from %CVC3 at other slopes (Figure 4.1.4c). Moreover, we did not observe any noticeable influence of aspect on %CVC1 and %CVC3 (Figure 4.1.4ab) [H1]. Slope also showed no significant relationship (Figure 4.1.4c) with either %CVC1 (r = -0.04, p = 0.74) or %CVC3 (r = 0.13, p = 0.21). As expected, %CVC1 was negatively and significantly (r = -0.39, p < 0.001) correlated with %CVC3.

Site index (SI) correlated positively and significantly (Figure 4.1.2a) with %CVC1 (r = 0.22, p = 0.04) and negatively with %CVC3 (r = -0.19, p = 0.07). We did not find any significant correlation between crown health condition metrics and foliar or soil nutrient concentrations (Figures 4.1.2 and 4.1.3). Soil texture did not have any significant effect on %CVC1 or %CVC3. However, %CVC3 tended to decrease as soil texture became finer mean %CVC3 was 4.0, 2.6, 1.7, 0.0, and 0.0% for sand, loamy sand, sandy loam, sandy clay loam, and clay loam (Figure 4.1.5).

We found a significant negative relationship between %CVC1 and time since the last thinning (r = -0.25, p = 0.02; Figure 4.1.6a), but time since last thinning showed no relationship with %CVC3. Neither of the burn measures (time since last burn and number of burns since 1985) showed significant relationships with %CVC1 or %CVC3 (Figures 4.1.6bc). We did not observe any relationships between %Dead and burning activity. Mean %Dead values were 8.6, 7.4, 9.7, and 7.0% for 0, 1, 2, and 3 years since last burn, respectively, and 0.0, 10.5, 0.0, 7.8, 9.6, 7.6, 8.4, 2.4, 8.3, 12.5, and 0.0% for 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 burns since 1985, respectively. Soil textures of the bottom 10% stands were sand (44.4%), loamy sand (44.4%), and sandy loam (11.2%), white sand, loamy sand, and sandy loam made up 36.0, 47.2, and 12.4% of total plots (89 plots). The bottom 10% experienced prescribed burning 6-10 times since 1985 with a mean of 7.3 times, which was not significantly different from the overall mean, 6.7 times.

4.1.3.3. Individual tree condition

We surveyed a total of 1,246 pine trees and observed 210 and 38 trees with fusiform rust and stem canker, respectively, while 37 trees showed both symptoms. Fusiform rust presence did not have a significant effect on CVC class (Chi-square p = 0.63, Kendall's Tau-b = 0.02 and p = 0.44). However, stem canker presence had a significant effect on CVC class (Chi-square p =

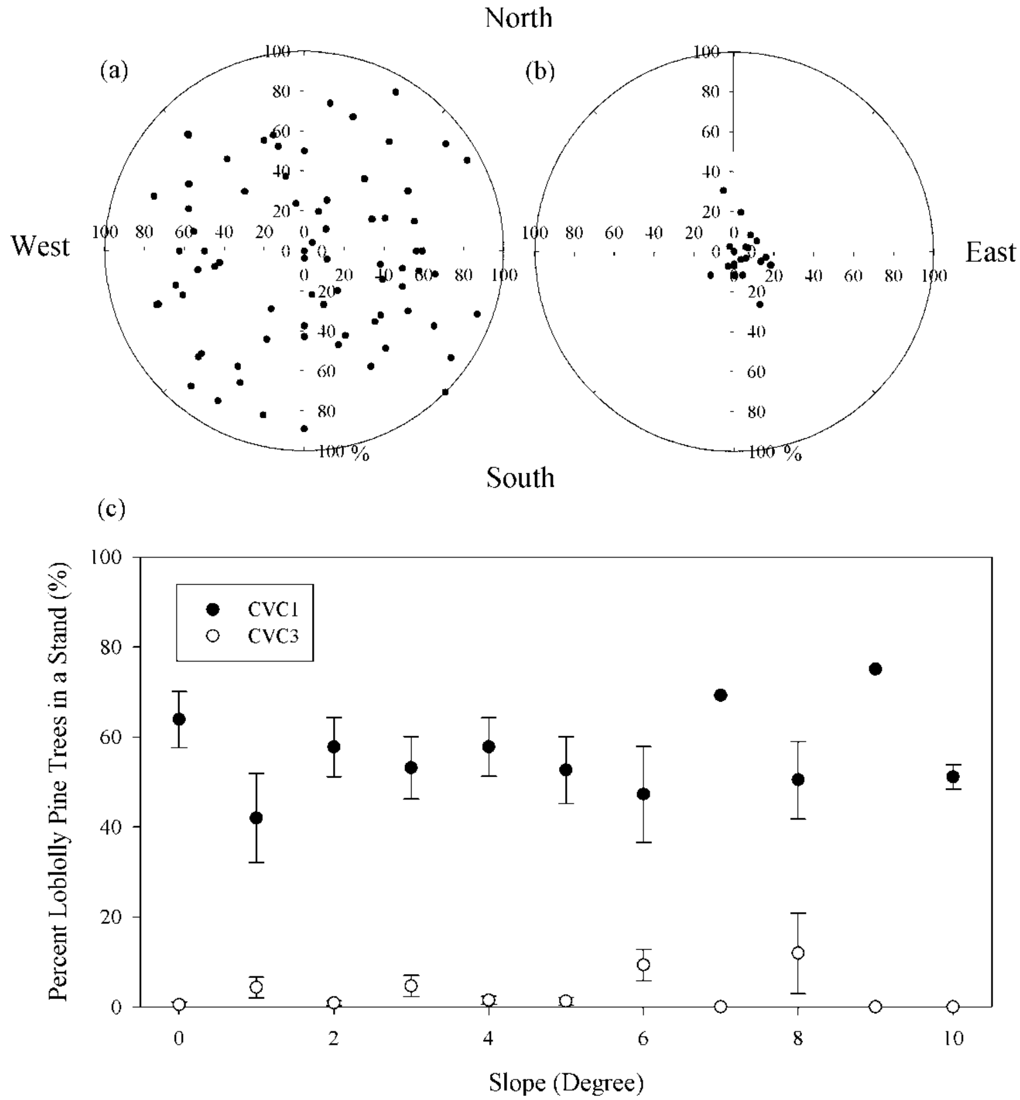


Figure 4.1.4. Distribution by aspect of stands classified as (a) Crown Vigor Class 1 and (b) Crown Vigor Class 3, and (c) mean of percentage of trees in Crown Vigor Class 1 and Crown Vigor Class 3 by slope (error bars = one standard error).

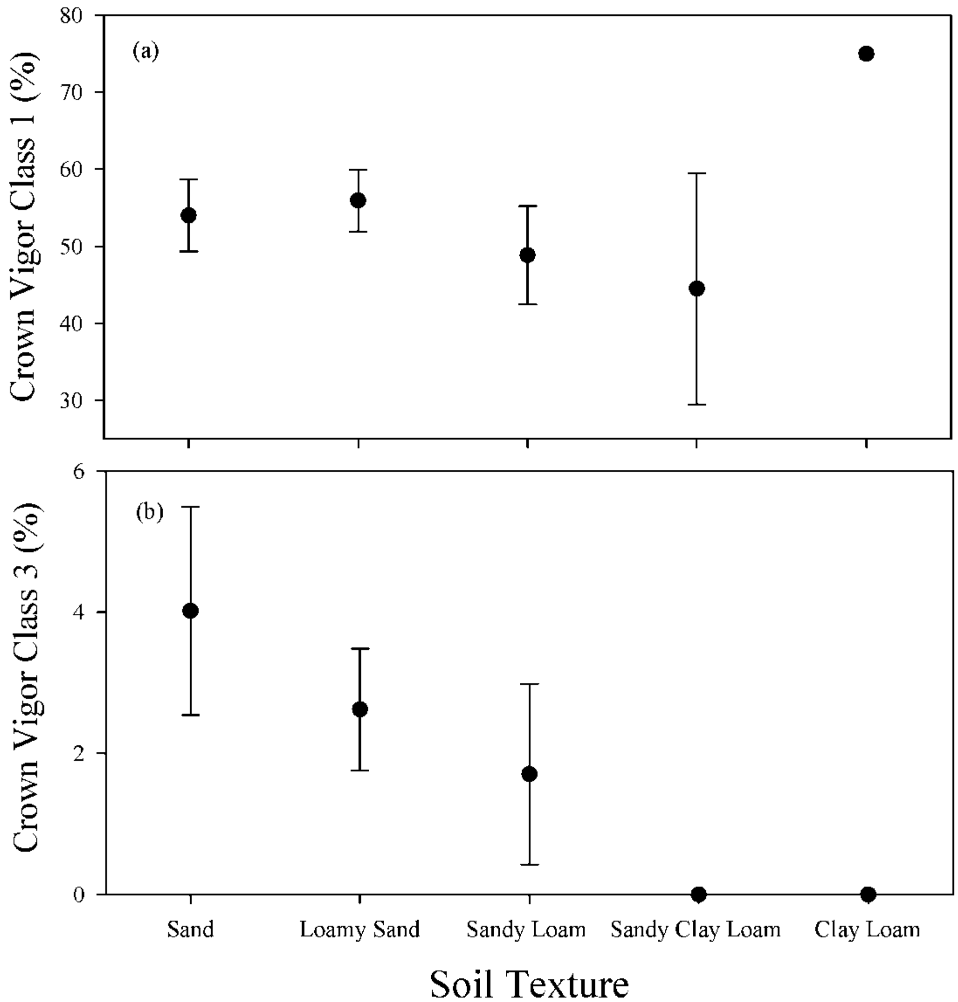


Figure 4.1.5. The distribution of loblolly pine trees classified as (a) Crown Vigor Class1 (%) and (b) Crown Vigor Class3 (%) by soil texture classes. The dot and error bar indicates mean and one standard error.

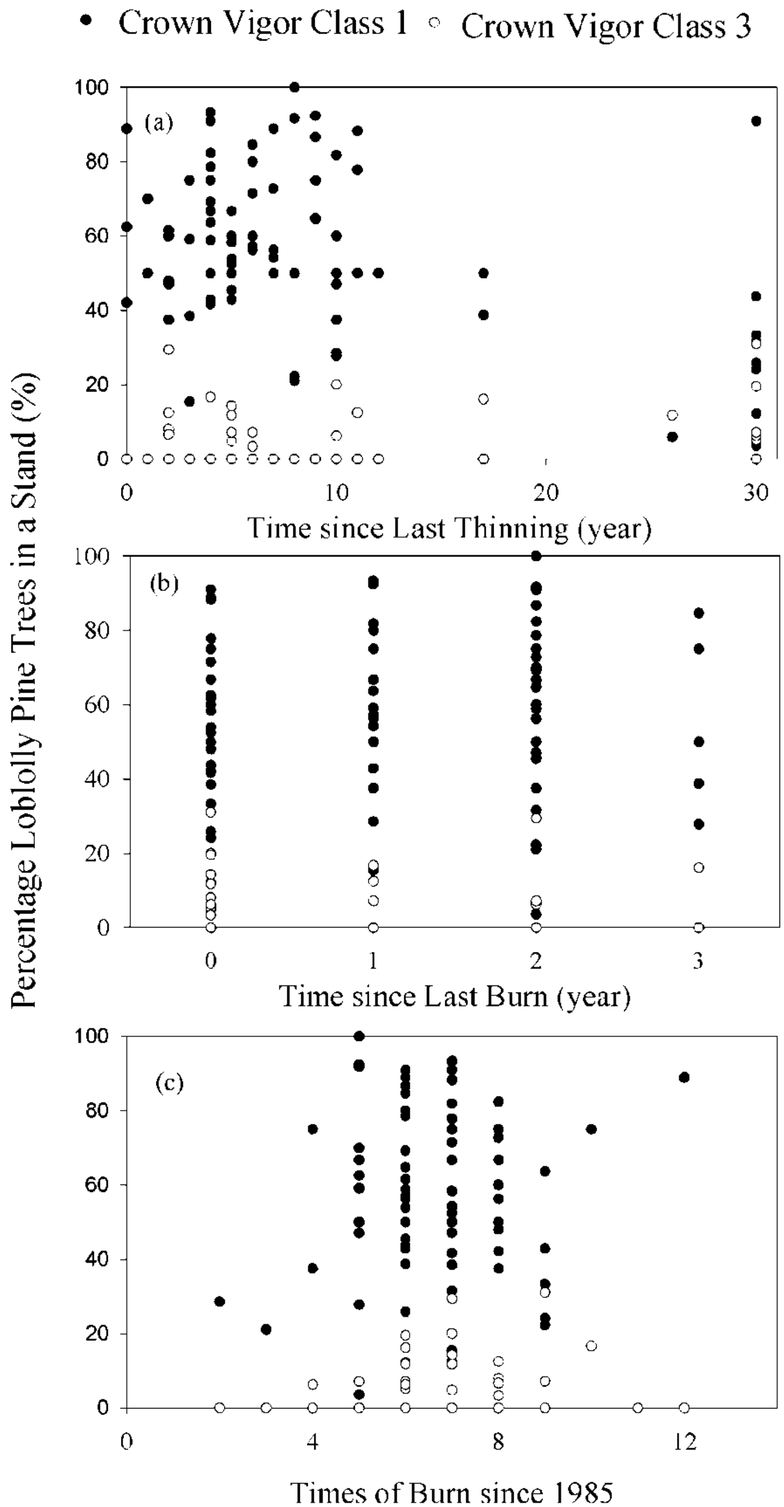


Figure 4.1.6. The relationship between loblolly pine trees classified as Crown Vigor Class 1 (%; closed circle) and Crown Vigor Class 3 (%; empty circle) with (a) time since last thinning, (b) time since last burn, and (c) number of burns since 1985.

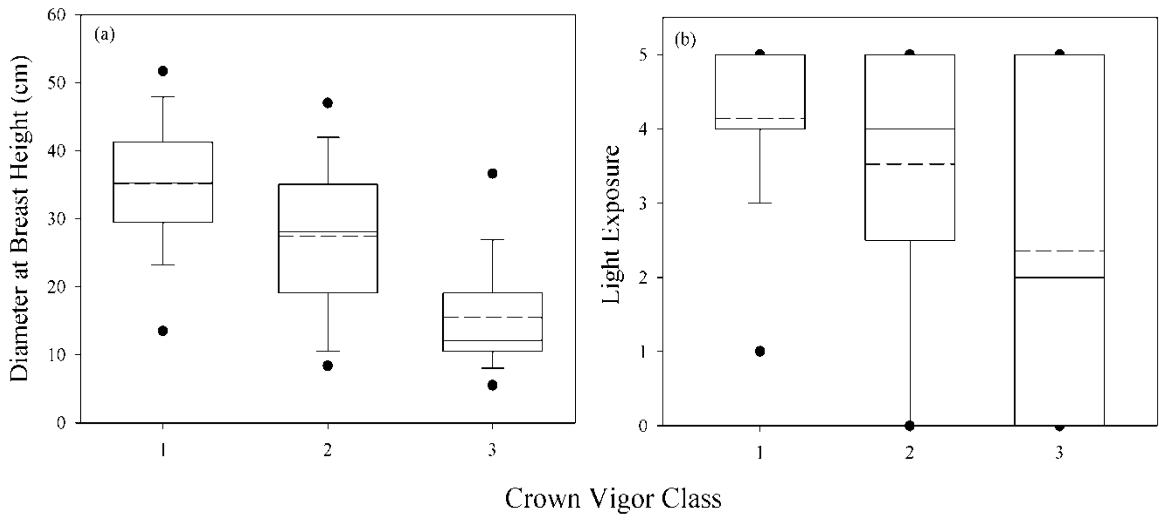


Figure 4.1.7. Box-and-whisker plots showing the range of (a) diameter at breast height (dbh) and (b) light exposure (higher means more light exposure; range 0 - 5) of loblolly pine trees by Crown Vigor Class. Solid bars of box-whisker plot represent 5, 25, 50, 75, and 95% values and dashed bar is a mean.

0.05, Kendall's Tau-b = 0.07 and p = 0.02), where 36.1, 58.3, and 5.6% of trees with stem cankers fell in CVC 1, 2, and 3, respectively, compared to 56.2, 39.8, and 4.0% without stem cankers, respectively. We also observed that 226 loblolly trees were physically damaged (e.g., by fire and logging) but did not find a significant effect on CVC (Chi-square $p = 0.23$, Kendall's Tau-*b* = -0.04 and $p = 0.10$). There were 139 loblolly pines with very abundant cones (2, 130, and 7 trees were super-dominant, dominant/codominant, and intermediate/overtopped trees), but the presence of many cones did not show a significant effect on CVC (Chi-square $p = 0.53$, Kendall's Tau-*b* = -0.03 and $p = 0.28$). There was a significant difference in dbh among CVCs ($p < 0.01$), with mean dbh of 35.3, 27.6, and 16.1 cm for CVC1, CVC2, and CVC3 (Figure 4.1.7a), respectively. We also found that healthier loblolly pines were exposed to higher light levels (Figure 4.1.7b; $p < 0.01$; Kendall's Tau-*b* = 0.11 and $p < 0.01$).

4.1.4. Discussion

Site index was the only variable showing a significant relationship with %CVC1 and %CVC3, which indicated that tree health was limited by poor site conditions (e.g., nutrient and water limitations). Generally, loblolly pine demands more nutrients and water than other pine species (Baker and Langdon 1990), and therefore nutrient and/or water deficiency could have stronger effects on loblolly health than on other pine species. This idea was further supported by the relationship between stands with poor health and soil texture (Figure 4.1.5), in which more trees classified in CVC3 were found on coarse-textured soils than fine-textured soils. Coarse-textured soils tend to have a low soil surface area and low CEC, resulting in poor nutrient and water holding capacity. However, we did not observe any significant influence of soil and foliar nutrients on crown health metrics (%CVC1 and %CVC3) in this study (Figures 4.1.2 and 4.1.3), which suggested that water stress could be the main causal factor determining loblolly crown health. Although we did not find an impact of slope and aspect on loblolly health, a study in central Alabama reported that higher slope and southern aspect increased loblolly pine decline (Eckhardt and Menard 2008). Theoretically, greater slopes tend to increase lateral water flow and soil erosion, resulting in decreased soil water-holding capacity (Miller and Donahue 1995), and, similarly, south-facing stands receive more direct sunlight than other aspects, resulting in increased soil temperatures, greater evaporation, and reduced water availability. Furthermore, prescribed burning has been implemented in Fort Benning since the 1980s, and the area burned for RCW habitat management has increased to about 12,000 ha per year on an approximately three-year rotation (USAIC 2006). Although fire can be an effective management tool (e.g. for reducing understory hardwood), it is also known to reduce nutrient availability (Raison et al. 1985; Landsberg 1993) and water availability (Boyer and Miller 1994; Busse et al. 2000; DeBano 2000). In addition, prescribed burns under some circumstances can attract root beetles (e.g. *Hylastes* spp.) that carry pathogenic fungi (Sullivan et al. 2003), which have been associated with thinning and discolored pine crowns (Hess et al. 1999). Stem canker results also support the impact of water stress on tree health. Stem canker presence was associated with decreased crown health and MacFall et al. (1994) showed stem canker caused by fusiform rust reduces water flow in the xylem leading to water stress. Klos et al. (2009) also showed a decrease in pine growth with increasing drought severity.

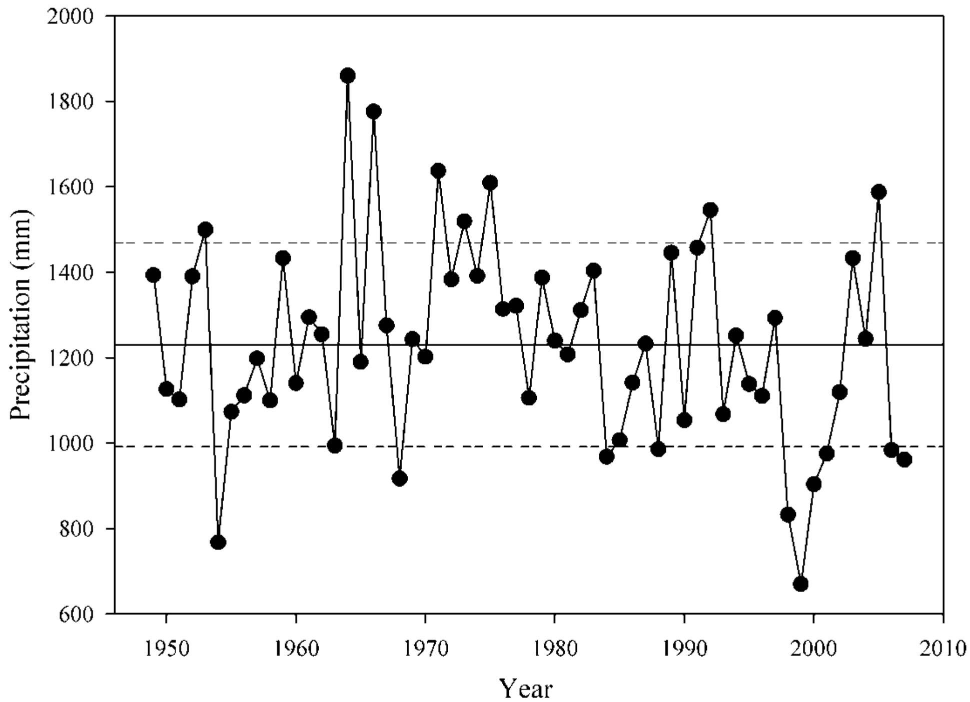


Figure 4.1.8. Historical (1949 – 2007) precipitation (mm) pattern of the region (data from Columbus airport approximately 10 km away from the study landscape). The solid line indicates the mean annual precipitation throughout the period and dashed lines show one standard deviation from the mean value.

Availability of base cations can decrease under high temperature and reduced precipitation condition (Tomlinson 1993). Severe drought in 1998–2001 could have caused nutrient stress to the loblolly pine forest as well (Figure 4.1.8); however, we did not find evidence of nutrient stress affecting tree health. A possible explanation is that the loblolly forest within our study area experienced nutrient stress during the drought period (1998–2001), but the stress was subsequently mitigated during favorable moisture conditions in 2002–2005. We observed that smaller trees tended to show poorer crown health (Figure 4.1.7), which could be due to mainly water and/or nutrient stress because it is harder for small trees to compete for nutrients and water (e.g. Binkley et al. 2002). The sampled pine stands were open, and light was not generally a limiting factor (e.g. 2–3 suppressed trees per 100 m^2).

We found only 4.0% of loblolly pines in CVC3. Cao (1994) reported that annual loblolly mortality could exceed 3% in thinned plots around age 30 in Louisiana. It was clear that loblolly pines in our study plots were not experiencing major dieback. However, our results indicated that loblolly pine stands in this area can have abnormally high mortality under high-stress weather, which will likely happen considering that Fort Benning experienced severe drought during four consecutive years (1998–2001, Figure 4.1.8) and we expect more abnormal weather under global climate change scenarios. Land managers may consider reducing the prescribed burn frequency or amending the soil physical property to decrease water stress. Furthermore, based on these results, conversion to longleaf pine should begin with stands on coarser soils (or lower SI) at Fort Benning.

4.1.5. Conclusions

Our results show that site index was the main factor in determining loblolly pine health. Poorer site index and coarser soil likely resulted in water stress during periods of drought leading to more CVC3 loblolly pine trees. Based on these results, conversion to longleaf pine should start with loblolly stands on coarser soils (or lower SI) at Fort Benning. This approach will retain healthy and mature loblolly stands for the RCW population to nest and forage, until longleaf pine stands become mature and large enough to support the RCW population. Additional studies are needed to understand how loblolly pine CVC classes can be related to the annual mortality rate. It will help us understand loblolly pine mortality dynamics in the study area and develop better management guidance.

4.2. Spatial components of mortality risk in managed loblolly pine forests on Fort Benning

This section addresses research objective O-10 focused on understanding the relationships between forest structure and the health of individual trees.

4.2.1. Introduction

In recent years, poor health or excessive mortality has been reported for mature loblolly pine stands on well-drained sites at Fort Benning and elsewhere (e.g. Hess et al. 2002; Eckhardt et al. 2007; Eckhardt and Menard 2008). This has produced a great deal of uncertainty about stand sustainability and RCW population recovery. Recent studies have suggested that pathogenic fungi (*Leptographium* spp.) interacting with topographic position were primary causes of the observed mortality patterns at Fort Benning and similar locations (Hess et al. 2002; Eckhardt 2003; Eckhardt et al. 2007). However, poor tree health and mortality are usually the result of multi-factor interactions. These factors may include resource competition, pathogen and insect attack, mechanical abrasion (by wind or snow), climate-induced environmental stress, and localized edaphic constraints (Franklin et al. 1987; Waring 1987; Das et al. 2008).

As sessile and long-lived organisms, trees are usually susceptible to competition related to their spatial distributions (Pacala and Deutschman 1996; Bolker et al. 2003; Das et al. 2008). Factors affecting tree competition, such as density or size of neighboring trees, are highly associated with tree mortality (e.g. Eid and Tuhus 2001; Canham et al. 2006; Temesgen and Mitchell 2005; Bravo-Oviedo et al. 2006; Das et al. 2008). Das et al. (2008) identified three possible ways that variations in distribution (e.g. inter-tree distance, sizes of the neighboring trees) may affect tree mortality risk: (1) increase stress due to resource competition; (2) raise the risk of pathogen or insect attack due to the proximity of like neighbors; and (3) enhance the risk of mechanical damage due to the proximity of large neighbors. Quantifying the relationships among distribution measures and tree mortality has provided insights for forest management practices and wildlife conservation (Biging and Dobbertin 1992; Das et al. 2008). However, we could find no studies that examine the effects of spatial patterns on tree health or mortality in open canopy, mature pine forests, such as those managed to provide suitable for RCWs.

In this analysis, we quantified the distribution and size of trees within neighborhoods of individual subject trees whose canopy health status was previously determined (Section 4.1). We then assessed relationships among canopy health and distribution metrics to determine under which conditions effects on morality were expressed in loblolly pine forests at Fort Benning.

4.2.2. Methods

Details of the study are given in Section 4.1.2.1.

4.2.2.1. Plot selection and data collection

Details of plot selection and field measurements are given in Section 4.1.2.2. We used data collected in ninety 30 m x 30 m plots located in mature loblolly (> 35 years old) stands. These plots were stratified by management compartment and distributed across the whole study area (see Figure 4.1.1). Field survey and data collection were conducted over two growing seasons during July–September 2006 and June–August 2007, respectively. The diameter at breast height (DBH) and height were measured for all trees with DBH > 5cm. The geographical location and mortality condition (dead or alive) of each tree were also recorded. Crown health condition was indexed as crown vigor class (CVC) based on crown ratio (ratio of live crown length to total tree length), % crown density (relative to the surrounding healthy trees), and crown dieback (% crown) and assigned to three classes following the USDA Forest Service Health Monitoring protocol (USDA Forest Service 1999). We classified sampled live trees into three health categories: good (CVC1), fair (CVC2), and poor (CVC3) based on the above crown measurements (Table 4.2.1). Trees in CVC3 were considered to be under stress with a high likelihood of mortality. All dead trees were classed as DC ("dead class").

4.2.2.2. Spatial metrics and analyses

PLOT LEVEL MEASURES OF DISTRIBUTION—To describe the overall pattern of tree distribution at the plot level, we calculated the Poisson index of dispersion (I_d, Cox and Lewis 1966):

$$I_d = \frac{s^2}{\bar{x}}$$

where x_i is the number of trees within quadrat *i*, s^2 is the variance of x_i, and $\bar{x}$ is the mean number of trees over all quadrats. $I_d < 1$ indicates a regular distribution, $I_d = 1$ indicates randomness, and $I_d > 1$ indicates aggregation. The null hypothesis of random spatial distribution is tested using a χ^2 test (Cox and Lewis 1966). We computed this index for both the 30 m × 30 m plots and the 10 m × 10 m sampling areas.

INDIVIDUAL SUBJECT TREE CENTERED METRICS—To avoid the problem that sample plots may not include all the neighbors of trees located at or close to the plot edges (Fortin and Dale 2005), we defined subject trees as stems located within the center 10 m x 10 m area of each plot. In the 90 sample plots, we tallied 310 subject trees. Of those subject trees, 21 were classified as DC, 19 as CVC3, 115 as CVC2, and 155 as CVC1. We calculated both total basal area and number of live trees within circular neighborhoods defined by sequentially increasing radii (r = 2, 3… 10 m) around each subject tree.

Table 4.2.1. Tree vigor classes and their definitions. Trees must meet all three specified criteria in order to be classified to CVC1 or CVC3.

Vigor class	Live crown ratio	Crown dieback	Crown density
CVC1	>35%	<5%	>80%
CVC2	All trees not assigned to CVC1 or CVC3		
CVC3	<35%	>50%	<20%

For each subject tree we also calculated the Hegyi index (*H*; Biging and Dobbertin 1992) for a set of neighborhoods defined by sequentially increasing radii (r = 2, 3… 10 m) up to 10 meters. The Hegyi index is a composite metric that considers both the size of and the distance to neighboring trees. A larger *H* indicates denser, bigger, or closer neighboring trees, which implies a higher competitive status around the subject tree. The index was calculated following the formula of Biging and Dobbertin (1992):

$$H = \sum_{j \neq i} \frac{DBH_j}{DBH_i \times (Dist_{ij} + 1)}$$

where DBH_i is the diameter (cm) of the subject tree, DBH_j is the diameter of the neighboring tree, and $DIST_y$ is the distance (m) between the subject and neighboring trees within a specified radius (Das et al. 2008).

STATISTICAL ANALYSES--We performed a series of analyses to determine whether spatial metrics were related to tree mortality. Statistical significance was determined at $\alpha = 0.05$. Derivation of variables and all the following statistical analyses were conducted in R (Version 2.11.1, R Development Core Team 2006).

We used a series of one-way analyses of variance (ANOVAs) to compare the total basal area, number of live stems, and *H* of the DC trees with each live CVC class (CVC1, CVC2, CVC3) for every neighborhood size (r = 2, 3, 4…, and 10 m). Tukey honest significant differences (HSD) were used for comparisons (Sokal 2011).

We used a simple experimental effect size measurement, Cohen's *d* (Cohen 1988; Rosnow and Rosenthal 1996), to test tree density differences among selected health classes. The formula for the index is $d = (M_1 - M_2)/\sigma_{pooled}$, where $\sigma_{pooled} = \sqrt{(\sigma_1^2 + \sigma_2^2)/2}$, M_1 and M_2 are the means, and σ_1 and σ_2 are the standard deviations of the two groups under comparison. Following Cohen's definition (Cohen 1988), the treatment effect sizes could be classified as large ($d \geq 0.8$), medium ($0.5 \leq d < 0.8$), or small ($d \leq 0.2$). We used both total basal area and total number of neighboring live trees within various radii as measurements of the effect. We performed two pairs of comparisons, dead (DC) versus live (CVC1+CVC2+CVC3) and poor health (CVC3+DC) versus healthy (CVC1+CVC2).

We also used a one-way ANOVA to test for health class effects on the size of and distance to the nearest neighbor.

Finally, using the results from previous analyses to inform the input parameters, we built a generalized linear model (GLM) to predict the probability of tree mortality based on measurements of the surrounding live trees and their distances to the subject trees. We fitted the GLM based on measurements of neighboring trees within the radius at which the spatial effect became small (r = 8 m) as determined from previous analyses. Predictive variables included total basal area, number of neighboring trees, mean height of neighboring trees, nearest neighbor distance, mean neighbor distance, and *H*. The best model was chosen based on Akaike's Information Criterion (AIC) scores (Clark 2007) among models fitted with all possible combinations of the predictive variables. Using the area under the curve (AUC) of a receiver operating characteristics (ROC) plot (Fawcett 2006), a threshold-independent measure of model discrimination, we assessed the model's ability to distinguish between live and dead trees. According to Hosmer and Lemeshow (1999), AUC values of 0.5 indicate no discrimination, 0.7–0.8 acceptable discrimination, and 0.8–0.9 excellent discrimination.

4.2.3. Results

At the plot level, I_d = 5.12, significantly greater than 1 and indicating a strongly aggregated tree spatial distribution in our study area. Even at a smaller sampling level (10 x 10 m^2), trees were significantly aggregated (I_d = 1.72).

Both total basal area and number of live trees became similar between the dead and the other three vigor classes as neighborhood size increased (Tables 4.2.2 and 4.2.3). The differences between DC and CVC1 were consistently significant when $r \leq 8$ m. The total basal area of DC and CVC2 were significantly different up to a 6 m radius (Table 4.2.2); but DC and CVC3 were not significantly different for either density metric at any radius. Likewise, no significant differences were found in either metric among the three live tree vigor classes.

Patterns of differences in *H* among health classes differed from those of basal area and number of live stems. Neither CVC2 or CVC3 subjects differed from dead subjects at any neighborhood size, while differences between CVC1 and DC were detected at only 3 scales, the largest being a 6 m radius (Table 4.2.4). For CVC2 and CVC3 trees, *H* values were similar to those of DC trees at all neighborhood sizes. *H* values of CVC1 and CVC2 trees became significantly different beyond a 4 m radius (Table 4.2.4), in contrast to other measurements. Differences between CVC1 and CVC3 were significant at various radii, but the pattern was not consistent.

Measured by Cohen's *d*, the comparison of dead and live trees resulted in a medium to large effect size ($d \geq 0.5$) for both total basal area and number of neighboring trees at radii < 8 m (Figures 4.2.2a and 4.2.2b). Comparison between unhealthy (CVC3 and DC) and healthy (CVC1 and CVC2) tree classes showed that total basal area was different at radii < 6 m (Figure 4.2.2c) and number of trees were different at radii < 8 m (Figure 4.2.2d).

Among all tree health classes, dead trees (DC) and healthy trees (CVC1) had the biggest nearest neighbors, with basal areas of 0.85 ± 0.12 m^2 and 0.94 ± 0.06 m^2, respectively. These were significantly larger that the similar CVC2 and CVC3 neighbors (0.68 ± 0.05 m^2 and 0.60 ± 0.13 m^2, respectively; Figure 4.2.3a). DC trees had the nearest neighbors (2.99 ± 0.37 m) and CVC1 trees had the farthest neighbors (4.54 ± 0.17 m) (Figure 4.2.3b), which were significantly different from each other. The nearest neighbor distances for the other two vigor classes (CVC2 and CVC3) were 3.86 ± 0.19 m and 3.64 ± 0.60 m, respectively, which were not significantly different from each other or from the other two classes (Figure 4.2.3b).

Table 4.2.2. Total basal area (standard error) (m^2) of live neighboring trees within different radii by classes. DC = dead class, CVC = crown vigor class. Significant levels are indications of the ANOVA multiple comparisons (Tukey Honest Significant Differences) between each of the vigor classes against DC. Significant codes: 0.001 '***', 0.01 '**', and 0.05 '*'. Comparisons between vigor classes showed no significant differences

Radius (m)	CVC1	CVC2	CVC3	DC
2	0.01 (0.01)**	0.05 (0.01)	0.04 (0.03)	0.10 (0.04)
3	0.08 (0.02)***	0.09 (0.02)***	0.14 (0.04)	0.28 (0.07)
4	0.16 (0.02)***	0.20 (0.02)**	0.25 (0.07)	0.43 (0.09)
5	0.27 (0.03)***	0.34 (0.03)**	0.40 (0.09)	0.63 (0.09)
6	0.44 (0.03)***	0.55 (0.04)*	0.67 (0.12)	0.84 (0.10)
7	0.64 (0.04)**	0.77 (0.05)	0.80 (0.12)	1.03 (0.10)
8	0.81 (0.04)*	1.01 (0.05)	1.05 (0.15)	1.18 (0.11)
9	1.12 (0.05)	1.29 (0.06)	1.35 (0.18)	1.35 (0.13)
10	1.45 (0.06)	1.55 (0.07)	1.65 (0.19)	1.63 (0.16)

Table 4.2.3. Number (standard error) of live neighboring trees within different radii by classes. DC = dead class, CVC = crown vigor class. Significant levels are indications of the ANOVA multiple comparisons (Tukey Honest Significant Differences) between each of the vigor classes against DC. Significant codes: 0.001 '***', 0.01 '**', and 0.05 '*'. Comparisons between vigor classes showed no significant differences

Radius	CVC1	CVC2	CVC3	DC
2	0.10 (0.03)	0.23 (0.05)	0.38 (0.15)	0.38 (0.15)
3	0.32 (0.05)***	0.51 (0.07)	0.95 (0.24)	0.95 (0.24)
4	0.66 (0.07)**	1.07 (0.12)	1.48 (0.31)	1.48 (0.31)
5	1.32 (0.11)**	1.83 (0.15)	2.62 (0.47)	2.62 (0.47)
6	1.68 (0.12)***	2.37 (0.17)	3.24 (0.46)	3.24 (0.46)
7	2.29 (0.14)***	3.14 (0.21)	4.10 (0.54)	4.10 (0.54)
8	2.99 (0.17)**	4.09 (0.25)	4.81 (0.67)	4.81 (0.67)
9	4.01 (0.22)	5.23 (0.31)	5.62 (0.82)	5.62 (0.82)
10	5.12 (0.26)	6.39 (0.38)	6.76 (0.97)	6.76 (0.97)

Table 4.2.4. *p*-values of one-way ANOVA multiple comparisons (Tukey Honest Significant Differences) of Hegyi index within different radii by classes. Significant codes: 0.001 ‘***’, 0.01 ‘**’, and 0.05 ‘*’

Radius (m)	DC-CVC1	DC-CVC2	DC-CVC3	CVC3-CVC2	CVC3-CVC1	CVC2-CVC1
2	0.155	0.872	0.995	0.726	0.094	0.061
3	0.003**	0.116	0.971	0.393	0.029*	0.096
4	0.023*	0.546	1.000	0.669	0.048*	0.024*
5	0.111	0.902	0.995	0.989	0.303	0.011*
6	0.027*	0.841	0.994	0.678	0.014*	0.001***
7	0.083	0.982	0.999	0.948	0.068	0.001***
8	0.198	0.999	0.889	0.857	0.025*	0.000***
9	0.588	0.939	0.679	0.817	0.041*	0.003**
10	0.816	0.842	0.568	0.825	0.058	0.007**

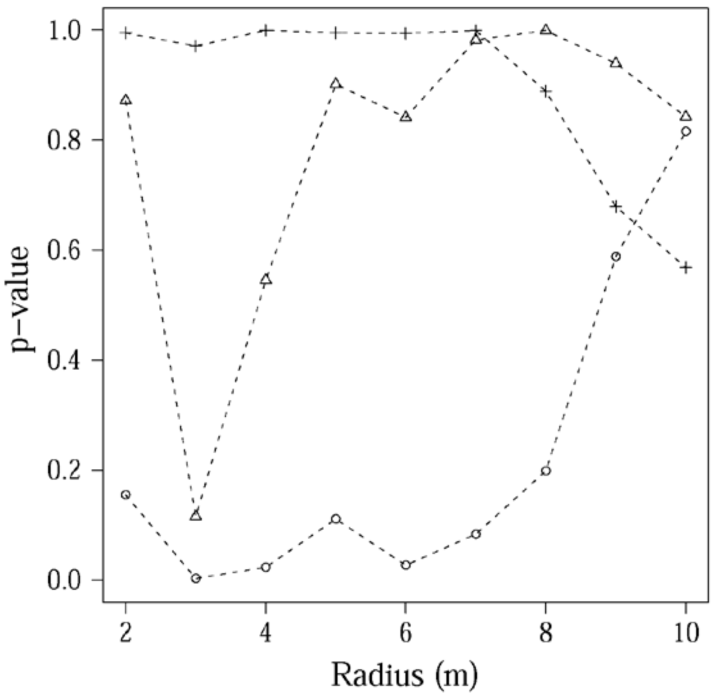


Figure 4.2.1. *p*-values of one-way ANOVA multiple comparisons (Tukey Honest Significant Differences) of Hegyi index within different radii between dead tree class (DC) and each health class (CVC) of loblolly pine trees. Circle = DC vs. CVC1, triangle=DC vs. CVC2, and cross=DC vs. CVC3.

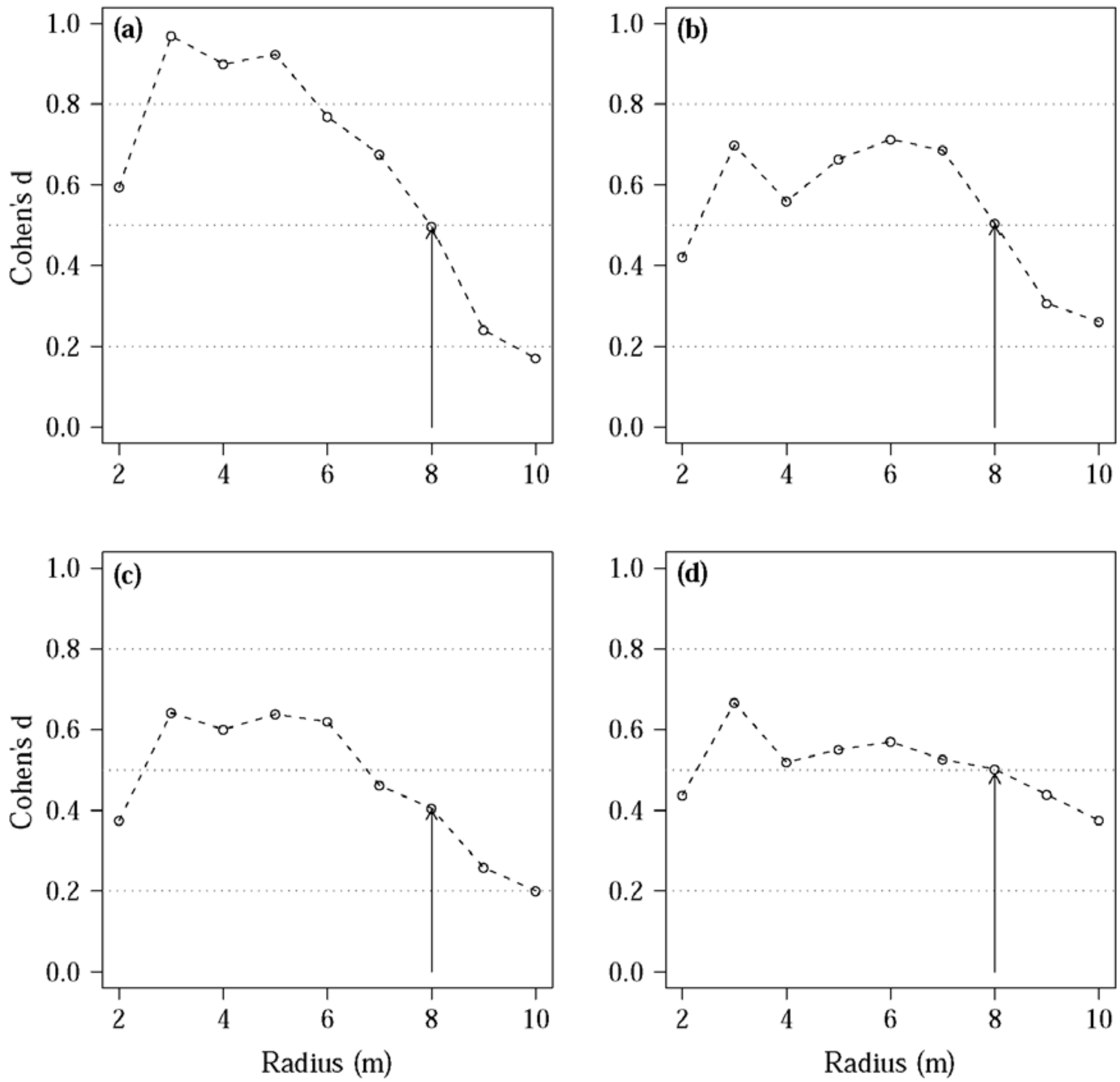


Figure 4.2.2. Treatment effect of total basal area and number of trees within various radii around trees between dead (treatment) and alive loblolly pine ((a) and (b)), and between healthy and unhealthy trees ((c) and (d)). Healthy = CVC1+CVC2, Unhealthy = CVC3+DC, where DC = dead class and CVC = crown vigor class.

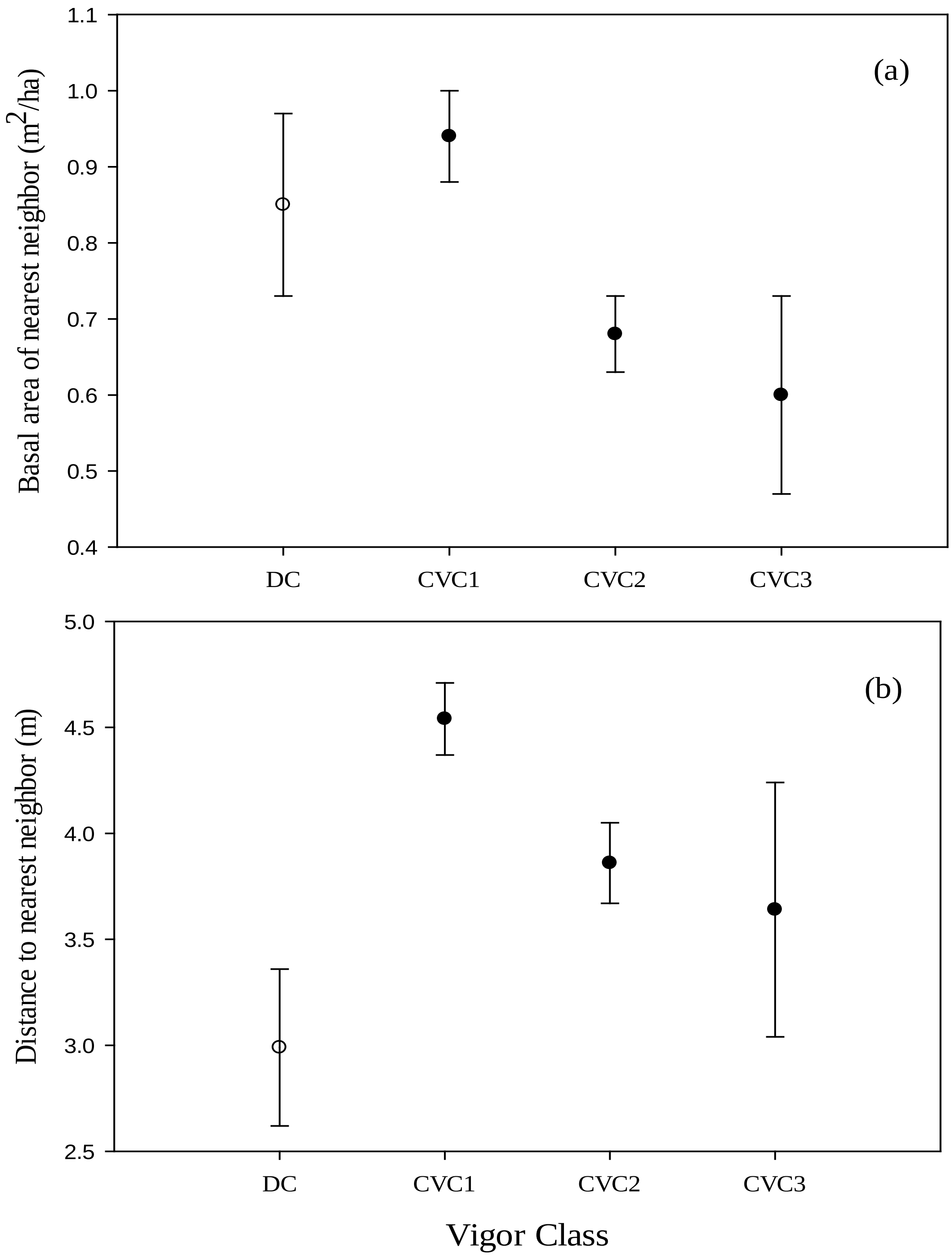


Figure 4.2.3. Mean (± SE) values for (a) basal area of the nearest neighbor and (b) nearest neighbor distance by crown vigor class.

Our fitted GLM showed that the number of trees (n), mean surrounding tree heights, and mean distance to the subject trees were the best combination of measurements to predict tree mortality (Table 4.2.5). The AUC value of this model was 0.7, which is on the low end of the acceptable discrimination (0.7–0.8) category (Hosmer and Lemeshow 1999).

4.2.4. Discussion

4.2.4.1. Influence of neighboring tree proximity, abundance and size on loblolly pine health and mortality prediction

Echoing the findings of previous research on other pine species (e.g. Biging and Dobbertin 1992; Das et al. 2008), our results show that the spatial distribution of trees provides information about the likelihood of loblolly pine mortality. Specifically, mortality of loblolly pine is associated with the density of and distance to surrounding trees. The strength of the associations between neighboring tree density and subject tree mortality decreased with distance from the subject tree. The effective distance of the neighbor's basal area influence was between 6 and 8 m according to Cohen's *d*, suggesting that 8 m was the conservative effective distance in the study area. This threshold was also supported by total basal area, number of trees, and *Hegyi* index.

The mortality of an individual loblolly pine tree in this study area was reasonably predicted using measurements of its neighboring trees. This result agreed with similar forms of prediction models for other species (e.g. Das et al. 2008). However, unlike other studies emphasizing tree growth rate as the major contributor to mortality prediction models (Das et al. 2008; Biging and Dobbertin 1992), our model was based primarily on spatial measurements that included the number and mean distance of trees within an 8 m radius of the subject trees. The prediction power of this model implies that competition had been a strong driver of mortality within the study area. We did not consider tree growth rate as a predictor variable in our model because our purpose was not to build the best mortality prediction model but rather to describe how the distribution of neighboring trees influenced mortality of the subject trees. The existence of this influence has important implications because spatial distribution of canopy pines can be managed.

4.2.4.2. Implications of loblolly pine spatial competition on RCW habitat management

To minimize loblolly pine mortality from competition, our results suggest that total basal area should be managed under 40 m^2/ha (< 0.81 m^2 within an 8 m radius (Table 4.2.2)) and the stem density (> 35 years old) should be less than 149 trees/ha (< 3 trees within 8 meters radius (Table 4.2.3)). Based on our sampling plots, the observed total basal area was 15.24 m^2/ha with a standard deviation of 4.29 m^2/ha, much lower than the maximum value suggested above. The observed mean stem density, on the other hand, was 154 ± 8 trees/ha and was close to the suggested maximum stem density. However, among all the sampled trees, only about half (51%) were in good condition (CVC1) and more than ten percent (12%) were either dead (DC) or in poor health (CVC3). Clearly, the spatial distribution of the individual trees at smaller scales ($r \leq$ 8 meters) played an important role in affecting tree health status. Our analyses suggest that the distance to the nearest neighbor should be greater than 2.98 meters to reduce mortality risk of the subject tree, but should be at least 4.54 meters to significantly reduce spatial competition.

Table 4.2.5. Optimal predictive GLM of tree mortality based on live tree measurements within 8 m of the subject trees. n = number of trees; $\bar{h}$ = mean surrounding tree heights; $\bar{d}$ = mean distance to the subject trees. AIC = 218.77 and AUC = 0.7

Parameters	Mean(±sd.err)	p-value
Intercept	-0.39 (1.40)	0.78
n	0.20 (0.08)	0.01
$\bar{h}$	0.02 (0.05)	0.66
$\bar{d}$	-0.53 (0.18)	0.00

Loblolly pine stands in our study area had been heavily thinned to improve RCW habitat, but a lack of explicit consideration of tree spacing could result in some trees being closely aggregated as they are in the study area.

Although our study indicates that the maximum basal area could be 40 m^2/ha without increasing mortality risk, such high densities are not realistic in stands managed for RCW habitat. Previous research has shown that RCWs prefer open pine stands, usually between 14 – 18 m^2/ha in loblolly or longleaf pine forests (e.g. Mitchell et al. 1991; Conner and Rudolph 1995). The major cause of cavity tree mortality in loblolly pine has been identified as southern pine beetle (*Dendroctonus frontalis* Zimmermann) infestation (Conner et al. 1991), an effect associated with high stand densities. It has been suggested that loblolly pine stands should be maintained at basal areas less than 18.4 m^2/ha or an average spacing of at least 7.6 m between mature pine trees to reduce the spread of beetle infestation (Thatcher et al. 1980; Hicks et al. 1987; Mitchell et al. 1991). Thus, 18 m^2/ha might be a more reasonable maximum basal area for loblolly pine forests managed for RCW habitat.

4.2.4.3. Suggestions for future research

Trees are spatially distributed because of the way they were regenerated (e.g., seed dispersal or root sprouts) and the constraints within the environment. Though there may be adverse effects with higher densities, trees may also benefit from growing in clusters; there may be improved opportunities to reproduce and resilience to certain disturbances such as wind throw. It would be helpful to know if increased mortality is associated with tree isolation; this information would give a range of the best inter-tree distances. Moreover, it would be valuable to gain information on the effect of tree spatial distribution on insect or disease dispersion or wind-throw events. The effects of stand age and site quality on the relation between tree health and spatial distribution would be an additional important topic. Studies based on sampling data from a wider range of site quality and age class may help us better understand the tree health and mortality dynamics.

4.2.5. Conclusions

Despite the fact that loblolly pine stands in our study area had been heavily thinned for RCW habitat, a strongly aggregated spatial distribution of canopy trees was evident. Clearly, a lack of explicit consideration of tree spacing during thinning renders some trees in close proximity to each other. As a result, the size and spatial distribution of neighboring trees becomes an important driver of loblolly pine mortality. To minimize neighbor effects on tree health and mortality, thinning operations should explicitly consider the spatial distribution of trees. We specifically recommend that for a mature loblolly pine forest managed for RCW habitat, its maximum total basal area be around 18 m^2/ha, inter-tree distance be greater than 3.4 meters, and the maximum stem density be less than 150 trees/ha.

5. Can individual tree mortality be predicted? (Question 3)

This section addresses research Question 3, objective O-11. It describes results of using dendrochronology to evaluate canopy health assessment classes and predict mortality of loblolly pine trees at Fort Benning, GA.

5.1. Introduction

Tree health is modulated through a web of ecophysiological interactions, and many methods have been used to assess tree health in the field (Dobbertin 2005), including crown transparency assessments (Eichhorn et al. 2004), needle size or shape (Kozlov and Niemela 1999), crown morphology analysis (Roloff 1987), tree diameter growth analysis (Waring et al. 1980), and foliar and sapwood nutrient analysis (Stefan et al. 1997). The USDA Forest Service developed a system of canopy measurements that can be used to readily assess tree health in the field (see Sections 4.1 and 4.2), and crown conditions have been found to relate well to tree growth for many species (e.g. Manion 1991, Kramer 1996, Dobbertin 2005) and specifically for loblolly pine (Anderson and Belanger 1987). Because tree growth is a good indication of vigor (e.g. Waring et al. 1980, Mitchell et al. 1983, Duchesne et al. 2003), it is logical that canopy assessment can be used to quantify tree vigor as well. The accuracy of the canopy assessment system used USDA Forest Service can be evaluated with chronosequential tree ring growth analyses that assess past patterns in tree growth for trees assigned to different crown health classifications.

Understanding patterns of tree mortality is important for development stand level management protocols and dendrochronological data can be used to reliably predict tree mortality (e.g. Monserud and Sterba 1999, Wyckoff and Clark 2002, Bigler and Bugmann 2004). In dendrochronological studies, multiple logistic regression models have frequently been used to predict the probability of tree mortality or the time of tree death (Hamilton 1986, Monserud and Sterba 1999, Bigler and Bugmann 2004). Studies have reported that tree rings showed a dramatic decrease in growth in the short-term prior to death. Specifically, the average ring width in 3 or 5 years immediately prior to death, basal area increment slope (e.g., basal area increment over 5 and 25 years), and the ratio of basal area increment to basal area were the important factors for evaluating tree mortality status (Cherubini et al. 2002, Bigler and Bugmann 2003, Bigler et al. 2004). Longitudinal data or repeated measurements may also be useful in prediction models (Liang and Zeger 1986, Bigler and Bugmann 2004). In longitudinal data analysis, the entire series of tree ring growth information, from the bark to the pith of a tree, is available to determine effects of both long- and short-term growth patterns (Botkin et al. 1972, Pederson 1998). Therefore, autocorrelation within an individual tree ring chronology was adopted to predict the current status of the tree and each year's survival probability.

The objectives of this study were to evaluate: (1) the validity of classifying tree vigor based directly on crown vigor classes (CVC) system (i.e., CVC1 = vigorous; CVC2 = fair; and Dead = dead tree) using tree ring growth pattern; and (b) the predictability of loblolly pine tree mortality using dendrochronological data. We hypothesized that: (a) tree ring growth of class CVC1 would be larger than those of less vigorous classes because current health status is related to past vigor; and (b) tree mortality may be predicted using measures of recent growth (within 3-10 years) in intensively managed loblolly pine stands.

5.2. Methods

5.2.1. Study sites

Refer to Section 4.1.2.1 for detailed descriptions of study sites.

5.2.2. Plot selection and field sampling

Details of plot selection are described in Section 4.1.2.2; methods specific to the analysis of tree data are included here. In this study we use 37 sampling plots installed in 2006 and 53 plots installed in 2007. In each 30 m x 30 m sampling plot, we measured diameter at breast height (DBH) at 1.3 m and tree height of each live loblolly pine tree. Live crown ratio, crown light exposure, crown position, crown density and crown dieback were assessed to evaluate the Crown Vigor Class for each loblolly pine tree in the plots (USDA Forest Service 1999; see Sections 4.2 and 4.3). We used an increment borer to sample tree cores at breast height from the north and south sides of 5 randomly selected live dominant trees and 5 randomly selected dead trees per plot. When there were less than 5 dead trees available for sampling in a plot, we sampled from dead trees near the plot and all of the dead trees were recorded as Dead group. Each tree core was immediately transferred to a plastic straw and stored in a cooler in the field. The cores were frozen from the day of sampling until mounting to prevent shrink and bending due to drying. Each live tree was assigned to a crown vigor class (CVC) in accordance with an established crown vigor classification system (Table 4.2.1); CVC3 trees were not included in this analysis because they were clearly in poor health and a model would not be needed to predict their imminent death. For analysis, dead trees were assigned to a Dead class

5.2.3. Tree ring measurements

Each tree core was mounted, sanded, and then measured with a Velmex measuring system (Bloomfield, New York). Data from north and south cores were averaged for analyses, unless only one core was available. Ring width was measured to quantify growth, and cross-dating was conducted using the memorization method and marker rings (Douglass 1941, Stokes and Smiley 1968, Toth et al. 2009, Speer 2010). As a quality measure for each tree ring series, we ran a specialized statistical program (COFECHA) that evaluates ring width chronologies to remove errors in ring width measurements (Holmes 1983, Speer 2010). Cores from dead trees were marked every tenth year from the recognizable outermost ring, and each tree ring measurement was compared to the ring measurements from living trees in the same plot to identify the year of death and to reduce measurement errors due to false and missing rings.

Tree ring measurements were divided into three age cohorts for selected analyses: older than 78 years (ring records start between 1898 and 1924); between 58 and 78 years (ring records start after 1925 and before 1950); and younger than 58 years (ring records start after 1950) (Figure 5.1.1). Because ring growth tends to be largest when stem diameter is small (i.e. young trees), classifying trees by age reduces analysis error.

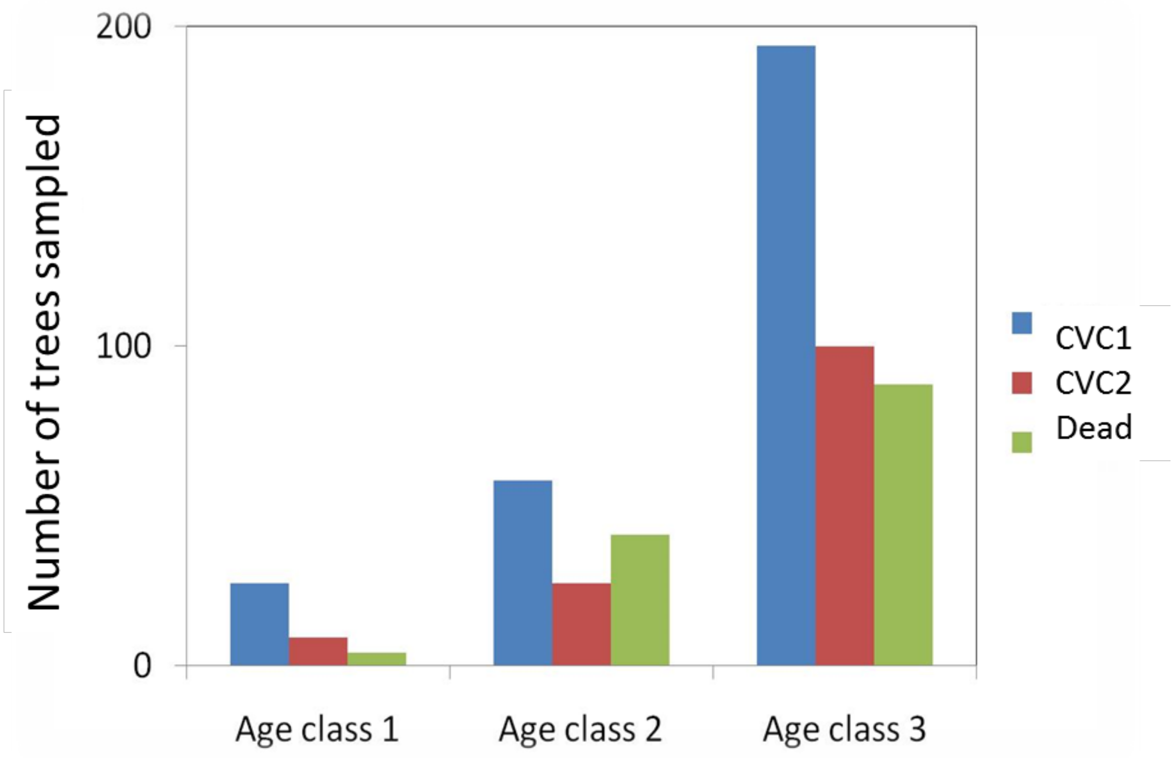


Figure 5.1.1. The number of trees sampled by age class. Age class 1 = the oldest age class (> 78 years); Age class 2 = the second age class (58 ≤ Age class 2 ≤ 78 years); Age class 3 = the youngest age class (58 years <).

Annual basal area growth was estimated from ring growth data. We first calculated the diameter inside the bark (DIB) by subtracting bark thickness from DBH, where bark diameter was estimated using Feduccia and Mann's bark thickness equation (1975):

$$\text{bark thickness at breast height} = (0.3989 + 0.1284 \times \text{DBH})/2)$$

Mean annual ring growth was calculated by averaging the ring growth of the north and south cores, then total ring growth was estimated by summing all available annual mean ring growth measurements. Total ring growth was proportionally adjusted to be equal to half of the DIB value for each tree. Weather data from Columbus Metropolitan Airport (1948~2007), located 19.8 km north from the study area, was used to determine relationships between tree ring variables and climate patterns.

5.2.3. Statistical analysis and logistic regression model development

We developed and evaluated logistic regression models of the following form to predict tree mortality based on individual tree growth:

$$\Pr(\text{Y}i,t = 1|\text{X}i,t) = \frac{1}{1 + \exp(\text{X}i,t\beta)^{-1}}$$

where Yi,t is the survival probability of a tree i at time t ($Yi,t = 1$ indicates a tree i is alive at year t, $Yi, t = 0$ means a tree i is dead at year t). Xi represents independent variables of tree i at time t and β is the regression coefficient of each independent variable. We considered three types of independent variables commonly used to increase the reliability of mortality prediction: growth level variables (Wyckoff and Clark 2002, Bigler and Bugmann 2003), growth trend variables (Bigler and Bugmann 2003), and relative growth variables (Bigler and Bugmann 2003). Growth level variables included mean basal area increment of every 3 (bai3), 5 (bai5), and 10 (bai10) years, and mean raw ring width for the same period (rw3, rw5, and rw10, respectively). Since most of the trees showed abruptly decreased diameter growth prior to death, negative growth trends could be useful in the mortality model. To take this into account, the slopes of local linear regression for every 5 years (locreg5), 10 years (locreg10) and 25 years (locreg25) were calculated as growth trend variables. Lastly, the basal area increment divided by basal area was considered a relative growth variable that standardizes tree growth based on tree size.

All of these variables were calculated from the year of sampling to the oldest ring in the core, and combinations of the variables were used to build the best prediction model. We had over 7000 measurements for each model and 28 combinations of independent variables (Table 5.1.1). Logistic regression models were run using glm (family='binomial') in the R statistical package, and AIC (Akaike Information Criterion) was used to choose the goodness-of-fit of the models (the lowest value indicates the best model).

If the survival probability dropped below a certain threshold level the tree was predicted to be dead. Bigler and Bugmann (2004) suggested a theoretical way of calculating the threshold as the number of measurements from living trees divided by the number of measurements from both live and dead trees, which is 0.9902 in our study (i.e., (7107-70)÷7107). However, we set the

Table 5.1.1. The combination of independent variables used in the mortality model

Model	Linear combination of independent variables	Number of measurements
1	log(bai3)	13406
2	log(bai5)	12831
3	log(bai10)	11401
4	log(relbai)	13406
5	locreg5	12831
6	locreg10	11401
7	locreg25	7107
8	log(bai3) + locreg5	12831
9	log(bai5) + locreg5	12831
10	log(bai10) + locreg5	11401
11	log(bai3) + locreg10	11401
12	log(bai5) + locreg10	11401
13	log(bai10) + locreg10	11401
14	log(bai3) + locreg25	7107
15	log(bai5) + locreg25	7107
16	log(bai10) + locreg25	7107
17	log(bai3) + log(relbai)	13406
18	log(bai5) + log(relbai)	12831
19	log(bai10) + log(relbai)	11401
20	log(bai3) + locreg5 + log(relbai)	12831
21	log(bai3) + locreg10 + log(relbai)	11401
22	log(bai3) + locreg25 + log(relbai)	7107
23	log(bai5) + locreg5 + log(relbai)	12831
24	log(bai5) + locreg10 + log(relbai)	11401
25	log(bai5) + locreg25 + log(relbai)	7107
26	log(bai10) + locreg5 + log(relbai)	11401
27	log(bai10) + locreg10 + log(relbai)	11401
28	log(bai10) + locreg25 + log(relbai)	7107

bai3=basal area increment of three year average (cm^2); bai5=basal area increment of five year average (cm^2); locreg5=slope of local linear regressions over five years of basal area increment; locreg10=slope of local linear regressions over ten years of basal area increment; locreg25=slope of local linear regressions over twenty-five years of basal area increment; rw3=raw ring width of three year average (0.001mm); relbai=ratio of basal area increment to basal area. The number of measurements was calculated from accumulated lengths of independent variables based on time-series of 150 trees from CVC1, 66 trees from CVC2, and 70 trees from Dead. The values are different due to different moving windows.

threshold at 0.9948 because at this level the model performance was best according to accuracy criteria and prediction error criteria (explained in detail below).

5.2.4. Model verification and validation

Half of the data was randomly chosen to build the model; verification of the model was conducted with the original dataset (Dead=70, CVC1=150, CVC2=66) and the rest of the data were used in validation of the model (Dead=44, CVC1=124, CVC2=66). Every tested model was applied to each individual tree for both verification and validation of the models. Although AIC is commonly used for model selection, other criteria may also be useful for logistic model selection. To assess our models, we used two criteria for prediction accuracy (i.e., correctly predicted to be dead (CPd), correctly predicted to be alive (CPl)), and two criteria for prediction error (i.e., predicted year of death within 5 years (PEd5) of true year of death, predicted year of death between 6 and 10 years (PEd6-10) of true year of death). The best tree mortality model was selected after we ranked each model according to those criteria.

5.3. Results

5.3.1. Canopy Vigor Classes and tree growth

Mean tree height was 24.33 m (SD = 3.59 m) for CVC1 and 24.08 m (SD = 4.03 m) for CVC2, and there was no statistical difference in tree height between the two vigor classes (Figure 5.1.2a; $p = 0.52$). The mean diameter at breast height (DBH) was 38.04 cm (SD = 7.96 cm), 34.91 cm (SD = 8.94 cm), and 40.27 cm (SD = 12.25 cm) for CVC 1, 2, and Dead, respectively (Figure 5.1.2b). DBH of CVC1 and Dead were significantly larger than that of CVC2 ($p = 0.004$, and $p < 0.001$, respectively), but there was no significant difference between CVC1 and Dead ($p = 0.06$).

In the oldest age class, CVC2 showed higher growth pattern than CVC1 ($p < 0.001$) between 1907 and 1922, however, CVC1 became higher in growth than CVC2 from 1923 to 1956 ($p < 0.001$, Figure 5.1.3a). After 1957, there was no significant difference in ring growth of CVC1 and CVC2 but the growth trend was almost identical. The growth patterns of CVC1 and CVC2 in the second age class seemed similar to that in the oldest age class (Figure 5.1.3b), and CVC2 was lower than CVC1 between 1930 and 1965 ($p < 0.001$). CVC2 had generally smaller ring growth than CVC1 in the youngest age class except during the period from 1952 to 1968 (Figure 5.1.3c). Unexpectedly, the Dead group had larger growth than both CVC1 and CVC2 in earlier years for the two younger age classes and generally showed similar growth pattern with CVC1. However, tree ring width significantly decreased about 5 year prior to death for trees in the Dead group.

When we ignored the age groups and analyzed ring width after 1970, growth patterns of the three health classes were distinctive (Figure 5.1.4). CVC1 and CVC2 were not significantly different between 1970 and 2008 ($p = 0.120$), but the amount of growth was significantly different between CVC1 and Dead ($p < 0.001$) and between CVC2 and Dead ($p < 0.001$) during the same period. Annual ring width of Dead trees decreased sharply after 2003 and fell well below that of CVC1 and CVC2.

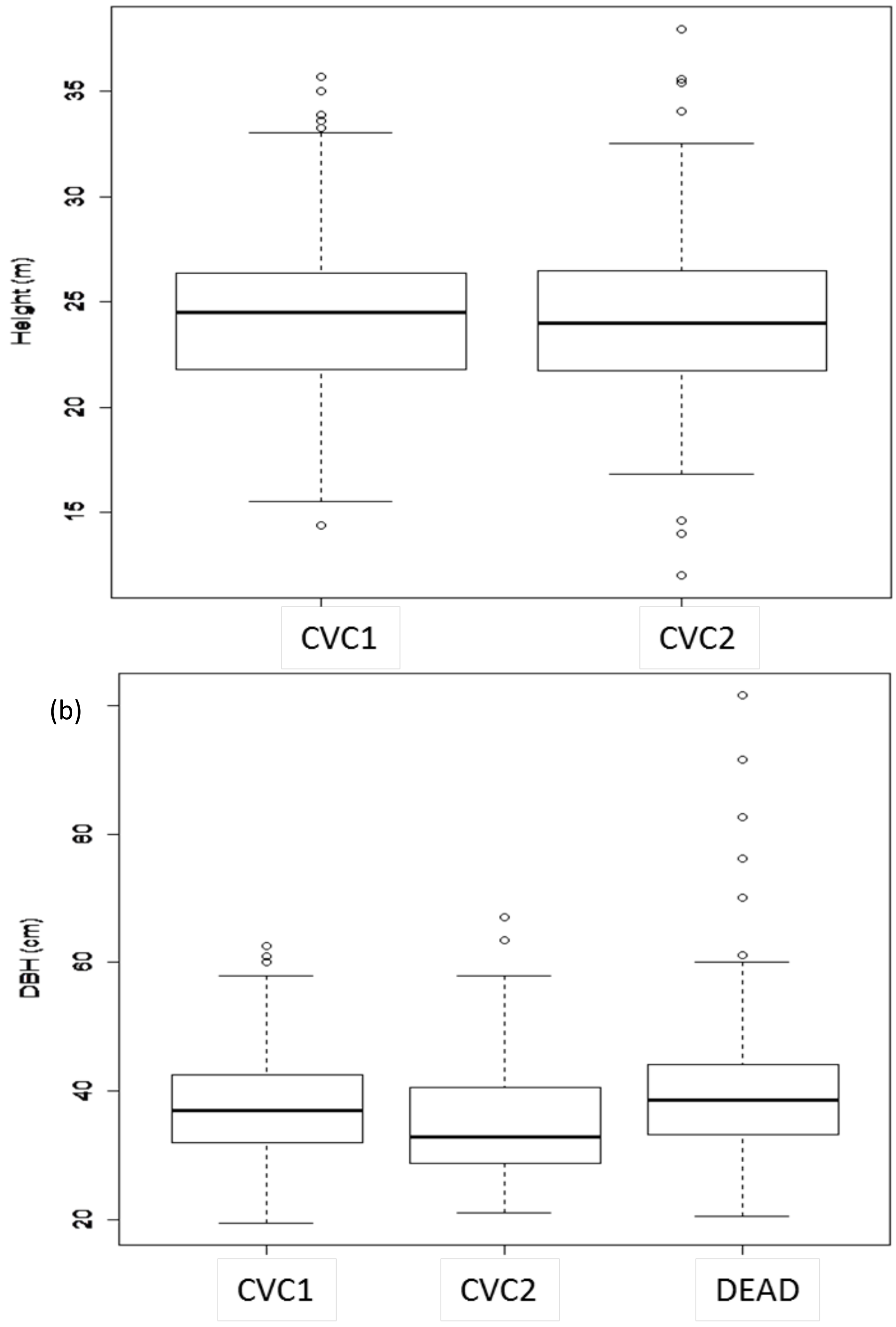


Figure 5.1.2. Box and whisker plots of height and diameter at breast height (DBH) of trees in each sample class; CVC1=vigor class 1, CVC2= vigor class 2, Dead=dead trees. Solid line inside the box = median; top of the box = 75th percentile; bottom of the box = 25th percentile; whiskers = the extreme values within the data set; points = outliers.

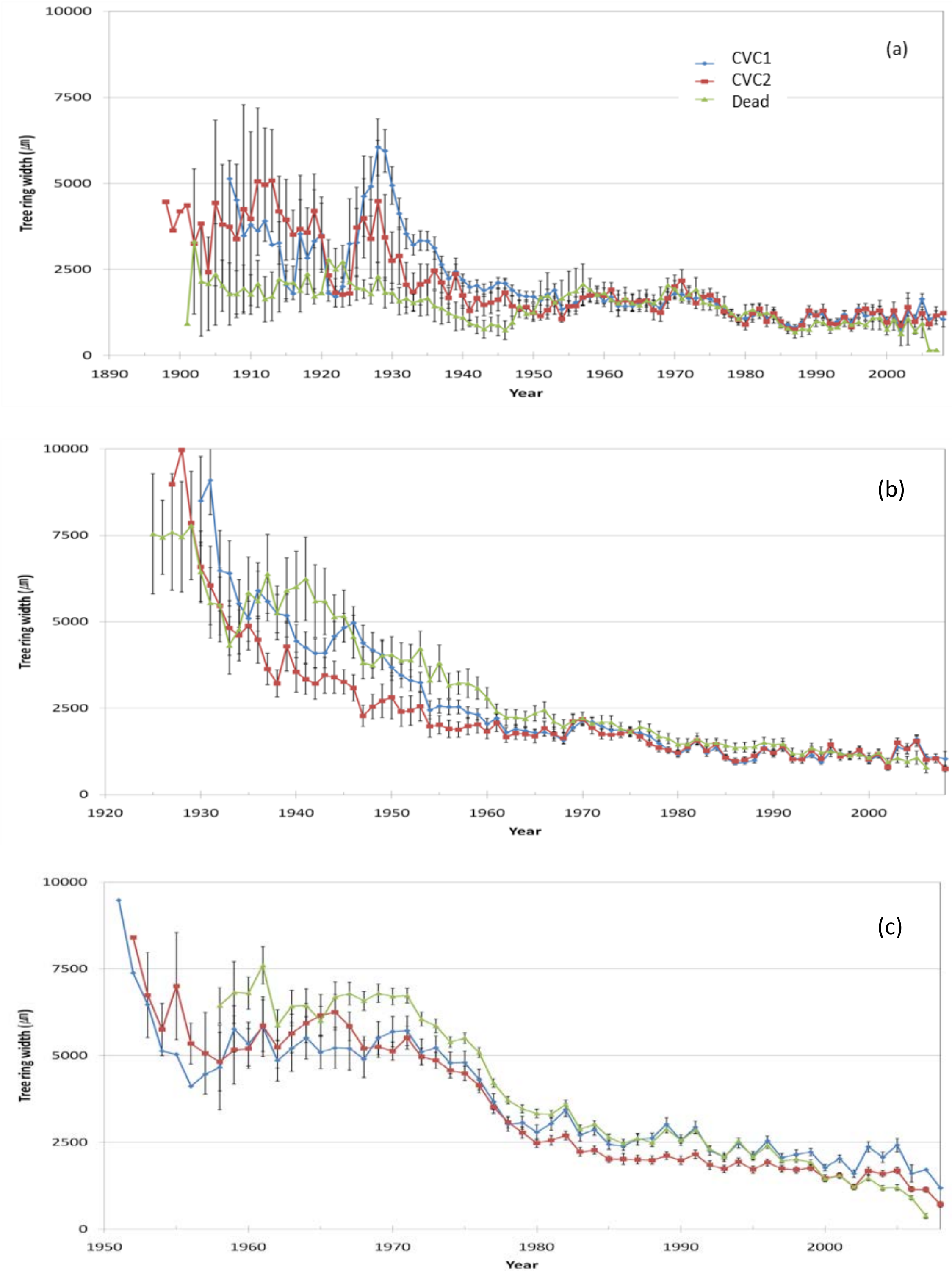


Figure 5.1.3. Ring growth of three age cohorts in the study sites. (a) The first age class was older than 78 years (from 1898); (b) the second age class was between 58 years and 78 years (1925~2008), and (c) the youngest age class was younger than 58 years (1950~2008). Blue line represents vigor class 1, red line represents vigor class 2 and green line represents dead trees. CVC1=vigor class 1, CVC2=vigor class 2, Dead=dead trees. Error bar indicates standard error.

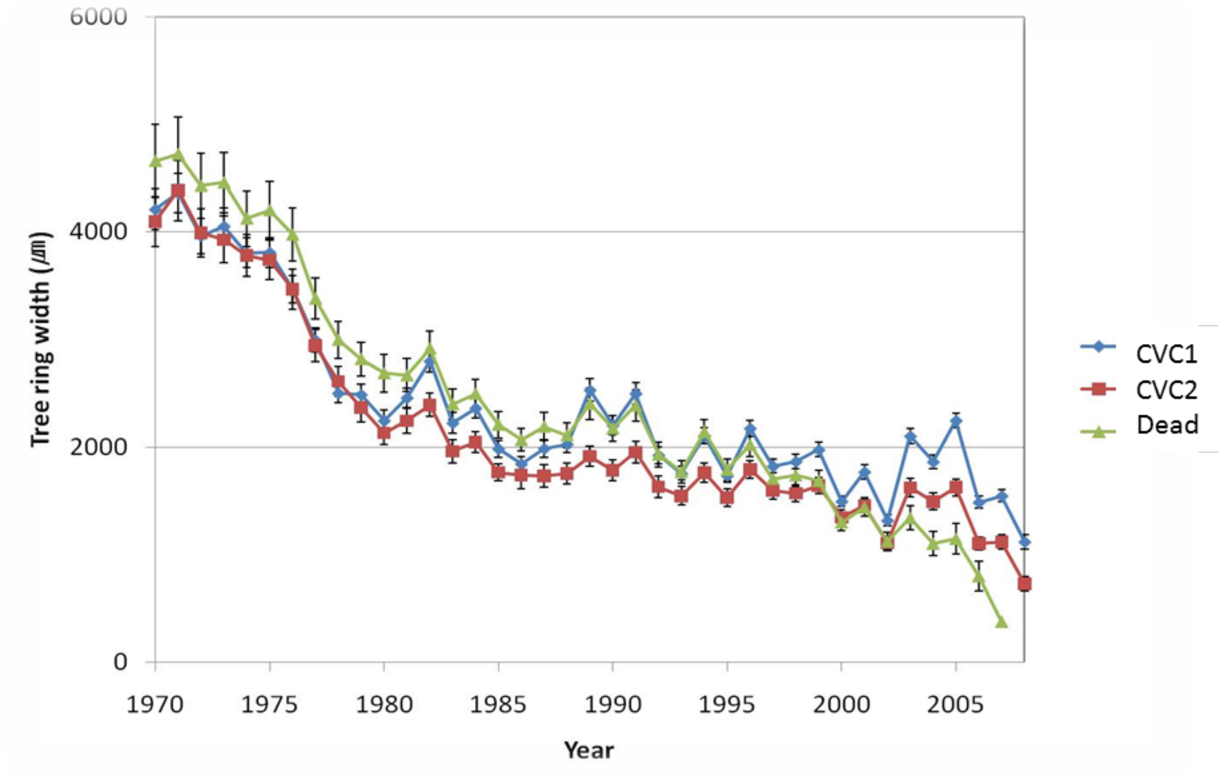


Figure 5.1.4. Mean ring growth of CVC1, CVC2, and Dead classes after 1970 (CVC1 n=282, CVC2 n=136, Dead n=133). The blue line represents CVC1, the red line represents CVC2 and the green line represents Dead. CVC1=vigor class 1, CVC2= vigor class 2, Dead=dead trees. Error bars indicate one standard error.

5.3.2. Tree mortality prediction model

MODEL DEVELOPMENT—The mortality models built with randomly chosen groups are shown in Table 5.1.1. Models with only one independent variable generally had highly significant *p*-values, with the exception of Model 1 (logbai3; $p = 0.426$) and Model 5 (locreg5; $p = 0.416$) (Table 5.1.2) Two combinations of variables generally had statistically significant p-values, but growth trend variables such as locreg5, locreg10, and locreg25 did not show significance when combined with growth level variables (see Models 10-16 in Table 5.1.3). Models with three combinations of variables generally had relatively low AIC values, ranging from 715.16 for Model 22 to 749.25 for Model 20. Model 22 had the lowest AIC value (715.16), followed by model 25 (715.21) and model 28 (715.41).

MODEL VERIFICATION—Model 7 was the best predictor of tree mortality, with 100% of the trees correctly predicted as dead, followed by Model 6 (95.6% CPd) (Table 5.1.3). Model 22 had the lowest AIC value (Table 5.1.2) and a relatively low CPd rate (75.7%; ranked 17.5). For correctly predicting trees to be alive (CPl), Model 2 was ranked first with 74.3% correct, followed by Model 17 with 73.4% correct. Interestingly, some models performed well for CPd but poorly for CPl; for example, Model 16 (ranked 3 for CPd at 88.6%), and Models 5, 14, and 15 (ranked 5 for CPd at 85.7%) had lower CPl rates than other models.

For the prediction error criteria, the percentage predicted as dead within 5 years of the actual year of death (PEd5) was highest for Model 4, which also had low CPd and CPl rates (Table 5.1.3). Models 5, 6, and 7 showed higher CPd rates than other models, but ranked the lowest in PEd5 and in PEd6-10. Models 17 and 18 ranked the highest according to overall performance criteria.

Model 17 was used to predict the mortality of randomly selected trees: ‘O7-SL-W1’ and ‘O1-1’ from the Dead group, ‘470’ and ‘1072’ from the CVC1 group, and ‘1754’ and ‘40’ from the CVC2 group. The model correctly predicted death of each Dead tree the year that the trees died, and did not predict mortality for the respective living trees from other vigor classes (Figure 5.1.5). Before death, a dramatic decrease was seen in both tree ring width and survival probability graphs of the trees from the Dead group.

MODEL VALIDATION—The model assessment criteria results of validation differed from that of verification (Table 5.1.4). For CPd, Models 7, 14, 15, and 16 showed the best performance with 100% correctly predicted mortality rates, and Model 4 was ranked the highest for CPl criteria. Similar to model verification results, Models 20, 21, 23, 24, 26, and 27 had the lowest ranks for CPd and higher ranks in CPl criteria. Models 5 to 7 consisted of only a growth trend variable and showed good performance for both CPd and CPl criteria; however, they were ranked the lowest in prediction error criteria because they predicted all measured periods of growth as dead and had consistently high AIC values. For PEd5, Model 4 performed the best, but we found that Models 6, 7, and 14-16 could not any predict tree mortality within 5 years of actual death (PEd5). However, we found that Models 17, 18, 20 and 23 showed good performance for CPl criteria of both model verification and validation (Table 5.1.3 and 5.1.4). The overall performance using the validation dataset was similar to the verification results, finding that Model 17 was best, followed by Model 18.

Table 5.1.2. Estimates of mortality models tested with logistic regression

Model	Independent variables	Estimate	AIC	Standard Error	*P*-value	
1	intercept	14.0628		1.1192	<2e-16	***
	log(bai3)	-3.6251	787.57	0.4256	0.426	
2	intercept	13.9617		1.1191	<2e-16	***
	log(bai5)	-3.6065	782.19	0.4271	<2e-16	***
3	intercept	13.1858		1.0948	<2e-16	***
	log(bai10)	-3.3501	780.85	0.4223	2.15E-15	***
4	intercept	10.2794		0.6027	<2e-16	***
	log(relbai)	3.1229	768.51	0.3177	<2e-16	***
5	intercept	5.2991		0.1692	<2e-16	***
	locreg5	-0.0098	872.65	0.0120	0.416	
6	intercept	5.3414		0.1568	<2e-16	***
	locreg10	-0.0249	851.01	0.0086	0.004	***
7	intercept	5.1353		0.1611	<2e-16	***
	locreg25	-0.0511	758.88	0.0084	1.44E-09	***
8	intercept	15.6992		1.3599	<2e-16	***
	log(bai3)	-4.4470		0.5355	<2e-16	***
	locreg5	0.0437	775.20	0.0162	0.007	***
9	intercept	15.4024		1.3326	<2e-16	***
	log(bai5)	-4.3396		0.5262	<2e-16	***
	locreg5	0.0404	774.34	0.0159	0.011	*
10	intercept	13.8887		1.1996	<2e-16	***
	log(bai10)	-3.7444		0.4760	3.67E-15	***
	locreg5	0.0280	777.90	0.0147	0.057	
11	intercept	15.1265		1.3841	<2e-16	***
	log(bai3)	-4.1485		0.5503	4.73E-14	***
	locreg10	0.0226	780.89	0.0123	0.065	
12	intercept	14.8959		1.3514	<2e-16	***
	log(bai5)	-4.0698		0.5386	4.14E-14	***
	locreg10	0.0205	779.58	0.0120	0.088	
13	intercept	13.6143		1.1922	<2e-16	***
	log(bai10)	-3.5710		0.4773	7.32E-14	***
	locreg10	0.0113	781.65	0.0110	0.306	
14	intercept	11.3347		1.6425	5.16E-12	***
	log(bai3)	-2.5909		0.6677	1.04E-03	***
	locreg25	-0.0146	744.80	0.0129	0.257	
15	intercept	11.2961		1.6079	2.13E-12	***
	log(bai5)	-2.5858		0.6556	8.01E-05	***
	locreg25	-0.0149	744.25	0.0127	0.242	

Table 5.1.2 (cont.). Estimates of mortality models tested with logistic regression.

Model	Independent variables	Estimate	AIC	Standard Error	*P*-value	
16	intercept	10.6502		1.4653	3.64E-13	***
	log(bai10)	-2.3411		0.6024	1.02E-03	***
	locreg25	-0.0191	745.01	0.0119	0.110	
17	intercept	14.9937		1.3341	<2e-16	***
	log(bai3)	-2.4545		0.5479	7.48E-06	***
	log(relbai)	2.2825	750.04	0.3788	1.68E-09	***
18	intercept	14.8269		1.3140	<2e-16	***
	log(bai5)	-2.4289		0.5468	8.91E-06	***
	log(relbai)	2.2412	750.19	0.3844	5.53E-09	***
19	intercept	14.1158		1.2552	<2e-16	***
	log(bai10)	-2.2058		0.5347	3.70E-05	***
	log(relbai)	2.1997	751.93	0.3944	2.45E-08	***
20	intercept	14.2437		1.3619	<2e-16	***
	log(bai3)	-1.6647		0.6939	0.016	*
	locreg5	-0.0263		0.0140	0.061	
	log(relbai)	2.8599	749.25	0.1956	7.88E-09	***
21	intercept	13.5703		1.3780	<2e-16	***
	log(bai3)	-1.2766		0.3828	0.062	
	locreg10	-0.0333		0.0119	0.005	**
	log(relbai)	2.9878	745.50	0.4609	9.05E-11	***
22	intercept	10.7159		1.5994	2.09E-11	***
	log(bai3)	-0.4222		0.7416	0.569	
	locreg25	-0.0514		0.0133	1.10E-04	***
	log(relbai)	2.5800	715.16	0.4429	5.7E-09	***
23	intercept	14.1322		1.3272	<2e-16	***
	log(bai5)	-1.6390		0.6836	0.017	*
	locreg5	-0.0269		0.0139	0.052	
	log(relbai)	2.8416	749.24	0.5007	1.39E-08	***
24	intercept	13.4940		1.3440	<2e-16	***
	log(bai5)	-1.2625		0.6744	0.061	
	locreg10	-0.0336		0.0118	0.004	**
	log(relbai)	2.9714	745.49	0.4664	1.88E-10	***
25	intercept	10.6323		1.5678	1.19E-11	***
	log(bai5)	-0.3854		0.7370	0.601	
	locreg25	-0.0520		0.0132	8.67E-05	***
	log(relbai)	2.5852	715.21	0.4475	7.63E-09	***

Table 5.1.2 (cont.). Estimates of mortality models tested with logistic regression.

Model	Independent variables	Estimate	AIC	Standard Error	*P*-value	
26	intercept	13.5334		1.2432	<2e-16	***
	log(bai10)	-1.3625		0.6462	0.035	*
	locreg5	-0.0320		0.0134	0.017	*
	log(relbai)	2.9002	749.53	0.5014	7.28E-09	***
27	intercept	13.1458		1.2342	<2e-16	***
	log(bai10)	-1.1171		0.6282	0.075	
	locreg10	-0.0360		0.0111	0.001	**
	log(relbai)	2.9890	745.88	0.4685	1.78E-10	***
28	intercept	10.2624		1.4659	2.55E-12	***
	log(bai10)	-0.1944		0.7075	0.783	
	locreg25	-0.0546		0.0128	2.07E-05	***
	log(relbai)	2.6381	715.41	0.4537	6.06E-09	***

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

bai3=basal area increment of three year average (㎠); bai5=basal area increment of five year average (㎠); locreg5=slope of local linear regressions over five years of basal area increment; locreg10=slope of local linear regressions over ten years of basal area increment; locreg25=slope of local linear regressions over twenty-five years of basal area increment; rw3=raw ring width of three year average (0.001mm); relbai=ratio of basal area increment to basal area. The number of measurements was calculated from accumulated lengths of independent variables based on time-series of 150 trees from CVC1, 66 trees from CVC2, and 70 trees from Dead.

Table 5.1.3. Verification of the models (CVC1 = 150, CVC2 = 66, Dead=70)

Model	CPd (%)	Rank	CPl (%)	Rank	PEd5 (%)	Rank	PEd6-10 (%)	Rank	Total Rank
1	80.0	10	65.3	13	12.9	18.5	8.6	23	16.1
2	80.0	10	74.3	1	12.9	18.5	8.6	23	13.1
3	80.0	10	12.0	26	10.0	18.5	8.6	23	19.4
4	72.9	21	9.6	27	41.4	1	10.0	16.5	16.4
5	85.7	5	0.0	28	1.4	26	0.0	26	21.3
6	95.6	2	67.8	9	0.0	27.5	0.0	26	16.1
7	100	1	66.6	12	0.0	27.5	0.0	26	16.6
8	80.0	10	60.7	17.5	14.3	16.5	18.6	1	11.3
9	80.0	10	61.3	14.5	15.7	15	12.9	4.5	11.0
10	80.0	10	60.7	17.5	14.3	16.5	11.4	9.5	13.4
11	78.6	14	61.3	14.5	10.0	19.5	10.0	16.5	16.1
12	57.6	28	61.1	16	8.6	22	10.0	16.5	20.6
13	80.0	10	59.4	19	8.6	22	11.4	9.5	15.1
14	85.7	5	34.2	23	4.3	24.5	10.0	16.5	17.3
15	85.7	5	34.1	24	4.3	24.5	12.9	4.5	14.5
16	88.6	3	33.1	25	8.6	22	11.4	9.5	14.9
17	75.7	17.5	73.4	2	25.7	13	15.7	2	**8.6**
18	75.7	17.5	72.0	4	28.6	8	12.9	4.5	**8.5**
19	75.7	17.5	67.7	10	30.0	5.5	11.4	9.5	10.6
20	71.4	24	73.0	3	25.7	13	12.9	4.5	11.1
21	71.4	24	70.4	6	27.1	10.5	10.0	16.5	14.3
22	75.7	17.5	48.9	22	31.4	3.5	10.0	16.5	14.9
23	71.4	24	71.2	5	25.7	13	11.4	9.5	12.9
24	71.4	24	69.9	7	28.6	8	8.6	23	15.5
25	75.7	17.5	49.9	20	31.4	3.5	10.0	16.5	14.4
26	71.4	24	68.6	8	27.1	10.5	10.0	16.5	14.8
27	71.4	24	67.6	11	28.6	8	8.6	23	16.5
28	75.7	17.5	49.7	21	30.0	4.5	11.4	9.5	13.1

CPd = correctly predicted as dead; CPl = correctly predicted as alive, PEd5 = prediction error of dead trees within 5 years since its actual death; PEd6-10 = prediction error of dead trees within 6-10 years since its actual death. Period for prediction error criteria was specifically divided for model's accuracy. Tied ranks were averaged.

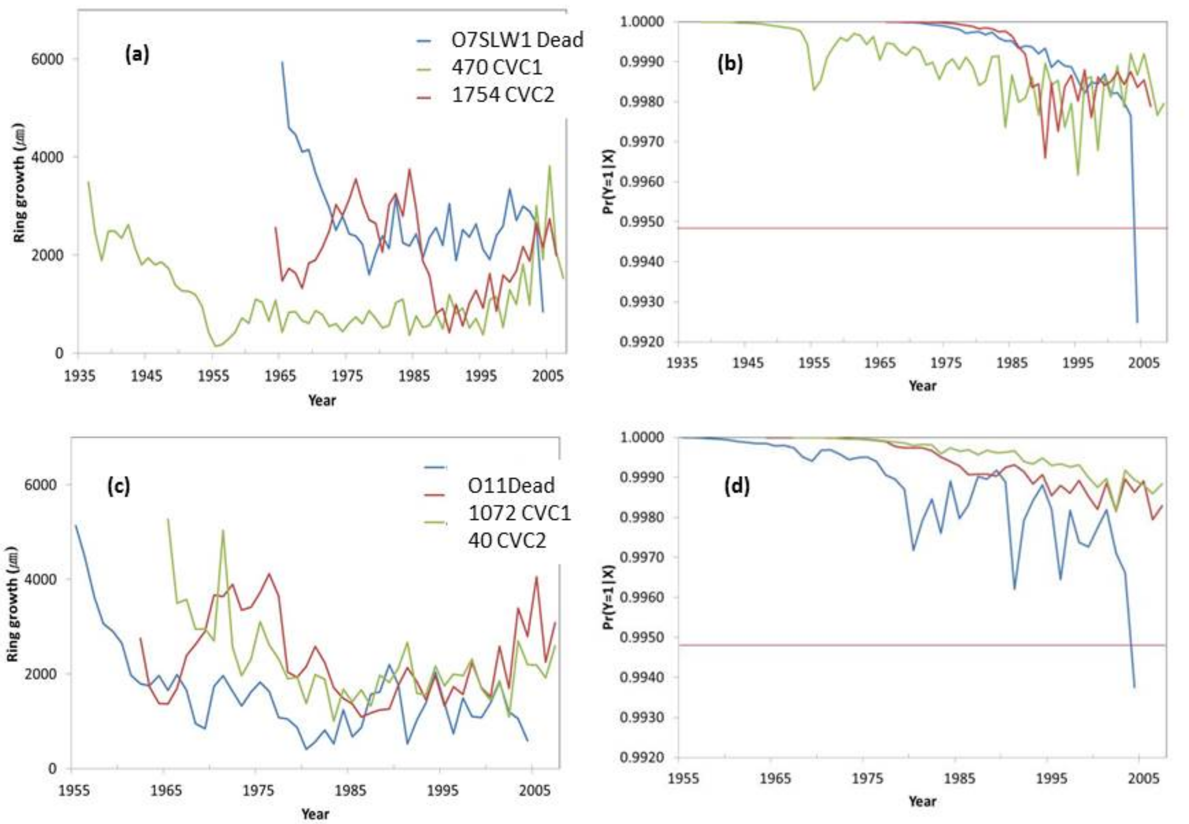


Figure 5.1.5. Model verification using Model 17, where (a) and (c) are tree ring width (㎛), (b) and (d) are corresponding survival probability (Pr(Y=1|X)). The solid line indicates the threshold of 0.9948.

Table 5.1.4. Validation of the models (CVC1 = 124, CVC2 = 66, Dead=40)

Model	CPd (%)	Rank	CPl (%)	Rank	PEd5 (%)	Rank	PEd6-10 (%)	Rank	Total Rank
1	95.5	12.5	64.2	13	6.8	19	29.5	1.5	11.5
2	95.5	12.5	62.5	14	2.3	22.5	29.5	1.5	12.6
3	97.7	7.5	33.1	23	11.4	16.5	22.7	6	13.3
4	77.3	27	72.7	1	27.3	1	11.4	24	13.3
5	72.7	28	50.8	20	2.3	22.5	0.0	27	24.4
6	95.5	12.5	7.9	27	0.0	25.5	0.0	27	23
7	100	2.5	0.0	28	0.0	25.5	0.0	27	20.8
8	97.7	7.5	65.1	11	13.6	13.5	18.2	14	11.5
9	97.7	7.5	65.1	12	11.4	16.5	22.7	6	**10.5**
10	97.7	7.5	59.2	15	13.6	13.5	15.9	18.5	13.6
11	95.5	12.5	58.6	16	6.8	19	20.5	10	14.4
12	97.7	7.5	58.3	17	6.8	19	20.5	10	13.4
13	97.7	7.5	58.2	18	4.5	21	18.2	14	15.1
14	100	2.5	23.2	25	0.0	25.5	11.4	24	19.3
15	100	2.5	23.5	24	0.0	25.5	15.9	18.5	17.6
16	100	2.5	23.0	26	0.0	25.5	25.0	3	14.3
17	79.6	23	71.9	2	22.7	3	18.2	14	**10.5**
18	81.8	18.5	70.4	5	20.5	6	18.2	14	**10.9**
19	81.8	18.5	66.0	10	15.9	10.5	22.7	6	11.3
20	79.6	23	71.4	3	18.2	8.5	11.4	24	14.6
21	79.6	23	67.8	6	22.7	3	15.9	18.5	12.6
22	86.4	16	39.4	21	15.9	10.5	22.7	6	13.4
23	79.6	23	71.3	4	18.2	8.5	15.9	21	14.1
24	79.6	23	67.6	7	20.5	6	18.2	14	12.5
25	86.4	16	54.6	19	13.6	13.5	20.5	10	14.6
26	79.6	23	67.3	9	22.7	3	13.6	22	14.3
27	79.6	23	67.6	8	20.5	6	15.9	18.5	13.9
28	86.4	16	38.2	22	13.6	13.5	22.7	6	14.4

CPd = correctly predicted as dead; CPl = correctly predicted as alive, PEd5 = prediction error of dead trees within 5 years since its actual death; PEd6-10 = prediction error of dead trees within 6-10 years since its actual death. Period for prediction error criteria was specifically divided for model's accuracy. Tied ranks were averaged.

We validated Model 17 with trees from each health class and found that Dead trees ‘C1-SCL’ and ‘K5-SL-N’ were each predicted to be dead 2 years earlier than actual death (Figure 5.1.6). Although ‘K5-SL-N’ showed a negative growth trend over the whole growth period, the survival probability graph clearly indicated the abruptly decreasing probability near the time of death. In contrast, ‘C1-SCL’ only showed an abruptly decreasing growth rate in the years prior to tree death. Trees ‘1498’ and ‘1781’ from CVC1, and trees ‘1436’ and ‘613’ from CVC2 were correctly predicted as alive at the time of sampling.

5.4. Discussion

Although we often assume that current tree health is a reflection of previous growth, we have only limited understanding of how previous tree growth affects current tree vigor. Our results showed that the healthiest trees (CVC1) grew better than CVC2 trees for 30 years prior to sampling. However, the dead tree class showed greater ring growth than live trees up until a few years prior to death, suggesting that dead trees were larger and grew rapidly when they were alive (Figure 5.1.3b and c). Results showed that the CVC2 group tended to have more rapid growth in diameter than CVC1 at the early stage (Figure 5.1.3a and c) consistent with Kaufmann and Watkins’ (1990) report that associated current poor tree health with rapid early growth. If confirmed with additional research and analysis, it begs the question of whether there is a critical growth rate threshold that signals future vulnerability, and how forest management practices can be used to moderate growth rates to avoid early mortality. Most tree deaths occurred in 2004 and 2006. Deaths in both years may have been due to severe drought in the region with large trees succumbing due to unmet high water demands; however, we did not find any significant correlation between weather and tree death in both years.

Our results suggested that vigor class evaluated from crown measurements reflects tree health and is a reliable tool to use in the field. A large, dense crown is regarded as an indicator of tree health (Ferretti 1998, Kramer 1996, Zarnoch et al. 2004) and Anderson and Belanger (1987) reported that high crown density was positively correlated with loblolly pine stem growth. We found that DBH was different between CVC1 and CVC2, suggesting that differences in diameter growth are reflected in crown condition. We also found that DBH was larger on clay loam soils than sands, indicating that high quality soils are important for loblolly pine tree health (see Section 4.1).

The best model from our study included both a growth level variable (bai3) and a relative growth variable (relbai), differing from the Bigler and Bugmann (2004) model that combined a growth trend variable (locreg5) with relative growth (relbai) to model mortality for Norway spruce in Switzerland. Among growth level variables, the moving 3-year average of basal area increment was the factor determining tree mortality, which is consistent with our hypothesis that a short-term factor would exert more influence on loblolly pine tree health than a longer-term factor in the region. Relative growth variables play an important role in increasing the power of the prediction model as they take tree size into account. We expected growth trend variables (locreg5, 10, 25) to affect our mortality model, and results showed that including locreg25 lowered the AIC values of Models 22, 25, and 28; however, we found growth trend variables to be less important to final model selection than relative growth or growth level variables. We also found that the accuracy of CPd and CPl were sensitive to the threshold level of the model.

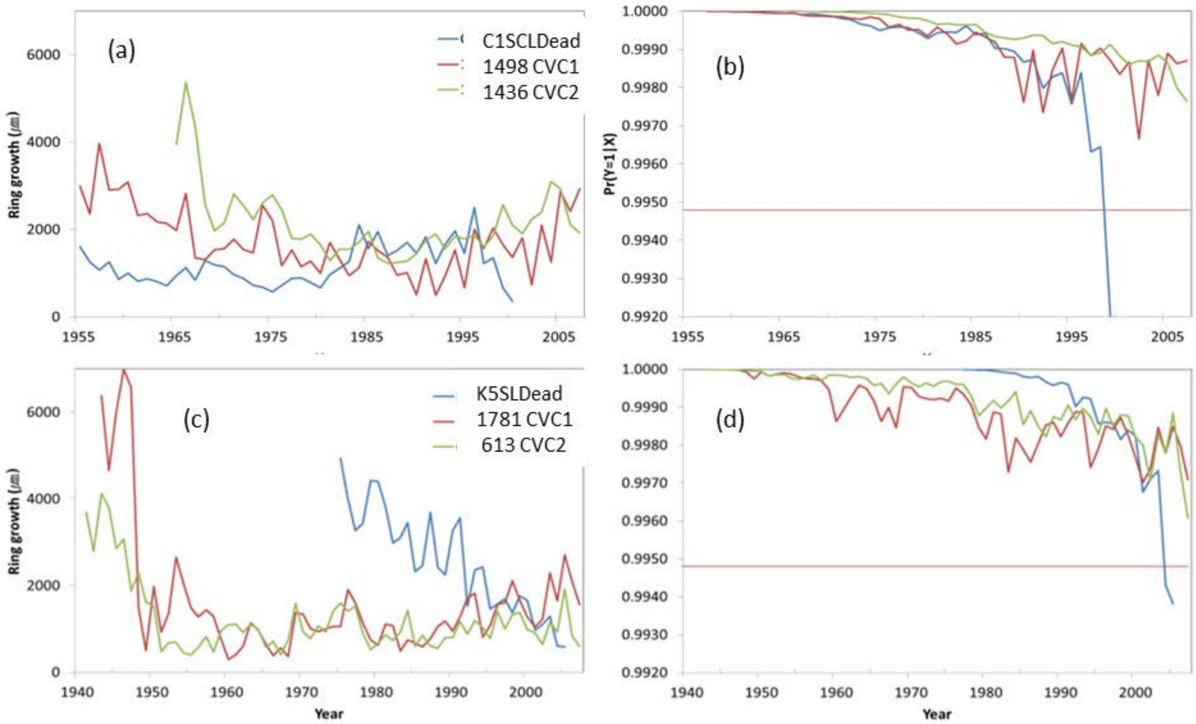


Figure 5.1.6. Model validation using the model 17. (a) and (c) are tree ring width (㎛), (b) and (d) are corresponding survival probabilities (Pr(Y=1|X)). The solid line indicates the threshold of 0.9948. The prediction error for C1-SCL (Dead) and K5-SL-N (Dead) was 2 years.

The theoretical guidelines suggested by Bigler and Bugmann (2004) indicate that we could set a threshold level for our model at 0.9902. However, we found that a threshold of 0.9948 gave the best balance of CPd, CPl, and PEd accuracy for our model. The results suggested that a theoretical threshold should be used to give a reference for the model, but it may have to be modified to fit the best model (Bigler and Bugmann 2004).

Careful model selection is critical for developing a useful predictor of tree mortality, and our results indicate that it is not practical to judge a model performance using only one criterion but rather multiple model selection procedures should be conducted (Reynolds and Ford 1999). Although AIC is often used for model selection, additional ways of assessing model performance are useful for logistic model selection (Hawkes 2000, Bigler and Bugmann 2004). We found that Model 22 had the lowest (best) AIC value, but Model 17 was selected as the best model based on multiple model assessment criteria. All of our models were good at correctly predicting tree death; with the exception of Model 12 all models had greater than 70% CPd. However, models with high CPd did not always have high CPl, suggesting that a balance of the two criteria is important for overall model utility.

6. Monitoring Recommendations

Results of a replicated field experiment installed at Fort Benning and Camp Lejeune are reported in Section 3 of this report. Because forest development continues over long periods, we recognize the value of continuing to monitor the experimental plots. This section recommends both which variables to measure and on what schedules.

6.1. Objectives

The restoration of the longleaf pine ecosystem, and the simultaneous development of high-quality RCW habitat, will occur over decades of fire management, and perhaps additional management intervention. The U.S. Fish and Wildlife Service recovery guidelines recommend a target basal area of at least 9.2 m^2/ha of pines larger than 25 cm DBH and that the basal area of pines smaller than 25 cm DBH be limited to less than 2.3 m^2/ha (US FWS 2003). Such guidelines suggest that longleaf pine plantations or underplanted forests will not be suitable for foraging habitat until the pines become 25 cm in DBH. Therefore, it is essential for managers to understand how the various components of the longleaf pine ecosystem change throughout stand development. Because underplanting and group selection are relatively new techniques for longleaf pine restoration, little is understood about stand development beneath variable retention of the canopy.

6.2. Longleaf pine development

6.2.1. Justification

We recommend continued monitoring of longleaf pine seedling growth and survival. Ultimately, the development of a longleaf pine stand depends on successful emergence of seedlings from the grass stage. Through three years of this study, only around 30% of surviving seedlings had emerged from the grass stage on the treatment plots with the most rapid growth (Clearcut plots). Longleaf pine seedlings have the potential to remain in the grass stage for over a decade (Pessin 1944) and in unfavorable conditions stand establishment may fail. Therefore, continued monitoring is critical to assess future development and long-term stand dynamics.

6.2.2. Field methods

We originally marked 30 randomly selected longleaf pine seedlings, but mortality over the course of the study has reduced the number of sampled seedlings. In each split-plot treatment area, we recommend continuing to measure all tagged seedlings. If the number of surviving, tagged seedlings is less than 20 in a split-plot, additional seedlings should be randomly selected to increase the sub-sample to 20 per split-plot. When fewer than 20 surviving seedlings are present, all seedlings should be measured. For each seedling, measure the ground line diameter (GLD) and height to the terminal bud. When seedlings are taller than 1.4 m, measure DBH; at the first measurement period when a seedling is tall enough for a DBH measurement, measure both GLD and DBH.

6.2.3. Schedule

We measured the study plots in the summer of 2012, the fifth growing season following planting. In the absence of additional management actions, the sampling schedule should occur on 5-year intervals. After the 2017 (10 year) measurement, evaluate the possibility of canopy removal to release seedlings remaining in the grass stage. Allow fire management to follow standard management prescriptions as defined by the installation. A 5-year interval is recommended because vegetation conditions can change rapidly in the warm, humid southeastern U.S.; if seedlings remain in the grass stage, they are susceptible to competition from canopy and groundlayer vegetation, and perhaps vulnerable to fire. The fate of grass stage seedlings is not well understood, and this sampling frequency will help fill this information gap.

6.3. Ground layer vegetation

6.3.1. Justification

Maintaining or improving the ground layer vegetation of the longleaf pine ecosystem is important for providing high-quality RCW habitat and supporting a high frequency surface fire regime. The development of pine plantations often changes the composition of the ground layer (Smith et al. 2002, Walker et al. 2007), and gaps in the forest canopy have been associated with encroachment of woody vegetation (Jack et al. 2006, Kirkman et al. 2006). To maintain the necessary fuels for continued fire management, it is essential to understand dynamics of ground layer vegetation through time.

6.3.2. Field methods

We recommend using vegetation methods described in this report (Sections 3.4-3.6) to monitor the abundance of ground layer vegetation (< 1 m tall) by functional group and midstory development (woody stems > 1 m tall with DBH < 2.5 cm). Previously established measurement transects have been monumented with nails and stake flags, and plot descriptions (Section 3.1) include the position of each transect relative to the split-plot corners. Following established methods, vegetation cover would be estimated in 20 1-m^2 quadrats per split-plot, and woody stems counted in two 2-m wide by 20-m long belt transects per split-plot. The established sampling protocol has yielded enough data to detect treatment differences without investing an excessive amount of time.

We previously surveyed experimental split-plots for species composition and presence at a series of small scales (range: 0.01 – 100 m^2) (See Section 3.5). While we think these data are informative with respect to community development and structure, we think the results will be most influenced by fire frequency (Glitzenstein et al. 2012), and therefore do not recommend frequent monitoring, as discussed in the following section. When this sampling is conducted we recommend using the previously established protocols (Section 3.5), as they are based on Carolina Vegetation Survey Methodology (Peet et al. 1998) and have yielded meaningful data in vegetation types with potentially rich, herbaceous ground layers. Following established protocols, complete species lists are generated for each split-plot, and if no differences are detected among them, subplot data could be aggregated at the plot level.

6.3.3. Schedule

We sampled vegetation in 2012 when tree seedlings were 5 years old, and we recommend sampling at approximately 5-year intervals. Because cover estimates for both herbaceous and (especially) woody species change with time since fire, we recommend sampling vegetation within 1 year following a prescribed fire. Measurements should be made at peak aboveground herbaceous cover (August-September). Additionally, in the event of additional overstory thinning, for example to release grass stage seedlings, vegetation sampling should be done in the first full growing season following thinning in order to assess any short term changes or potential weedy species introductions.

We suggest infrequent sampling for total species composition and richness, specifically at ages approximately 10 and 20 years. The vegetation is dominated by perennial species with relatively few weedy or short-lived species. Further, we found no significant conservation target plant species (G1-G2 or S1-S2; NatureServe Classification System) in any of the experimental plots. In the absence of significant ground-disturbance, there is no reason to expect rapid changes in composition. With regular burning (fire return interval ≈ 3-4 years), we would also not expect there to be large changes in small scale (< 10 m^2) richness. Additional sampling would be indicated if changes that might affect compositional change are suspected. These could include the appearance of any new invasive species threat, long periods of extreme weather conditions (e.g., high or low precipitation or temperatures), long periods of fire exclusion (> 7-10) years.

6.4. Fuels and fire management

6.4.1. Justification

One outcome of longleaf pine restoration must be the ability to maintain the desired structure and composition through fire management. The ground layer vegetation is tightly connected to the fuel complex and fire response, suggesting that changes in vegetation will affect the effectiveness of fire. It is important that managers understand how stand development affects the use of prescribed fire on restored longleaf pine forestlands.

6.4.2. Field methods and schedule

We recommend that the study plots be incorporated into the standard management burn schedule for each study location, which may differ between installations. However, we strongly recommend that managers make a concerted effort (1) to burn the study plots on a frequent (3-4) year interval because it is likely that woody growth since the previous fire should be able to be topkilled by most prescribed fires, and (2) to burn following the 2022 growing season. If all plots are burned at approximately age 15 years (in 2022) and then sampled for all variables, the data would provide an updated comparison point for continued evaluation across locations.

Quantifying fuels and fire behavior is usually labor intensive, and we doubt that intensive sampling will provide information worth the investment. Careful records of date, fire weather, firing techniques, and immediate post-fire assessment with respect to continuity of fuel consumption should be made for every fire, if possible. With this information, fire history can be reconstructed, even using remote sensing approaches to estimate fire severity. We think it would be valuable to repeat pre- and post-fire fuels assessments, fire behavior measures, and vegetation responses as described in Section 3.9 for prescribed fires at about age 15 (after the 2022 growing season, in uniform treatment plots and medium gap plots). Re-measuring at this time would allow an assessment of treatment effects on ability to use fire effectively to restore desired forest structure.

A summary of monitoring recommendations is provided in Table 6.1.1

Table. 6.1.1. Summary of recommended monitoring activities.

Variable	Unit/metric	2012	2017	2022	2027	Sect./Note
Longleaf pine Seedlings						*3.3/*
Survival	Live or Dead	●	●	●	●	
Size	GLD and/or DBH	●	●	●	●	
Number in grass stage		●	●			*3.3/1*
Ground Layer Vegetation, < 1 m tall						*3.4/2*
Abundance, forbs	Cover class	●	●	●	●	
Abundance, graminoids	Cover class	●	●	●	●	
Abundance, ferns and fern allies	Cover class	●	●	●	●	
Abundance, woody stems	Cover class	●	●	●	●	
Abundance, woody vines	Cover class	●	●	●	●	
Midstory Vegetation, woody stems > 1m tall, dbh<2.5 cm						*3.4/2*
Abundance, by species	# stems, by species	●	●	●	●	
Species Composition						
Identify of species in nested plots	Presence, by species	●		●		*3.5/*
Prescribed fire, fuels, fire behavior						*3.9/3*
Pre-fire fuels (1, 10, 100 hr fuels)	Brown's transects			●		
Post-fire fuels (1, 10, 100 hr fuels)	Brown's transects			●		
Percent (surface) area burned	Line intercept counts (burned/unburned) on established vegetation measurement transects			●		
Scorch height	Scorch height on mature pine boles			●		
Smallest unconsumed woody stem	Diameter of smallest unconsumed woody stem			●		

Notes:

1) At age 10 (2017) evaluate need to release grass stage seedlings by canopy thinning.

2) Sample within 1 year of burning, after maximum leaf area achieved (August-September) and before leaf-off and dieback.

3) Experimental plots should be returned to normal fire rotation for the unit, as defined by the installation. Recommend fire return interval of 3-4 years. Recommend burning after 2022 growing season for ALL plots so that a 15-yr benchmark measurement could be established.

7. Synthesis, Management Implications and Recommendations, and Future Work

This synthesis section includes two sub-sections. The first develops representative stand-level management prescriptions and projects resulting ecosystem conditions based on experimental results from the Fort Benning and Camp Lejeune field experiment. The second provides more general management recommendations and discusses the applicability of results from this project to other longleaf pine landscapes across the range of longleaf pine.

7.1. Integrating ecosystem responses into stand-level management prescriptions

7.1.1. Background information and study findings in brief

7.1.1.1 The need for converting loblolly stands to longleaf pine

The historical conversion of pine sites from longleaf pine to loblolly pine throughout the southeastern United States has greatly changed the landscape and has resulted in a shift in stand structure and composition. As a result, species that rely on the longleaf pine ecosystems for habitat have been threatened by habitat loss and fragmentation. Notably, the federally endangered red-cockaded woodpecker (RCW) prefers open pine stands dominated by large, old longleaf pine trees for nesting and foraging but will use loblolly pine stands if needed. On many DoD installations in the southeast, RCW recovery and management is a primary objective of land managers; therefore, there is great interest in the conversion of existing loblolly pine stands to fire-maintained longleaf pine forests. However, in areas currently supporting RCW populations, restoration protocols will require a level of canopy retention consistent with stand-level RCW recovery guidelines.

Given the broad geographic extent of longleaf pine and the natural variability in site conditions, it is unlikely that restoration protocols will be immediately exportable from site to site. It is important to understand the ecological factors that control the process of regeneration under an existing canopy of loblolly pine trees.

7.1.1.2. Loblolly pine decline on Fort Benning

Our results suggest that loblolly pine decline is not currently a widespread problem on Fort Benning. We sampled ninety mature loblolly pine stands that covered a range of site conditions (slope, aspect, soil type) and stand structure (density, age) combinations across Fort Benning, and we found that only three plots contained greater than 20% of trees showing symptoms of reduced canopy health; on average, only 4% of trees were considered in poor health within our study plots. We found that stands with trees in poor health were more common on coarsely-textured soils than on finely-textured soils and that site productivity was positively correlated with stand health. Because loblolly pine trees are better suited to more mesic, productive sites than longleaf pine, these results indicate that nutrient and water stressors are drivers of poor loblolly pine health at Fort Benning. Moreover, dendrochronological analyses confirmed that canopy condition assessment is an effective field method for evaluating general tree health. We found that crown condition reflected general growth patterns throughout stand development and that dendrochronology could be used to predict individual tree mortality.

One of the primary objectives of forest management is the improvement of existing forest stands, and the careful application of thinning can improve the health of pine stands. We found that spacing of loblolly pine trees was related to tree health in thinned stands, suggesting that natural thinning continues to occur after prescribed thinning operations. Density-dependent mortality is a natural part of stand development and is not necessarily an indication of pine decline, but our results show that maintaining spacing of at least 5 m between trees will reduce competition among residual trees. Forest management for RCW habitat is compatible with reductions in density-dependent mortality, because guidelines recommend basal area densities of 9 to 14 m^2/ha.

7.1.1.3. Forest management for RCW habitat

Forest management on southeastern military installations that support RCW populations must comply with RCW recovery management guidelines, and converting loblolly pine stands to longleaf pine requires a balance between canopy retention and longleaf pine seedlings release. The US Fish and Wildlife Service recovery guidelines define good quality foraging habitat as having the following (US FWS 2003):

- 45 stems per hectare > 60 years in age and ≥ 35 cm in DBH, with minimum basal area of 4.6 m^2/ha
- Basal area of pines 25.4 – 35 cm DBH is between 0 and 9.2 m^2/ha
- Basal area of pines < 25.4 cm DBH is below 2.3 m^2/ha and below 50 stems/ha
- Basal area of all pines ≥ 25.4 cm is at least 9.2 m^2/ha
- Groundcover of native bunchgrasses and/or herbs ≥ 40% cover and are dense enough to carry fire once every 5 years
- No hardwood midstory exists or is less than 2.1 m tall
- Canopy hardwoods are absent or < 10% the number of canopy trees in longleaf pine forests and < 30% the number of canopy trees in loblolly pine or shortleaf pine forests
- All this habitat is within 0.8 km of the center of the cluster, and preferably 50 percent or more is within 0.4 km of the center of the cluster

The proximity of a given stand to an active RCW cluster determines the application of these guidelines, suggesting that silvicultural techniques for stand conversion may differ depending on current RCW habitat use.

Creating and maintaining good-quality RCW habitat requires attention to three main components that contribute to the desired ecosystem structure and function: 1) establishing longleaf pines as the dominant canopy species with the appropriate canopy structure; 2) establishing a ground layer component dominated by herbaceous vegetation; and 3) maintaining a frequent surface fire regime. These three components are synergistic in that longleaf pines and herbaceous vegetation provide suitable fuels for frequent surface fires, and frequent surface fires eliminate woody competition and sustain the desired stand structure.

7.1.1.4. Longleaf pine establishment with alternative silvicultural techniques

On many sites requiring conversion from loblolly pine to longleaf pine, artificial regeneration is necessary because there are no canopy pines to provide seed for natural regeneration. Longleaf pine seedlings are understood to be intolerant of competition from canopy trees, with observed reductions in seedling establishment and growth under dense canopies (Grace and Platt 1995, Palik et al. 1997). Our results confirm a strong relationship between overstory competition and longleaf pine seedling growth in loblolly pine forests, but canopy trees had variable effects on the survival of planted longleaf pine seedlings; in the first year after planting at Fort Benning we observed a facilitation effect of canopy pines that was not evident in the following years or at any point at Camp Lejeune. These results indicate that canopy retention may additionally benefit restoration by reducing first-year mortality that was likely associated with desiccation of the outplanted seedling during the adjustment period immediately following planting.

Based on results from our study, underplanting longleaf pine seedlings beneath uncut loblolly pine stands (basal area ≥ 14 m^2/ha) is not a feasible option for establishing longleaf pine because there were no seedlings in height growth after three growing seasons. Height growth might yet be initiated for seedlings under loblolly pine canopies of this study in the future but prolonged periods in the grass stage delay the development of suitable RCW foraging habitat. Height growth was observed on all other study treatments, suggesting that additional seedling emergence can be expected at some point in the future on those treatments. In many cases, it may be acceptable for the objectives of restoration forestry to be met on a timescale different from that of traditional forestry.

In natural stands, longleaf pine regeneration is often observed within canopy gaps and patch cutting has been suggested as a silvicultural technique for establishing longleaf pine seedlings and retaining canopy pines (McGuire et al. 2001, Palik et al. 2002). The observed dome-shaped appearance of longleaf pine seedlings in gaps, with the largest seedlings in the middle of gaps, was observed in our study at Fort Benning but not at Camp Lejeune. However, gaps generally resulted in greater seedling growth than uncut plots at both sites. At Fort Benning, greater seedling mortality on the north half compared to the south half of gaps further supports that first year mortality may be associated with desiccation of planted seedlings caused by increased exposure to solar radiation. Previous research has suggested that varying the shape and orientation of canopy openings may be a viable option for reducing first-year seedling mortality (Rodriguez-Trejo et al. 2003).

Results from our study do not support the use of fertilizer for improving longleaf pine seedling establishment, despite the low nutrient status of our sites. Generally, we found that foliar nutrients (N, P, and K) remained above sufficiency levels for the species and that fertilizers did not increase growth. However, herbicide release improved seedling growth at both sites after five growing seasons. The herbicide prescriptions differed at the two study locations because woody vegetation was dominant at Camp Lejeune but herbaceous vegetation was more common at Fort Benning. Herbicide release prescriptions must be developed on a site specific basis to considering initial site conditions and competitive pressures.

7.1.1.5. Enhancing the condition of ground layer and mid-story vegetation

The condition of the ground layer vegetation in longleaf pine forests is critical to maintaining a frequent fire regime and providing good-quality RCW habitat. Fire-maintained longleaf pine ecosystems are among the most diverse in North America, supporting a rich array of herbaceous species that includes many species of conservation concern. Canopy removal increases resource availability for ground layer plants as well as planted pine seedlings, and there are concerns that canopy removal will release woody competitors during longleaf pine restoration.

Our results show that canopy removal releases ground layer vegetation, with greater cover and biomass of both herbaceous and woody vegetation following timber harvest. Generally, vegetation cover increased to the maximum within 10-20 m from the forest edge in canopy gaps. Although vegetation cover increased, we did not observe changes in the proportional abundance of vegetation groups; in other words, woody vegetation did not take over the ground layer, although woody stem development in the mid-story reduced ground layer abundance. The functional group composition of the ground layer vegetation was similar in each year of the study, suggesting that the initial condition of the ground layer strongly dictates subsequent ground layer composition. Herbicides were an effective method of reducing the cover of woody vegetation at Camp Lejeune, and sites with abundant woody vegetation may require the use of herbicides to improve the ground layer. Natural regeneration of loblolly pine can present a challenge to stand conversion with canopy retention, and our data suggest that site-specific or annual variation will strongly affect loblolly pine regeneration density. However, chemical control of woody mid-story stems increases growing space availability for loblolly pine regeneration, making control with prescribed fire essential in the presence of abundant regeneration.

Species richness of the ground layer vegetation was not strongly affected by canopy treatments in our study. Generally, we found that Fort Benning had higher species richness than Camp Lejeune, reflecting the relatively higher abundance of herbaceous species at Fort Benning at the beginning of the study. The composition of the study plots was more strongly controlled by the block location than by the study treatments at both sites, suggesting that the varied block management and land use histories exert a strong influence on current vegetation composition. However, the canopy treatments affected composition within each block; ruderal, disturbance species tended to be indicators of Clearcut plots and perennial forbs were more commonly indicators of uncut Control plots. Such changes in composition are common following canopy removal, and continued monitoring will provide additional information about the dynamics of the ground layer community during stand development.

There are many questions about the best methods for establishing native grasses during longleaf pine restoration (Glitzenstein et al. 2001, Walker and Silletti 2006), so we established a pilot study to evaluate establishment techniques and study treatment effects on different species of native grasses (Appendix A-1.1.1). At Fort Benning, we found that little bluestem nursery grown and outplanted plugs responded to increased resource availability following timber harvest and fertilizer application, suggesting that planting little bluestem following thinning would improve establishment. Direct seedling trials at Fort Benning resulted in virtually no seedling establishment. At Camp Lejeune, we were able to improve success of seeding wiregrass by raking the study sites, and with site preparation that exposes mineral soil broadcasting wiregrass seed proved to be a viable alternative for wiregrass establishment.

7.1.1.6. Managing restored stands with frequent surface fire

The fuel complexes created by inputs of highly flammable longleaf pine needles dropped onto a well-aerated bed of bunchgrass-dominated herbaceous vegetation are ideal for maintaining the high-frequency surface fires that perpetuate the longleaf pine ecosystem. The ability for land managers to apply effective prescribed fires depends largely on the available fuels and the conditions during burning. In many stands requiring restoration, the ground layer vegetation includes a hardwood component that may inhibit the use of prescribed fire. Further, canopy removal reduces the input of needles as a source of fine fuels, creating concerns about fire movement throughout gaps following the use of patch-cutting for longleaf pine restoration (Mitchell et al. 2006).

The treatments used in our study affected the fuel complexes at each study site. Generally, litter depth and pine needle cover decreased with canopy removal, and the cover of live and standing dead graminoid and woody vegetation cover increased with canopy removal. We generally found that fires burned hotter and more completely under an intact canopy than following canopy removal, and our results suggest that fires burn more completely at the forest edge than within the center of canopy gaps.

The ability to use prescribed fire as a management tool is critical for the restoration of longleaf pine within loblolly pine forests. Canopy retention in loblolly pine forests provides seed trees for natural loblolly pine regeneration, and logging and site preparation create favorable sites for loblolly pine germination. Because loblolly pine seedlings are susceptible to fire-induced mortality, prescribed burning is an essential tool for managers to control loblolly pine regeneration. In our study, we found abundant loblolly pine regeneration at Camp Lejeune but only moderate loblolly pine regeneration at Fort Benning; the prescribed burns at Fort Benning were sufficient for controlling loblolly pine regeneration, but the survival of loblolly pine seedlings threatens the successful establishment of longleaf pine seedlings at Camp Lejeune.

The available fuels play an important role in the ability to use prescribed fire, but the conditions during prescribed burning are also critical to meeting objectives of the burn. In many cases, two different fuel complexes can be burned to the same objective through careful consideration of fire weather, fuel moisture, and other burn conditions. In our study, prescribed fires were applied under a range of weather conditions, and the resulting burns reflected the combination of available fuels and burn conditions. It is important for land managers to understand the fuel complexes and schedule prescribed fires to meet burning objectives. For instance, stands with canopy gaps or clearcut areas should be burned under burn conditions that favor fire movement (warmer, higher wind speeds, lower humidity).

7.1.2. Developing silvicultural protocols for restoring longleaf pine to loblolly pine stands

Silvicultural decisions for converting existing loblolly pine stands that currently support RCW populations require attention to several critical restoration objectives, including retaining trees for RCW habitat, enabling successful longleaf pine seedling establishment, limiting natural loblolly pine regeneration, enhancing ground layer vegetation, and maintaining or reintroducing a frequent fire regime. Prescriptions must begin with an understanding of site conditions relative to RCW guidelines, including stand size, overstory tree size and density, and distance from RCW clusters, and in many cases, the allowable cut will be limited to maintain good quality habitat.

Various silvicultural techniques can be integrated at the stand level in order to meet different objectives during longleaf pine restoration. For example, specific basal area targets at the stand level can be reached by maintaining a uniform canopy distribution or by using group-selection to localize canopy removal within an uncut forest matrix. Such an approach may be applicable to stands in which portions fall within RCW clusters and silvicultural cutting is discouraged. In this section, we present several scenarios that demonstrate the integration of alternative silvicultural treatments within a single stand to meet specific objectives. Based on the results from our study, we describe and discuss the expected outcomes of each scenario on selected ecosystem components at the stand level.

7.1.2.1. Modeling approach

The canopy treatments used in our field study included four that varied the basal area of the stand through uniform canopy distribution (Control: 17 m^2/ha basal area; MedBA: 9 m^2/ha basal area; LowBA: 5 m^2/ha basal area and Clearcut: 0 m^2/ha basal area) and three different sized gap treatments (LG, gap area = 0.5027 ha and radius = 40 m; MG: gap area = 0.2827 ha and radius = 30 m; SG: gap area = 0.1257 ha and radius = 20 m). Within the gap plots, we quantified response variables by gap position along the north/south axis but also calculated gap-level means for comparison to means of uniform canopy treatments. However, the interpretation of response variables in uniform plots and gap plots differs, because responses in uniform plots are assumed to be consistent for stands of any size receiving a uniform treatment, whereas gap treatment responses are localized and apply only to the gap area. In practice forest managers have the flexibility to combine uniform thinning with group selection to control the spatial distribution of residual trees within a stand.

To illustrate how different practices applied within a stand affect the stand-level response of different ecosystem components, we consider a hypothetical loblolly pine stand that is 25 hectares in size, with a starting basal area of 17 m^2/ha, approximately 175 trees per hectare, and a quadratic mean diameter of 35 cm. At least 4.6 m^2/ha of this basal area is in trees > 35 cm DBH and the basal area of pines between 25 and 35 cm DBH is < 9 m^2/ha; therefore, by definition the canopy structure currently satisfies the criteria for good quality RCW foraging habitat. In all scenarios, we assume longleaf pine seedlings were underplanted at a density of 1500 trees per hectare.

In this modeling exercise, our management objective is to convert the loblolly pine stand to longleaf pine while retaining loblolly pine trees for RCW habitat objectives or for other ecosystem services. To demonstrate how different silvicultural practices can be used within this context, we present eight scenarios that combine levels of uniform thinning with group selection to reach stand-level basal area targets. In each scenario, we calculate the proportional area of the total stand that falls within each canopy treatment type and then determine the weighted average of the following response variables: basal area, light availability, longleaf pine seedling establishment (root collar diameter, height, survival, number of trees in height growth), cover of ground layer vegetation (total, herbaceous, and woody vegetation), and mid-story stem density (total, loblolly pine, and hardwood). Longleaf pine seedling and vegetation responses are following the fifth growing season. For the analyses, we used mean values from the NT split-plot treatments because in some cases the application of split-plot treatments interacted with the overstory treatments. Due to site differences in some response variables, each site is presented separately; at Camp Lejeune, loblolly pine stem densities were not collected in SG or LG plots in 2012 and therefore cannot be included in the models; instead, we assume that loblolly pine stems in MG plots is similar to that in SG and LG plots for such scenarios.

7.1.2.2. Management scenarios

UNCUT—In the uncut stand, basal area remained at 17 m^2/ha and was uniformly distributed throughout the stand (Figure 7.1.1A). Longleaf pine seedling density after five growing seasons was around 620 seedlings/ha at each study site, and root collar size is close to 20 mm at each site (Tables 7.1.1 and 7.1.2). At Fort Benning, there were no seedlings in height growth and only 22 seedlings/ha were in height growth at Camp Lejeune. Ground layer vegetation cover was low at both sites, and the cover of herbaceous vegetation was well below the 40% requirement of good quality RCW habitat. At Fort Benning, mid-story stem density was low, with less than 500 stems per hectare, but at Camp Lejeune there were more than 5500 stems per hectare, with hardwoods and shrubs dominating that population.

UNIFORM BASAL AREA 9 M^2/HA—In this scenario, managers reduce the stand-level basal area to 9 m^2/ha, with the objectives of increasing light availability to improve longleaf pine seedling growth while maintaining good quality RCW habitat structure and maintaining higher canopy density for other ecosystem services. Because 9 m^2/ha represents the lower basal area limit for large canopy trees, the uniform thinning will be retain a level of basal area consistent with good quality RCW habitat in all areas of the stand (Figure 7.1.1B).

As a result, root collar diameter was 25.6 mm at Fort Benning and 24.8 mm at Camp Lejeune. There were 180 and 247 seedlings per hectare in height growth at Fort Benning and Camp Lejeune, respectively. The cover of ground layer vegetation remained below the recommendation of 40% cover in the RCW Recovery Plan at both sites, and the density of mid-story stems was 775 stems/ha at Fort Benning and 6450 stems/ha at Camp Lejeune.

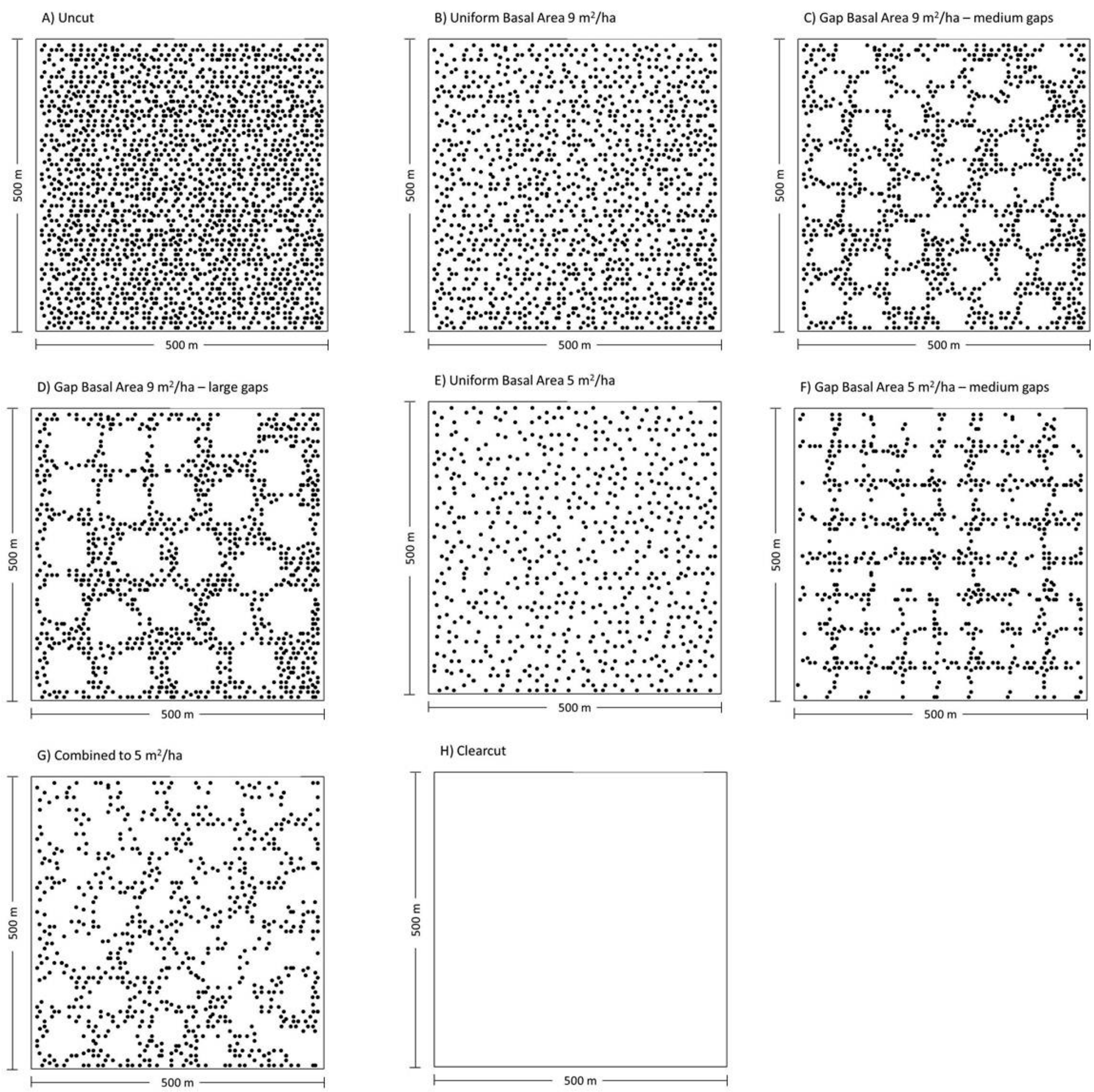


Figure 7.1.1. Illustrations of management scenarios for restoring longleaf pine to loblolly pine stands while retaining loblolly pines for RCW habitat.

GAP BASAL AREA 9 M^2/HA – MEDIUM GAPS—Managers have the option to reduce stand density to a target basal area using group selection rather than uniform thinning. Such an approach could be used to maintain high canopy densities in areas where thinning is not favorable due to existing habitat quality or restrictions. In this scenario, medium-sized gaps (0.2827 ha) were used throughout the stand to reduce stand basal area from 17 to 9 m^2/ha. This required that 47%, or 11.8 ha, of the stand be converted to gap openings, resulting in the cutting of 41 medium-sized gaps (Figure 7.1.1C).

Mean seedling size in the medium gap plots was larger than that in the uncut areas at both study sites, with a root collar diameter of 28.2 mm in group openings at Fort Benning and a root collar diameter of 24.1 mm in group openings at Camp Lejeune. Likewise, 286 seedlings per hectare were in height growth in group openings at Fort Benning and 202 seedlings per hectare were in height growth at Camp Lejeune. Within the group openings, vegetation cover and mid-story stem densities were greater than in the uncut portions of the stands, with over 28,000 mid-story stems in gaps at Camp Lejeune, the majority of which were loblolly pine.

GAP BASAL AREA 9 M^2/HA – LARGE GAPS—By changing the size of canopy openings, forest managers can exert control over localized growing conditions throughout the stand. Reaching a target basal area at the stand level using gap openings requires that a certain percentage of the total basal area in the stand be removed. However, this can be done with gaps of different sizes, with the gap size determining the number of gaps required. To reduce stand-level basal area from 17 to 9 m^2/ha, 23 large-sized gaps (0.5027 ha) would be required (Figure 7.1.1D).

Because the same percentage of the stand is converted to gaps in this scenario as with use of gaps of any size, differences in stand-level means will be dependent on the gap-specific response. At Fort Benning, mean seedling root collar diameter in LG plots was 29.8 mm and 257 seedlings were in height growth, resulting in stand-level means of 24.8 mm and 121 seedlings in height growth, respectively. At Camp Lejeune, root collar diameter was 25.9 mm within LG plots, for a stand-level mean of 22.3 mm, and there were 246 seedlings/ha in height growth within gaps, for a stand-level mean of 127 seedlings/ha.

UNIFORM BASAL AREA 5 M^2/HA—Reducing_ the stand-level basal area below the 9 m^2/ha recommended for good quality RCW habitat would allow for more rapid longleaf pine seedling growth and may be desirable in some situations. By applying a uniform thinning across the stand to reach a target basal area of 5 m^2/ha (Figure 7.1.1E), light levels can be expected to be around 70% at both sites. At Fort Benning, nearly 375 seedlings/ha were in height growth compared to 195 seedlings/ha at Camp Lejeune. Ground layer vegetation cover and the abundance of woody stems also increased with greater canopy removal, resulting in 3000 mid-story stems per hectare at Fort Benning and 12,594 stems per hectare at Camp Lejeune.

GAP BASAL AREA 5 M^2/HA – MEDIUM GAPS—To achieve greater reductions in basal area using only gaps, more canopy openings must be created in the stand. Reducing stand-level basal area from 17 to 5 m^2/ha requires that 71% of the stand be converted to canopy gaps, equaling 62 medium-sized gaps within our 25 hectare stand (Figure 7.1.1F). Following such a prescription, the stand-level light availability would be 58% at Fort Benning and 65% at Camp Lejeune. Because a greater area of the stand is in gaps, stand-level response variables are weighted more heavily toward gap means. For example, mid-story stem density in gap openings averaged 2375 stems per hectare at Fort Benning, and the stand-level mean was 1802 stems per hectare.

COMBINED TO 5 M^2/HA—The scenarios presented thus far used either group openings or uniform thinning to reach the target basal areas. Managers can increase the flexibility for reaching different objectives by combining those two methods of canopy reduction by reducing the forest matrix to a specified level and then creating group openings. In this example, managers thin the canopy to 9 m^2/ha using uniform thinning and then use medium-sized gaps to further reduce the stand-level basal area to 5 m^2/ha. To reach the desired basal area, 55% of the stand is left at 9 m^2/ha and the remaining 44% of the stand area is removed with the application of 39 medium-sized group openings.

CLEARCUT—In this scenario, complete canopy removal is used to increase the growth rate of planted longleaf pine seedlings. Clearcutting has commonly been used with artificial regeneration of longleaf pine to increase growing space and resource availability for planted seedlings.

7.1.2.3. Stand-level prescriptions

Using experimental results to model stand outcomes under designated stand prescriptions are shown in Tables 7.1.1-7.1.16. Silvicultural prescriptions are created to target specific objectives, and, as such, several different practices may be appropriate for reaching different objectives within a stand. Our results support previous findings that clearcutting results in the greatest seedling growth and consequently the greatest number of seedlings in height growth after five growing seasons. Successful seedling establishment is a primary objective of longleaf pine restoration with underplanting, but metrics for suitable seedling densities in a restoration framework are not available. Guidelines for artificial regeneration have suggested the survival of at least 740 seedlings per hectare after the first year (Barnett et al. 1990), and other sources have suggested that at least 1000 seedlings per hectare in height growth after 3 or 4 years would develop into a manageable stand (Brockway et al. 2005). However, traditional approaches require adequate densities to create a fully stocked stand and often assume that stands will be managed with a focus on timber. For sustaining RCW habitat, lower densities may be acceptable, provided that adequate survival is maintained to provide suitable stocking over time.

Integrating uniform thinning and group selection silvicultural methods can provide forest managers with increased flexibility for meeting multiple management objectives. Converting existing loblolly pine stands to longleaf pine on DoD installations is often motivated by RCW habitat needs, and therefore conversion practices must commonly be implemented in stands that currently serve as habitat for local populations. In such cases, it may be necessary to distribute areas of canopy retention and canopy removal throughout the stand in order to simultaneously maintain good quality habitat while establishing underplanted longleaf pine seedlings.

Our results indicate that underplanting longleaf pine in stands that have not been thinned will result in inadequate numbers of seedlings in height growth after five growing seasons (Tables 7.1.15 and 7.1.16). Retaining unthinned portions of the stand may be feasible, however, provided that other areas are cut to allow for seedling establishment. We used a basal area of 9 m^2/ha as a

Table 7.1.1. Summary of selected response variables at the stand level for a 25 hectare, uncut stand with a starting basal area of 17 m^2/ha at Fort Benning

"Uncut" – Fort Benning Response variable Proportion of stand	Uniform 25 ha 1.00	LG 0.00	MG 0.00	SG 0.00	Stand Level
Basal area (m^2/ha)	17.0	.	.	.	17.0
Light availability (GLI; %)	38.3	.	.	.	38.3
Longleaf pine seedlings (after five years)					
Root collar diameter (mm)	20.4	.	.	.	20.4
Seedling density (tph)	625.7	.	.	.	625.7
Height (cm)	3.8	.	.	.	3.8
Seedlings in height growth (tph)	0.0	.	.	.	0.0
Ground layer vegetation (after five years)					
Total cover (%)	17.6	.	.	.	17.6
Herbaceous cover (%)	12.7	.	.	.	12.7
Woody cover (%)	4.4	.	.	.	4.4
Mid-story stem density					
Total (tph)	400.0	.	.	.	400.0
Loblolly pine (tph)	25.0	.	.	.	25.0
Hardwoods (tph)	375.0	.	.	.	375.0

Table 7.1.2. Summary of selected response variables at the stand level for a 25 hectare, uncut stand with a starting basal area of 17 m^2/ha at Camp Lejeune

"Uncut" – Camp Lejeune Response variable Proportion of stand	Uniform 25 ha 1.00	LG 0.00	MG 0.00	SG 0.00	Stand Level
Basal area (m^2/ha)	17.0	.	.	.	17.0
Light availability (GLI; %)	47.8	.	.	.	47.8
Longleaf pine seedlings (after five years)					
Root collar diameter (mm)	19.0	.	.	.	19.0
Seedling density (tph)	621.3	.	.	.	621.3
Height (cm)	6.3	.	.	.	6.3
Seedlings in height growth (tph)	21.7	.	.	.	21.7
Ground layer vegetation (after five years)					
Total cover (%)	45.5	.	.	.	45.5
Herbaceous cover (%)	8.1	.	.	.	8.1
Woody cover (%)	37.3	.	.	.	37.3
Mid-story stem density					
Total (tph)	5671.9	.	.	.	5671.9
Loblolly pine (tph)	15.6	.	.	.	15.6
Hardwoods (tph)	5656.3	.	.	.	5656.3

Table 7.1.3. Summary of selected response variables at the stand level for a 25 hectare with a starting basal area of 17 m^2/ha at Fort Benning that is thinned to 9 m^2/ha to create a uniform distribution of residual canopy trees

"Uniform Basal Area 9 m^2/ha" – Fort Benning Response variable Percentage of stand	Uniform 25 ha 1.00	LG 0.00	MG 0.00	SG 0.00	Stand Level
Basal area (m2/ha)	9.0	.	.	.	9.0
Light availability (GLI; %)	54.9	.	.	.	54.9
Longleaf pine seedlings (five year response)					
Root collar diameter (mm)	25.6	.	.	.	25.6
Seedling density (tph)	846.8	.	.	.	846.8
Height (cm)	13.4	.	.	.	13.4
Seedlings in height growth (tph)	179.5	.	.	.	179.5
Ground layer vegetation (five year response)					
Total cover (%)	23.4	.	.	.	23.4
Herbaceous cover (%)	17.6	.	.	.	17.6
Woody cover (%)	7.3	.	.	.	7.3
Mid-story stem density					
Total (tph)	775.0	.	.	.	775.0
Loblolly pine (tph)	25.0	.	.	.	25.0
Hardwoods (tph)	750.0	.	.	.	750.0

Table 7.1.4. Summary of selected response variables at the stand level for a 25 hectare with a starting basal area of 17 m^2/ha at Camp Lejeune that is thinned to 9 m^2/ha to create a uniform distribution of residual canopy trees

"Uniform Basal Area 9 m^2/ha" – Camp Lejeune Response variable Percentage of stand	Uniform 25 ha 1.00	LG (0.50 ha) 0	MG (0.28 ha) 0	SG (0.13 ha) 0	Stand Level
Basal area (m2/ha)	9.0	.	.	.	9.0
Light availability (GLI; %)	61.7	.	.	.	61.7
Longleaf pine seedlings (five year response)					
Root collar diameter (mm)	24.8	.	.	.	24.8
Seedling density (tph)	850.1	.	.	.	850.1
Height (cm)	16.4	.	.	.	16.4
Seedlings in height growth (tph)	246.7	.	.	.	246.7
Ground layer vegetation (five year response)					
Total cover (%)	53.6	.	.	.	53.6
Herbaceous cover (%)	8.9	.	.	.	8.9
Woody cover (%)	44.8	.	.	.	44.8
Mid-story stem density					
Total (tph)	6437.5	.	.	.	6437.5
Loblolly pine (tph)	62.5	.	.	.	62.5
Hardwoods (tph)	6375.0	.	.	.	6375.0

Table 7.1.5. Summary of selected response variables at the stand level for a 25 hectare with a starting basal area of 17 m^2/ha at Fort Benning that is reduced to 9 m^2/ha through the application of medium-sized canopy openings

"Gap Basal Area 9 m^2/ha – MG" - Fort Benning Response variable Proportion of stand	Uniform 13.2 ha 0.53	LG 0	MG 11.8 ha 0.47	SG 0 0	Stand Level 1.00
Basal area (m^2/ha)	17.0	.	0.0	.	9.0
Light availability (GLI; %)	38.3	.	65.8	.	51.2
Longleaf pine seedlings (five year response)					
Root collar diameter (mm)	20.4	.	28.2	.	24.1
Seedling density (tph)	625.7	.	652.5	.	638.3
Height (cm)	3.8	.	33.6	.	17.8
Seedlings in height growth (tph)	0.0	.	285.8	.	134.5
Ground layer vegetation (five year response)					
Total cover (%)	17.6	.	45.4	.	30.7
Herbaceous cover (%)	12.7	.	29.9	.	20.8
Woody cover (%)	4.4	.	17.7	.	10.7
Mid-story stem density					
Total (tph)	400.0	.	2375.0	.	1329.4
Loblolly pine (tph)	25.0	.	375.0	.	189.7
Hardwoods (tph)	375.0	.	1962.5	.	1122.1

Table 7.1.6. Summary of selected response variables at the stand level for a 25 hectare with a starting basal area of 17 m^2/ha at Camp Lejeune that is reduced to 9 m^2/ha through the application of medium-sized canopy openings

"Gap Basal Area 9 m^2/ha – MG" - Camp Lejeune Response variable Percentage of stand	Uniform 13.2 ha 0.53	LG 0	MG 11.8 ha 0.47	SG 0	Stand Level 1.00
Basal area (m^2/ha)	17.0	.	0.0	.	9.0
Light availability (GLI; %)	47.8	.	72.5	.	59.4
Longleaf pine seedlings (five year response)					
Root collar diameter (mm)	19.0	.	24.1	.	21.4
Seedling density (tph)	621.3	.	642.0	.	631.0
Height (cm)	6.3	.	15.6	.	10.7
Seedlings in height growth (tph)	21.7	.	201.6	.	106.2
Ground layer vegetation (five year response)					
Total cover (%)	45.5	.	60.4	.	52.5
Herbaceous cover (%)	8.1	.	20.9	.	14.1
Woody cover (%)	37.3	.	39.4	.	38.3
Mid-story stem density					
Total (tph)	5671.9	.	28325.4	.	16319.0
Loblolly pine (tph)	15.6	.	17861.1	.	8403.0
Hardwoods (tph)	5656.3	.	10464.3	.	7916.0

Table 7.1.7. Summary of selected response variables at the stand level for a 25 hectare stand with a starting basal area of 17 m^2/ha at Fort Benning that is reduced to 9 m^2/ha using large-sized canopy openings

"Gap Basal Area 9 m^2/ha – LG" - Fort Benning Response variable Proportion of stand	Uniform 13.2 ha 0.53	LG 11.8 ha 0.47	MG 0.00	SG 0 0	Stand Level 1.00
Basal area (m^2/ha)	17.0	0.0	.	.	9.0
Light availability (GLI; %)	38.3	73.2	.	.	54.7
Longleaf pine seedlings (five year response)					
Root collar diameter (mm)	20.4	29.8	.	.	24.8
Seedling density (tph)	625.7	544.5	.	.	587.5
Height (cm)	3.8	29.7	.	.	16.0
Seedlings in height growth (tph)	0.0	257.0	.	.	120.9
Ground layer vegetation (five year response)					
Total cover (%)	17.6	56.6	.	.	35.9
Herbaceous cover (%)	12.7	36.5	.	.	23.9
Woody cover (%)	4.4	19.0	.	.	11.3
Mid-story stem density					
Total (tph)	400.0	3625.0	.	.	1917.6
Loblolly pine (tph)	25.0	150.0	.	.	83.8
Hardwoods (tph)	375.0	3475.0	.	.	1833.8

Table 7.1.8. Summary of selected response variables at the stand level for a 25 hectare stand with a starting basal area of 17 m^2/ha at Camp Lejeune that is reduced to 9 m^2/ha using large-sized canopy openings

"Gap Basal Area 9 m^2/ha – LG" - Camp Lejeune Response variable Percentage of stand	Uniform 13.2 ha 0.53	LG 11.8 ha 0.47	MG	SG 0	Stand Level 1.00
Basal area (m^2/ha)	17.0	0.0	.	.	9.0
Light availability (GLI; %)	47.8	78.8	.	.	62.4
Longleaf pine seedlings (five year response)					
Root collar diameter (mm)	19.0	25.9	.	.	22.3
Seedling density (tph)	621.3	838.5	.	.	723.4
Height (cm)	6.3	15.0	.	.	10.4
Seedlings in height growth (tph)	21.7	245.7	.	.	127.0
Ground layer vegetation (five year response)					
Total cover (%)	45.5	62.0	.	.	53.2
Herbaceous cover (%)	8.1	26.1	.	.	16.6
Woody cover (%)	37.3	35.9	.	.	36.6
Mid-story stem density					
Total (tph)	5671.9	27177.8	.	.	15779.7
*Loblolly pine (tph)**	15.6	17861.1	.	.	8403.0
Hardwoods (tph)	5656.3	9316.7	.	.	7376.6

*loblolly pines were measured in MG plots only, so the values presented for LG and SG plots here are those collected in MG plots

Table 7.1.9. Summary of selected response variables at the stand level for a 25 hectare with a starting basal area of 17 m^2/ha at Fort Benning that is thinned to 5 m^2/ha to create a uniform distribution of residual canopy trees

"Uniform Basal Area 5 m^2/ha" - Fort Benning Response variable Proportion of stand	Uniform 25 ha 1.00	LG 0.00	MG 0.00	SG 0.00	Stand Level 1.00
Basal area (m^2/ha)	5.0	.	.	.	5.0
Light availability (GLI; %)	68.8	.	.	.	68.8
Longleaf pine seedlings (five year response)					
Root collar diameter (mm)	29.7	.	.	.	29.7
Seedling density (tph)	640.5	.	.	.	640.5
Height (cm)	35.4	.	.	.	35.4
Seedlings in height growth (tph)	363.8	.	.	.	363.8
Ground layer vegetation (five year response)					
Total cover (%)	56.3	.	.	.	56.3
Herbaceous cover (%)	30.5	.	.	.	30.5
Woody cover (%)	16.7	.	.	.	16.7
Mid-story stem density					
Total (tph)	3000	.	.	.	3000.0
Loblolly pine (tph)	450	.	.	.	450.0
Hardwoods (tph)	2490	.	.	.	2490.0

Table 7.1.10. Summary of selected response variables at the stand level for a 25 hectare with a starting basal area of 17 m^2/ha at Camp Lejeune that is thinned to 5 m^2/ha to create a uniform distribution of residual canopy trees

"Uniform Basal Area 5 m^2/ha" - Camp Lejeune Response variable Proportion of stand	Uniform 21 ha 1.00	LG 0.00	MG 0.00	SG 0.00	Stand Level 1.00
Basal area (m^2/ha)	5.0	.	.	.	5.0
Light availability (GLI; %)	69.6	.	.	.	69.6
Longleaf pine seedlings (five year response)					
Root collar diameter (mm)	25.3	.	.	.	25.3
Seedling density (tph)	633.0	.	.	.	633.0
Height (cm)	17.1	.	.	.	17.1
Seedlings in height growth (tph)	193.7	.	.	.	193.7
Ground layer vegetation (five year response)					
Total cover (%)	49.0	.	.	.	49.0
Herbaceous cover (%)	6.4	.	.	.	6.4
Woody cover (%)	42.7	.	.	.	42.7
Mid-story stem density					
Total (tph)	12593.8	.	.	.	12593.8
Loblolly pine (tph)	4625.0	.	.	.	4625.0
Hardwoods (tph)	7968.8	.	.	.	7968.8

Table 7.1.11. Summary of selected response variables at the stand level for a 25 hectare with a starting basal area of 17 m^2/ha at Fort Benning that is reduced to 5 m^2/ha through the application of medium-sized canopy openings

"Gap Basal Area 5 m^2/ha – MG" - Fort Benning Response variable	Uniform 7.4 ha	LG	MG 17.6 ha	SG 0	Stand Level
Percentage of stand	0.29	0	0.71	0	1.00
Basal area (m^2/ha)	17.0	.	0.0	.	4.9
Light availability (GLI; %)	38.3	.	65.8	.	57.9
Longleaf pine seedlings (five year response)					
Root collar diameter (mm)	20.4	.	28.2	.	25.9
Seedling density (tph)	625.7	.	652.5	.	644.7
Height (cm)	3.8	.	33.6	.	25.0
Seedlings in height growth (tph)	0.0	.	285.8	.	202.9
Ground layer vegetation (five year response)					
Total cover (%)	17.6	.	45.4	.	37.3
Herbaceous cover (%)	12.7	.	29.9	.	24.9
Woody cover (%)	4.4	.	17.7	.	13.9
Mid-story stem density					
Total (tph)	400.0	.	2375.0	.	1802.3
Loblolly pine (tph)	25.0	.	375.0	.	273.5
Hardwoods (tph)	375.0	.	1962.5	.	1502.1

Table 7.1.12. Summary of selected response variables at the stand level for a 25 hectare with a starting basal area of 17 m^2/ha at Camp Lejeune that is reduced to 5 m^2/ha through the application of medium-sized canopy openings

"Gap Basal Area 5 m^2/ha – MG" - Camp Lejeune Response variable Percentage of stand	Uniform 7.4 ha 0.29	LG 0	MG 17.6 ha 0.71	SG 0 0	Stand Level 1.00
Basal area (m^2/ha)	17.0	.	0.0	.	4.9
Light availability (GLI; %)	47.8	.	72.5	.	65.4
Longleaf pine seedlings (five year response)					
Root collar diameter (mm)	19.0	.	24.1	.	22.7
Seedling density (tph)	621.3	.	642.0	.	636.0
Height (cm)	6.3	.	15.6	.	12.9
Seedlings in height growth (tph)	21.7	.	201.6	.	149.4
Ground layer vegetation (five year response)					
Total cover (%)	45.5	.	60.4	.	56.0
Herbaceous cover (%)	8.1	.	20.9	.	17.2
Woody cover (%)	37.3	.	39.4	.	38.8
Mid-story stem density					
Total (tph)	5671.9	.	28325.4	.	21755.9
Loblolly pine (tph)	15.6	.	17861.1	.	12685.9
Hardwoods (tph)	5656.3	.	10464.3	.	9070.0

Table 7.1.13. Summary of selected response variables at the stand level for a 25 hectare with a starting basal area of 17 m^2/ha at Fort Benning that is reduced to 5 m^2/ha through the application of uniform thinning to 9 m^2/ha and the use of medium-sized canopy openings

"Combined - Basal Area 5 m^2/ha" - Fort Benning Response variable Proportion of stand	Uniform 13.9 ha 0.55	LG 0.00	MG 11.1 ha 0.44	SG 0.00	Stand Level 0.99
Basal area (m^2/ha)	9.0		0.0		5.0
Light availability (GLI; %)	54.9		65.8		59.2
Longleaf pine seedlings (five year response)					
Root collar diameter (mm)	25.6		28.2		26.5
Seedling density (tph)	847.5		652.5		753.2
Height (cm)	13.4		33.6		22.2
Seedlings in height growth (tph)	179.7		285.8		224.6
Ground layer vegetation (five year response)					
Total cover (%)	23.4		45.4		32.9
Herbaceous cover (%)	17.6		29.9		22.8
Woody cover (%)	7.3		17.7		11.8
Mid-story stem density					
Total (tph)	775.0		2375.0		1471.3
Loblolly pine (tph)	25.0		375.0		178.8
Hardwoods (tph)	750.0		1962.5		1276.0

Table 7.1.14. Summary of selected response variables at the stand level for a 25 hectare with a starting basal area of 17 m^2/ha at Camp Lejeune that is reduced to 5 m^2/ha through the application of uniform thinning to 9 m^2/ha and the use of medium-sized canopy openings

"Combined - Basal Area 5 m^2/ha" - Camp Lejeune Response variable Proportion of stand	Uniform 13.9 ha 0.55	LG 0.00	MG 11.1 ha 0.44	SG 0.00	Stand Level 0.99
Basal area (m^2/ha)	9.0		0.0		5.0
Light availability (GLI; %)	61.7		72.5		65.8
Longleaf pine seedlings (five year response)					
Root collar diameter (mm)	24.8		24.1		24.3
Seedling density (tph)	850.1		642.0		750.0
Height (cm)	16.4		15.6		15.9
Seedlings in height growth (tph)	246.7		201.6		224.4
Ground layer vegetation (five year response)					
Total cover (%)	53.6		60.4		56.0
Herbaceous cover (%)	8.9		20.9		14.1
Woody cover (%)	44.8		39.4		42.0
Mid-story stem density					
Total (tph)	6437.5		28325.4		16003.8
*Loblolly pine (tph)**	62.5		17861.1		7893.3
Hardwoods (tph)	6375.0		10464.3		8110.5

Table 7.1.15. Summary of stand-level responses of ecosystem components following simulated application of alternative management prescriptions at Fort Benning

Fort Benning	Scenario							
Response variable	Uncut	Uniform BA9	Gap BA9-MG	Gap BA9-LG	Uniform BA5	Gap BA5-MG	Combined BA5	Clearcut
Basal area (m^2/ha)	17.0	9.0	9.0	9.0	5.0	4.9	5.0	0.0
Light availability (GLI; %)	38.3	54.9	51.2	54.7	68.8	57.9	59.2	94.4
Longleaf pine seedlings (five year response)								
Root collar diameter (mm)	20.4	25.6	24.1	24.8	29.7	25.9	26.5	38.6
Seedling density (tph)	625.7	846.8	638.3	587.5	640.5	644.7	753.2	544.5
Height (cm)	3.8	13.4	17.8	16.0	35.4	25.0	22.2	73.7
Seedlings in height growth (tph)	0.0	179.5	134.5	120.9	363.8	202.9	224.6	406.2
Ground layer vegetation (five year response)								
Total cover (%)	17.6	23.4	30.7	35.9	56.3	37.3	32.9	48.9
Herbaceous cover (%)	12.7	17.6	20.8	23.9	30.5	24.9	22.8	24.3
Woody cover (%)	4.4	7.3	10.7	11.3	16.7	13.9	11.8	22.6
Mid-story stem density								
Total (tph)	400.0	775.0	1329.4	1917.6	3000.0	1802.3	1471.3	5725.0
*Loblolly pine (tph)**	25.0	25.0	189.7	83.8	450.0	273.5	178.8	325.0
Hardwoods (tph)	375.0	750.0	1122.1	1833.8	2490.0	1502.1	1276.0	5400.0

Table 7.1.16. Summary of stand-level responses of ecosystem components following simulated application of alternative management prescriptions at Camp Lejeune

Camp Lejeune	Scenario							
Response variable	Uncut	Uniform BA9	Gap BA9-MG	Gap BA9-LG	Uniform BA5	Gap BA5-MG	Combined BA5	Clearcut
Basal area (m2/ha)	17.0	9.0	9.0	9.0	5.0	4.9	5.0	0.0
Light availability (GLI; %)	47.8	61.7	59.4	62.4	69.6	65.4	65.8	93.7
Longleaf pine seedlings (five year response)								
Root collar diameter (mm)	19.0	24.8	21.4	22.3	25.3	22.7	24.3	32.2
Seedling density (tph)	621.3	850.1	631.0	723.4	633.0	636.0	750.0	1093.5
Height (cm)	6.3	16.4	10.7	10.4	17.1	12.9	15.9	41.0
Seedlings in height growth (tph)	21.7	246.7	106.2	127.0	193.7	149.4	224.4	528.2
Ground layer vegetation (five year response)								
Total cover (%)	45.5	53.6	52.5	53.2	49.0	56.0	56.0	58.6
Herbaceous cover (%)	8.1	8.9	14.1	16.6	6.4	17.2	14.1	18.1
Woody cover (%)	37.3	44.8	38.3	36.6	42.7	38.8	42.0	40.5
Mid-story stem density								
Total (tph)	5671.9	6437.5	16319.0	15779.7	12593.8	21755.9	16003.8	17656.3
*Loblolly pine (tph)**	15.6	62.5	8403.0	8403.0	4625.0	12685.9	7893.3	5437.5
Hardwoods (tph)	5656.3	6375.0	7916.0	7376.6	7968.8	9070.0	8110.5	12218.8

target in several scenarios because it is the lower-limit of stand density for good quality RCW foraging habitat. Interestingly, when we compared a stand-level weighted mean of a uniform application of thinning to basal area 9 m^2/ha in to a stand reduced to stand-level basal area of 9 m^2/ha using medium-sized gaps, we found that uniform thinning resulted in larger stand-level root collar diameters and more seedlings in height growth at both sites. The strong reduction in seedling growth beneath an uncut residual matrix makes the use of only group selection less desirable than the combination of uniform thinning of the residual matrix with group selection.

Gaps present the option of canopy retention throughout the stand but localized openings to increase seedling growth. Palik et al. (2003) discussed variable canopy retention at the stand level in longleaf pine forests and found that seedling growth could be maximized at the stand level by creating large canopy gaps, despite the same stand level basal area for each treatment. Their results suggested that the creation of large canopy openings increased stand-level responses because seedling growth increased exponentially with decreased basal area and a higher proportion of the stand would be in ‘open-grown’ conditions. Moreover, it is likely that large gap openings increase the penetration of diffuse light to the forest matrix, potentially increasing seedling growth outside of the gaps themselves. However, our results indicate that using uniform thinning results in greater stand-level mean seedling size than reaching the same basal area with gaps. It is likely that our model, using gap-level mean seedling size, used too coarse a resolution to detect the effects of gap position and seedling size on mean seedling response at the stand level. Moreover, we observed patterns of seedling response across canopy openings that differed at our two study sites, with an increase in seedling size by gap position at Fort Benning but no difference in seedling size by gap position at Camp Lejeune (Section 3.2). These patterns suggest that canopy gap size, while expected to affect the number of seedlings in height growth, is not always strongly linked to seedling response.

The differences in stand-level mean seedling size among target basal area scenarios were generally small compared to the difference in mid-story stems. With the exception of the treatments designed to reach a basal area of 5 m^2/ha at Fort Benning, the use of group selection to reach a target basal area resulted in higher mid-story stem densities than uniform thinning at both sites. These results generally support the previous research findings that creating canopy openings releases woody vegetation and increases the mid-story component of longleaf pine forests (Kirkman et al. 2007, Pecot et al. 2007). As a result, minimizing the size of canopy openings may be desirable to reduce mid-story development while allowing longleaf pine seedlings to establish.

To restore longleaf pine to loblolly pine stands that support RCWs, we recommend adaptive management based on stand size and initial stand conditions relative to RCW habitat requirements. Uniform retention of canopy pines will increase pine needle inputs as a fuels source, limit increases in competition from ground layer vegetation, and may facilitate seedling survival in some situations. In areas with spatial constraints to heavy thinning, or habitats where thinning is not favorable, nearby canopy gaps can be used to establish longleaf pine seedlings. We recommend the use of small canopy gaps (0.1 ha) in order to reduce the likelihood of seedling mortality and to reduce the release of mid-story vegetation that can reduce the quality of RCW habitat and create challenges for fire management.

7.2. Management guidance and applicability of project results

In drafting our proposal we explicitly recognized the variability among longleaf pine forests across the region, and the potential for variable responses to treatments. Understanding the variation was important because Department of Defense installations span the longleaf pine range (Figure 7.2.1). To provide some insight into that variation we established the field experiment in Camp Lejeune and Fort Benning. In the first section we provide management recommendations based on robust results from our study, that is, results where patterns on both sites converged.

7.2.1. Recommendations for longleaf pine restoration in loblolly pine stands

While management objectives and starting conditions of the stand will determine the appropriate silvicultural practices for converting loblolly pine stands to longleaf pine dominance, common restoration objectives include conserving biodiversity and providing habitat for wildlife. In such cases, complete canopy removal conflicts with long-term goals by changing the composition of the ground layer vegetation and disrupting ecosystem function. We recommend using single-tree selection with residual basal areas between 5 and 8 m^2/ha to encourage longleaf pine seedling establishment, limit encroachment by hardwoods, reduce compositional shifts of ground-layer vegetation to ruderal species, and maintain fuels for fire management. In some cases, particularly if management is constrained by spatial requirements for RCW habitat, group selection can be used to initiate longleaf pine establishment in discrete locations within a stand while maintaining existing RCW habitat in critical areas (Section 7.1). We recommend using small gaps (0.1 ha) to minimize seedling mortality and maintain the desirable structure of the ground layer vegetation structure. We derived these recommendations based on the results of the experiments established at Fort Benning and Camp Lejeune. Although the results varied in detail, mostly attributable to initial (or post site preparation) vegetation composition and structure, the effects of canopy treatments on longleaf pine seedling survival and growth were strongly convergent across sites.

Among cultural treatments, we do not recommend fertilization for improving longleaf pine establishment, as it was not beneficial in either location on any soil type in the study. Herbicides can be used for competition control, but may not be necessary if site preparation methods effectively reduced potential competitors. If woody vegetation develops, herbicides can be used to reduce midstory stems, release herbaceous vegetation, and facilitate prescribed fire management. On sites abundant herbaceous vegetation, herbaceous control may improve longleaf pine seedling establishment. In such cases, we recommend band or spot applications to localize effects around longleaf pine seedlings and to minimize stand-level effects on remnant vegetation.

The potential for natural loblolly pine establishment during a gradual conversion to longleaf pine under partial canopy retention is recognized as the unique significant challenge to this process. Our work showed that the threat from loblolly invasion is variable. Loblolly pine seedlings are susceptible to drought (as are planted longleaf pines) and competition with other vegetation. However, loblolly seedlings, unlike longleaf pine seedlings, rapidly begin height growth, and this provides an advantage for surviving with competition during stand development.

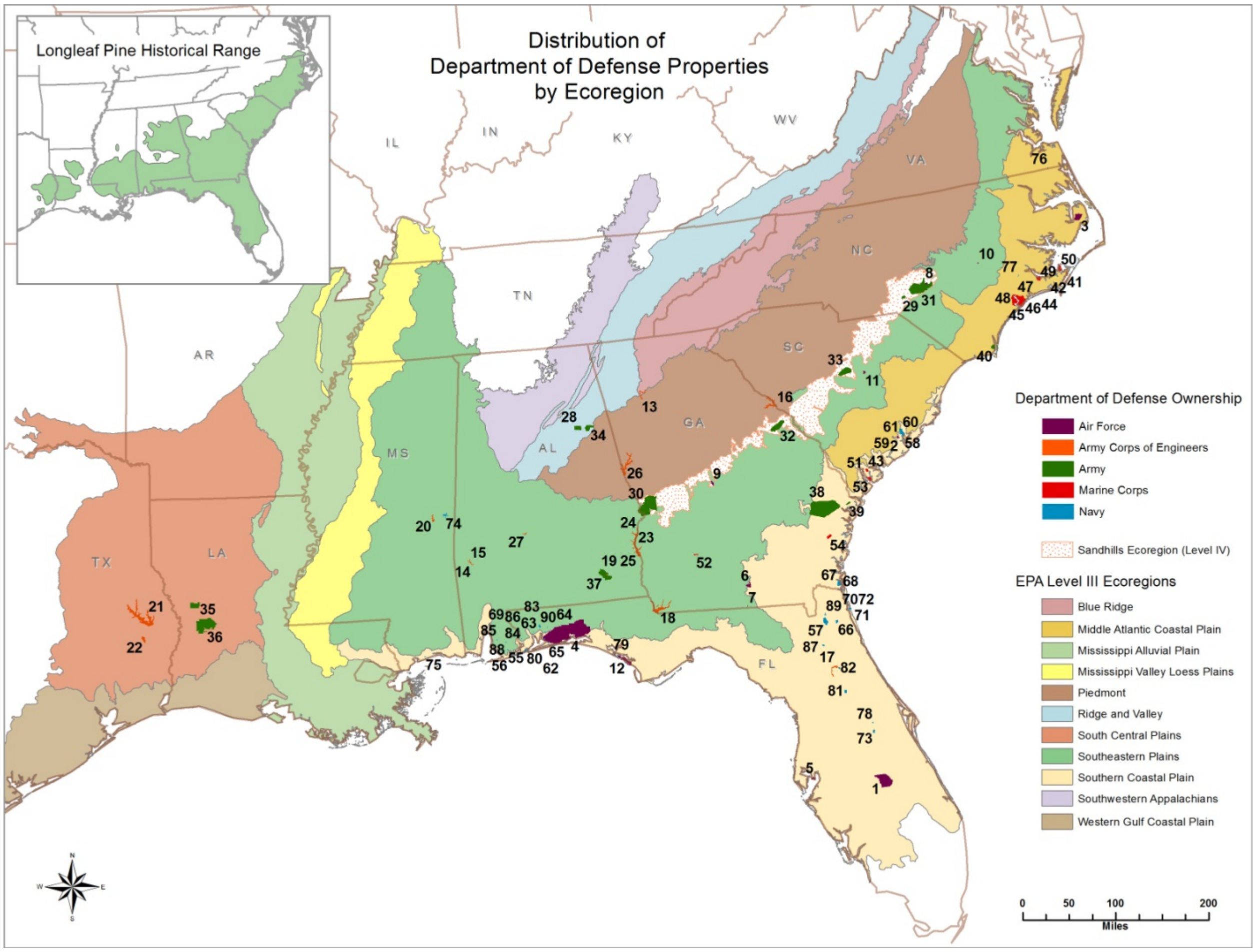


Figure 7.2.1. Ecoregion map with locations of Department of Defense properties located within the historic range of longleaf pine. Numbers refer to individual properties: 1 Avon Park Bombing Range; 2 Charleston AFB; 3 Dare County Range; 4 Eglin AFB, MacDill AFB; Moody AFB; Moody AFB Annex; 8 Pope AFB; 9 Robins AFB; 10 Seymour Johnson AFB; 11 Shaw AFB; 12 Tyndall AFB; 13 Allatoona Lake; 14 Coffeeville Lake; 15 Coffeeville Lake; 16 J. Strom Thurmond Lake; 17 Lake Oklawaha; 18 Lake Seminole;; 19 Lake Tholococco; 20 Oktibbee Lake; 21 Sam Rayburn Reservoir; 22 Steinhagen Lake; 23-25 Walter F. George Lake; 26 West Point Lake; 27 Dannelly Reservoir; 28 Anniston Army Depot; 29 Camp MacKall; 30 Fort Benning; 31 Fort Bragg; 32 Fort Gordon; 33 Fort Jackson; 35-36 Fort Polk; 37 Fort Rucker; 38 Fort Stewart; 39 Huner Airfield; 40 MOT Sunny Point; 41-42 Atlantic Field MCAS; 43 Beaufort MCAS; 44 Bogue Field; 45-48 MCB Camp Lejeune; 49-50 Cherry Point MCAS; 51 Laurel Bay; 52 MC Logistics Support; 53 Parris Island; 54 Townsend Range; 55 Barin Field; 56 Bronson Field; 59-61 Charleston Station; 62 Choctaw Field; 63 Corry Field; 64 Holley Field; 66 Jacksonville NAS; 67-69 Kings Bay; 70-72 Mayport NS; 73 McCoy Annes NTC; 74 Meridian NAS; 75 Naval Construction; 76 Naval Fac. Eng. Command; 77 Oak Grove Holt Navy Airfield; 79 Panama City Naval Coastal Systems Center; 80 Pensacola NAS; 81 Pinecastle Impact Range; 82 Rodman BR; 83 Santa Rosa Field; 84 Saufley Field; 85 Silverhill Field; 86 Spener Field; 87 Stevens Lake BR; 88 Summerdale Field; 89 Whitehouse field; 90 Whiting Field NAS.

Further, the greatest problems are likely to be encountered on wetter sites that support rapid loblolly growth. There is currently no chemical alternative that can be applied to target loblolly pine without harming planted longleaf pine seedlings; the only treatment for controlling loblolly pine competition is prescribed fire. Silvicultural treatments that include complete canopy removal (e.g. gaps or clearcuts) maximize growth of established loblolly pine seedlings, increase the probability of surviving prescribed burning for a given seedling size, and shorten the window of opportunity for control with prescribed fire. The probability of a loblolly pine to survive prescribed fire increases with size (becoming resistant at about 4 m), but stems of all sizes may be killed. In such cases, the fire return interval may have to be shortened or additional mechanical treatments may be required to control loblolly pine regeneration, with the potential risk of damage to planted longleaf pine seedlings. Note that abundant loblolly recruitment will likely occur after every prescribed fire, so prescribed fire must be applied throughout stand development. A burning interval of 2-3 years is recommended (Section 3.3).

7.2.2. Generality of findings and applicability to other locations or to stands dominated by pines other than loblolly pine

The above recommendations were based on patterns in longleaf pine seedling mortality, effects of canopy density and gap size on longleaf pine seedling growth, on ingrowth of loblolly pine seedlings, midstory and ground layer vegetation development, and on fire behavior. We also considered the effects of gap size and position on resources that control seedling survival and growth (light, soil moisture, soil nitrogen). In this section we consider published results of other studies in order to evaluate the generality of our recommendations.

7.2.2.1. Longleaf pine seedling growth and mortality

We examined the published results of similar studies of longleaf pine seedling performance conducted elsewhere in the longleaf pine range (Table 7.2.1, Figure 7.2.2). While we cite numerous studies with direct parallels to our work, they were conducted in only a few locations. Our work represents a significant contribution to understanding which results are geographically robust, that is, apply across ecoregions. Additionally, most of the studies that evaluated effects of canopy density or gap size were conducted within established longleaf pine canopies; one study described experimentally underplanting longleaf pine in established slash pine stands (Kirkman et al. 2007), and one measured and compared the light environments of slash pine and longleaf pine stands (Sharma et al. 2012).

Canopy removal clearly results in increased growth of longleaf pine seedlings (e.g., Palik et al. 1997, McGuire et al. 2001, Kirkman and Mitchell 2006). Mitchell et al. 2006 described a model in which longleaf pine seedling growth increased exponentially below basal areas of around 8 m^2/ha, was greatly reduced between 10 and 16 m^2/ha basal area, and resulted in seedling mortality over time at higher levels of basal area in longleaf pine forests. Our results mirror the results of these studies in longleaf pine and conducted in different parts of the range. Overall, greater growth of longleaf pine seedlings can be expected following canopy removal, but in situations with abundant sub-canopy vegetation, additional treatments will be necessary to reduce competition.

Patterns of longleaf pine seedling mortality are more difficult to generalize than patterns of seedling growth. Previous studies show that mortality rates in the early years following planting

Table 7.2.1. Summary of selected published research projects. All studies included field experiments allowing the assessment of effects of canopy density and gap size on longleaf pine seedling survival and growth, and measures of resource availability.

Reference	Category	Response variables	Key findings
Battaglia et al. 2003	Canopy density	Light availability	Exponential decrease in light availability with increasing overstory competition
Kirkman et al. 2007	Canopy density	Seedling establishment Light availability Vegetation response	Higher gap fraction in longleaf pine stands than slash pine stands at a given basal area
Kirkman and Mitchell 2006	Canopy density	Seedling establishment Vegetation response	Three stage model of longleaf pine seedling establishment patterns to longleaf pine canopy density
Mitchell et al. 2006	Canopy density	Seedling establishment	Three stage model of longleaf pine seedling establishment patterns to longleaf pine canopy density
Palik et al. 1997	Canopy density	Seedling establishment Light availability Nitrogen availability Water availability	Exponential increase in seedling growth with reduced canopy density; Curvilinear decrease in light availability with increasing basal area; Curvilinear decrease in nitrogen availability with increasing basal area; No effect of basal area on soil moisture
Palik et al. 2003	Canopy density	Seedling establishment Light availability Nitrogen availability Water availability	Exponential decrease in seedling biomass with increasing overstory competition (measured as OAI); Exponential decrease in light availability with increasing overstory competition; Exponential decrease in nitrogen availability with increasing overstory competition; Stand-level resource availability and seedling response is affected by canopy distribution as well as density
Pecot et al. 2007	Canopy density	Seedling establishment Light availability Nitrogen availability Water availability Vegetation response	Incorporated trenching and understory removal to separate above and below-ground competition effects; Exponential decrease in light with increasing overstory competition; Exponential decrease in nitrogen availability with increasing overstory competition ONLY in the absence of understory vegetation; Both above-ground and below-ground competition affect seedling growth
Sharma et al. 2012	Canopy density	Light availability	Light availability was higher for a longleaf pine canopy than for a slash pine canopy

Table 7.2.1 Continued.

Reference	Category	Response variables	Key findings
Brockway and Outcalt 1998	Gap dynamics	Seedling establishment Canopy cover Light availability Root biomass	Increased seedling density with distance from gap edge; Reduced canopy cover with distance from gap edge; Light was not affected with distance from gap edge; Reduced root biomass with distance from gap edge; Established a seedling exclusion zone from 12-16 m from gap edge
Gagnon et al. 2003	Gap dynamics	Seedling establishment Light availability Soil moisture	Greater seedling growth in gap center; Lower seedling survival in gap center; Higher light availability in gap center; No differences in soil moisture across gap positions
Gagnon et al. 2004	Gap dynamics	Natural gap characteristics Seedling establishment	Seedling stocking was unrelated to gap size; Seedling density increased for distances ≥ 5m from canopy trees
Grace and Platt 1995	Gap dynamics	Seedling establishment	Seedling survival was affected by canopy trees within 18 m; Seedling growth was affected by canopy trees up to 15 m
McGuire et al. 2001	Gap dynamics	Seedling establishment Light availability Nitrogen availability Soil moisture Vegetation response	Light increased with gap size; Variability reported in nitrogen availability by gap size and position; Seedling size increased with distance from gap edge, with 75% of maximum seedling size within 10 m of the forest edge
Palik et al. 2003	Gap dynamics	Seedling establishment Light availability Nitrogen availability Water availability	Reaching a basal area objective with large canopy gaps results in greater stand-level light availability and seedling growth than using small openings or uniform thinning
Rodriguez-Trejo et al. 2003	Gap dynamics	Seedling establishment Bud break Light availability	Light increased from the center of gaps to the forest edge; Temperature extremes were within canopy gaps; Seedling survival was lowest in canopy gaps
Gagnon et al. 2003	Seedling survival	Seedling survival	Evidence of canopy facilitation; Lower seedling survival in gap center
McGuire et al. 2001	Seedling survival	Seedling survival	First year survival was moderately high but a drought in year two resulted in low survival after two growing seasons
Palik et al. 1997	Seedling survival	Seedling survival	High first year survival in a year without drought conditions
Rodriguez-Trejo et al. 2003	Seedling survival	Seedling survival	Temperature extremes were within canopy gaps; Seedling survival was lowest in canopy gaps; Evidence of canopy facilitation in year of drought

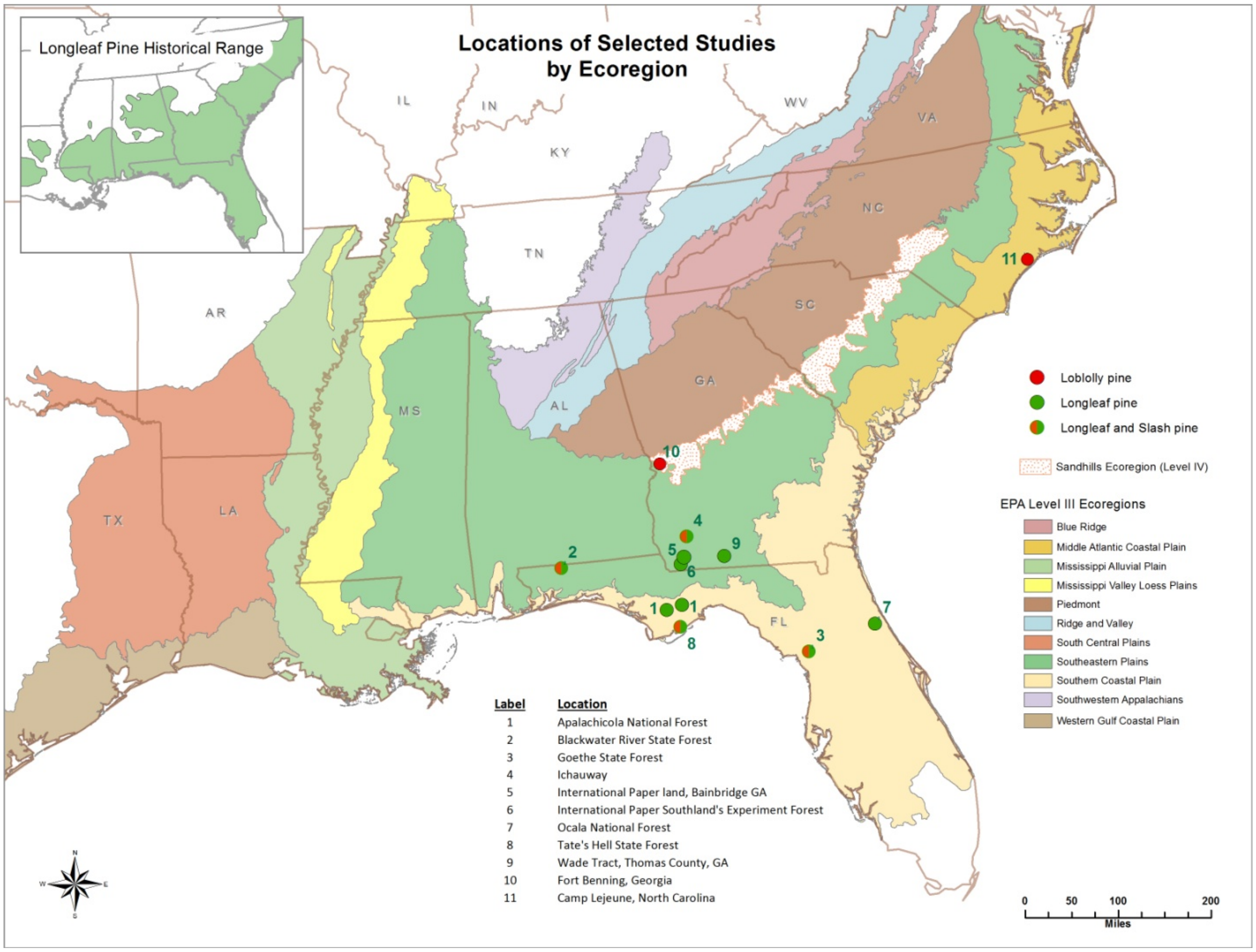


Figure 7.2.2. Locations of selected studies directly comparable to this project. Comparable sites included field experiments allowing the assessment of effects of canopy density and gap size on longleaf pine seedling survival and growth, and measures of resource availability. Previous comparable work was conducted in the southern part of the longleaf pine range, and most studies were conducted in established longleaf pine stands.

can be high during drought years (Rodriguez-Trejo et al. 2003; McGuire et al. 2001), contrasting with high survival during normal rainfall (Palik et al 1997). In general, given the facilitation effect of canopy pines for seedling survival observed at multiple sites, higher rates of canopy retention may be desired to reduce seedling mortality on sites prone to drought stress, e.g., on soils with higher clay content than on sandy soils.

Our findings of the value of moderate canopy thinning are consistent with studies in other parts of the range, and where underplanting was conducted in longleaf pine rather than loblolly pine stands.

7.2.2.2. Resource availability effects on longleaf pine seedlings

As in our study, light was found to exert the largest effect on longleaf pine seedling establishment and growth under longleaf pine canopies. For this reason several researchers examined the light availability under slash pine (Kirkman et al. 2007, Sharma et al. 2012). Both showed light to be more available under longleaf than under slash; we found availability under loblolly pine to be intermediate. Light availability was similar regardless of the canopy species, suggesting that density recommendations based on our study will be applicable in sites with slash pine dominance.

7.2.2.3. Gap size suitable for longleaf pine regeneration in gaps

Across the region, gaps of 0.1 ha were found to be suitable for longleaf pine seedling survival and early growth (McGuire et al. 2001, Palik et al. 2003). Although larger gaps would increase growth rates (consistent with light limitation), larger gaps resulted in reduced availability of pine needles needed in gap centers to carry fire through the landscape. Gap studies in longleaf pine forests show results similar to our studies in loblolly pine.

7.2.2.3. Sub-canopy vegetation

Previous research showed that canopy removal results in increased abundance of sub-canopy vegetation, both in the ground-layer and in the mid-story (Grelen and Enghardt 1973, McGuire et al. 2001, Pecot et al. 2007). During longleaf pine restoration, increased abundance of herbaceous ground layer vegetation is desirable, but increased abundance of woody vegetation or mid-story stems is not generally desirable. In general, results from both of our study sites indicate increased abundance of vegetation following canopy removal. Previous publications have discussed the importance of canopy retention for controlling the development of mid-story vegetation in longleaf pine ecosystems. Although our results demonstrate this pattern, the contrast in stem density between the study sites and the overall high density of mid-story woody stems at Camp Lejeune demonstrate the role of additional factors on sub-canopy vegetation dynamics. Although not directly addressed with our research, the combination of physical site factors, legacies of past land use or management and site preparation likely contributed to the observed responses. These data suggest that specific responses of sub-canopy vegetation strongly depend on the condition of the vegetation prior to treatment application, and therefore management prescriptions for managing sub-canopy vegetation should be made on a site-specific basis.

7.2.3 Conclusion

The key findings from our two study locations are similar to previous work conducted in other parts of the longleaf pine range. While regional variation in the ecosystem is to be expected, notably in species composition with species turnover across ecoregions and along soil moisture gradients within ecoregions (Peet 2006, Kirkman et al. 2007), both the structure and the processes governing responses to canopy manipulations at the stand level appear to converge. The convergence evidence in published studies from across the region suggests that our general management recommendations for stand density or gap size suitable for underplanting should be applicable across the region. Additionally, the need for controlling competition is recognized (Nelson et al. 1985, Haywood 2005, Knapp et al. 2006), but the specific methods for controlling woody and possible dense herbaceous vegetation must be selected to meet the site specific challenges.

There are two areas where we are less certain about the applicability of our results. First, we did not account for unique conditions that may characterize sites with a history of tillage agriculture. The legacies of previous land use and especially of tillage agriculture are becoming more evident (Hedman et al. 2000, Vellend et al. 2007, Brudvig and Damschen 2011), and may exert effects on using partial retention strategies for restoring longleaf pine to loblolly pine stands. Mechanisms for hypothesized effects are unknown, but may results from changes in soil properties including altered nutrient availability or increased hardness. Secondly, there are no relevant published studies conducted in the Ridge and Valley or Blue Ridge ecoregions. The physical environment, community composition, and land use histories in this region differ markedly from sites in the coastal plains and sandhills ecoregions (Peet 2006). While some of the ecological drivers for successful longleaf pine restoration under existing canopies (such as light and moisture controlling survival and growth) may translate directly to mountain longleaf, some differences may be important, for example, the relative dominance of deciduous trees on steep slopes that may affect fire use and fire effects. More work needs to be done in both of these areas.

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APPENDICES

Page

A-1.1.1 Effects of longleaf pine restoration management on establishment of new populations of native grasses at Camp Lejeune, NC and Fort Benning, GA

This section is modified from a manuscript prepared for *Natural Areas Journal*.

A-1.1.1. Introduction

In the longleaf pine (*Pinus palustris* Mill.) forests of the southeastern United States, the desirable habitat structure typically includes a monotypic overstory dominated by longleaf pine over a species rich herbaceous ground layer. Maintenance of the characteristic stand structure, in either natural stands or restored areas, is most effectively achieved with a high-frequency, low-severity fire regime that was historically common throughout this region (Van Lear et al. 2005). Fire is considered the most important ecological process in these systems (Peet and Allard 1993, Mitchell et al. 2006), and in its presence the longleaf pine ecosystem may be perpetuated through both successful longleaf pine regeneration and maintenance of the critical ground layer vegetation component.

It is the richness of the ground layer vegetation, with up to 42 species at small spatial scales (0.25 m^2; Walker and Peet 1983) and over 100 species at the 1000 m^2 scale (Peet 2006), that is responsible for levels of diversity that place the longleaf pine ecosystem among the most diverse in North America (Mitchell et al. 2006, Peet 2006). The open-canopy stand structure allows for high light levels to reach the forest floor relative to other forest systems, and with frequent surface fires woody species are reduced or eliminated as competitors (Brockway and Lewis 1997, Haywood et al. 2001). Consequently, above- and below-ground site resources are more available for herbaceous species (Harrington and Edwards 1999), many of which are perennials adapted to respond to surface fires with rapid aboveground re-growth. The conditions created by the frequent disturbance regime across a range of site types within the longleaf pine range have allowed for incredible diversity, resulting in approximately one-fourth of all the species found in the United States and Canada occurring within this ecosystem (Mitchell et al. 2006) and an estimated 187 species associated with the ecosystem currently identified as rare or threatened (Walker 1993).

Functionally, the ground layer vegetation serves as a critical fuel source for maintaining the frequent fire regime. The ‘canopy’ of the ground layer is typically dominated by large bunchgrasses: northern wiregrass (*Aristida stricta* Michx.) in the Atlantic Coastal Plain of North Carolina and northern South Carolina, southern wiregrass (*A. beyrichiana* Trin. and Rupr.) in southern South Carolina southward into Florida, and bluestems (*Andropogon* spp., *Schizachyrium scoparium* (Michx.) Nash) or Indiangrass (*Sorghastrum* spp.) in areas of the Middle Coastal Plain that fall outside the range of wiregrass (Peet 2006). The morphology of large bunchgrasses creates a matrix of overlapping plant tissue that forms an often continuous layer of well-aerated fuels that, when combined with needlefall from canopy pines, burn readily as low-intensity surface fires (e.g. Clewell 1989, Noss 1989, Glitzenstein et al. 1995). In addition many of the ground layer species are well-adapted to frequent burning. For example, wiregrass requires growing season fire for successful flowering and seed production (Streng et al. 1993, Outcalt 1994, Mulligan and Kirkman 2002a). The importance of ground-layer vegetation (particularly large bunchgrasses) as a fuel source, coupled with the dependence of the structure and composition of the vegetation layer on a frequent fire regime for self-perpetuation, represents a positive feedback system that becomes difficult to re-establish once disrupted.

In the centuries following European settlement of the southeastern US, land use and management practices (including fire exclusion) resulted in widespread reduction of the longleaf pine ecosystem (Frost 1993, 2006). Across much of the range, longleaf pine sites have been converted to other southern pines, such as loblolly (*Pinus taeda* L.) or slash (*Pinus elliottii* Engelm.) pines, and in many cases the current stands lack the desired structure and composition typically associated with longleaf pine forests. In these stands restoration of the ground layer vegetation is critical, particularly for re-establishing the high frequency fire regime in stands from which fire has been excluded and species composition has shifted to woody vegetation.

Where desirable species are no longer present in the ground layer, restoration must include the establishment of new plant populations. The most common methods of starting new populations of plants in a restoration context are direct seeding or out-planting nursery grown individuals (Glitzenstein et al. 2001, Walker and Silletti 2006). Each method has been used successfully to establish new populations of ground layer plants in longleaf pine restoration (e.g. Glitzenstein et al. 2001, Mulligan et al. 2002, Aschenbach et al. 2009), but should be done following general guidelines to increase the probability of success (Glitzenstein et al. 2001). For each method, seed should be collected from nearby populations, and the habitat requirements of selected species should match site conditions. Further, direct seeding or out-planting is most successful during periods of rainfall because adequate soil moisture is an important factor controlling seedling germination, survival, and growth (Glitzenstein et al. 2001, Pfaff et al. 2002, Walker and Silletti 2006).

Despite general agreement within the research community about the importance of ground layer restoration, in many cases longleaf pine restoration begins with the establishment of longleaf pine seedlings. A large number of sites needing restoration within the range lack longleaf pines in the canopy, necessitating the use of artificial regeneration for stand establishment, and the availability of quality nursery-produced, container-grown seedlings has greatly improved planting success (Barnett 2002). Considered intolerant to competition for resources (Boyer 1990), longleaf pine seedling growth is reduced by competition with canopy trees (McGuire et al. 2001, Gagnon et al. 2003, Palik et al. 2003) and therefore successful establishment requires some degree of canopy removal. Additional management techniques that are commonly used to improve pine seedling establishment in the southeast, such as fertilizer or chemical release treatments, have also been used with varying success for longleaf pine (e.g. Ramsey et al. 2003, Gagnon et al. 2003, Haywood 2007).

Given the emphasis on longleaf pine seedling establishment in most restoration projects, it is important to understand how management practices that target pine seedling establishment will affect the success of restoration planting and/or seeding of ground layer plant species. Moreover, the large and ecologically variable range of longleaf pine suggests that ground layer restoration may require techniques specific to the site or species planted. This study was designed to determine the effects of management practices commonly used in conjunction with longleaf pine establishment on restoration of native grasses in two ecologically distinct areas within the longleaf pine range. Our specific objectives are to: 1) determine the effects of canopy density, prescribed fire, and soil scarification on direct seeded *Aristida stricta* Michx.; 2) compare establishment of *A. stricta* broadcast from seed to that of planted nursery-grown plugs; 3) determine effects of canopy density on early growth and survival of nursery-grown grass plugs of species native to each study area; 4) determine the effects of herbicide and fertilizer treatments that may be used for longleaf pine restoration on nursery-grown grass plugs; and 5) discuss practical considerations that must be addressed when restoring native grasses in longleaf pine stands. This research was conducted as two studies differentiated by site, with each study modified from the same overall experimental design.

A-1.1.2. Methods

This study was a part of the field experiment replicated at Fort Benning, GA and Camp Lejeune, NC. For this study, we used only the main plot canopy treatments and the experiment in this section was conducted just outside the 20 x 20 m sub-plot measurement areas used for other measurements in the study. A complete description of study sites, experimental design and treatments is provided in Section 3.1.

1.1.2.1. Study 1: wiregrass establishment at Camp Lejeune

We expanded the study design to a randomized complete block split-split-plot to test effects of management actions (main-plot effect = timber harvest, split-plot effect = prescribed fire, split-split-plot effect = soil scarification) on early establishment of wiregrass from seed. Within each main-plot canopy treatment, we identified areas that had burned during the prescribed fire and areas that had not burned. From the candidate burn conditions in each main plot, we randomly selected a location to establish one 5 x 20 m seeding plot such that half the plot was positioned in an area that had been exposed to prescribed fire and half the plot had not burned. Within each level of the prescribed fire effect (burned/not burned), we scarified the soil in a randomly selected 2 x 5 m area by manually raking the soil surface with a garden rake.

A. stricta seed was collected from nearby sites at Camp Lejeune in fall of 2007, and greenhouse trials established an average germination rate of 43%. In April 2008, we hand broadcast seed throughout the study plots at a rate of 5-6 kg pure live seed per hectare. After one growing season (October 2008) we quantified *A. stricta* establishment by counting the number of seedlings in each of ten 1-m^2 quadrats for each split-split-plot level. Measured quadrats included all areas that had been raked and an additional randomly selected 2 x 5 m area without soil scarification in each of the burned and unburned areas of the main plots.
Aristida stricta Plug Experiment

The following year, we established one randomly located 10 x 10 m planting plot in each main-plot to test the effect of canopy density on first year survival and growth of outplanted nursery-grown *A. stricta* plugs. Plugs were grown at the Taylor Tree Nursery (Trenton, SC) from wiregrass seed collected at Camp Lejeune in November 2007 by base forestry personnel. In April 2008, seeds were sown in a 40:40:20 mixture of peat, vermiculite, and perlite placed in 4.1 cm diameter x 12.7 cm deep containers. In February 2009, plugs were lifted and planted at 1 x 1 m spacing in each planting plot. We monitored survival of all plugs in May and October 2009. In May, 20 plugs were randomly selected from each plot for growth measurements. We counted the number of tillers per plant at the beginning of the growing season (May) and at the end of the growing season (October), and we consider the change in the number of tillers throughout the growing season to be a measure of plug growth.

1.1.2.2. Study 2: little bluestem and Indiangrass establishment at Fort Benning

The Fort Benning study utilized the full randomized complete block split-plot design of the field experiment, with canopy density as the main-plot treatment and additional management activities with potential benefit for longleaf pine restoration as the split-plot treatment.

Within each split-plot area, we randomly established one 4 x 10 m planting area, with at least 20 m buffer between each planting area and the main-plot boundary and at least 5 m buffer between the planting area and split-plot boundary. The six study blocks at Fort Benning vary in soil texture and site characteristics (see Section 3.1), and the species planted in each area were selected based on ecological considerations for each site. Three blocks were located in the Sand Hills, and each was planted with little bluestem (*Schizachyrium scoparium* (Michx.) Nash). Two blocks, located along the Chattahoochee River in the Upper Loam Hills, were planted with yellow Indiangrass (*Sorghastrum nutans* (L.) Nash). The final block, also located in the Upper Loam Hills, was on soils with a sandy surface layer and clay in the subsurface horizons, and we selected slender Indiangrass (*Sorghastrum elliottii* (C. Mohr) Nash) for planting. The *Sc. scoparium* and *So. elliottii* plugs were produced by Deep South Growers (Douglas, GA), using a mixture of composted pine bark and tobacco float mix grown in 3.8 cm diameter x 14 cm deep Styrofoam containers. The *So. nutans* plugs were produced by ATS Nursery (Bainbridge, GA) and were grown in 4 x 10 cm hard plastic containers using a 50:50 vermiculite and peat moss mixture. Seeds were sown in the spring of 2008, plugs were lifted in the late fall/winter of 2008, and all grass plugs were planted at 1 x 1 m spacing within each of the planting areas in January 2009.

We monitored survival of each planted plug in May and October 2009. In each split-plot, we randomly selected 20 plugs and counted the number of tillers on each selected plug in May and October 2009. During the October tiller counts, we noted the flowering status of each plug to determine treatment effects on flowering during the first year after planting.

1.1.2.2. Data analysis

In Study 1, the mean number of *A. stricta* seedlings per square meter was calculated at the split-split-plot level and analyzed using split-split-plot analysis of variance (ANOVA) with a random block effect using PROC MIXED in SAS software (version 9.1; SAS Institute, Inc., Cary, NC). However, data did not meet the normality and constant variance assumptions required for the analysis; consequently, we used Friedman’s non-parametric rank test to evaluate and report the effects of canopy density, our prescribed fire, and raking on abundance of wiregrass seedlings. Additionally, frequency of seedling presence was calculated as the proportion of square meter quadrats sampled at the split-split-plot level ($n = 10$) that contained at least one wiregrass seedling. Frequency data were analyzed with a split-split-plot analysis of variance (ANOVA) with a random block effect and the Satterthwaite approximation of degrees of freedom, and data met the assumptions for the analysis.

We used ANOVA with a random block effect to evaluate the effects of canopy density on planted *A. stricta* plug mean survival, the mean number of tillers per plug in May and October 2009, and mean plug growth during first season following planting. Similarly, grass plug survival, growth, and flowering in Study 2 were analyzed using split-plot ANOVA with a random block effect. Data from Fort Benning (Study 2) were analyzed separately for each species planted because each species was selected according to site, based on the assumption that the growing conditions on a given site type were best suited for the selected species. Because *Sorghastrum elliottii* plugs were planted on only one block, there was no replication of main plot treatments, and we could only test the effects of split-plot treatments on survival, growth, and flowering. For all tests, we determined statistical significance when $p < 0.05$.

A-1.10.3. Results

1.1.3.1. Wiregrass seedlings at Camp Lejeune

Wiregrass abundance was not significantly affected by canopy density ($\chi^2 = 4.95$, p = 0.1749) despite increases in both the mean and median seedling density with increasing canopy cover (Table 3.10.1). Likewise, prescribed burning applied to these study sites had no effect on seedling density ($\chi^2 = 0.42$, p = 0.5186). However, soil scarification through manual raking increased the median abundance from 0.30 to 1.00 seedlings/m^2 ($\chi^2 = 5.74$, p = 0.0166) and more than doubled the mean abundance from 0.77 to 1.76 seedlings/m^2.

We found no significant interaction effects of the treatments on the frequency of seedlings observed per quadrat (Table 3.10.2), and frequency results were similar to those for abundance. There was no significant effect of canopy density on seedling frequency (F = 2.14; *p* = 0.1013), although treatment plots with higher canopy density (Control/MedBA) generally had a higher proportion of quadrats with seedlings present than plots with lower or no canopy density (LowBA/Clearcut) (Figure 3.10.1). There was no effect of the prescribed burn on frequency (F = 0.07; *p* = 0.7967); however, raking significantly increased frequency (F = 7.04; *p* = 0.0097), with 36% of the quadrats sampled containing seedlings in raked areas compared to 23% in quadrats that had not been raked.

1.1.3.2. Wiregrass plugs at Camp Lejeune

Survival of wiregrass plugs was high in both May and October of the first growing season following planting (Figure 3.10.2). There was a significant effect of canopy density on survival in May (F = 3.34; *p* = 0.0478), with survival higher on the Control plots (99% survival) than on the Clearcut plots (96% survival). By October, the treatment effect was no longer significant, and survival ranged from 98% on the Control plots to 93% on the Clearcut plots. There was no treatment effect on the mean number of tillers per *A. stricta* plug counted in May (*F* = 0.90; *p* = 0.4364) or October (F = 1.01; p = 0.4144) of the first growing season following out-planting (Figure 3.10.3). Similarly, there was no effect of canopy density treatment on mean *A. stricta* plug growth (*F* = 1.82; *p* = 0.1862), measured as the change in number of tillers from May through October (Figure 3.10.2, inset), with an average of 37 tillers per plug in May and 39 tillers per plug in October.

1.1.3.3. Little bluestem and Indiangrass plugs at Fort Benning

The three species planted at Fort Benning showed different patterns in grass plug survival within the first year after planting. *Sc. scoparium* and *So. elliottii* each had high survival in May that generally remained high by the end of the growing season (October), but *So. nutans* survival averaged only 56% among treatments in May and dropped to 47% survival by October (Table 3.10.3). *Sc. scoparium* survival was not significantly affected by main plot (F = 0.62; p = 0.6081) or sub-plot (F = 1.57; p = 0.2297) treatments in May, but we found a significant main*split-plot interaction in October (F = 3.67; p = 0.0174). In Clearcut plots, survival was higher on the NT split-plots (96% survival) than on the H split-plots (77% survival), but this pattern did not exist for the other main plot treatments. There were no treatment effects on survival of *So. nutans* in May (main plot F = 0.11, p = 0.9547; split-plot F = 3.13, p = 0.0840) or October (main-plot F = 1.12, p = 0.3787; split-plot F = 1.19, p = 0.3386). In the one replication planted with *So. elliottii*, survival in October ranged from 95% in the Control main-plots to 64% in the Clearcut main-plots, suggesting increased mortality with canopy removal. There were no split-plot effects on survival of *So. elliottii* in May (F = 0.62, p = 0.5707) or October (F = 0.76, p = 0.5094)

There was no significant main*split-plot interaction effect on either the growth of *Sc. scoparium* (F = 1.46, p = 0.2367) or *So. nutans* (F = 1.00, p = 0.4835) plugs during the first growing season after planting. *Sc. scoparium* growth increased inversely proportional to canopy density (F = 9.95, p = 0.0002), with the greatest growth on Clearcut plots (Figure 3.10.5). We found no main-plot effect on the growth of *So. nutans* (F = 5.09, p = 0.0749), despite nearly twice the growth on the Control plots (9.2 tillers per plug) as compared to the LowBA plots (4.8 tillers per plug). The split-plot treatments also significantly affected *Sc. scoparium* plug growth (F = 5.61, p = 0.0108), with greater tiller growth on the H + F plots than the NT plots. *So. elliottii* exhibited the least amount of growth among the three species, ranging from 1.7 tillers per plug on Control main-plots to 3.1 tillers per plug on MedBA main-plots. There was no significant split-plot effect (F = 3.30, p = 0.0840), with growth ranging from 1.3 tillers per plug on H split-plots to 3.6 tillers per plug on H + F split-plots.

The percentage of grass plugs in flower at the end of the first growing season did not significantly differ among the canopy density treatments for *Sc. scoparium* (F = 0.43, p = 0.7351), ranging from 22% on MedBA main-plots to 29% on LowBA plots (Figure 3.10.6). Likewise, there was no significant canopy density effect on *So. nutans* (F = 3.2, p = 0.1454), although there was a clear pattern in which flowering was highest on the Control plots (43% of the plugs), decreased with canopy removal, and was lowest on the Clearcut plots (4% of the plugs). There was a significant split-plot treatment effect on *Sc. scoparium* grass plug flowering (F = 5.33, p = 0.0138), in which the use of herbicides and fertilizer (H+F split-plots) had around twice the percentage of plugs in flower (36%) than that of the untreated split-plots (17%). Flowering of *So. elliottii* was higher than the other species, ranging from 59% on the LowBA main-plots to 90% on the MedBA main-plots. There was no effect of the split-plot treatments (F = 2.51, p = 0.1617), with a range of 63% on the H split-plots to 86% on the H + F split-plots.

A-1.1.4. Discussion

Seedling establishment following direct seeding requires both successful germination of seed and subsequent seedling survival during the initial stages of growth. Provided that high quality seed is used, germination is largely dependent on microsite suitability relative to an individual species' germination requirements, with particular importance placed on soil surface condition and moisture availability (e.g. Harper et al. 1965, Grubb et al. 1977, Fowler 1986, Glitzenstein et al. 2001). Wiregrass germination benefits from seed contact with the mineral soil, and favorable seedbed conditions may be created via soil disturbance associated with common site preparation treatments (Walker and Silletti 2006). Additional treatments that ensure seed remains in contact with mineral soil, such as rolling over the seed to press it into the soil, have been found to increase wiregrass establishment (Hattenbach et al. 1998, Seamon 1998). The raking treatment used in our study exposed mineral soil of the seedbed, but also created uneven micro-topography that may have helped to keep the seed in place.

Similar to Cox et al. (2004), we found little benefit of prescribed fire on wiregrass seedling establishment following direct seeding, despite an expectation for fire to remove standing biomass and heavy litter that could prevent seed from contacting the soil. It is possible that the low intensity of the prescribed fire applied in this study, which resulted in a mosaic of burned and unburned areas within the stand and allowed comparison of the burn effect, was insufficient for preparing the site for seeding in areas that had burned. It is unclear from this study how a prescribed fire of higher intensity would affect the success of direct seeding.

We found no effect of canopy density on early wiregrass establishment from seed, although there was a non-significant pattern of greater seedling number and frequency in plots with higher canopy density. In extreme habitats, surrounding vegetation can facilitate early establishment of individuals by relieving unfavorable conditions (Holmgren et al. 1997). Adequate soil moisture is important to the success of young wiregrass seedlings (Wenk 2009), and harsh conditions during a drought in the 2008 growing season were likely exacerbated by increased solar radiation reaching the forest floor following canopy removal. It is possible that seeding earlier in the winter, when conditions are typically wetter, or during a year that does not experience drought, would result in different patterns of seedling establishment. In a study designed to explore effects of competition and facilitation on early survival and growth of southern wiregrass (*A. beyrichiana* Trin. and Rupr.), Mulligan and Kirkman (2002b) found no evidence of facilitation by canopy trees on early survival of young out-planted nursery-grown wiregrass seedlings in southwest Georgia, although their results suggest that the presence of mature wiregrass plants facilitated early survival. Because of the critical role that microsite conditions play in germination, facilitation effects of canopy trees are likely more important for establishment using direct seeding methods than following out-planting of seedlings.

Average natural density of wiregrass has been reported to be five clumps per square meter (Clewell 1989), and previous studies on direct seeding have reported a range of densities of established plants (e.g. Bissett 1996, Hattenbach et al. 1998, Seamon 1998). Outcalt et al. (1999) recommend planting wiregrass at 1 x 1 m spacing to create suitable fuels for ecosystem restoration. Mean densities in our study range from less than one to nearly two individuals per square meter, and direct seeding resulted in a similar number of established seedlings as out-planting in our study. Despite similar average densities between the two methods, the distribution of individuals was very different; direct seeding resulted in scattered groups of seedlings that became established in patches of suitable micro-habitat as opposed to the controlled spacing of out-planting. Treatments that create more uniform, favorable microsites, like the raking treatment in this study, result in more evenly distributed seedlings following direct seeding, demonstrated by the higher frequency of individuals occurring in raked quadrats.

We found that wiregrass establishment from out-planted plugs was successful regardless of overstory canopy density, with greater than 90% survival by the end of the first growing season. Similarly, Mulligan et al. (2002) reported high survival (> 80%) of wiregrass plugs planted under longleaf pine canopies at three densities (basal areas of 8, 16, and 25 m^2/ha). After four years, however, survival under high density stands had dropped to 20% but remained relatively high (70%) under stands thinned to 8 m^2/ha basal area. In longleaf pine stands with 10 m^2/ha basal area, Outcalt et al. (1999) reported a survival rate after four growing seasons of 56% for wiregrass plugs, with the majority of the mortality occurring during the first growing season. It is likely that the size and vigor of wiregrass plugs at the time of planting are related to initial mortality (Outcalt et al. 1999), and the six month old seedlings used in this study were considerably larger than those described in Outcalt et al. (1999) (data not shown).

At Fort Benning, both *Sc. scoparium* and *So. elliottii* had high first year survival rates (~ 90%), but survival of *So. nutans* was almost half that of the other species (47%). Few studies have reported survival of out-planted grass plugs of these species, but Glitzenstein et al. (2001) found relatively high survival rates (mostly > 90%) of *So. nutans* shortly over one year after planting. The causal factors for the low survival rates of *So. nutans* in this study are not evident; however, most of the mortality occurred in the few months between planting and the initial survival counts in May, suggesting that poor establishment immediately after planting was likely responsible. The soils of the Upper Loam Hills of Fort Benning, particularly those on sites for which *So. nutans* was selected in this study, contain a clay component (~20% clay) that may make establishment of out-planted plugs difficult. Following planting, soils with clay are less likely than sandier soils to settle and fill air spaces left between the plug and cavity walls, making clay soil less forgiving of improper planting.

Previous studies have demonstrated competitive effects of surrounding vegetation on the growth of young wiregrass seedlings (Mulligan and Kirkman 2002b, Aschenbach et al. 2009, Wenk 2009), with controls on growth attributed to both light availability (Mulligan et al. 2002) and competition for below-ground resources (Mulligan and Kirkman 2002b, Wenk 2009). Soil moisture is understood to be important to early establishment of wiregrass, but the role of moisture in controlling wiregrass growth may be variable. Mulligan et al. (2002) found little evidence of a relationship between moisture and seedling growth, but Wenk (2009) reported greater growth associated with higher soil moisture in sandhill sites. As wiregrass is well adapted to dry sites, it is possible that soil moisture only limits wiregrass growth under extreme conditions. On the study sites at Camp Lejeune, soil moisture is generally not limiting except during periods of severe drought. However, despite modification of the light environment through canopy removal, we found no effect of overstory competition on the number of tillers of plugs during the first growing season. It is possible that competitive pressures of surrounding vegetation will become more pronounced as seedlings adjust to the post-planting environment in subsequent years.

The strongest effect of canopy density on plug growth in this study was seen for *Sc. scoparium*, and previous research has demonstrated that *Sc. scoparium* responds strongly to reductions in competition for resources (Wilson and Tilman 1991, Wilson and Tilman 1993). The pattern of increased growth with reduced canopy density suggests that overstory trees limit resources for *Sc. scoparium* but have a lesser effect on the two *Sorghastrum* species. In a greenhouse study and an absence of competition, Tilman (1986) found that nitrogen availability was positively related to growth of both *Sc. scoparium* and *So. nutans*, and accounted for > 95% of the variation in plant mass over a range of soil nitrogen levels. Therefore, we expected an increase in growth of each species following the herbicide plus fertilizer treatment, but only *Sc. scoparium* showed such a response. C_4 grasses that are considered 'ecologically equivalent' have shown unique responses to resource availability in other systems (e.g. Silletti and Knapp 2001, Silletti et al. 2004), and the differential responses we observed may reflect inherent differences in the species' ability to compete for and utilize rapid increases in resources (i.e. nutrient flush following fertilization). However, site characteristics and initial competitive conditions also affect resource availability and individual response, and direct comparisons between species are not possible because only one species was planted in each block.

Over the long term, the success of understory restoration will depend not only on the survival and vigor of established individuals but also on ability of the population to reproduce and expand. Sexual propagation requires allocation of resources to reproductive structures, and we found that the percentage of plugs in flower after one growing season may be affected by management actions. Although not statistically significant, a clear pattern existed among the main treatments for *So. nutans* plugs in which the presence of the canopy appeared to facilitate flowering. For *Sc. scoparium*, only the herbicide plus fertilizer treatment increased the percentage of plugs in flower, concurrent with previous research reporting that reduced competition and increased resources increase flowering of *Sc. scoparium* (Wilson and Tilman 1991).

A-1.1.5. Management implications

Longleaf pine ecosystem restoration requires the establishment of a functional ground layer vegetation component, and dominant bunchgrasses are critical to sustaining a frequent fire regime. Our results indicate that both direct seeding and transplanting nursery-grown plugs can be used to successfully establish wiregrass in Coastal Plain sites. Each method has advantages and disadvantages, and the appropriate method for a restoration project will depend on the objectives and resources of the management team. Direct seeding requires the collection of large quantities of seed, with reported seeding rates for wiregrass ranging from around 3 kg/ha of clean seed (Pfaff et al. 2002) to 133 kg/ha for seed mixed with other material (Seamon 1998). The total area that can be restored with direct seeding is often limited by the amount of seed collected. On the other hand, nursery-grown plugs require significantly fewer seeds, but the costs of nursery production can be high, and the additional labor costs of out-planting plugs at close spacing make large scale transplanting efforts difficult (Hattenbach et al. 1998).

Complete restoration of the longleaf pine ecosystem requires attention to the major ecological components: structure, composition, and function (Van Lear et al. 2005, Brockway et al. 2010). Throughout the range, sites in need of restoration vary in their level of degradation as well as their dissimilarity from target conditions, and restoration must begin with an understanding of the starting conditions for each stand. Some stands include highly diverse, intact ground layer communities, while others contain few or no remnants of the characteristic ground layer vegetation. Prior to restoration, our study sites included a midstory component of encroaching hardwoods that required removal through site preparation. While site preparation treatments can be effective for increasing survival or growth of target species, effects on the vegetation community often include compositional shifts or changes in diversity, and managers must consider the costs of such treatments on ecological restoration. The evaluation of the effects of management activities on other aspects of the ground layer vegetation was beyond the scope of this publication.

When appropriate, integrating management for native grass establishment with that used for the benefit of longleaf pine seedlings may simultaneously restore both ecosystem components. Disturbance events such as timber harvest or site preparation often create favorable microsites for seedling establishment via direct seeding, similar to the raking treatment used in this study. On sandhill sites outside the range of wiregrass, competition control treatments will likely benefit both longleaf pine seedlings and planted *Sc. scoparium* plugs. However, herbicide release additional to site preparation provided few, if any, benefits to planted plugs, suggesting that the fertilizer treatment was responsible for the growth and flowering response of *Sc. scoparium*. It should be noted, however, that the true effect of herbicide for release of planted plugs is likely underestimated in this study due to the chemical treatment applied as site preparation. Because different species exhibit unique responses to management activities, and given the wide ecological range of longleaf pine, it is critical to consider site characteristics and the behavior of each restoration species when developing a management plan. The ultimate success of ground layer restoration requires the persistence and expansion of established populations, and additional research that monitors the long-term response of individual species to common management practices is needed.

A-1.1.6. Literature cited

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Table A-1.1.1. Summary of results from Friedman's non-parametric rank test and median, mean, and standard error for the number of wiregrass seedlings/m^2 for canopy treatments, burn condition, and the raking treatment.

Effect	Levels	χ^2 Stat	p-value	Number of seedlings/m^2 Median	Mean	St. error
Canopy treatment		*4.95*	*0.1749*			
	Control			1.20	1.88	0.42
	MedBA			0.76	1.38	0.39
	LowBA			0.20	0.85	0.22
	Clearcut			0.40	0.92	0.33
Burning		*0.42*	*0.5186*			
	Burned			0.65	1.41	0.33
	Unburned			0.60	1.15	0.19
Raking		*5.74*	*0.0166*			
	Rake			1.00[a]	1.76	0.32
	No rake			0.30[b]	0.77	0.13

Table A-1.1.2. Summary of mixed model split-split-plot ANOVA for wiregrass seedling frequency

Effect	Num DF	Den DF	F-statistic	p-value
Canopy	3	18.8	1.57	0.2297
Burn	1	20.9	0.08	0.7793
Rake	1	43	8.04	0.0069***
Canopy*Burn	3	20.5	0.3	0.8277
Canopy*Rake	3	43	0.27	0.8491
Burn*Rake	1	43	0.44	0.5083
Canopy*Burn*Rake	3	43	1.72	0.1762

***significant at $\alpha = 0.01$

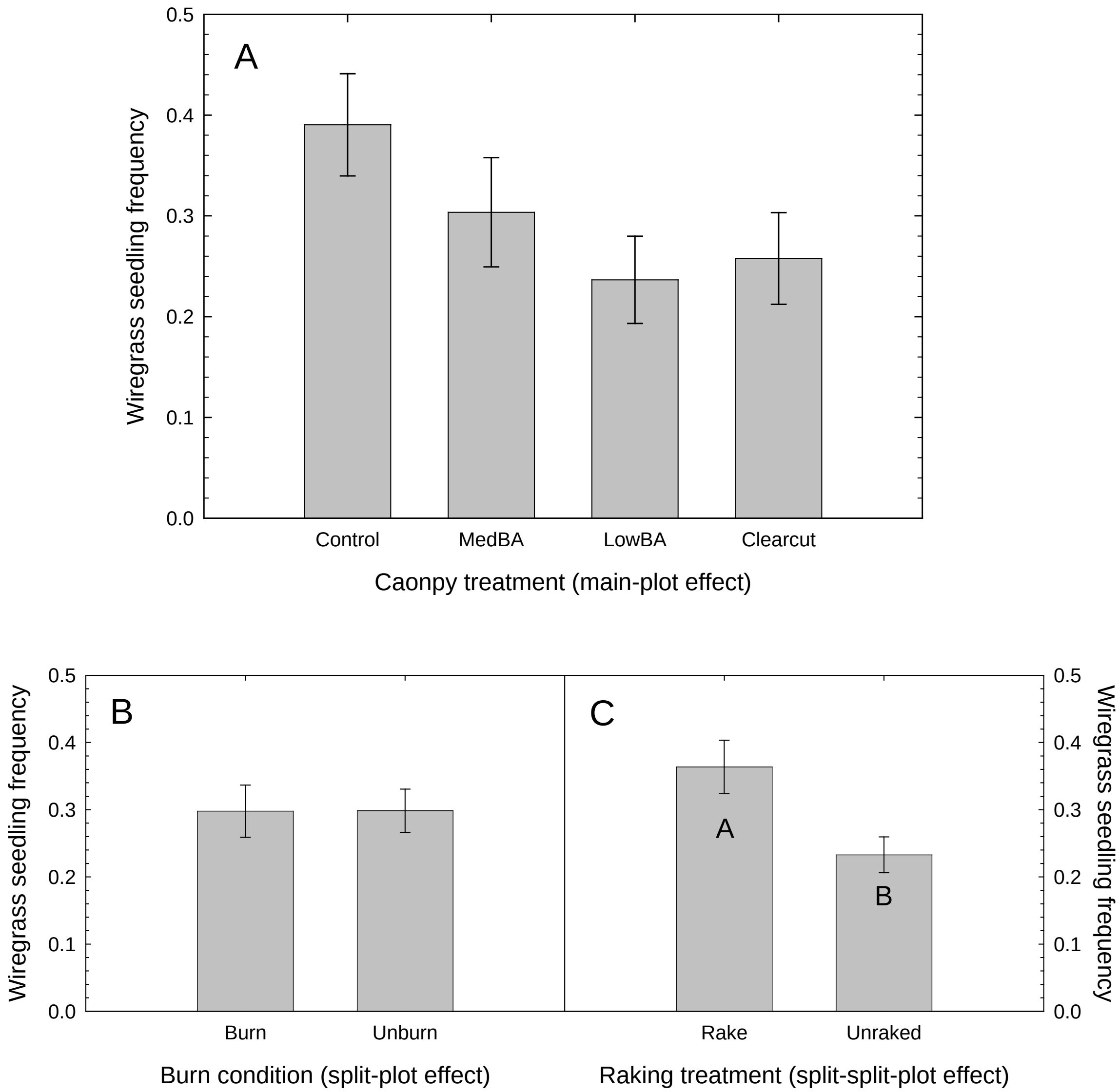


Figure A-1.1.1. Seedling frequency, measured as proportion of 1 m^2 quadrats (n = 10) in which germinants were present (mean ± one standard error), for A) canopy density; B) burn condition; and C) raking treatment. Letters denote significant differences at $\alpha = 0.05$.

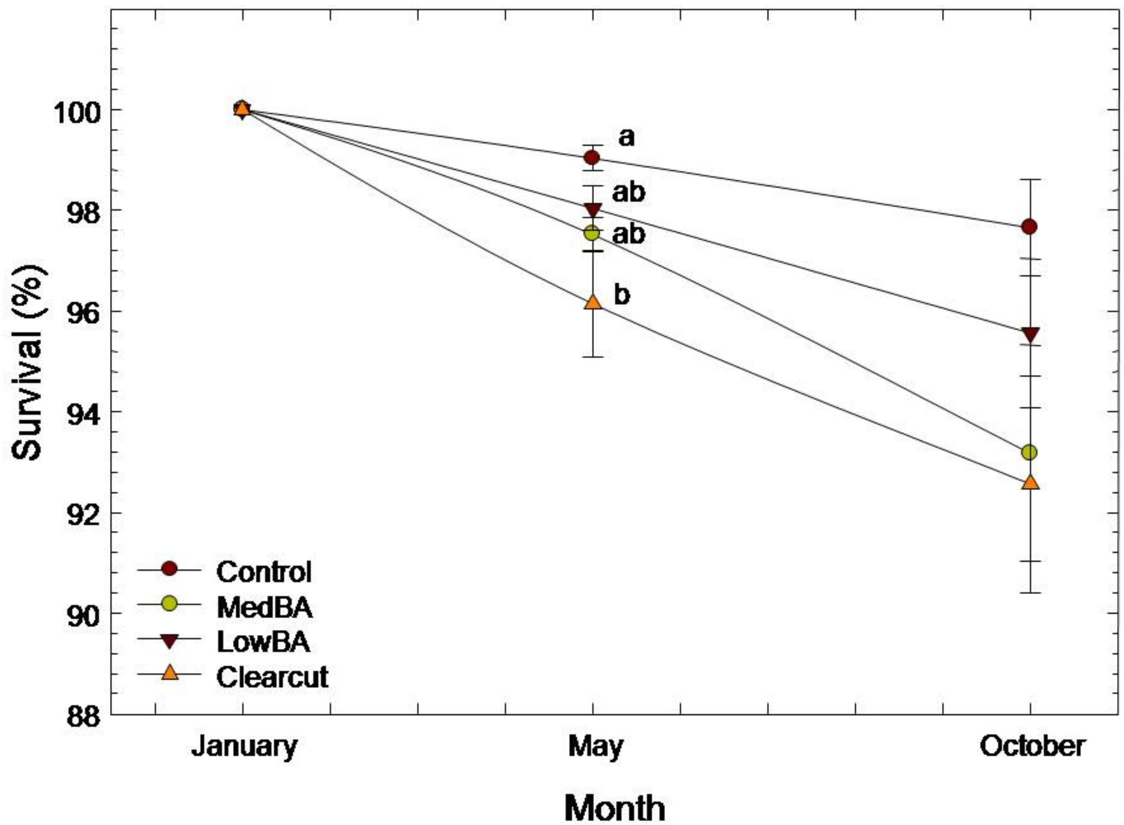


Figure A-1.1.2. Survival of out-planted wiregrass plugs by canopy treatment in January (month of planting), May, and October 2009 (mean ± one standard error). Similar letters indicate no significant difference at $\alpha = 0.05$.

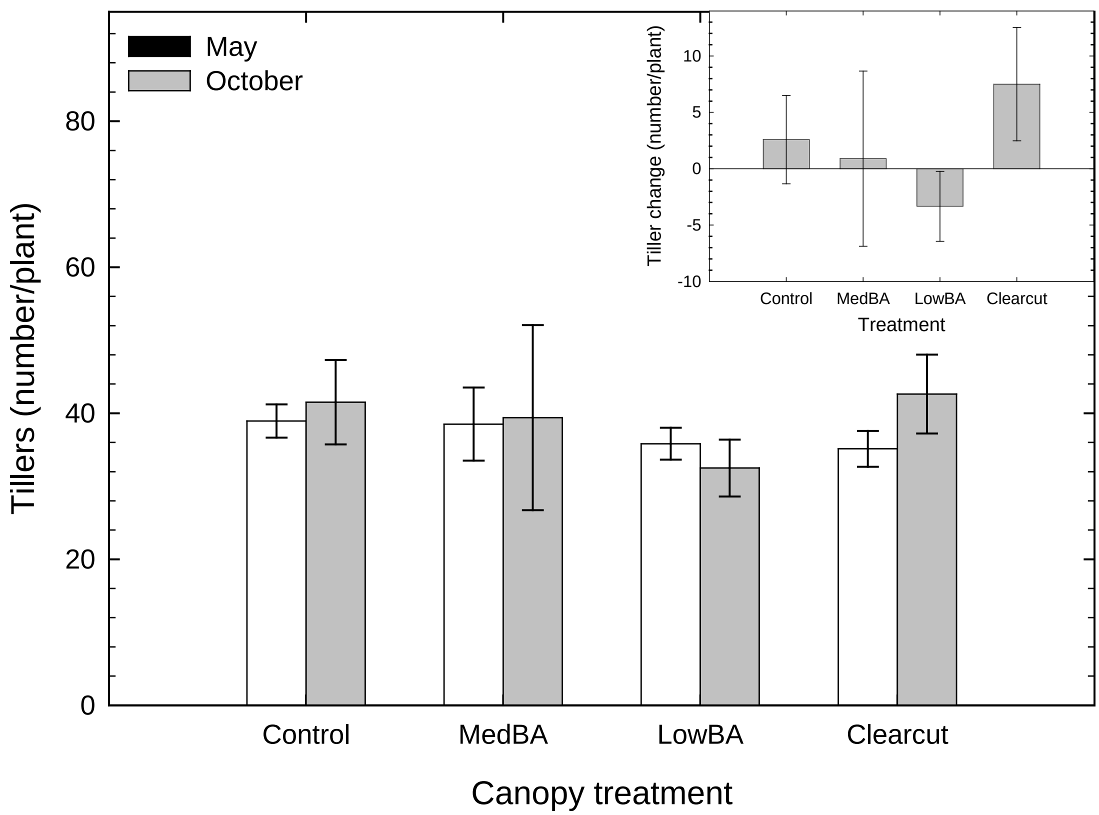


Figure A-1.1.3. Number of tillers per wiregrass plug in May and October 2009 (first growing season) by canopy treatment (mean ± one standard error). Inset: change in tiller number from May to October 2009 by canopy treatment (mean ± one standard error).

Table A-1.1.3. Percentage of grass plug survival (mean and standard error) by main-plot and split-plot treatment in May and October for *Schizachyrium scoparium* (n = 3 blocks), *Sorghastrum nutans* (n = 2 blocks), and *Sorghastrum elliottii* (n = 1 block) plugs out-planted at Fort Benning, GA.

		Schizachyrium scoparium				*Sorghastrum nutans*				*Sorghastrum elliottii*			
		May		October*		May		October		May		October	
Effect	Level	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Main-plot	Control	93.56	1.79	93.11	0.99	56.83	4.34	50.50	3.62	96.00	.	95.00	.
treatment	MedBA	90.78	0.68	86.11	0.48	55.33	2.62	48.33	1.82	94.00	.	90.67	.
	LowBA	95.22	1.95	91.56	1.75	54.33	2.52	42.17	1.89	92.67	.	87.00	.
	Clearcut	93.67	3.06	86.44	5.58	56.00	3.25	46.17	4.17	89.00	.	64.33	.
Sub-plot	NT	94.17	1.84	91.58	2.29	60.88	1.63	49.63	2.24	94.00	0.71	87.50	3.97
treatment	H	91.75	2.03	86.42	3.59	51.00	0.89	43.38	2.24	91.25	3.47	82.75	7.60
	H + F	94.00	1.50	89.92	2.10	55.00	1.51	47.38	1.55	93.50	0.96	82.50	9.37

*ANOVA resulted in a significant main-plot and sub-plot interaction (F-statistic = 3.67; p-value = 0.0174)

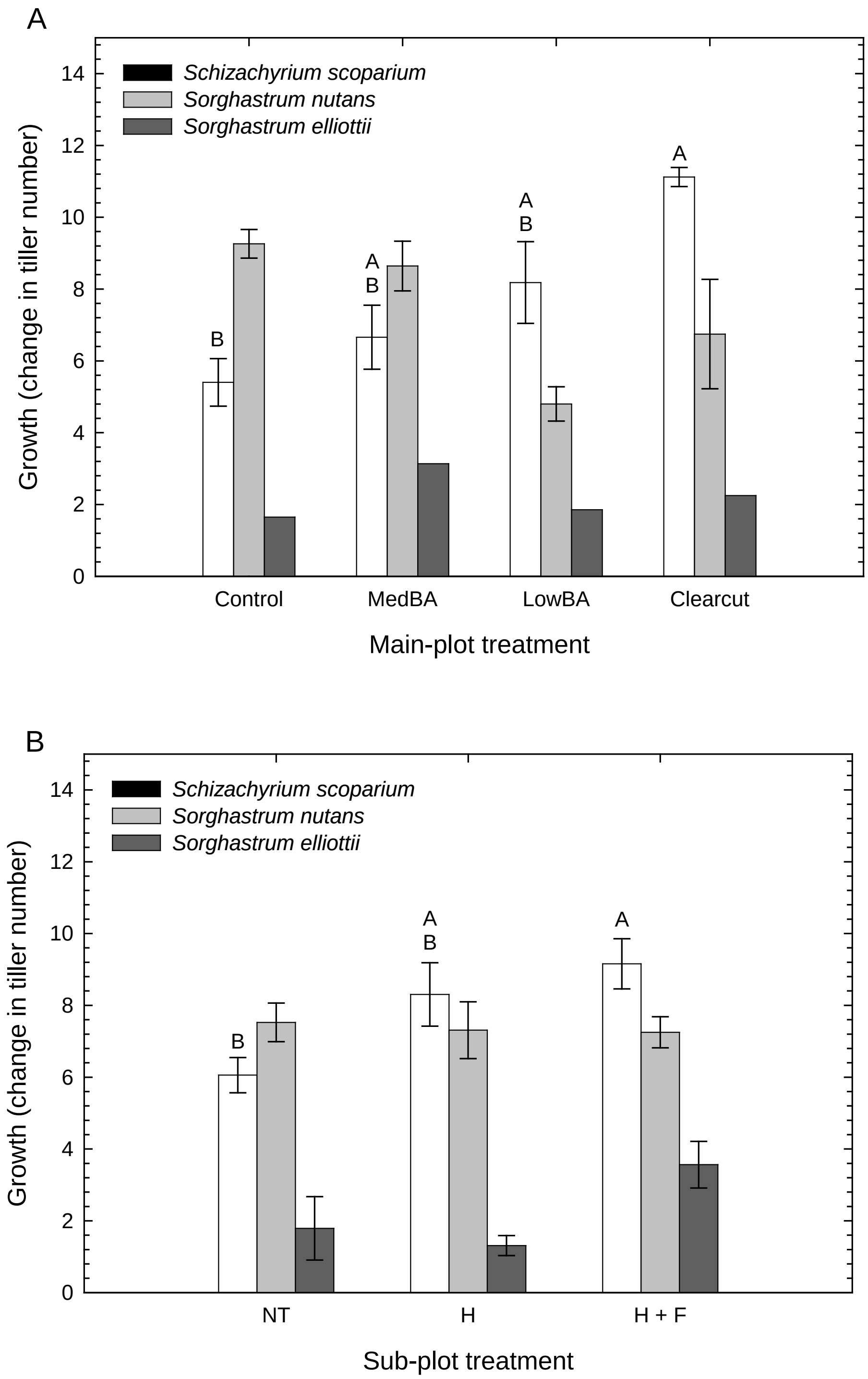


Figure A-1.1.4. Grass plug growth (mean ± one standard error) measured as the change in the number of tillers from May to October by A) main-plot treatment and B) split-plot treatment for *Schizachyrium scoparium* (n = 3 blocks), *Sorghastrum nutans* (n = 2 blocks), and *Sorghastrum elliottii* (n = 1 block). Letters denote significant differences within each species at α = 0.05. Sub-plot treatments: NT = check, H = herbicide, H + F = herbicide plus fertilizer.

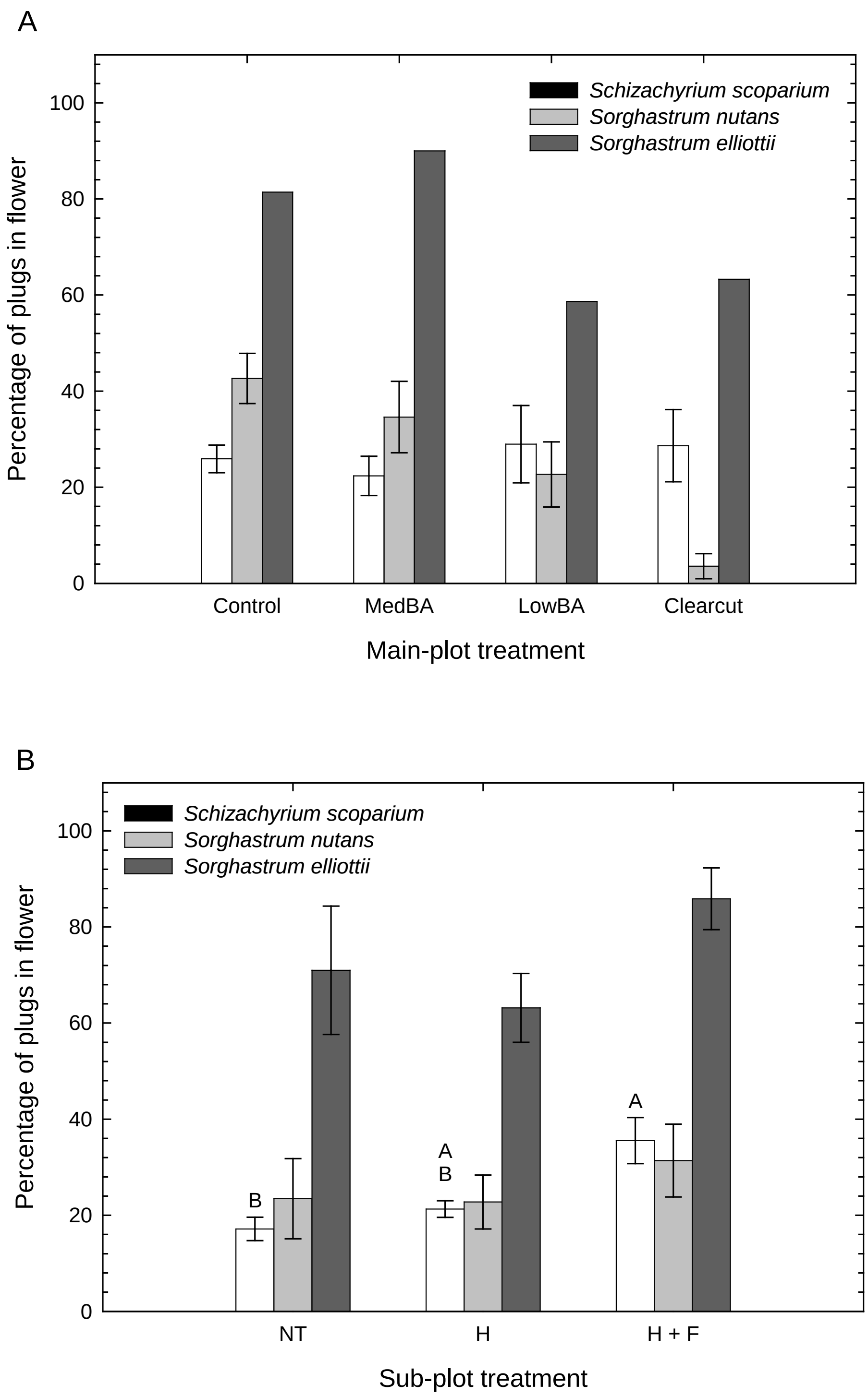
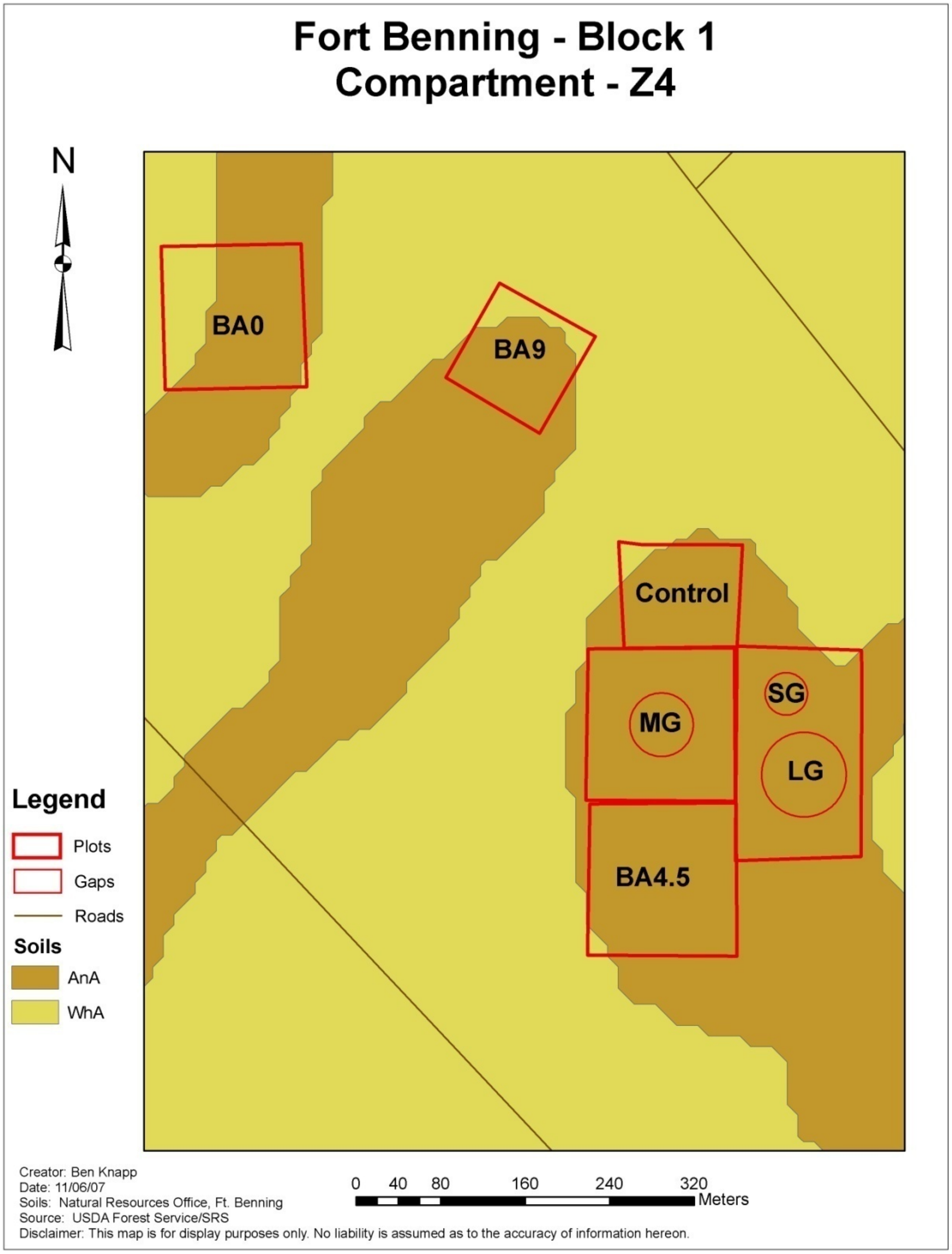


Figure A-1.1.5. Percentage of grass plugs in flower (mean ± one standard error) in October by A) main-plot treatment and B) split-plot treatment for *Schizachyrium scoparium* (n = 3 blocks), *Sorghastrum nutans* (n = 2 blocks), and *Sorghastrum elliottii* (n = 1 block). Letters denote significant differences within each species at α = 0.05. Split-plot treatments: NT = check, H = herbicide, H + F = herbicide plus fertilizer.

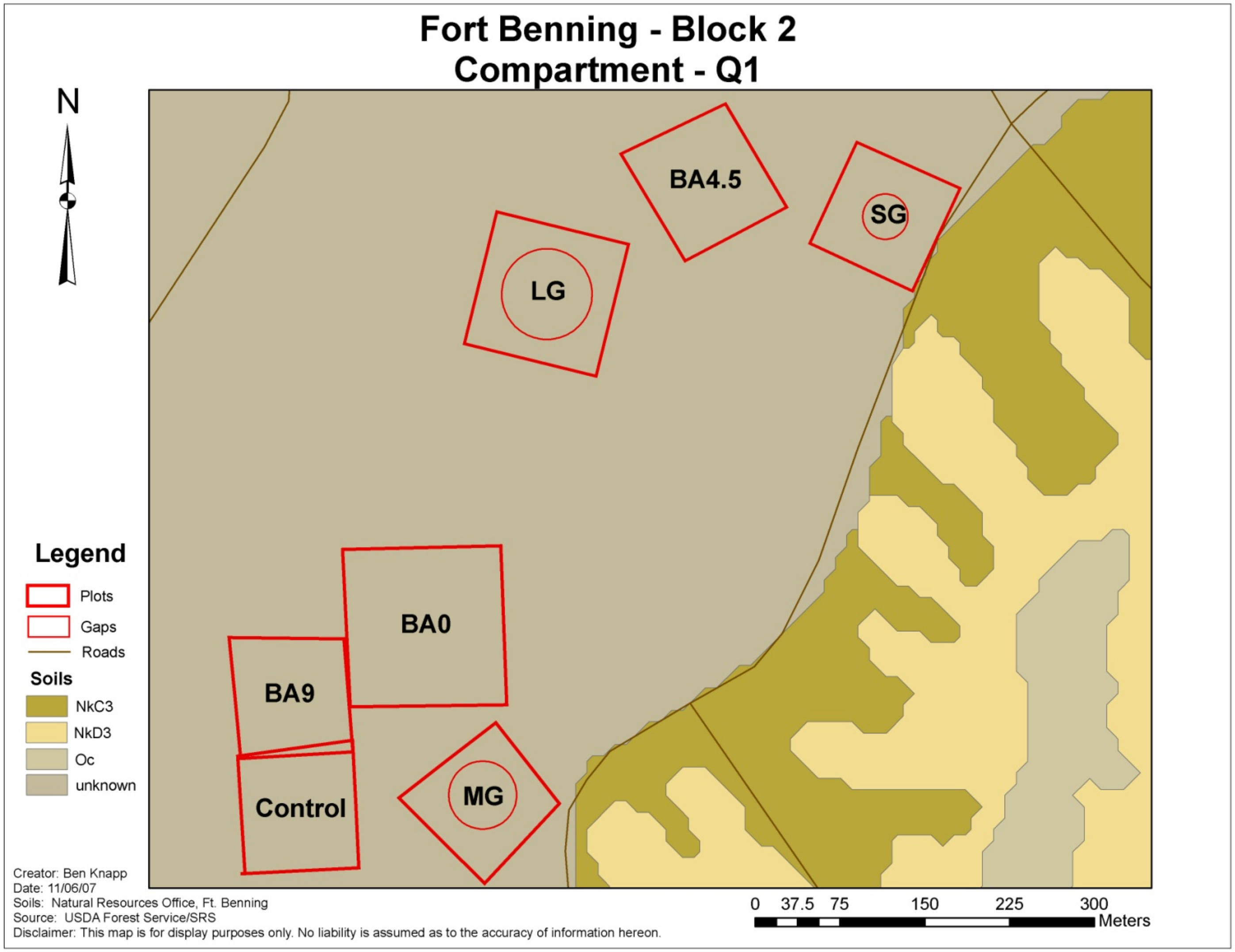
A-3.1.1. Key to soil names associated with study plots on Fort Benning

Soil Type	Soil Name	Slope
AaB	Ailey loamy course sand	2 to 5
AaC	Ailey loamy course sand	5 to 8
AnA	Annemaine fine sandy loam	0 to 2
BeA	Bladen loam	0 to 1
Bh	Bibb sandy loam	0
CaA	.	.
EmB	Esto sandy loam	2 to 5
EtA	Eunola sandy loam	0 to 3
NaB	Nankin sandy loam	2 to 5
NkC3	Nankin sandy clay loam	5 to 12
NkD3	Nankin sandy clay loam	12 to 18
Oc	Ochlockonee sandy loam	0
Pm	Pelham loamy sand	0 to 2
SuB	Susquehanna sandy loam	2 to 5
SuC	Susquehanna sandy loam	5 to 8
TrB	Troup loamy sand	2 to 5
TrC	Troup loamy sand	5 to 12
TSD	Troup and Esto loamy sands	5 to 15
TVD	Troup, Vaucluse, and Pelion loamy sands	8 to 12
VeC	Vaucluse sandy loam	5 to 8
VeD	Vaucluse sandy loam	8 to 15
WaC	Wagram loamy sand	5 to 8
WhA	Wickham fine sandy loam	0 to 2

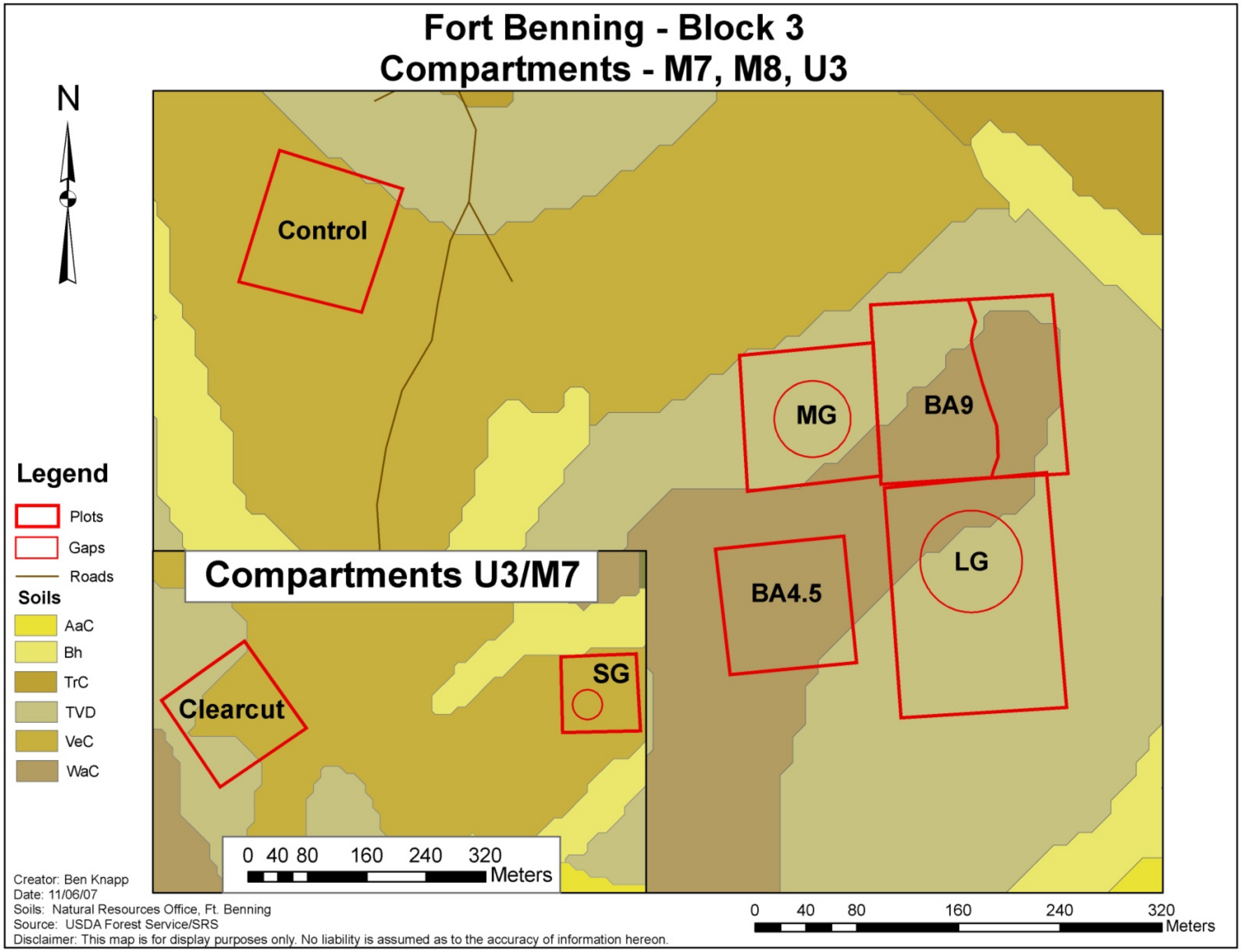
A-3.1.2. Study site and associated soils of Block 1 at Fort Benning. Soils information is shown for reference but is not updated with the 2003 Russell County Soil Survey.



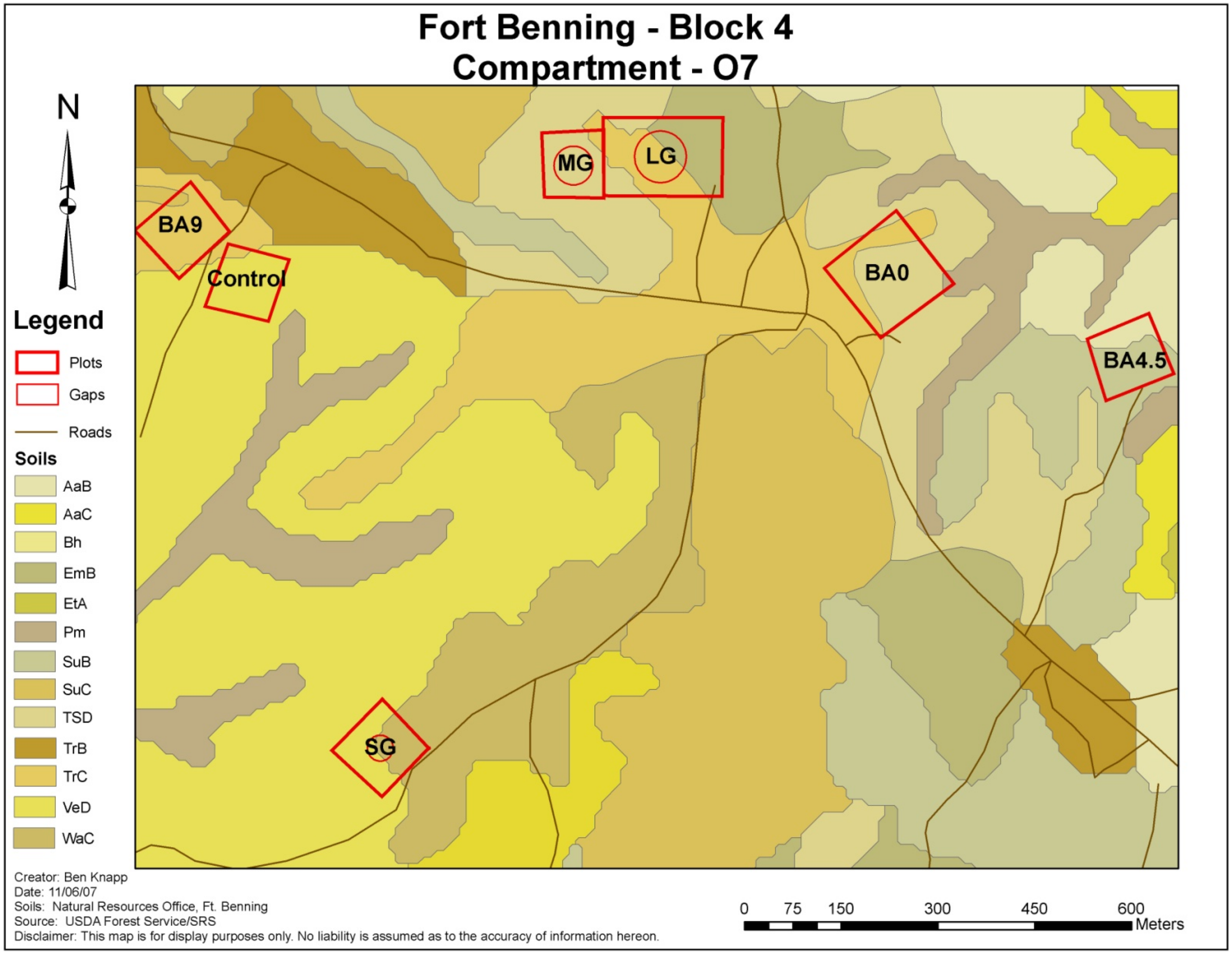
A-3.1.3. Study site and associated soils of Block 2 at Fort Benning.



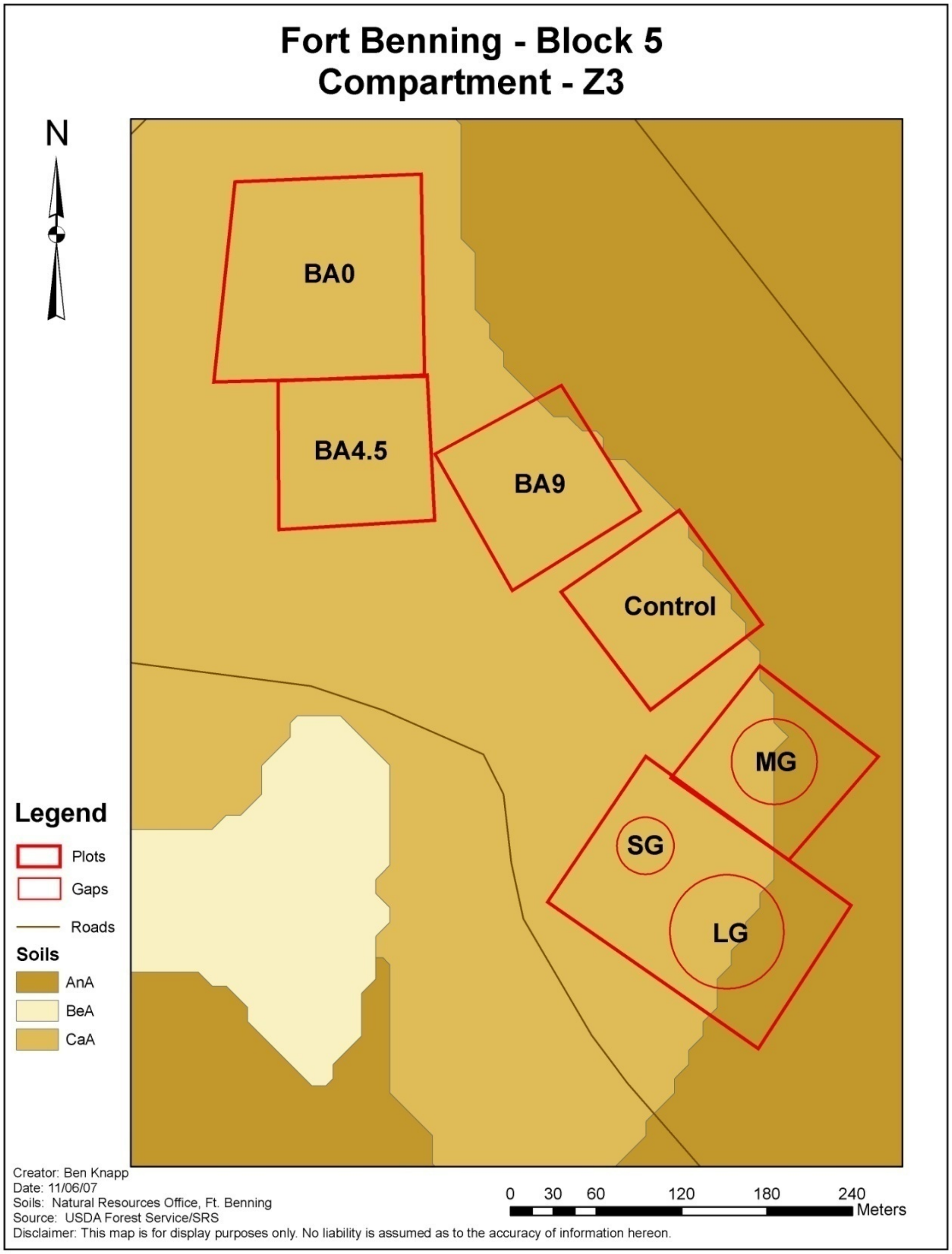
A-3.1.4. Study site and associated soils of Block 3 at Fort Benning.



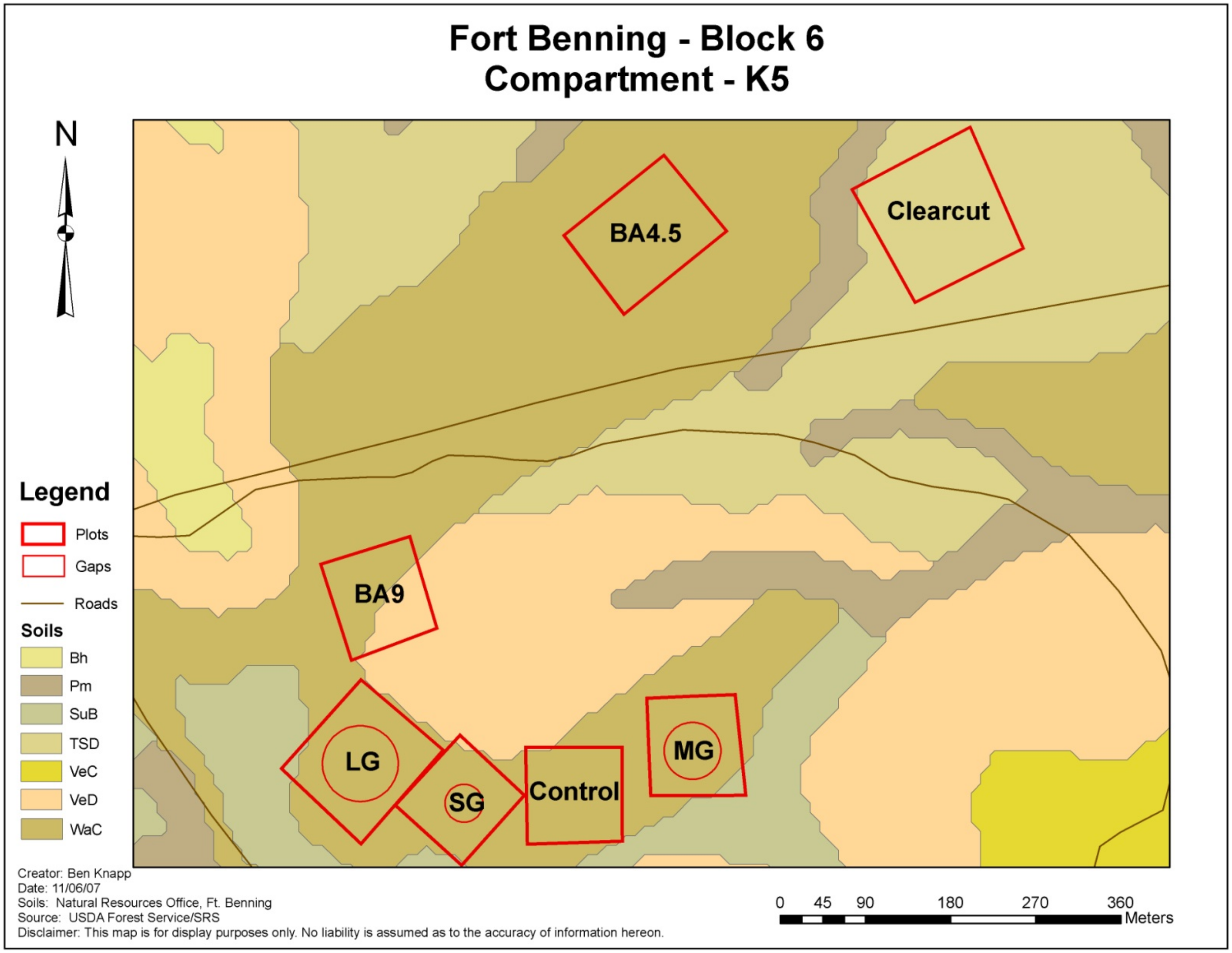
A-3.1.5. Study site and associated soils of Block 4 at Fort Benning.



A-3.1.6. Study site and associated soils of Block 5 at Fort Benning. Soils information is shown for reference but is not updated with the 2003 Russell County Soil Survey.



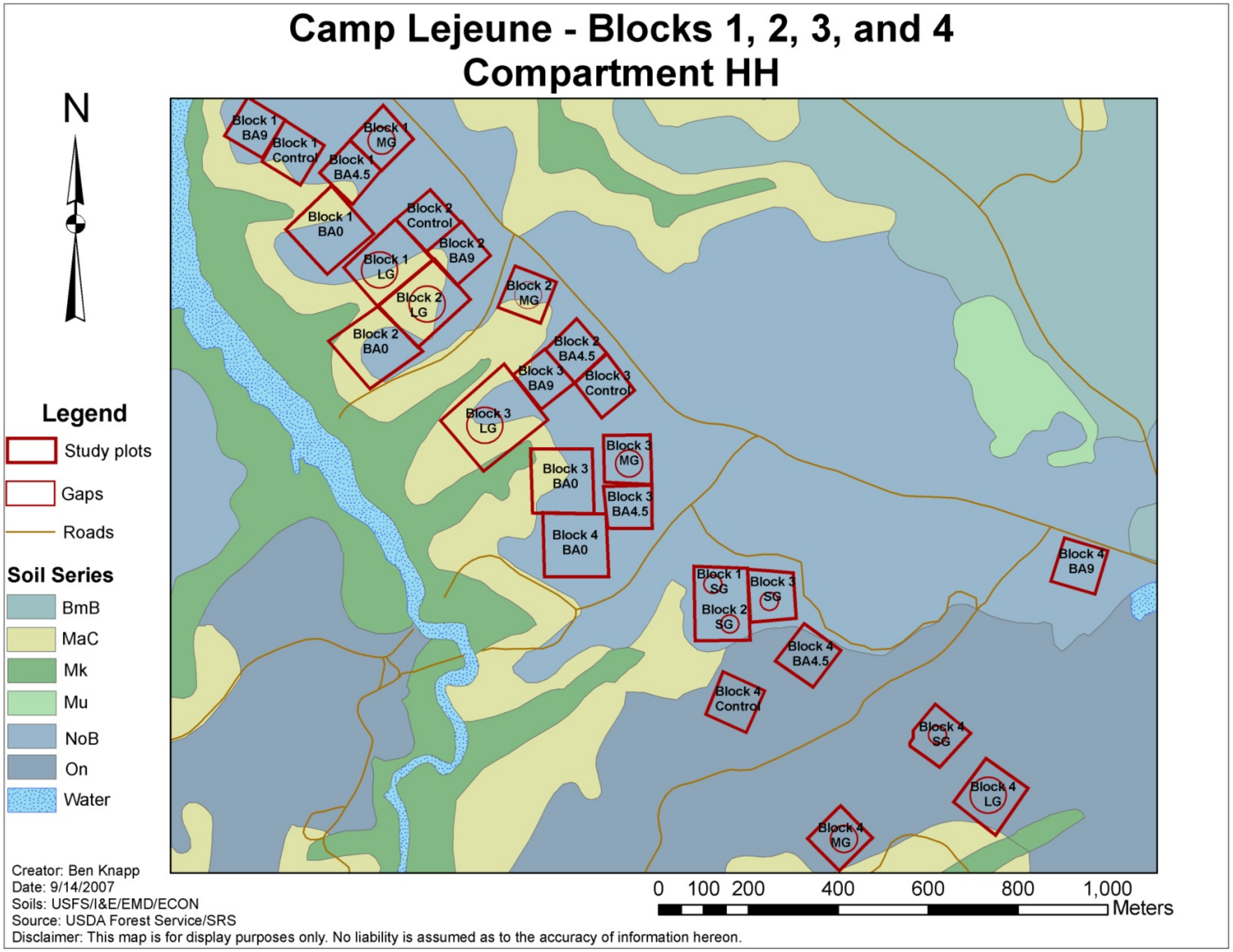
A-3.1.7. Study site and associated soils of Block 6 at Fort Benning.



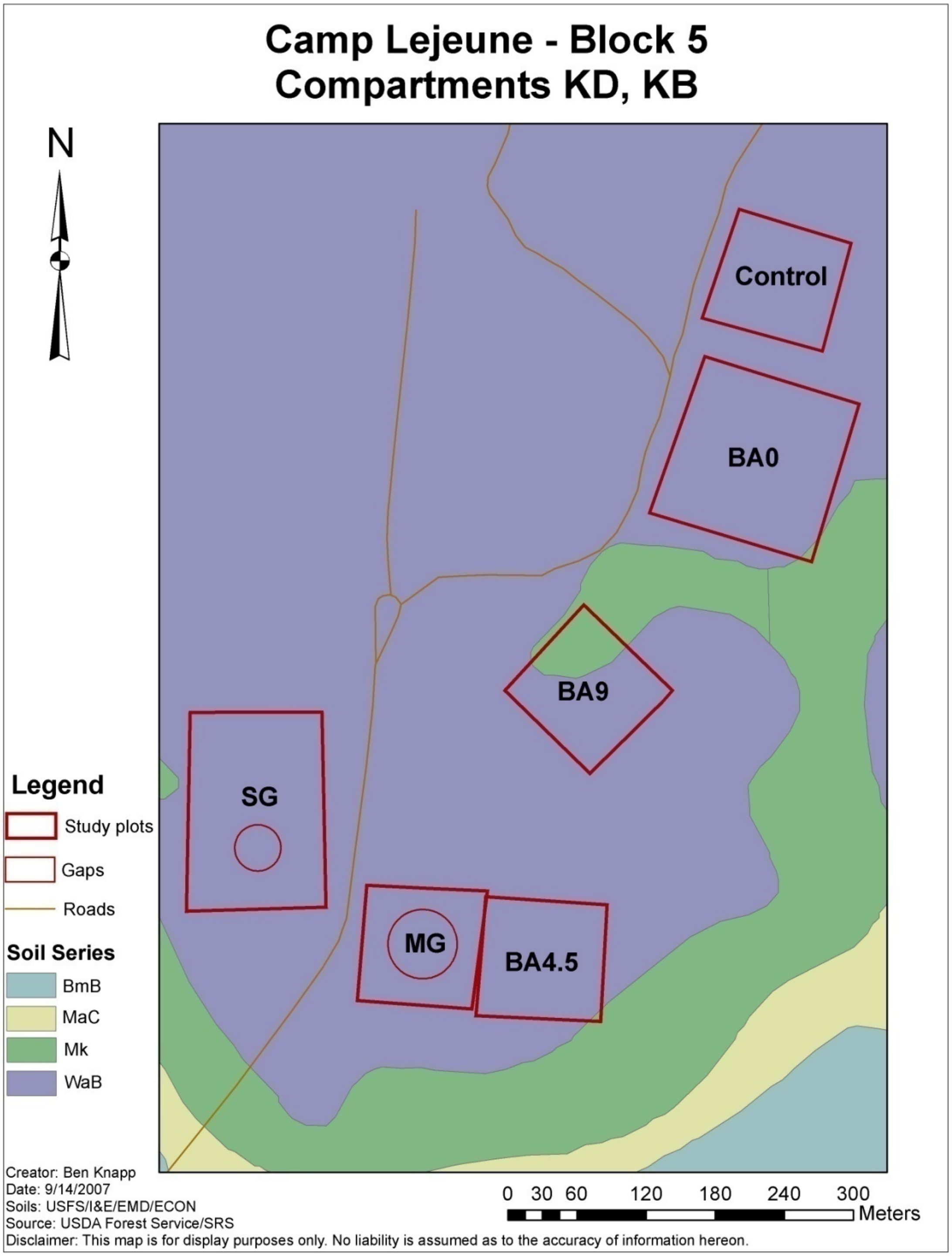
A-3.1.8. Key to soil names associated with study plots on Camp Lejeune

Soil Type	Soil Name	Slope
AnB	Alpin fine sand	1 to 6
BmB	Baymeade-Urban land complex	0 to 6
GoA	Goldsboro fine sandy loam	0 to 2
MaC	Marvyn loamy fine sand	6 to 15
Mk	Muckalee loam	0
Mu	Murville fine sand	0
NoB	Norfolk loamy fine sand	2 to 6
On	Onslow loamy fine sand	0
WaB	Wando fine sand	1 to 6

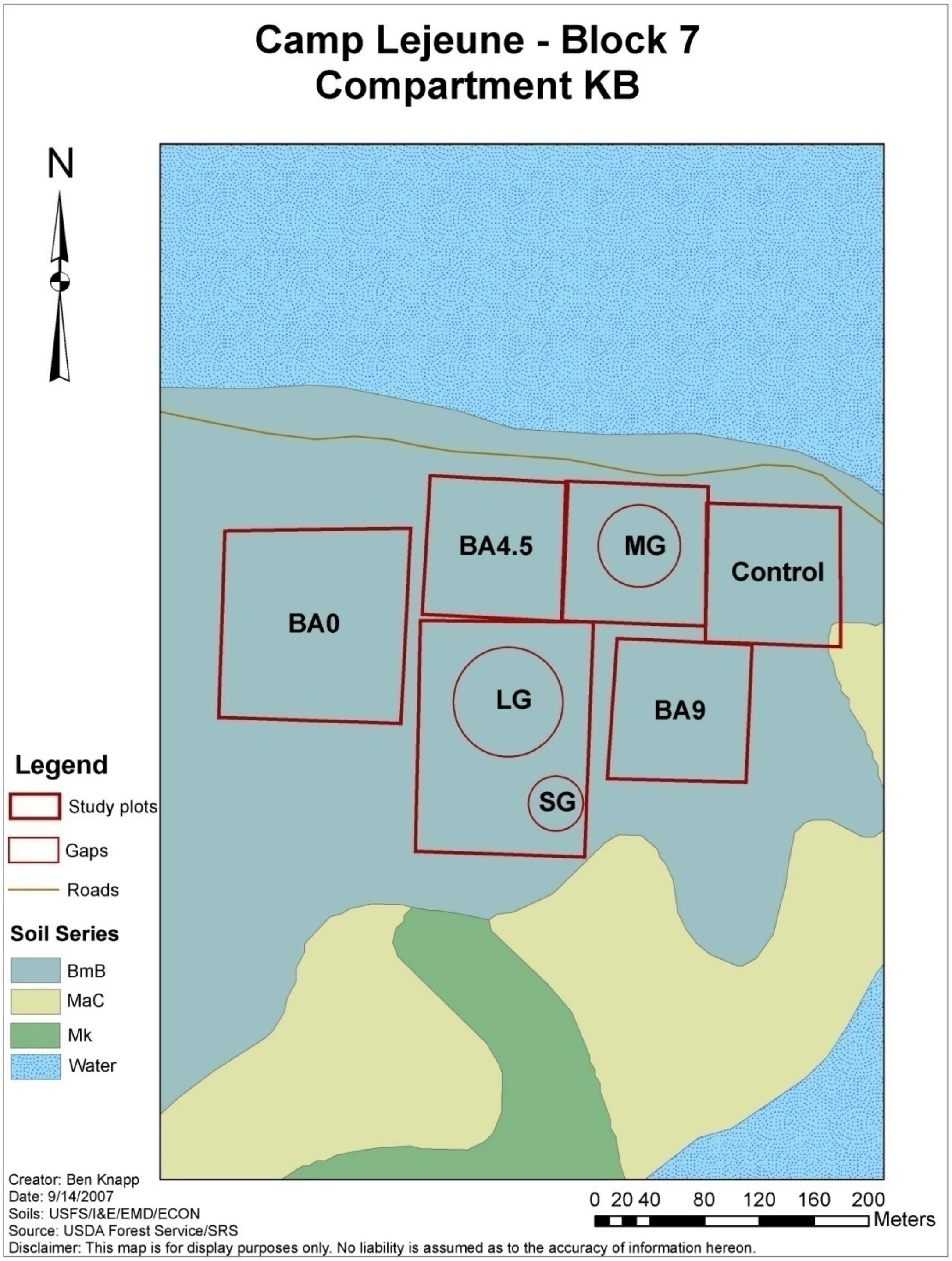
A-3.1.9. Study site and associated soils of Blocks 1-4 at Camp Lejeune.



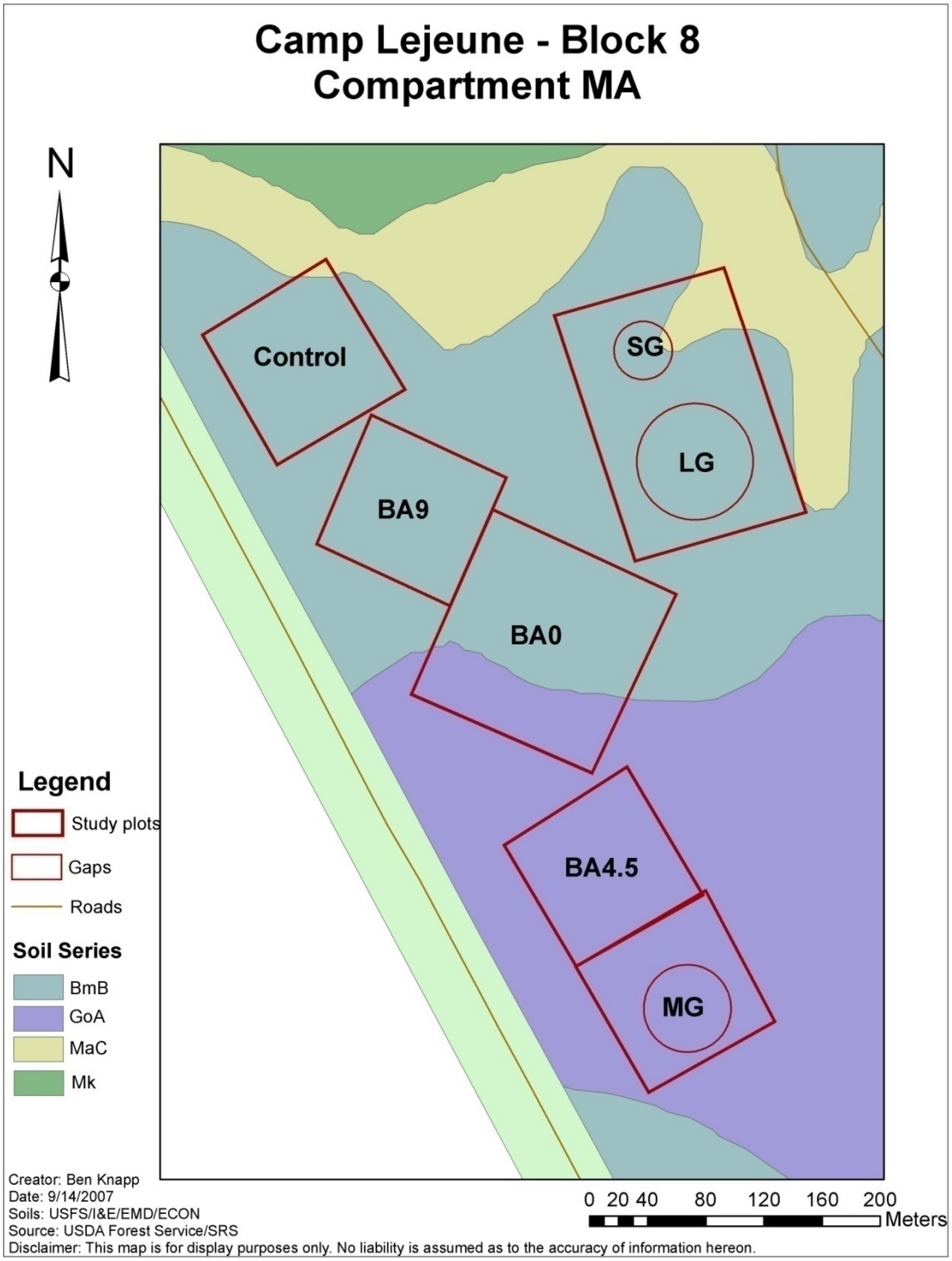
A-3.1.10. Study site and associated soils of Block 5 at Camp Lejeune.



A-3.1.11. Study site and associated soils of Block 7 at Camp Lejeune.



A-3.1.12. Study site and associated soils of Block 8 at Camp Lejeune.



A-3.1.13. Summary of plot size, TPH (trees per hectare), BA (basal area), mean DBH (diameter at breast height) and mean height for Control treatments at (A) Fort Benning and (B) Camp Lejeune

Control

A) Fort Benning			**Block**					
			1	2	3	4	5	6
	Plot Size (ha)		1.09	1.10	1.06	1.01	1.02	1.02
	TPH	Pine	146.00	147.13	470.43	307.08	176.23	153.44
		Hardwood	0.00	89.91	68.15	35.78	6.89	11.80
		Total	146.00	237.04	538.58	342.85	183.12	165.25
BA	**(m^2/ha)**	Pine	15.14	11.08	19.24	17.36	18.97	14.94
		Hardwood	0.00	3.32	1.91	0.61	0.07	0.17
		Total	15.14	14.39	21.15	17.97	19.04	15.12
DBH	**(cm)**	Pine	34.32	29.94	21.58	25.93	36.40	34.44
		Hardwood	0.00	19.99	17.01	14.32	11.66	13.35
Height	**(m)**	Pine	25.67	21.58	18.29	18.46	25.87	22.05

B) Camp Lejeune			**Block**						
			1	2	3	4	5	7	8
	Plot Size (ha)		1.07	1.00	0.98	1.03	1.03	1.00	1.04
	TPH	Pine	161.89	205.28	216.32	206.55	90.30	165.93	204.86
		Hardwood	0.00	1.99	2.05	1.95	0.97	3.00	23.93
		Total	161.89	207.27	218.37	208.50	91.27	168.93	230.71
BA	**(m^2/ha)**	Pine	13.86	16.16	13.08	14.68	13.36	19.03	21.71
		Hardwood	0.00	0.02	0.49	0.08	0.06	0.14	0.69
		Total	13.86	16.18	13.57	14.76	13.42	19.17	22.40
DBH	**(cm)**	Pine	32.46	30.95	27.15	29.54	42.00	37.17	33.52
		Hardwood	0.00	10.80	54.45	22.50	27.50	23.57	15.82
Height	**(m)**	Pine	24.08	22.79	21.57	19.11	22.99	26.12	22.47

A-3.1.14. Summary of plot size, TPH (trees per hectare), BA (basal area), mean DBH (diameter at breast height) and mean height for MedBA treatments at (A) Fort Benning and (B) Camp Lejeune

MedBA

A) Fort Benning		**Block**					
		1	2	3	4	5	6
Plot Size (ha)		1.08	1.04	1.21	1.10	1.11	1.01
TPH	Pine	76.96	110.61	159.14	86.10	78.51	117.89
	Hardwood	0.93	28.85	49.73	5.44	2.71	43.59
	Total	77.88	139.46	208.88	91.54	81.22	161.47
BA (m^2/ha)	Pine	9.93	8.87	8.14	7.62	9.93	8.32
	Hardwood	0.01	0.83	1.87	0.35	0.03	1.04
	Total	9.94	9.70	10.01	7.97	9.96	9.36
DBH (cm)	Pine	39.96	31.16	24.38	31.97	39.30	29.00
	Hardwood	11.50	18.08	20.52	25.93	11.63	15.96
Height (m)	Pine	25.32	23.04	16.76	20.31	25.49	19.54

B) Camp Lejeune		**Block**						
		1	2	3	4	5	7	8
Plot Size (ha)		0.97	1.02	0.92	1.03	1.07	1.02	0.98
TPH	Pine	81.60	107.97	127.80	126.68	71.26	69.86	57.20
	Hardwood	0.00	0.98	0.00	0.00	8.44	2.95	14.30
	Total	81.60	108.95	127.80	126.68	79.70	72.81	71.49
BA (m^2/ha)	Pine	8.25	7.98	6.46	6.57	8.72	8.98	10.33
	Hardwood	0.00	0.01	0.00	0.00	0.22	0.03	0.43
	Total	8.25	7.98	6.46	6.57	8.94	9.00	10.76
DBH (cm)	Pine	35.40	30.04	24.88	25.19	38.01	39.69	45.69
	Hardwood	0.00	11.00	0.00	0.00	17.23	10.70	17.96
Height (m)	Pine	24.44	21.99	18.91	18.10	21.63	27.68	26.33

A-3.1.15. Summary of plot size, TPH (trees per hectare), BA (basal area), mean DBH (diameter at breast height) and mean height for LowBA treatments at (A) Fort Benning and (B) Camp Lejeune

LowBA

A) Fort Benning		**Block**					
		1	2	3	4	5	6
Plot Size (ha)		2.01	1.10	1.00	1.09	1.11	1.43
TPH	Pine	53.64	138.29	80.76	64.17	52.37	47.48
	Hardwood	18.38	23.65	18.94	40.33	4.51	2.09
	Total	72.02	161.94	99.71	104.50	56.88	49.57
BA (m^2/ha)	Pine	5.91	7.56	4.78	5.33	6.89	5.08
	Hardwood	0.30	0.62	0.88	0.84	0.09	0.03
	Total	6.20	8.18	5.66	6.17	6.98	5.11
DBH (cm)	Pine	35.07	24.84	26.29	30.20	40.57	34.99
	Hardwood	13.85	16.91	21.49	15.59	15.66	13.23
Height (m)	Pine	21.33	18.90	17.35	20.36	25.84	21.78

B) Camp Lejeune		**Block**						
		1	2	3	4	5	7	8
Plot Size (ha)		0.98	0.98	0.98	1.0581	1.09	1.03	0.99
TPH	Pine	60.10	111.52	100.18	68.05	40.20	51.48	30.18
	Hardwood	0.00	2.05	4.09	0.00	11.88	0.00	8.05
	Total	60.10	113.57	104.27	68.05	52.08	51.48	38.23
BA (m^2/ha)	Pine	5.55	5.81	5.96	5.62	6.19	6.36	6.96
	Hardwood	0.00	0.20	0.21	0.00	0.43	0.00	0.13
	Total	5.55	6.02	6.18	5.62	6.62	6.36	7.09
DBH (cm)	Pine	33.71	25.22	27.05	31.87	43.62	39.18	53.67
	Hardwood	0.00	35.65	25.48	0.00	19.98	0.00	13.74
Height (m)	Pine	23.00	19.71	19.21	19.99	24.98	25.77	30.54

A-3.1.16. Summary of plot size, TPH (trees per hectare), BA (basal area), mean DBH (diameter at breast height) and mean height within the residual matrix of trees surrounding the gap of SG treatments at (A) Fort Benning and (B) Camp Lejeune

SG

A) Fort Benning		**Block** 1	2	3	4	5	6
Plot size (ha)		1.13	1.13	1.06	1.13	2.18	0.94
TPH	Pine	108.76	169.77	145.89	307.70	161.81	183.03
	Hardwood	37.14	29.18	0.00	2.65	13.26	5.31
	Total	145.89	198.94	145.89	310.35	175.07	188.33
BA (m^2/ha)	Pine	13.65	13.44	12.35	13.36	16.74	17.52
	Hardwood	0.66	0.60	0.00	0.03	0.71	0.09
	Total	14.31	14.04	12.35	13.39	17.44	17.61
DBH (cm)	Pine	39.67	30.63	31.35	22.47	34.54	33.73
	Hardwood	14.64	15.32	0.00	11.00	22.82	14.50
Height (m)	Pine	25.01	22.38	20.59	15.77	26.99	22.70

B) Camp Lejeune		**Block** 1	2	3	4	5	7	8
Plot size (ha)		1.97	1.97	1.11	1.02	2.01	2.13	2.16
TPH	Pine	175.07	225.47	183.03	220.16	137.93	188.33	98.15
	Hardwood	0.00	0.00	0.00	5.31	0.00	37.14	18.57
	Total	175.07	225.47	183.03	225.47	137.93	225.47	116.71
BA (m^2/ha)	Pine	14.83	15.62	14.73	10.28	20.37	24.94	18.61
	Hardwood	0.00	0.00	0.00	0.07	0.00	1.22	0.80
	Total	14.83	15.62	14.73	10.35	20.37	26.16	19.42
DBH (cm)	Pine	32.36	29.21	31.45	23.96	42.18	39.99	47.74
	Hardwood	0.00	0.00	0.00	12.95	0.00	18.76	19.81
Height (m)	Pine	20.98	20.52	19.19	18.07	26.79	28.42	29.67

A-3.1.17. Summary of plot size, TPH (trees per hectare), BA (basal area), mean DBH (diameter at breast height) and mean height within the residual matrix of trees surrounding the gap of MG treatments at (A) Fort Benning and (B) Camp Lejeune

MG

A) Fort Benning			**Block**					
			1	2	3	4	5	6
Plot size (ha)			2.01	1.01	1.12	0.97	1.01	1.02
TPH		Pine	230.77	175.07	204.91	272.55	161.14	183.03
		Hardwood	7.96	13.93	87.54	43.77	13.93	7.96
		Total	238.73	189.00	292.45	316.32	175.07	190.99
BA	**(m^2/ha)**	Pine	13.71	14.44	11.23	15.43	17.88	17.87
		Hardwood	0.30	0.34	1.96	1.26	0.21	0.38
		Total	14.01	14.78	13.19	16.69	18.09	18.26
DBH	**(cm)**	Pine	24.10	31.55	25.49	25.21	36.96	34.14
		Hardwood	18.65	17.24	15.26	18.37	13.56	21.35
Height	**(m)**	Pine	18.32	22.47	18.76	17.32	24.89	21.64

B) Camp Lejeune			**Block**						
			1	2	3	4	5	7	8
Plot size (ha)			1.02	0.99	1.12	1.04	1.04	1.07	1.02
TPH		Pine	109.42	286.48	208.89	212.87	141.25	157.17	105.44
		Hardwood	0.00	0.00	0.00	1.99	45.76	7.96	25.86
		Total	109.42	286.48	208.89	214.86	187.01	165.12	131.30
BA	**(m^2/ha)**	Pine	14.12	14.11	11.75	11.84	20.49	17.22	19.52
		Hardwood	0.00	0.00	0.00	0.02	2.23	0.93	0.90
		Total	14.12	14.11	11.75	11.85	22.71	18.16	20.42
DBH	**(cm)**	Pine	40.12	24.48	26.14	26.01	40.95	36.52	48.03
		Hardwood	0.00	0.00	0.00	10.40	22.57	32.45	17.20
Height	**(m)**	Pine	24.86	19.62	19.08	18.61	24.29	25.00	29.61

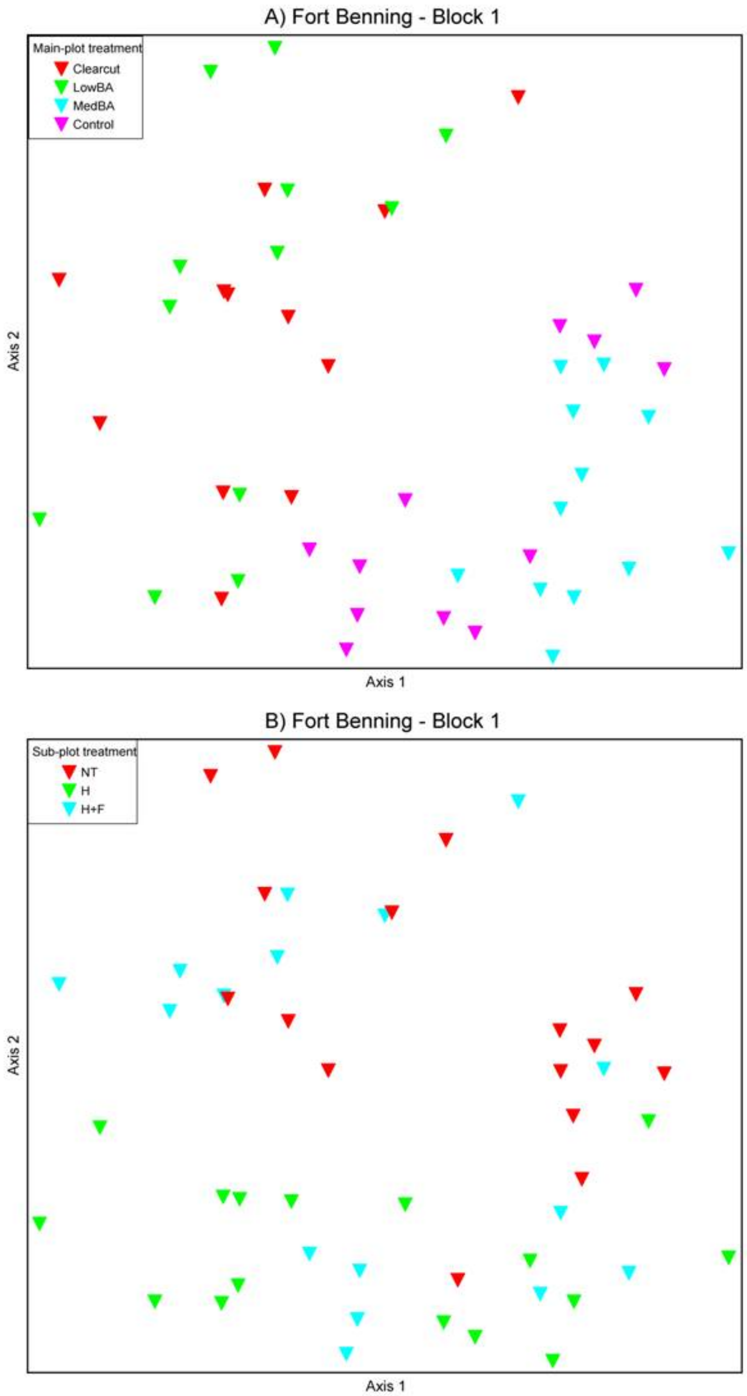
A-3.1.18. Summary of plot size, TPH (trees per hectare), BA (basal area), mean DBH (diameter at breast height) and mean height within the residual matrix of trees surrounding the gap of LG treatments at (A) Fort Benning and (B) Camp Lejeune

LG

A) Fort Benning			Block					
			1	2	3	4	5	6
	Plot size (ha)		2.36	2.23	2.37	2.25	2.18	1.48
	TPH	Pine	133.69	305.58	237.14	208.49	187.80	176.66
		Hardwood	3.18	41.38	93.90	71.62	22.28	9.55
		Total	136.87	342.18	331.04	280.11	210.08	186.21
BA	(m^2/ha)	Pine	14.17	14.60	12.05	15.69	19.12	15.10
		Hardwood	0.06	0.78	2.85	1.82	0.47	0.30
		Total	14.23	15.18	14.90	17.51	19.60	15.41
DBH	(cm)	Pine	35.08	23.39	24.01	30.00	35.25	32.03
		Hardwood	15.75	14.90	18.21	17.24	15.89	17.78
Height	(m)	Pine	24.18	18.05	17.72	19.51	26.00	21.66

B) Camp Lejeune			Block						
			1	2	3	4	5	7	8
	Plot size (ha)		1.90	1.98	2.85	1.45	-	2.13	2.16
	TPH	Pine	176.66	221.23	190.99	198.94	-	183.03	105.04
		Hardwood	1.59	0.00	9.55	3.18	-	11.14	30.24
		Total	178.25	221.23	200.54	202.13	-	194.17	135.28
BA	(m^2/ha)	Pine	13.12	14.09	7.92	8.76	-	21.60	18.08
		Hardwood	0.02	0.00	1.39	0.16	-	0.36	0.52
		Total	13.14	14.09	9.31	8.92	-	21.97	18.60
DBH	(cm)	Pine	30.17	27.75	22.28	22.87	-	38.02	44.04
		Hardwood	12.00	0.00	39.27	25.15	-	17.86	13.93
Height	(m)	Pine	22.11	20.86	18.83	16.09	-	26.03	28.60

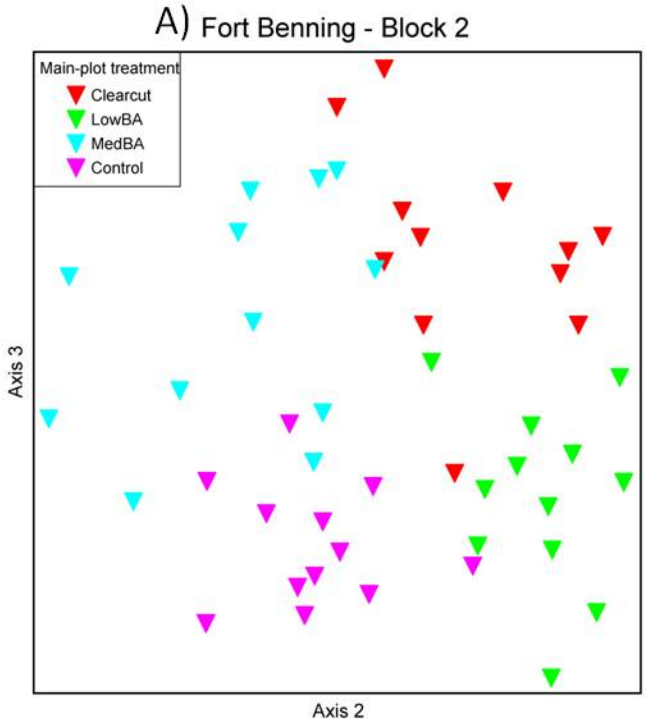
A-3.5.1. Ordination plots of species data at the 10 m^2 using non-metric multidimensional scaling and grouped by A) main-plot treatment, and b) split-plot treatment in Block 1 at Fort Benning.

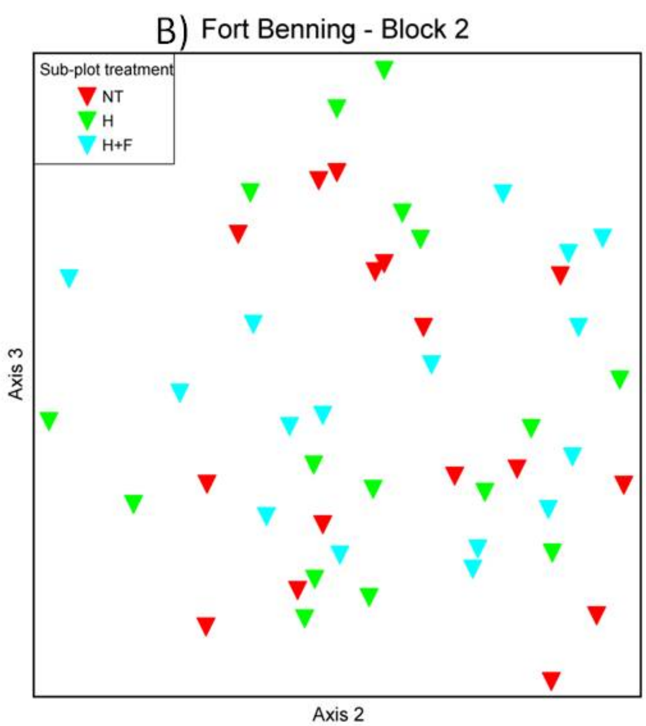


A-3.5.2. Summary of Pearson and Kendall tau correlations with ordination axes at the 10 m^2 scale in Block 1 at Fort Benning.

Fort Benning – Block 1	Axis 1			Axis 2			Axis 3		
Variable	r	r-square	tau	r	r-square	tau	r	r-square	tau
Basal area (m/ha)	0.612	0.374	0.415	-0.563	0.317	-0.373	-0.254	0.065	-0.229
DBH (cm)	0.339	0.115	0.276	-0.375	0.141	-0.298	-0.319	0.102	-0.083
Gap light index (%)	-0.622	0.387	-0.409	0.424	0.179	0.319	0.183	0.033	0.137
Soil moisture	0.280	0.530	0.621	-0.257	0.066	-0.158	0.302	0.091	0.170
Soil temperature	-0.290	0.089	-0.156	0.039	0.001	0.015	0.561	0.314	0.453
Total vegetation cover (%)	-0.364	0.133	-0.236	0.660	0.436	0.539	0.148	0.022	0.046
Herbaceous vegetation cover (%)	-0.336	0.113	-0.207	0.154	0.024	0.030	0.337	0.114	0.185
Woody vegetation cover (%)	-0.132	0.017	0.038	0.748	0.560	0.535	-0.172	0.030	-0.093
Graminoid cover (%)	-0.053	0.003	0.013	-0.143	0.020	-0.106	0.553	0.306	0.328
Forb cover (%)	-0.443	0.160	-0.328	0.386	0.149	0.323	-0.124	0.015	0.090
Fern cover (%)	-0.336	0.113	-0.238	0.428	0.183	0.281	-0.150	0.022	-0.131
Shrub cover (%)	-0.128	0.016	0.038	0.743	0.552	0.535	-0.170	0.032	-0.093
Woody vine cover (%)	-0.217	0.047	-0.095	0.146	0.021	-0.098	0.429	0.184	0.162
Clay content (%)	0.773	0.598	0.478	-0.545	0.297	-0.387	0.051	0.003	-0.008
Sand content (%)	-0.700	0.624	-0.596	0.542	0.294	0.342	-0.030	0.001	0.045
Silt content (%)	0.794	0.630	0.596	-0.534	0.285	-0.342	0.009	0.000	-0.045
Total soil N (%)	0.696	0.485	0.559	-0.413	0.171	-0.326	0.393	0.154	0.289
Total soil C (%)	0.699	0.489	0.632	-0.410	0.168	-0.391	0.382	0.146	0.158
Soil P (ppm)	-0.774	0.600	-0.596	0.460	0.246	0.342	0.040	0.002	0.045
Soil K (ppm)	0.668	0.446	0.596	-0.405	0.164	-0.342	-0.158	0.025	-0.045
Soil pH	0.777	0.603	0.596	-0.457	0.209	-0.342	0.153	0.023	-0.045
Soil organic matter (%)	0.751	0.563	0.596	-0.476	0.227	-0.342	-0.090	0.006	-0.045
Cation exchange capacity	0.778	0.605	0.632	-0.533	0.284	-0.391	0.209	0.044	0.158

A-3.5.3. Ordination plots of species data at the 10 m^2 using non-metric multidimensional scaling and grouped by A) main-plot treatment, and b) split-plot treatment in Block 2 at Fort Benning.

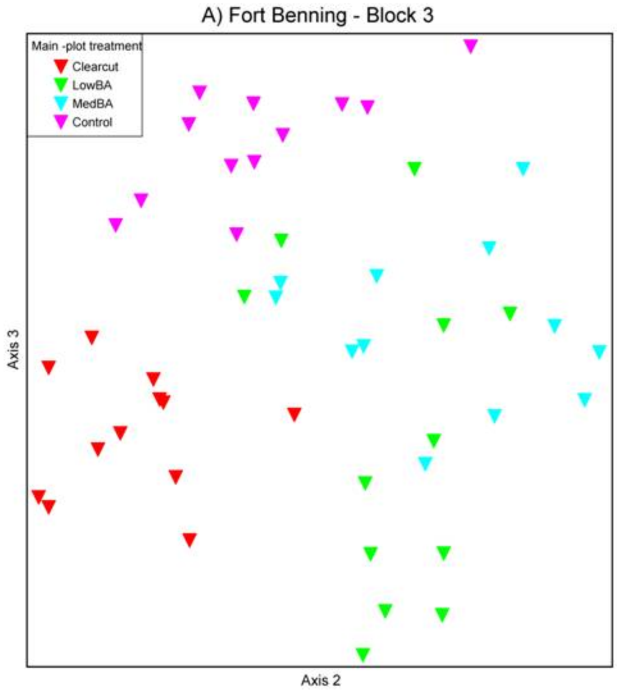


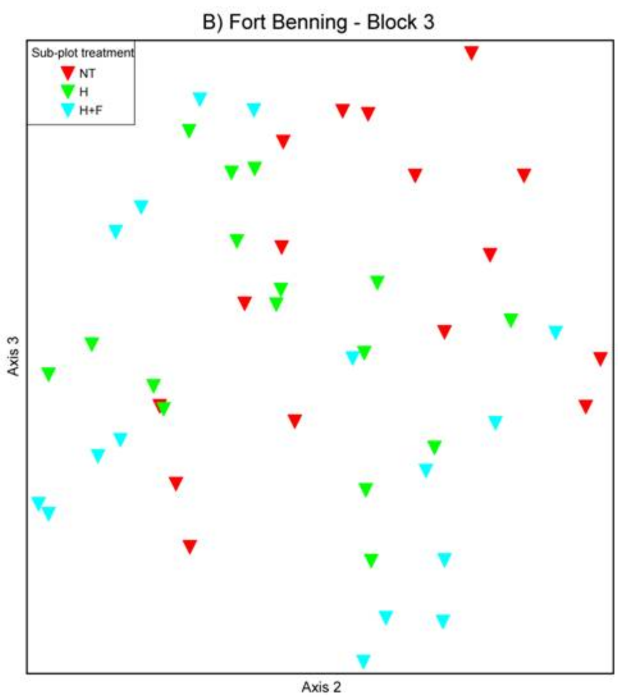


A-3.5.4. Summary of Pearson and Kendall tau correlations with ordination axes at the 10 m^2 scale in Block 2 at Fort Benning

Fort Benning - Block 2	Axis 1			Axis 2			Axis 3		
Variable	r	r-square	tau	r	r-square	tau	r	r-square	tau
Basal area (m/ha)	0.292	0.085	0.195	-0.504	0.254	-0.430	-0.597	0.356	-0.407
DBH (cm)	-0.138	0.019	-0.225	-0.337	0.114	-0.283	-0.521	0.272	-0.152
Gap light index (%)	-0.199	0.040	-0.244	0.449	0.201	0.372	0.650	0.422	0.412
Soil moisture	-0.340	0.116	-0.258	0.397	0.157	0.200	-0.534	0.285	-0.343
Soil temperature	-0.216	0.047	-0.167	0.152	0.023	0.137	0.538	0.289	0.423
Total vegetation cover (%)	-0.221	0.049	-0.060	0.367	0.135	0.262	0.604	0.365	0.434
Herbaceous vegetation cover (%)	-0.246	0.061	-0.145	0.378	0.143	0.233	0.616	0.379	0.504
Woody vegetation cover (%)	-0.133	0.018	-0.053	0.292	0.085	0.262	0.496	0.246	0.420
Graminoid cover (%)	-0.414	0.172	-0.178	0.235	0.055	0.101	0.535	0.287	0.416
Forb cover (%)	0.276	0.076	0.133	0.086	0.007	0.105	0.739	0.546	0.467
Fern cover (%)	-0.109	0.012	-0.052	0.610	0.372	0.525	-0.307	0.094	-0.113
Shrub cover (%)	-0.179	0.032	-0.082	0.157	0.025	0.104	0.588	0.345	0.460
Woody vine cover (%)	0.003	0.000	-0.042	0.393	0.154	0.218	0.121	0.015	0.240
Clay content (%)	0.406	0.165	0.277	0.047	0.002	0.124	0.113	0.013	0.135
Sand content (%)	-0.069	0.005	-0.067	-0.755	0.569	-0.547	-0.066	0.004	-0.130
Silt content (%)	-0.212	0.045	-0.221	0.801	0.642	0.571	-0.001	0.000	0.134
Total soil N (%)	-0.077	0.006	-0.097	-0.310	0.096	-0.287	-0.584	0.341	-0.453
Total soil C (%)	0.302	0.091	0.213	0.180	0.032	0.142	-0.732	0.536	-0.547
Soil P (ppm)	0.423	0.179	0.307	-0.304	0.092	-0.304	-0.542	0.294	-0.481
Soil K (ppm)	-0.135	0.018	-0.038	0.823	0.677	0.681	-0.108	0.012	-0.142
Soil pH	-0.311	0.097	-0.221	0.719	0.517	0.571	0.170	0.029	0.134
Soil organic matter (%)	0.026	0.001	0.067	0.601	0.361	0.547	0.403	0.162	0.130
Cation exchange capacity	-0.130	0.017	-0.038	0.797	0.636	0.681	-0.225	0.051	-0.142

A-3.5.5. Ordination plots of species data at the 10 m^2 using non-metric multidimensional scaling and grouped by A) main-plot treatment, and b) split-plot treatment in Block 3 at Fort Benning.

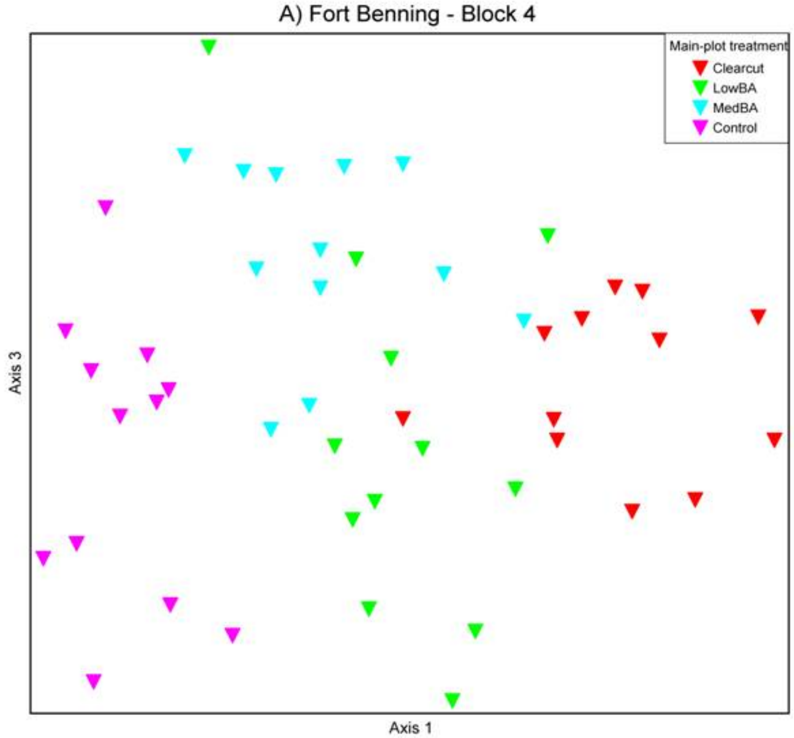


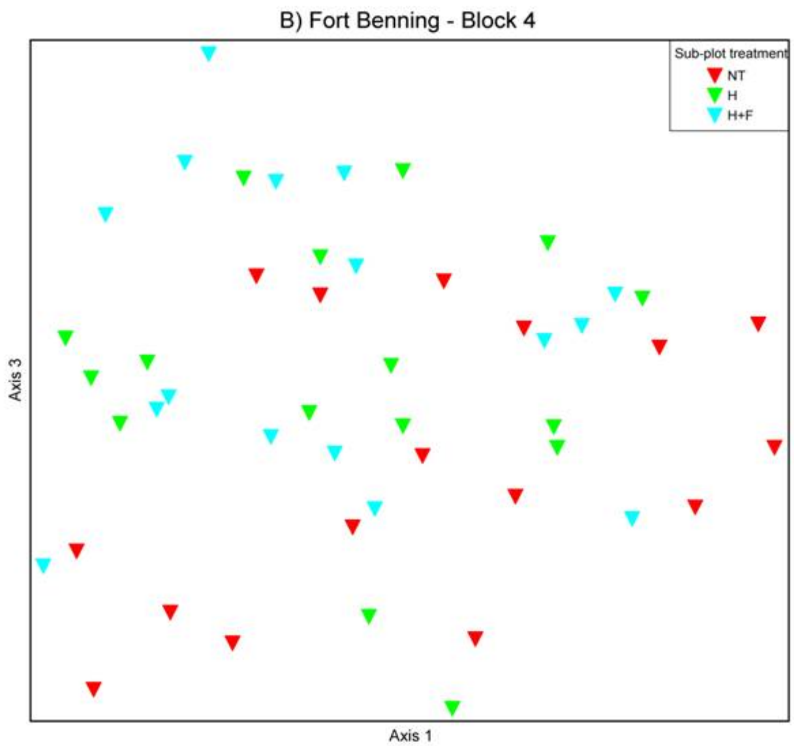


A-3.5.6. Summary of Pearson and Kendall tau correlations with ordination axes at the 10 m^2 scale in Block 3 at Fort Benning.

Fort Benning - Block 3	Axis 1			Axis 2			Axis 3		
Variable	r	r-square	tau	r	r-square	tau	r	r-square	tau
Basal area (m/ha)	0.164	0.027	0.114	0.264	0.070	0.229	0.752	0.565	0.565
DBH (cm)	0.011	0.000	-0.137	0.700	0.490	0.469	0.265	0.070	0.066
Gap light index (%)	-0.206	0.042	-0.170	-0.401	0.161	-0.246	-0.677	0.459	-0.502
Soil moisture	0.440	0.194	0.255	0.161	0.026	0.051	0.715	0.511	0.568
Soil temperature	-0.145	0.021	-0.024	-0.653	0.426	-0.418	-0.455	0.207	-0.418
Total vegetation cover (%)	-0.390	0.152	-0.233	0.005	0.000	-0.033	-0.783	0.613	-0.601
Herbaceous vegetation cover (%)	-0.375	0.141	-0.291	0.083	0.007	0.033	-0.811	0.658	-0.612
Woody vegetation cover (%)	-0.253	0.064	-0.218	-0.114	0.013	-0.114	-0.424	0.180	-0.220
Graminoid cover (%)	-0.224	0.050	-0.189	-0.130	0.017	-0.022	-0.235	0.055	-0.172
Forb cover (%)	-0.357	0.127	-0.207	0.091	0.008	0.062	-0.807	0.651	-0.634
Fern cover (%)	0.385	0.148	0.113	0.381	0.145	0.401	0.316	0.100	0.218
Shrub cover (%)	-0.253	0.064	-0.218	-0.114	0.013	-0.114	-0.424	0.180	-0.220
Woody vine cover (%)	-0.208	0.043	-0.063	-0.075	0.006	-0.148	-0.356	0.126	-0.284
Clay content (%)	0.326	0.106	0.251	0.292	0.085	0.201	0.719	0.518	0.573
Sand content (%)	-0.436	0.190	-0.317	-0.165	0.027	-0.064	-0.745	0.555	-0.637
Silt content (%)	0.473	0.224	0.328	0.001	0.000	-0.083	0.681	0.464	0.590
Total soil N (%)	0.246	0.061	0.138	-0.621	0.386	-0.515	0.388	0.150	0.260
Total soil C (%)	-0.238	0.057	-0.251	-0.512	0.262	-0.201	-0.568	0.322	-0.573
Soil P (ppm)	-0.422	0.178	-0.328	0.234	0.055	0.083	-0.677	0.458	-0.590
Soil K (ppm)	-0.368	0.135	-0.304	-0.623	0.388	-0.436	-0.337	0.113	-0.294
Soil pH	0.236	0.056	0.218	-0.189	0.036	-0.166	0.726	0.527	0.602
Soil organic matter (%)	-0.440	0.194	-0.381	0.193	0.037	-0.152	-0.484	0.234	-0.310
Cation exchange capacity	0.406	0.165	0.203	-0.198	0.039	-0.055	0.333	0.111	0.018

A-3.5.7. Ordination plots of species data at the 10 m^2 using non-metric multidimensional scaling and grouped by A) main-plot treatment, and b) split-plot treatment in Block 4 at Fort Benning.

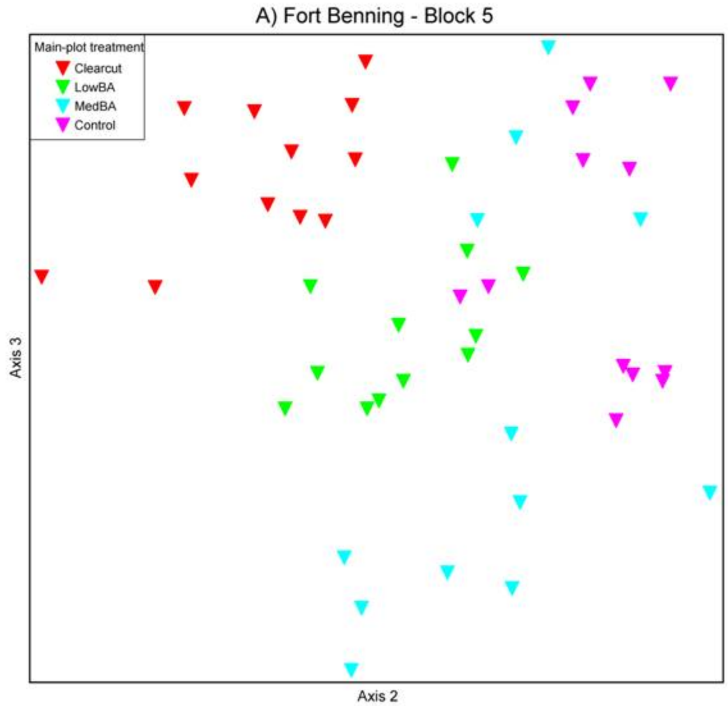


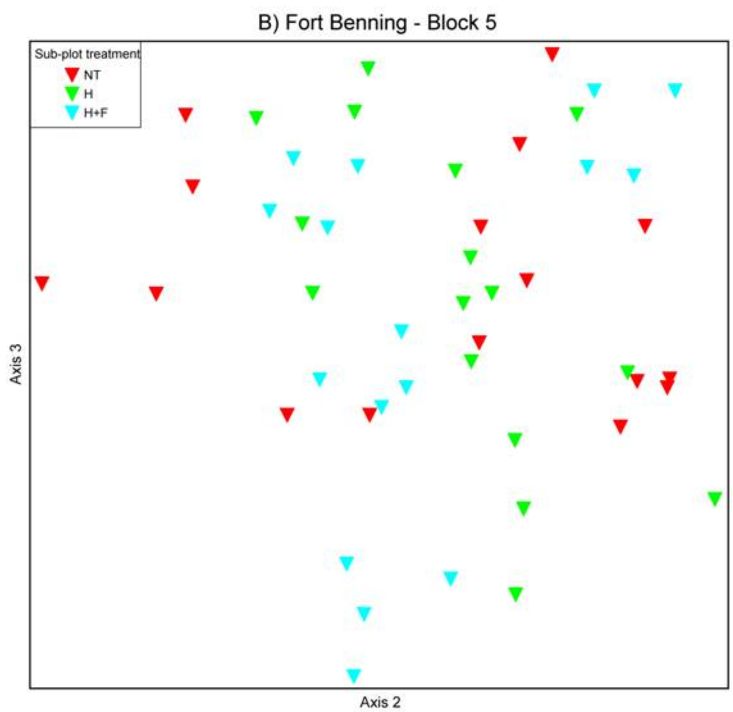


A-3.5.8. Summary of Pearson and Kendall tau correlations with ordination axes at the 10 m^2 scale in Block 4 at Fort Benning.

Fort Benning - Block 4	Axis 1			Axis 2			Axis 3		
Variable	r	r-square	tau	r	r-square	tau	r	r-square	tau
Basal area (m/ha)	-0.877	0.769	-0.745	-0.357	0.127	-0.293	-0.074	0.005	0.013
DBH (cm)	-0.518	0.268	-0.073	-0.244	0.060	-0.131	0.073	0.005	0.122
Gap light index (%)	0.902	0.813	0.728	0.449	0.201	0.284	0.072	0.005	0.026
Soil moisture	-0.397	0.158	-0.187	-0.022	0.000	0.059	-0.585	0.342	-0.465
Soil temperature	0.230	0.053	0.475	0.471	0.222	0.362	-0.475	0.225	-0.182
Total vegetation cover (%)	0.006	0.000	0.057	-0.035	0.001	-0.046	0.017	0.000	-0.004
Herbaceous vegetation cover (%)	-0.257	0.066	-0.141	-0.302	0.091	-0.233	0.097	0.009	0.073
Woody vegetation cover (%)	0.244	0.059	0.269	0.235	0.055	0.134	-0.068	0.005	-0.073
Graminoid cover (%)	-0.339	0.115	-0.200	-0.102	0.010	-0.035	-0.092	0.009	-0.048
Forb cover (%)	0.045	0.002	0.024	-0.327	0.107	-0.214	0.266	0.071	0.202
Fern cover (%)	.	.	.	.	.	.	.	.	.
Shrub cover (%)	0.234	0.055	0.269	0.231	0.054	0.134	-0.077	0.006	-0.073
Woody vine cover (%)	0.175	0.031	-0.049	0.064	0.004	-0.179	0.140	0.020	0.037
Clay content (%)	0.158	0.025	0.229	0.355	0.126	0.379	-0.323	0.105	-0.310
Sand content (%)	0.033	0.001	0.063	-0.281	0.079	-0.201	0.352	0.124	0.399
Silt content (%)	-0.122	0.015	-0.063	0.238	0.056	0.201	-0.353	0.124	-0.399
Total soil N (%)	-0.076	0.006	-0.069	-0.329	0.108	-0.215	0.410	0.168	0.286
Total soil C (%)	0.480	0.231	0.229	0.500	0.250	0.379	-0.317	0.100	-0.310
Soil P (ppm)	-0.402	0.162	-0.229	-0.502	0.252	-0.379	0.375	0.140	0.310
Soil K (ppm)	-0.100	0.010	-0.222	0.125	0.016	-0.073	-0.181	0.033	-0.082
Soil pH	-0.553	0.306	-0.346	0.049	0.002	-0.010	-0.403	0.162	-0.184
Soil organic matter (%)	-0.817	0.667	-0.784	-0.227	0.052	-0.302	-0.251	0.063	-0.002
Cation exchange capacity	0.088	0.008	-0.063	0.313	0.098	0.201	-0.312	0.097	-0.399

A-3.5.9. Ordination plots of species data at the 10 m^2 using non-metric multidimensional scaling and grouped by A) main-plot treatment, and b) split-plot treatment in Block 5 at Fort Benning.

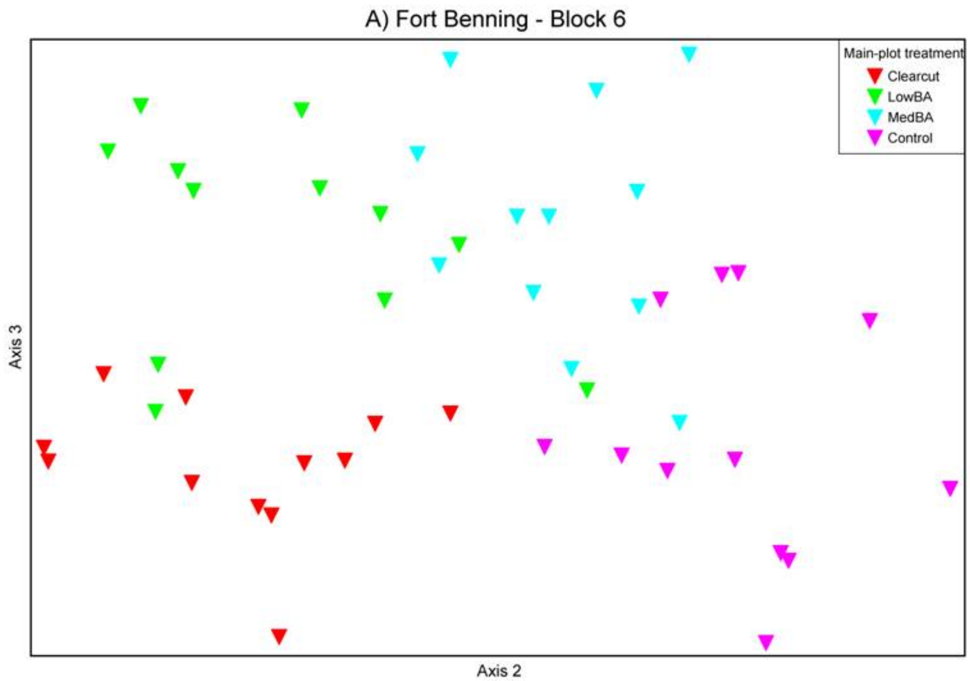


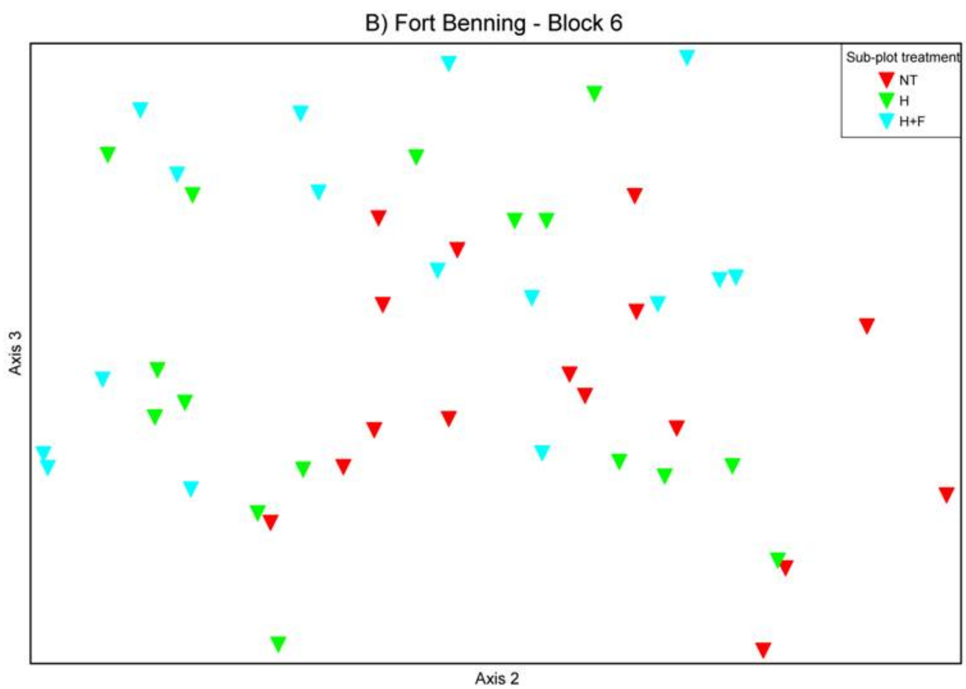


A-3.5.10. Summary of Pearson and Kendall tau correlations with ordination axes at the 10 m^2 scale in Block 5 at Fort Benning.

Fort Benning - Block 5	Axis 1			Axis 2			Axis 3		
Variable	r	r-square	tau	r	r-square	tau	r	r-square	tau
Basal area (m/ha)	0.247	0.061	0.178	0.849	0.721	0.715	-0.188	0.035	-0.113
DBH (cm)	0.124	0.015	0.163	0.619	0.383	0.144	-0.537	0.288	-0.443
Gap light index (%)	-0.327	0.107	-0.339	-0.797	0.635	-0.575	0.334	0.111	0.180
Soil moisture	0.478	0.229	0.409	0.419	0.175	0.279	0.109	0.012	-0.004
Soil temperature	-0.332	0.110	-0.283	-0.444	0.197	-0.388	-0.228	0.052	0.310
Total vegetation cover (%)	0.023	0.001	-0.046	-0.678	0.460	-0.597	-0.256	0.066	-0.029
Herbaceous vegetation cover (%)	0.184	0.034	0.130	-0.758	0.575	-0.513	0.087	0.008	0.048
Woody vegetation cover (%)	-0.161	0.026	-0.299	-0.362	0.131	-0.385	-0.544	0.296	-0.220
Graminoid cover (%)	0.118	0.014	0.288	-0.683	0.466	-0.356	0.427	0.182	0.246
Forb cover (%)	0.177	0.031	-0.009	-0.340	0.116	-0.305	-0.649	0.421	-0.349
Fern cover (%)	-0.386	0.149	-0.320	0.264	0.069	0.223	-0.217	0.047	-0.243
Shrub cover (%)	-0.227	0.051	-0.332	-0.421	0.177	-0.348	-0.489	0.239	-0.242
Woody vine cover (%)	0.372	0.138	0.279	0.220	0.049	0.332	-0.678	0.460	-0.277
Clay content (%)	0.011	0.000	-0.104	0.442	0.196	0.175	0.268	0.072	0.231
Sand content (%)	-0.057	0.003	0.104	-0.489	0.239	-0.175	-0.237	0.056	-0.231
Silt content (%)	0.084	0.007	-0.104	0.516	0.266	0.175	0.218	0.048	0.231
Total soil N (%)	-0.451	0.204	-0.364	-0.213	0.045	-0.172	0.461	0.212	0.312
Total soil C (%)	-0.610	0.372	-0.490	-0.376	0.141	-0.286	0.335	0.112	0.107
Soil P (ppm)	-0.326	0.106	-0.409	-0.642	0.412	-0.448	-0.088	0.008	-0.043
Soil K (ppm)	-0.338	0.114	-0.097	-0.498	0.248	-0.249	0.561	0.315	0.444
Soil pH	0.287	0.083	0.267	0.683	0.466	0.683	0.052	0.003	-0.205
Soil organic matter (%)	-0.295	0.087	-0.024	-0.039	0.001	0.043	0.475	0.225	0.334
Cation exchange capacity	0.184	0.034	-0.020	0.671	0.451	0.541	0.068	0.005	-0.099

A-3.5.11. Ordination plots of species data at the 10 m^2 using non-metric multidimensional scaling and grouped by A) main-plot treatment, and b) split-plot treatment in Block 6 at Fort Benning.

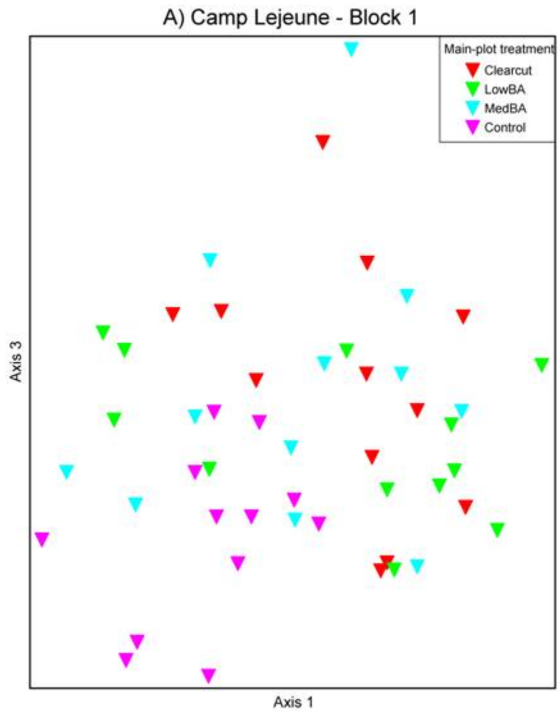


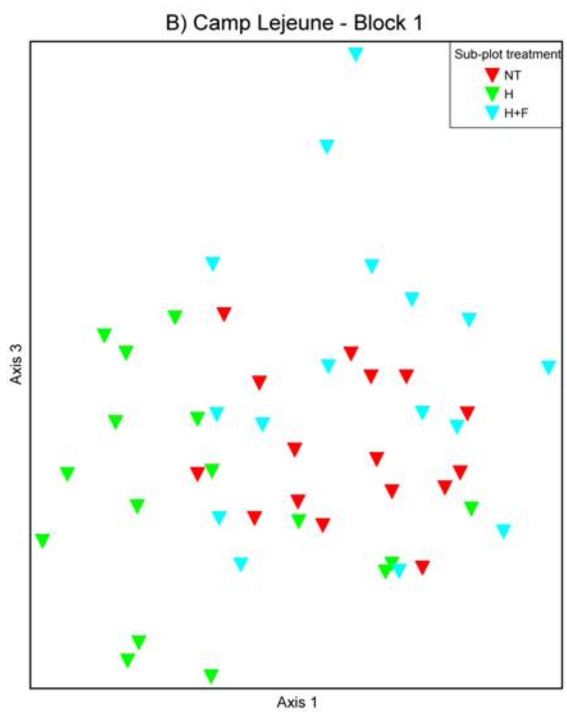


A-3.5.12. Summary of Pearson and Kendall tau correlations with ordination axes at the 10 m^2 scale in Block 6 at Fort Benning.

Fort Benning - Block 6	Axis 1			Axis 2			Axis 3		
Variable	r	r-square	tau	r	r-square	tau	r	r-square	tau
Basal area (m/ha)	0.660	0.436	0.435	0.845	0.713	0.623	0.036	0.001	0.105
DBH (cm)	0.413	0.170	0.281	0.649	0.421	0.536	0.366	0.134	0.105
Gap light index (%)	-0.599	0.358	-0.396	-0.795	0.632	-0.596	-0.226	0.051	-0.117
Soil moisture	-0.455	0.207	-0.337	-0.639	0.408	-0.398	-0.328	0.108	-0.301
Soil temperature	0.532	0.283	0.363	0.141	0.020	0.079	-0.088	0.008	-0.073
Total vegetation cover (%)	-0.628	0.394	-0.451	-0.732	0.536	-0.570	-0.173	0.030	-0.081
Herbaceous vegetation cover (%)	-0.157	0.025	-0.121	-0.181	0.033	-0.108	-0.253	0.064	-0.198
Woody vegetation cover (%)	-0.719	0.517	-0.509	-0.840	0.706	-0.651	-0.083	0.007	-0.011
Graminoid cover (%)	-0.117	0.014	-0.169	-0.503	0.253	-0.170	0.073	0.005	0.176
Forb cover (%)	-0.110	0.012	-0.073	0.215	0.046	0.159	-0.418	0.175	-0.297
Fern cover (%)	-0.192	0.037	-0.175	-0.252	0.063	-0.211	-0.322	0.104	-0.265
Shrub cover (%)	-0.722	0.521	-0.539	-0.831	0.691	-0.621	-0.088	0.008	-0.015
Woody vine cover (%)	-0.161	0.026	-0.405	-0.522	0.272	-0.655	0.133	0.018	0.152
Clay content (%)	-0.632	0.400	-0.494	-0.613	0.375	-0.417	-0.095	0.009	-0.022
Sand content (%)	0.711	0.506	0.494	0.833	0.693	0.648	0.010	0.000	-0.217
Silt content (%)	-0.684	0.467	-0.462	-0.869	0.755	-0.693	0.037	0.001	-0.063
Total soil N (%)	-0.708	0.502	-0.586	-0.826	0.682	-0.680	-0.075	0.006	-0.052
Total soil C (%)	-0.571	0.326	-0.462	-0.757	0.572	-0.693	-0.296	0.088	-0.063
Soil P (ppm)	-0.106	0.011	0.031	-0.251	0.063	-0.042	-0.538	0.290	-0.444
Soil K (ppm)	-0.676	0.457	-0.494	-0.847	0.718	-0.648	0.183	0.033	0.217
Soil pH	-0.407	0.166	-0.462	-0.592	0.350	-0.693	-0.423	0.179	-0.063
Soil organic matter (%)	-0.462	0.213	-0.462	-0.656	0.430	-0.693	-0.372	0.138	-0.063
Cation exchange capacity	-0.626	0.391	-0.494	-0.600	0.361	-0.417	-0.065	0.004	-0.022

A-3.5.13. Ordination plots of species data at the 10 m^2 using non-metric multidimensional scaling and grouped by A) main-plot treatment, and b) split-plot treatment in Block 1 at Camp Lejeune.

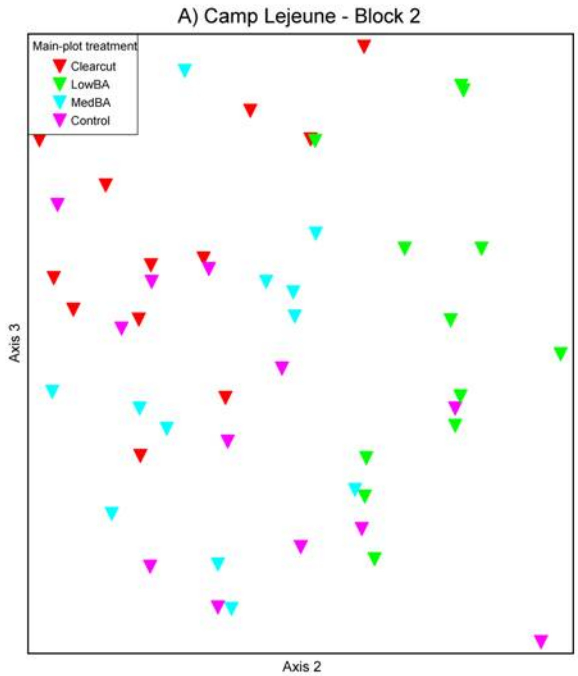


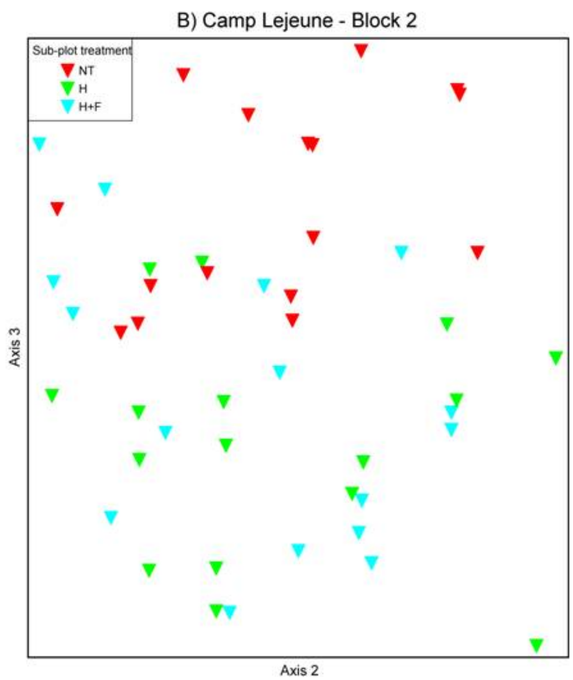


A-3.5.14. Summary of Pearson and Kendall tau correlations with ordination axes at the 10 m^2 scale in Block 1 at Camp Lejeune.

Camp Lejeune - Block 1	Axis 1			Axis 2			Axis 3		
Variable	r	r-square	tau	r	r-square	tau	r	r-square	tau
Basal area (m/ha)	-0.065	0.004	0.002	0.166	0.028	0.083	0.736	0.542	0.626
DBH (cm)	-0.205	0.042	-0.091	0.319	0.102	0.164	0.600	0.360	0.221
Gap light index (%)	0.144	0.021	0.101	-0.055	0.003	-0.038	0.341	0.116	0.236
Soil moisture	0.039	0.002	0.064	0.164	0.027	0.068	-0.082	0.007	-0.053
Soil temperature	-0.372	0.138	-0.222	0.233	0.054	0.148	0.413	0.170	0.346
Total vegetation cover (%)	0.344	0.118	0.225	-0.131	0.017	-0.152	-0.008	0.000	-0.137
Herbaceous vegetation cover (%)	-0.264	0.070	-0.211	0.098	0.010	-0.042	-0.140	0.019	-0.104
Woody vegetation cover (%)	0.419	0.175	0.317	-0.159	0.025	-0.097	0.024	0.001	-0.031
Graminoid cover (%)	-0.021	0.000	-0.157	-0.103	0.011	-0.050	-0.173	0.030	-0.111
Forb cover (%)	-0.394	0.156	-0.310	0.277	0.077	0.086	-0.053	0.003	0.024
Fern cover (%)	-0.360	0.130	-0.265	-0.067	0.005	-0.049	0.285	0.081	0.260
Shrub cover (%)	0.357	0.127	0.222	-0.248	0.062	-0.240	-0.021	0.000	-0.181
Woody vine cover (%)	0.236	0.056	0.152	0.170	0.029	-0.101	0.107	0.011	0.108
Clay content (%)	0.206	0.042	0.188	-0.084	0.007	-0.079	0.591	0.350	0.460
Sand content (%)	-0.223	0.050	-0.213	0.097	0.009	0.087	-0.561	0.315	-0.302
Silt content (%)	0.011	0.000	-0.002	-0.058	0.003	-0.083	-0.618	0.383	-0.626
Total soil N (%)	-0.213	0.046	-0.175	0.323	0.104	0.249	0.612	0.375	0.510
Total soil C (%)	-0.203	0.041	-0.091	0.319	0.102	0.164	0.583	0.339	0.221
Soil P (ppm)	-0.227	0.051	-0.186	0.336	0.113	0.237	0.505	0.255	0.173
Soil K (ppm)	-0.039	0.001	0.026	0.190	0.036	0.075	0.602	0.362	0.468
Soil pH	0.082	0.007	0.084	-0.143	0.020	-0.149	-0.670	0.449	-0.617
Soil organic matter (%)	-0.262	0.069	-0.249	0.356	0.127	0.269	0.429	0.184	0.095
Cation exchange capacity	-0.293	0.086	-0.156	0.342	0.117	0.188	0.537	0.288	0.500

A-3.5.15. Ordination plots of species data at the 10 m^2 using non-metric multidimensional scaling and grouped by A) main-plot treatment, and b) split-plot treatment in Block 2 at Camp Lejeune.

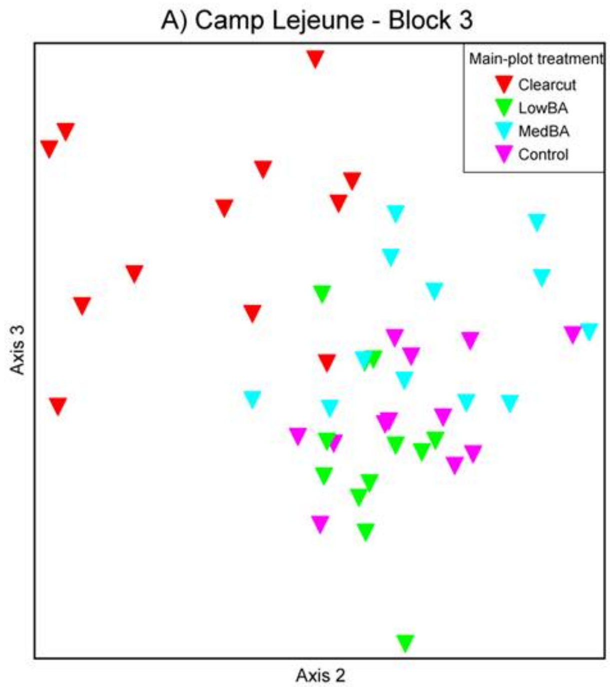


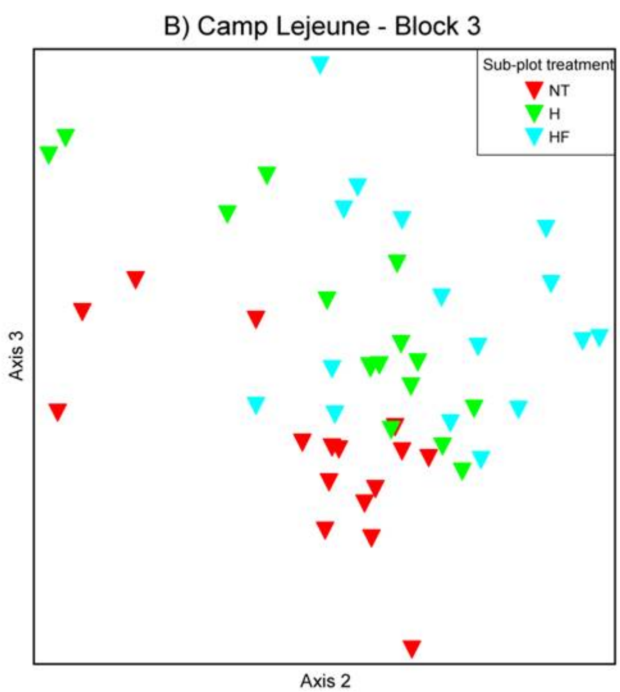


A-3.5.16. Summary of Pearson and Kendall tau correlations with ordination axes at the 10 m^2 scale in Block 2 at Camp Lejeune.

Camp Lejeune - Block 2	Axis 1			Axis 2			Axis 3		
Variable	r	r-square	tau	r	r-square	tau	r	r-square	tau
Basal area (m/ha)	0.309	0.095	0.235	0.112	0.012	0.008	-0.440	0.193	-0.338
DBH (cm)	0.378	0.143	0.235	0.306	0.093	0.008	-0.414	0.171	-0.338
Gap light index (%)	-0.160	0.025	-0.106	-0.182	0.033	-0.134	0.145	0.021	0.084
Soil moisture	0.361	0.130	0.235	0.299	0.090	0.258	-0.119	0.014	-0.059
Soil temperature	-0.342	0.117	-0.194	0.311	0.097	0.251	0.280	0.078	0.216
Total vegetation cover (%)	-0.010	0.000	-0.011	-0.139	0.019	-0.068	0.642	0.412	0.495
Herbaceous vegetation cover (%)	0.031	0.001	0.070	0.274	0.075	0.258	0.220	0.048	0.048
Woody vegetation cover (%)	-0.024	0.001	0.015	-0.273	0.074	-0.225	0.601	0.361	0.443
Graminoid cover (%)	0.003	0.000	0.022	0.201	0.040	0.200	0.166	0.028	0.022
Forb cover (%)	-0.056	0.003	-0.073	0.262	0.069	0.255	0.137	0.019	0.018
Fern cover (%)	0.343	0.118	0.292	0.349	0.122	0.305	0.391	0.153	0.314
Shrub cover (%)	-0.039	0.002	0.033	-0.225	0.051	-0.130	0.591	0.349	0.436
Woody vine cover (%)	0.039	0.002	-0.009	-0.201	0.040	-0.074	0.157	0.025	0.207
Clay content (%)	-0.316	0.100	-0.219	0.276	0.076	0.280	0.377	0.142	0.253
Sand content (%)	0.326	0.106	0.219	-0.231	0.053	-0.280	-0.394	0.155	-0.253
Silt content (%)	-0.310	0.096	-0.085	-0.299	0.089	-0.292	0.429	0.184	0.278
Total soil N (%)	0.238	0.057	0.175	0.119	0.014	0.164	-0.410	0.168	-0.337
Total soil C (%)	0.204	0.041	0.085	0.166	0.028	0.292	-0.395	0.156	-0.278
Soil P (ppm)	0.134	0.018	0.074	-0.053	0.003	-0.052	-0.327	0.107	-0.264
Soil K (ppm)	-0.121	0.015	-0.113	0.374	0.140	0.207	-0.163	0.027	-0.120
Soil pH	0.223	0.050	0.249	-0.100	0.010	-0.149	-0.374	0.140	-0.324
Soil organic matter (%)	0.410	0.168	0.235	-0.113	0.013	0.008	-0.442	0.195	-0.338
Cation exchange capacity	0.410	0.168	0.235	0.135	0.018	0.008	-0.453	0.205	-0.338

A-3.5.17. Ordination plots of species data at the 10 m^2 using non-metric multidimensional scaling and grouped by A) main-plot treatment, and b) split-plot treatment in Block 3 at Camp Lejeune.

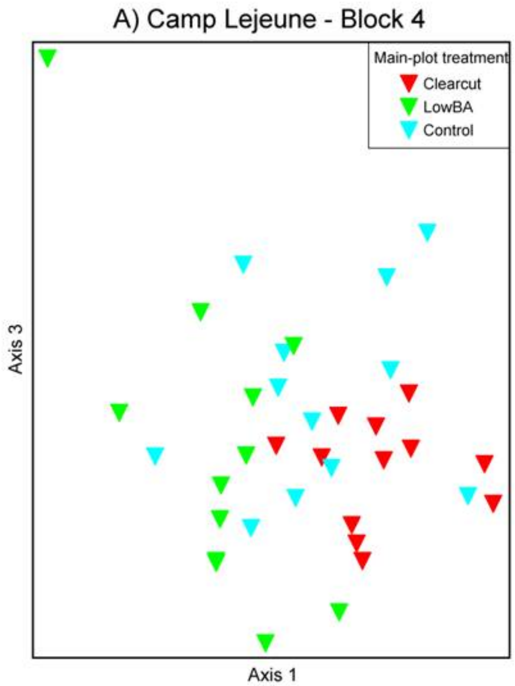


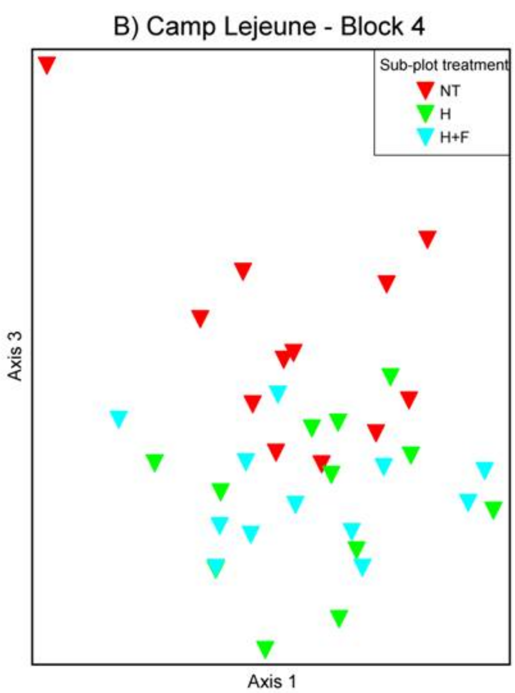


A-3.5.18. Summary of Pearson and Kendall tau correlations with ordination axes at the 10 m^2 scale in Block 3 at Camp Lejeune.

Camp Lejeune - Block 3	Axis 1			Axis 2			Axis 3		
Variable	r	r-square	tau	r	r-square	tau	r	r-square	tau
Basal area (m/ha)	-0.154	0.024	-0.041	0.567	0.322	0.294	-0.538	0.289	-0.367
DBH (cm)	0.261	0.068	-0.008	0.723	0.523	0.533	-0.630	0.397	-0.403
Gap light index (%)	0.509	0.259	0.388	0.399	0.159	0.310	-0.312	0.097	-0.200
Soil moisture	-0.228	0.052	-0.128	-0.572	0.328	-0.427	0.268	0.072	0.137
Soil temperature	-0.074	0.005	-0.029	0.262	0.069	0.101	-0.185	0.034	-0.093
Total vegetation cover (%)	0.328	0.107	0.209	-0.309	0.095	-0.189	-0.163	0.027	-0.174
Herbaceous vegetation cover (%)	-0.307	0.094	-0.264	-0.754	0.569	-0.431	0.582	0.339	0.310
Woody vegetation cover (%)	0.551	0.303	0.418	0.232	0.054	0.123	-0.583	0.340	-0.390
Graminoid cover (%)	-0.255	0.065	-0.330	-0.805	0.649	-0.511	0.470	0.221	0.203
Forb cover (%)	-0.372	0.139	-0.304	-0.327	0.107	-0.240	0.701	0.491	0.412
Fern cover (%)	-0.142	0.020	-0.255	-0.658	0.433	-0.219	0.378	0.143	0.365
Shrub cover (%)	0.548	0.301	0.421	0.233	0.054	0.152	-0.574	0.330	-0.361
Woody vine cover (%)	0.302	0.091	0.181	0.058	0.003	0.069	-0.515	0.265	-0.502
Clay content (%)	-0.186	0.034	-0.182	-0.270	0.073	-0.156	0.365	0.133	0.310
Sand content (%)	0.209	0.044	0.182	0.295	0.087	0.156	-0.381	0.145	-0.310
Silt content (%)	-0.007	0.000	-0.061	0.065	0.004	-0.136	-0.219	0.048	-0.083
Total soil N (%)	0.388	0.150	0.333	0.423	0.179	0.215	-0.447	0.200	-0.324
Total soil C (%)	0.171	0.029	0.182	0.208	0.043	0.156	-0.319	0.102	-0.310
Soil P (ppm)	-0.431	0.186	-0.379	-0.711	0.505	-0.597	0.526	0.277	0.379
Soil K (ppm)	-0.116	0.013	-0.124	-0.743	0.553	-0.628	0.596	0.355	0.426
Soil pH	-0.297	0.088	-0.227	0.338	0.114	0.310	-0.193	0.037	-0.205
Soil organic matter (%)	-0.022	0.000	0.008	-0.713	0.508	-0.533	0.592	0.351	0.403
Cation exchange capacity	0.162	0.026	-0.061	-0.062	0.004	-0.136	-0.098	0.010	-0.083

A-3.5.19. Ordination plots of species data at the 10 m^2 using non-metric multidimensional scaling and grouped by A) main-plot treatment, and b) split-plot treatment in Block 4 at Camp Lejeune.

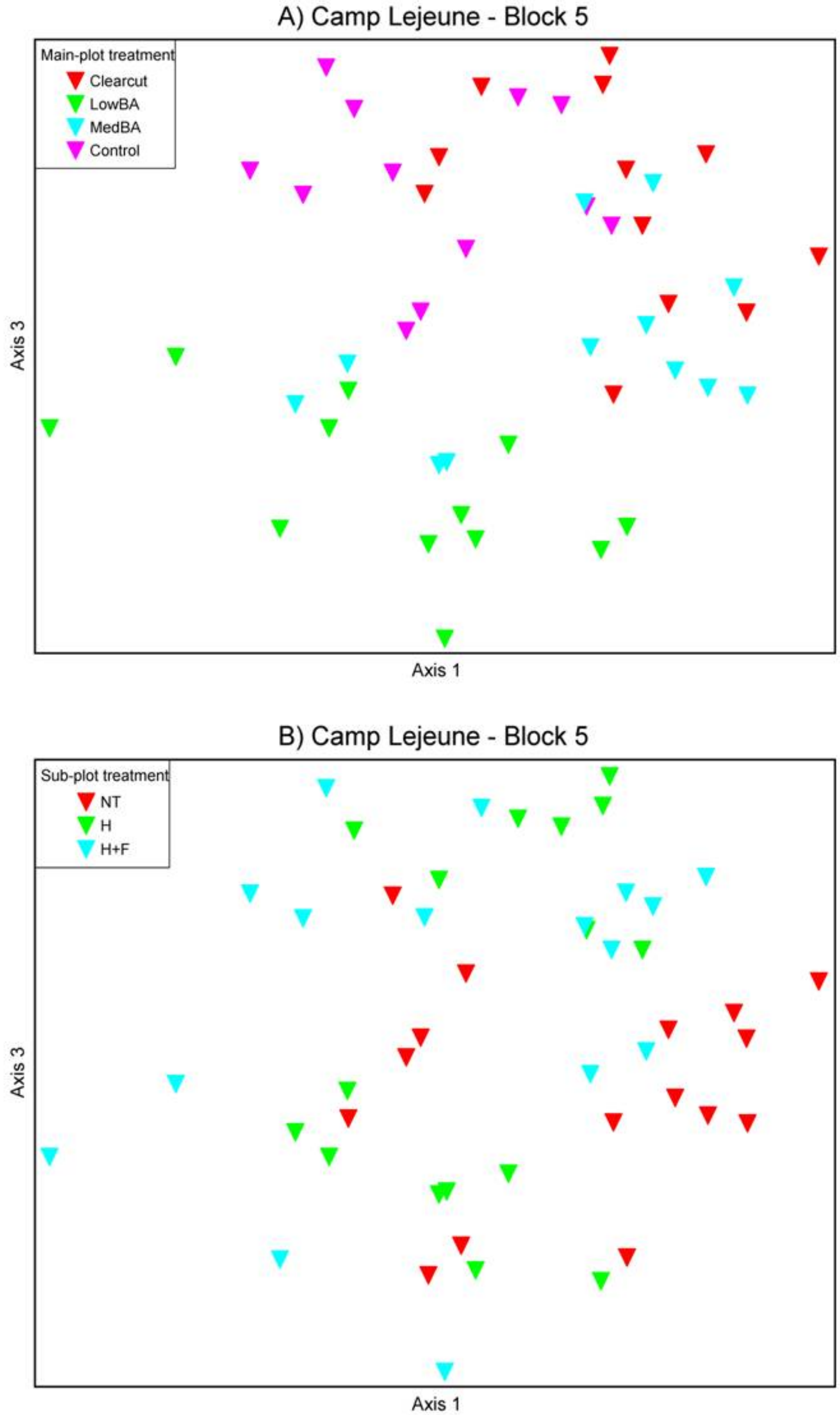




A-3.5.20. Summary of Pearson and Kendall tau correlations with ordination axes at the 10 m^2 scale in Block 4 at Camp Lejeune.

Camp Lejeune - Block 4	Axis 1			Axis 2			Axis 3		
Variable	r	r-square	tau	r	r-square	tau	r	r-square	tau
Basal area (m/ha)	-0.216	0.047	-0.199	-0.451	0.203	-0.303	0.273	0.075	0.199
DBH (cm)	-0.471	0.222	-0.199	-0.394	0.155	-0.303	0.228	0.052	0.199
Gap light index (%)	0.284	0.080	0.222	-0.180	0.033	-0.100	0.434	0.189	0.239
Soil moisture	0.086	0.007	0.010	0.494	0.244	0.246	0.025	0.001	0.000
Soil temperature	-0.069	0.005	-0.156	-0.546	0.299	-0.305	0.152	0.023	0.053
Total vegetation cover (%)	0.461	0.213	0.269	0.535	0.287	0.418	0.092	0.008	0.080
Herbaceous vegetation cover (%)	0.389	0.151	0.309	0.607	0.369	0.471	0.101	0.010	0.073
Woody vegetation cover (%)	0.416	0.173	0.315	0.425	0.181	0.305	0.074	0.005	0.033
Graminoid cover (%)	0.421	0.177	0.302	0.538	0.289	0.365	-0.111	0.012	-0.080
Forb cover (%)	0.175	0.031	0.023	0.484	0.234	0.259	0.203	0.041	0.133
Fern cover (%)	-0.255	0.065	-0.204	-0.041	0.002	-0.063	0.736	0.541	0.574
Shrub cover (%)	0.426	0.182	0.315	0.419	0.175	0.305	0.058	0.003	0.033
Woody vine cover (%)	-0.253	0.064	-0.096	0.386	0.149	0.438	0.608	0.370	0.392
Clay content (%)	0.639	0.408	0.552	-0.020	0.000	0.119	0.038	0.001	-0.038
Sand content (%)	-0.541	0.293	-0.322	0.161	0.026	0.142	-0.122	0.015	-0.199
Silt content (%)	-0.372	0.138	-0.199	-0.429	0.184	-0.303	0.254	0.064	0.199
Total soil N (%)	.	.	.	.	.	.	.	.	.
Total soil C (%)	-0.573	0.328	-0.552	-0.329	0.108	-0.119	0.183	0.034	0.038
Soil P (ppm)	0.532	0.283	0.460	0.360	0.130	0.258	-0.204	0.042	-0.146
Soil K (ppm)	0.625	0.390	0.552	0.271	0.073	0.119	-0.145	0.021	-0.038
Soil pH	0.665	0.443	0.552	0.176	0.031	0.119	-0.084	0.007	-0.038
Soil organic matter (%)	-0.664	0.441	-0.552	-0.054	0.003	-0.119	0.007	0.000	0.038
Cation exchange capacity	-0.546	0.298	-0.552	-0.351	0.123	-0.119	0.198	0.039	0.038

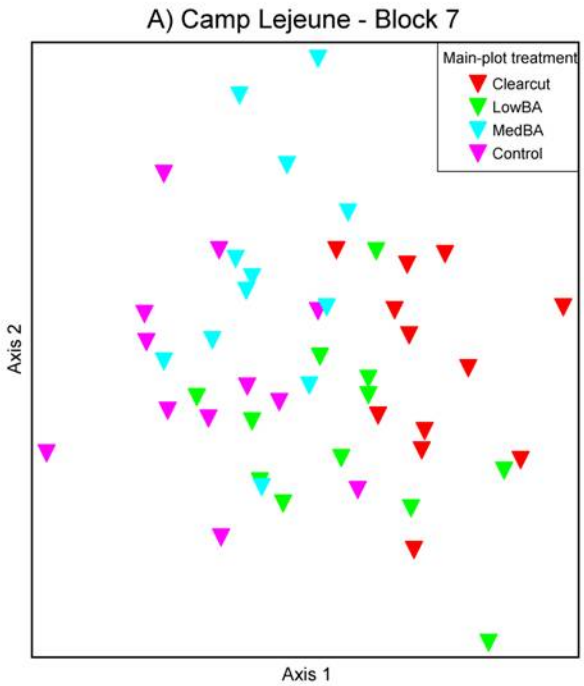
A-3.5.21. Ordination plots of species data at the 10 m^2 using non-metric multidimensional scaling and grouped by A) main-plot treatment, and b) split-plot treatment in Block 5 at Camp Lejeune.

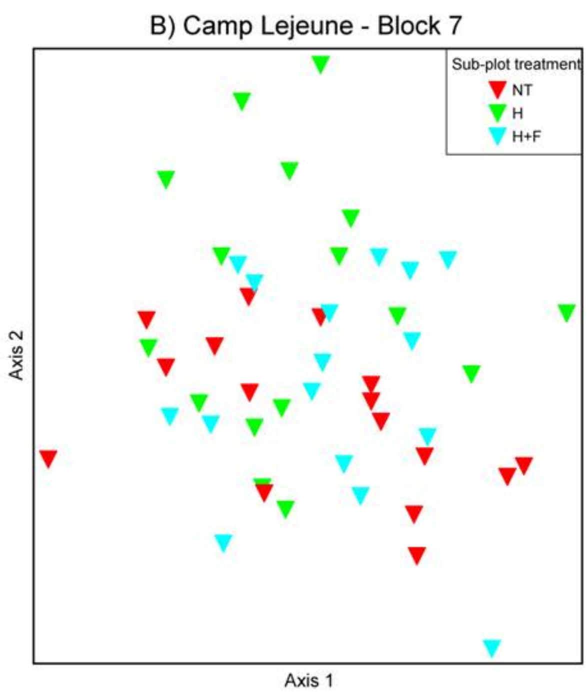


A-3.5.22. Summary of Pearson and Kendall tau correlations with ordination axes at the 10 m^2 scale in Block 5 at Camp Lejeune.

Camp Lejeune - Block 5	Axis 1			Axis 2			Axis 3		
Variable	r	r-square	tau	r	r-square	tau	r	r-square	tau
Basal area (m/ha)	-0.333	0.111	-0.219	0.593	0.351	0.411	0.003	0.000	0.126
DBH (cm)	-0.436	0.190	-0.401	0.526	0.277	0.383	-0.427	0.182	-0.389
Gap light index (%)	-0.017	0.000	-0.026	-0.119	0.014	-0.106	0.180	0.033	0.042
Soil moisture	-0.602	0.363	-0.469	0.448	0.201	0.425	-0.565	0.319	-0.383
Soil temperature	0.276	0.076	0.059	-0.158	0.025	-0.099	0.845	0.713	0.654
Total vegetation cover (%)	-0.315	0.099	-0.092	0.421	0.177	0.293	-0.604	0.365	-0.350
Herbaceous vegetation cover (%)	-0.583	0.340	-0.358	0.144	0.021	0.037	-0.185	0.034	0.120
Woody vegetation cover (%)	0.004	0.000	-0.026	0.435	0.189	0.370	-0.640	0.409	-0.449
Graminoid cover (%)	-0.619	0.383	-0.401	0.200	0.040	0.074	-0.234	0.055	0.041
Forb cover (%)	-0.141	0.020	0.055	-0.280	0.079	-0.209	0.266	0.071	0.262
Fern cover (%)	-0.364	0.133	-0.326	0.292	0.085	0.383	-0.537	0.289	-0.345
Shrub cover (%)	0.005	0.000	-0.026	0.436	0.190	0.370	-0.631	0.398	-0.449
Woody vine cover (%)	-0.064	0.004	0.017	0.165	0.027	0.125	-0.651	0.424	-0.504
Clay content (%)	-0.175	0.031	0.008	-0.129	0.017	-0.180	-0.556	0.309	-0.409
Sand content (%)	0.398	0.158	0.377	-0.181	0.033	-0.322	0.668	0.447	0.174
Silt content (%)	-0.534	0.285	-0.401	0.491	0.241	0.383	-0.586	0.343	-0.389
Total soil N (%)	-0.418	0.175	-0.243	0.272	0.074	0.160	-0.761	0.578	-0.624
Total soil C (%)	-0.459	0.210	-0.243	0.335	0.112	0.160	-0.725	0.526	-0.624
Soil P (ppm)	0.333	0.111	0.243	-0.254	0.064	-0.160	0.689	0.474	0.624
Soil K (ppm)	-0.118	0.014	-0.146	0.395	0.156	0.253	0.628	0.394	0.401
Soil pH	0.513	0.263	0.401	-0.409	0.167	-0.383	0.598	0.357	0.389
Soil organic matter (%)	-0.478	0.228	-0.401	0.360	0.129	0.383	-0.705	0.497	-0.389
Cation exchange capacity	-0.507	0.257	-0.401	0.403	0.163	0.383	-0.651	0.424	-0.389

A-3.5.23. Ordination plots of species data at the 10 m^2 using non-metric multidimensional scaling and grouped by A) main-plot treatment, and b) split-plot treatment in Block 7 at Camp Lejeune.



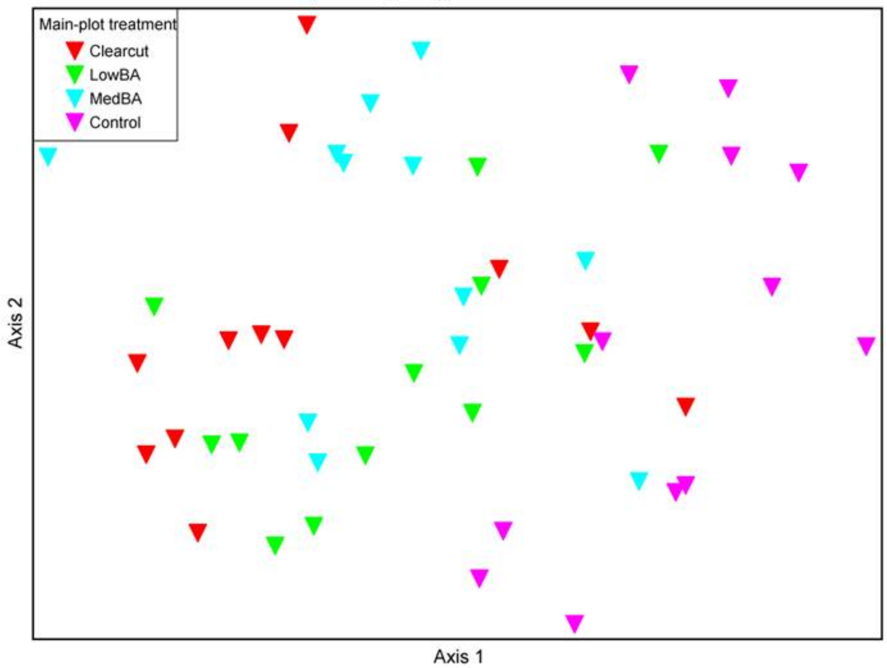


A-3.5.24. Summary of Pearson and Kendall tau correlations with ordination axes at the 10 m^2 scale in Block 7 at Camp Lejeune.

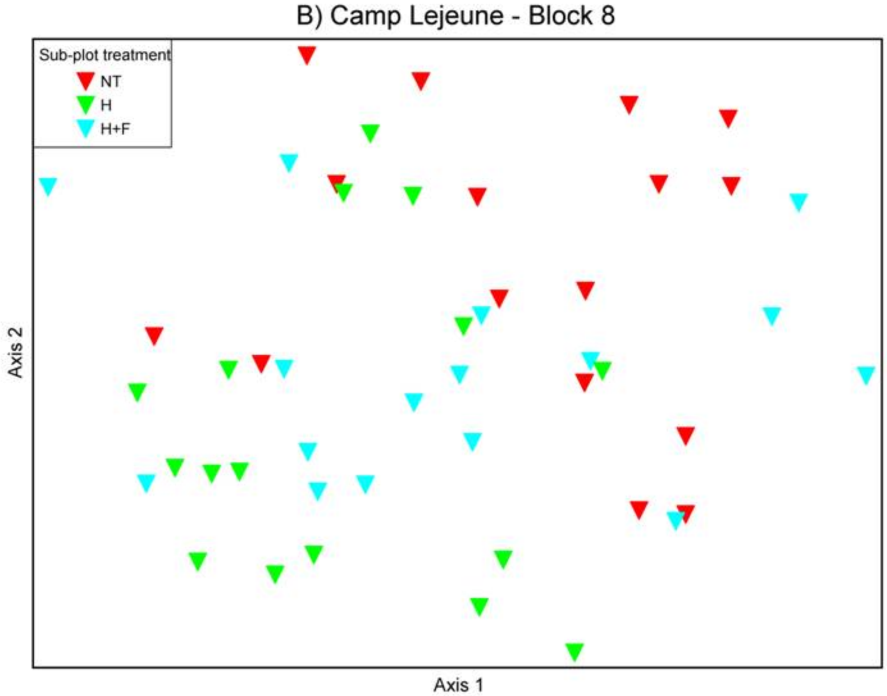
Camp Lejeune - Block 7	Axis 1			Axis 2			Axis 3		
Variable	r	r-square	tau	r	r-square	tau	r	r-square	tau
Basal area (m/ha)	-0.725	0.525	-0.634	0.037	0.001	0.069	-0.219	0.048	-0.111
DBH (cm)	-0.599	0.359	-0.282	0.029	0.001	0.126	0.073	0.005	0.144
Gap light index (%)	0.366	0.134	0.284	0.163	0.027	0.075	-0.257	0.066	-0.163
Soil moisture	-0.209	0.044	-0.218	0.598	0.358	0.295	0.018	0.000	0.053
Soil temperature	-0.675	0.455	-0.475	0.135	0.018	0.090	0.097	0.009	0.060
Total vegetation cover (%)	0.575	0.331	0.464	-0.174	0.030	-0.079	-0.093	0.009	-0.075
Herbaceous vegetation cover (%)	-0.141	0.020	-0.079	0.389	0.152	0.203	0.241	0.058	0.167
Woody vegetation cover (%)	0.583	0.340	0.398	-0.242	0.059	-0.130	-0.136	0.018	-0.086
Graminoid cover (%)	-0.174	0.030	-0.137	0.334	0.111	0.137	0.245	0.060	0.148
Forb cover (%)	0.008	0.000	-0.039	0.356	0.127	0.240	0.123	0.015	0.092
Fern cover (%)	.	.	.	.	.	.	.	.	.
Shrub cover (%)	0.660	0.435	0.456	-0.250	0.063	-0.119	-0.103	0.011	-0.060
Woody vine cover (%)	-0.327	0.107	-0.038	0.014	0.000	0.207	-0.185	0.034	-0.134
Clay content (%)	-0.648	0.419	-0.468	-0.120	0.014	-0.146	-0.121	0.015	-0.107
Sand content (%)	0.687	0.472	0.468	0.067	0.005	0.146	0.153	0.023	0.107
Silt content (%)	-0.726	0.527	-0.634	0.143	0.021	0.069	-0.247	0.061	-0.111
Total soil N (%)	-0.613	0.375	-0.599	0.019	0.000	0.142	-0.318	0.101	-0.160
Total soil C (%)	-0.675	0.455	-0.634	0.074	0.005	0.069	-0.290	0.084	-0.111
Soil P (ppm)	0.685	0.469	0.504	-0.162	0.026	-0.227	-0.013	0.000	-0.018
Soil K (ppm)	0.542	0.294	0.245	0.111	0.012	0.247	-0.057	0.003	-0.018
Soil pH	0.671	0.450	0.504	-0.348	0.121	-0.227	0.051	0.003	-0.018
Soil organic matter (%)	-0.407	0.165	-0.180	-0.247	0.061	-0.271	-0.280	0.078	-0.164
Cation exchange capacity	-0.695	0.483	-0.634	0.055	0.003	0.069	-0.269	0.072	-0.111

A-3.5.25. Ordination plots of species data at the 10 m^2 using non-metric multidimensional scaling and grouped by A) main-plot treatment, and b) split-plot treatment in Block 8 at Camp Lejeune.

A) Camp Lejeune - Block 8



B) Camp Lejeune - Block 8



A-3.5.26. Summary of Pearson and Kendall tau correlations with ordination axes at the 10 m^2 scale in Block 8 at Camp Lejeune.

Camp Lejeune - Block 8	Axis 1			Axis 2			Axis 3		
Variable	r	r-square	tau	r	r-square	tau	r	r-square	tau
Basal area (m/ha)	0.653	0.427	0.488	-0.008	0.000	0.016	-0.229	0.052	-0.154
DBH (cm)	0.153	0.023	-0.034	0.007	0.000	-0.036	0.387	0.150	0.405
Gap light index (%)	0.344	0.118	0.119	0.384	0.148	0.280	-0.292	0.085	-0.225
Soil moisture	0.711	0.506	0.574	0.126	0.016	0.060	0.080	0.006	0.167
Soil temperature	-0.156	0.024	-0.119	0.047	0.002	-0.009	-0.651	0.424	-0.489
Total vegetation cover (%)	-0.374	0.140	-0.207	-0.005	0.000	0.031	0.685	0.470	0.475
Herbaceous vegetation cover (%)	-0.521	0.271	-0.394	-0.357	0.127	-0.167	-0.125	0.016	-0.101
Woody vegetation cover (%)	-0.133	0.018	-0.141	0.151	0.023	0.163	0.715	0.511	0.449
Graminoid cover (%)	-0.352	0.124	-0.280	-0.296	0.088	-0.119	0.036	0.001	0.071
Forb cover (%)	-0.474	0.225	-0.339	-0.273	0.074	-0.115	-0.230	0.053	-0.372
Fern cover (%)	0.082	0.007	0.081	0.177	0.031	0.153	0.260	0.067	0.238
Shrub cover (%)	-0.082	0.007	-0.115	0.182	0.033	0.145	0.690	0.476	0.478
Woody vine cover (%)	-0.253	0.064	-0.277	0.005	0.000	0.089	0.573	0.328	0.349
Clay content (%)	-0.302	0.091	-0.359	0.271	0.074	0.194	-0.168	0.028	-0.069
Sand content (%)	-0.402	0.162	-0.229	-0.169	0.029	-0.109	0.329	0.108	0.118
Silt content (%)	0.677	0.458	0.480	-0.079	0.006	-0.118	-0.174	0.030	0.077
Total soil N (%)	0.363	0.132	0.321	0.016	0.000	-0.014	0.192	0.037	0.178
Total soil C (%)	0.214	0.046	-0.034	-0.032	0.001	-0.036	0.406	0.165	0.405
Soil P (ppm)	0.418	0.174	0.304	0.178	0.032	0.140	-0.540	0.291	-0.455
Soil K (ppm)	0.656	0.431	0.480	-0.135	0.018	-0.118	-0.089	0.008	0.077
Soil pH	-0.466	0.217	-0.393	-0.117	0.014	-0.069	0.214	0.046	0.149
Soil organic matter (%)	0.050	0.002	-0.034	0.032	0.001	-0.036	0.409	0.168	0.405
Cation exchange capacity	0.414	0.171	0.225	-0.082	0.007	-0.130	0.297	0.088	0.369

A-3.5.27. Significant species and associated Importance Values and p-values identified from indicator species analysis from Control plots at Fort Benning.

Fort Benning - Control	Block 1		Block 2		Block 3		Block 4		Block 5		Block 6	
Species name	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value
Ageratina aromatica			75.8	0.0002			25	0.0474				
Aristida purpuresences											37.1	0.0092
Aristida spp.											37.1	0.0064
Bulbostylis ciliaris											25	0.0498
Centrosema virginiana	58.3	0.0002										
Danthonia sericea							39.7	0.0032			33.3	0.0082
Desmodium ciliare							37.9	0.0158			36.2	0.0232
Desmodium laevigatum									34	0.019		
Desmodium lineatum									61.4	0.0002		
Desmodium marilandica									37.9	0.0012		
Desmodium paniculatum	37.9	0.001										
Desmodium strictum											42.2	0.0008
Dichanthelium boscii			53.3	0.0004								
Dichanthelium erectifolia									26.7	0.0458		
Dichanthelium laxifolium	35.6	0.0152										
Elephantopus tomentosa							48.5	0.001	34.7	0.0084		
Eupatorium hyssopifolium	38.7	0.007										
Euphorbia pubitissima							26.7	0.043				
Galactia volubilis			51.9	0.0004								
Galium pilosa							30	0.0186				
Gymnopogon ambiguus							26.7	0.0412				
Hieracium gronovii									55.6	0.0002		
Ionactis linerifolia					61.4	0.0002						
Ipomoea pandurata											44.4	0.0008
Lechea minor					34.7	0.0082						
Lespedeza procumbens	33.3	0.0122										

A-3.5.27 (cont.). Significant species and associated Importance Values and p-values identified from indicator species analysis from Control plots at Fort Benning.

Fort Benning - Control	Block 1		Block 2		Block 3		Block 4		Block 5		Block 6	
Species name	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value
Liatris spp.							25	0.0478				
Morella cerifera							26.7	0.047				
Pinus taeda			34.7	0.0324								
Pityopsis aspera											60	0.0002
Rhychospera harveyi			25	0.0468								
Rhynchosia reniformes											33.3	0.026
Smilax glauca							37.1	0.0094				
Solidago odora							46.3	0.001				
Stylostanthes biflora							92.3	0.0002				
Symphyotrichum dumosum							42	0.0026				
Tephrosia florida											69.4	0.0002
Tephrosia spicata							33.3	0.0176	42.9	0.0014		
Tephrosia virginiana					56.2	0.0002						
Tragia urens											33.7	0.0336
Vaccinium myrsentites					37.1	0.008						

A-3.5.28. Significant species and associated Importance Values and p-values identified from indicator species analysis from MedBA plots at Fort Benning.

Fort Benning - MedBA	Block 1		Block 2		Block 3		Block 4		Block 5		Block 6	
Species name	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value
Ageratina altissima			56.2	0.0002								
Ambrosia artemisiifolia	55.6	0.0060							31.4	0.0248		
Campsis radicans							34.7	0.0104	45.8	0.0010		
Centrosema virginiana											42.2	0.0008
Clitoria mariana							38.1	0.0110				
Conoclinium coelestria									26.7	0.0406		
Cornus florida					26.7	0.0420						
Desmodium strictum							34.0	0.0176				
Dicanthelium aciculare	45.0	0.0012										
Dichanthelium acuminatum	34.0	0.0152										
Diospyros virginiana							28.1	0.0456				
Eupatorium hyssopifolia							37.5	0.0132			34.8	0.0392
Galactia regularis							34.0	0.0176				
Helianthus longifolia					35.5	0.0108						
Hieracium gronovii											43.8	0.0024
Juncus spp.									26.7	0.0442		
Lespedeza cuneata									29.8	0.0318		
Lonicera japonica									33.3	0.0180		
Lygonia japonica									25.0	0.0460		
Panicum anceps	38.1	0.0086										
Pinus palustris	48.0	0.0004										
Pinus taeda	40.3	0.0026										
Pityopsis graminifolia					26.0	0.0482						
Pteridum aquilinium					40.0	0.0058						
Rhus copallina					33.3	0.0166						
Saccharum alepecuroides	44.4	0.0012	33.3	0.0128					31.4	0.0290		

A-3.5.28 (cont.). Significant species and associated Importance Values and p-values identified from indicator species analysis from MedBA plots at Fort Benning.

Fort Benning - MedBA	Block 1		Block 2		Block 3		Block 4		Block 5		Block 6	
Species name	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value
Scleria ciliata			41.7	0.0028								
Scutellaria integrifolia			33.3	0.0094								
Solidago altissima									41.7	0.0020		
Tragia urens							33.3	0.0182				
Tridens flava	29.8	0.0298										
Vernonia angustifolia									29.2	0.0396		
Vitus rotundifolia									26.7	0.0420		

A-3.5.29. Significant species and associated Importance Values and p-values identified from indicator species analysis from LowBA plots at Fort Benning.

Fort Benning - LowBA	Block 1		Block 2		Block 3		Block 4		Block 5		Block 6	
Species name	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value
Albizia julibrissin											33.3	0.0110
Aristida purpuresense			29.6	0.0148								
Campsis radicans	26.7	0.0460									25.0	0.0492
Chamaecrista nictitans									44.4	0.0012		
Cnidoscolus stimulosa					31.4	0.0232						
Conyza canadensis					31.4	0.0332						
Desmodium ciliare									37.5	0.0164		
Desmodium marilandica			35.5	0.0164								
Desmodium paniculatum									37.9	0.0122		
Dichanthelium acuminatum			41.7	0.0024							37.5	0.0056
Dichanthelium sphaerocarpon											25.0	0.0420
Diospyros virginiana					29.8	0.0302						
Elephantopus tomentosa											29.2	0.0490
Eupatorium compositifolia					34.8	0.0422						
Eupatorium rotundifolia											26.7	0.0422
Euphorbia pubentissima					34.8	0.0098						
Galactia regularis			44.4	0.0018								
Lespedeza hirta			25	0.0456								
Lespedeza repens			44.4	0.0022								
Liquidambar styraciflua							42.2	0.0048			39.7	0.0078
Lonicera japonica											33.3	0.0104
Mimosa quadrivialis					26.7	0.0422						
Phaseolus polystichoides					33.3	0.0082						
Pteridum aquilinium			66.7	0.0002								
Quercus marilandica							29.8	0.0318				

A-3.5.29 (cont.). Significant species and associated Importance Values and p-values identified from indicator species analysis from LowBA plots at Fort Benning.

Fort Benning - LowBA	Block 1		Block 2		Block 3		Block 4		Block 5		Block 6	
Species name	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value
Quercus spp.							33.3	0.0112				
Rhynchospera spp											25.0	0.0446
Rubus cuniformes	39.7	0.0032										
Saccharum alepecuroides											33.3	0.0172
Saccharum gigantea									51.0	0.0006		
Silphium compositifolia			37.0	0.0078								
Smilax glauca									26.7	0.0438	30.0	0.0178
Solidago odora					31.6	0.0484						
Sorghum halpense	42.9	0.0016										
Stylostanthes biflora											37.5	0.0060
Sympiotrychum patens					41.7	0.0016						
Ulmus alata									56.2	0.0002		
Vaccinium stamineum			33.3	0.0096								

A-3.5.30. Significant species and associated Importance Values and p-values identified from indicator species analysis from Clearcut plots at Fort Benning.

Fort Benning - Clearcut	Block 1		Block 2		Block 3		Block 4		Block 5		Block 6	
Species name	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value
Acalypha gracilens											31.6	0.0488
Agalinus fasciculata							34.7	0.0094			30.0	0.0370
Bulbostylis ciliata							66.7	0.0002				
Chamaecrista nictitans					37.5	0.0082						
Conyza canadensis											38.7	0.0098
Coreopsis major			35.5	0.0094								
Crataegus flava					25.0	0.0474						
Desmodium strictum					53.3	0.0002						
Dichanthelium aciculare							34.7	0.0378				
Dichanthelium scoparium			50.0	0.0008								
Dichanthelium spp.	33.6	0.0542										
Digitaria ciliaris							25.0	0.0492				
Diodia teres							37.5	0.0062				
Eragrostis spp							45.4	0.0018				
Eupatorium capifollia											41.7	0.0048
Galium pilosa											35.5	0.0090
Helianthus angustifolia			33.3	0.0094								
Hypericum gentinoides					33.7	0.0316	45.8	0.0012				
Kummerowia striata											50.0	0.0004
Lechea mucronota							80.0	0.0002				
Lespedeza procumbens											33.3	0.0112
Lespedeza repens											33.3	0.0144
Lespedeza stuevei					33.3	0.0106					48.2	0.0002
Morella cerifera											37.5	0.0120
Polyprenum procumbens					46.3	0.0016	42.0	0.0032				

A-3.5.30 (cont.). Significant species and associated Importance Values and p-values identified from indicator species analysis from Clearcut plots at Fort Benning.

Fort Benning - Clearcut	Block 1		Block 2		Block 3		Block 4		Block 5		Block 6	
Species name	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value
Pseudognaphalium obtusifolium					39.7	0.0066						
Quercus laevis							33.3	0.0106				
Quercus marilandica			29.3	0.0242								
Rhychosia reniformes					39.7	0.0068						
Rhynchospera harveyii					41.7	0.0014						
Rubus cuniformes					37.5	0.0052						
Rubus flagellaris											40.0	0.0046
Setaria glauca	25.0	0.0494										
Solidago altissima			41.7	0.0026								
Solidago nemoralis			39.7	0.0046								
Stylostanthes biflora					43.8	0.0008						
Tephrosia florida					34.0	0.0160						
Vitus rotundifolia			36.2	0.0196								

A-3.5.31. Significant species and associated Importance Values and p-values identified from indicator species analysis from Control plots at Camp Lejeune.

Camp Lejeune - Control	Block 1		Block 2		Block 3		Block 4		Block 5		Block 7		Block 8	
Species name	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value
Acalypha gracilens	31.4	0.0210	29.2	0.0494										
Arundinaria gigantea									70.6	0.0002				
Bignonia capreolata							33.3	0.0256						
Carya pallida											25.0	0.0488	34.7	0.0106
Centella erecta					26.0	0.0472	33.3	0.0278						
Chamaecrista nictitans	38.1	0.0046			32.1	0.0134								
Chasmanthium sessiliflorum					54.5	0.0008					33.3	0.0300		
Cirsium horridulum					58.7	0.0002								
Clethra alnifolia							33.3	0.0294						
Desmodium nuttallii					25.0	0.0260								
Desmodium paniculatum	26.7	0.0384												
Dichanthelium commutatum					42.9	0.0136								
Elephantopus tomentosus									64.1	0.0002			29.8	0.0274
Eupatorium capillifolium					37.1	0.0084								
Euthamia caroliniana									37.5	0.0080				
Hieracium gronovii									25.0	0.0456				
Liriodendron tulipifera	38.7	0.0058												
Mitchella repens			36.4	0.0202			43.9	0.0278			70.6	0.0002	34.0	0.0172
Morella cerifera					40.3	0.0238								
Panicum verrucosum									44.4	0.0014				
Parthenocissus quinquefolia											37.1	0.0092		
Prunus serotina	34.0	0.0180												
Quercus nigra					37.1	0.0110								
Rhexia mariana	29.8	0.0266												
Rubus spp.					33.3	0.0156	53.1	0.0034						

A-3.5.31 (cont.). Significant species and associated Importance Values and p-values identified from indicator species analysis from Control plots at Camp Lejeune.

Camp Lejeune - Control	Block 1		Block 2		Block 3		Block 4		Block 5		Block 7		Block 8	
Species name	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value
Smilax bona-nox					44.4	0.0026								
Smilax glauca					38.8	0.0430								
Solidago fistulosa					39.7	0.0202			25.0	0.0476				
Viola lanceolata	26.7	0.0444												

A-3.5.32. Significant species and associated Importance Values and p-values identified from indicator species analysis from MedBA plots at Camp Lejeune.

Camp Lejeune - MedBA	Block 1		Block 2		Block 3		Block 4		Block 5		Block 7		Block 8	
Species name	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value
Andropogon capillipes											41.7	0.0026		
Bignonia capreolata	42.0	0.0036											40.3	0.0034
Carya glabra													31.4	0.0300
Carya pallida									29.8	0.0268				
Dichanthelium aciculare											35.5	0.0200	31.4	0.0284
Erechtites hieracifolia													37.3	0.0140
Eupatorium capillifolium											41.7	0.0062		
Gaylussacia frondosa			37.5	0.0062										
Ilex opaca											36.2	0.0064		
Liriodendron tulipifera											26.7	0.0486		
Oldenlandia uniflora											33.3	0.0126		
Persea borbonia											44.4	0.0028		
Quercus marilandica													29.8	0.0312
Rhexia mariana											25.0	0.0456		
Smilax rotundifolia			26.7	0.0454					37.1	0.0096				

A-3.5.33. Significant species and associated Importance Values and p-values identified from indicator species analysis from LowBA plots at Camp Lejeune.

Camp Lejeune - LowBA	Block 1		Block 2		Block 3		Block 4		Block 5		Block 7		Block 8	
Species name	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value
Acalypha gracilens													35.5	0.0192
Andropogon glaucopsis							33.3	0.0272						
Bulbostylis stenophylla											26.7	0.0450		
Callicarpa americana									33.3	0.0108			33.3	0.0192
Chamaecrista nictitans			37.1	0.0100										
Cirsium horridulum	43.9	0.0014												
Cornus florida					38.8	0.0078								
Dichanthelium aciculare					43.9	0.0100								
Dichanthelium acuminatum											49.0	0.0010		
Eupatorium pilosum							34.7	0.0322						
Gelsemium sempervirens									46.3	0.0004				
Liriodendron tulipifera									41.7	0.0022				
Nyssa sylvatica			51.0	0.0008										
Parthenocissus quinquefolia					20.8	0.0456								
Quercus nigra			39.7	0.0084										
Rhynchospora microcephala									33.3	0.0092				
Rubus spp.													33.3	0.0170
Solidago rugosa			26.7	0.0408										
Toxicodendron radicans			29.2	0.0490										

A-3.5.34. Significant species and associated Importance Values and p-values identified from indicator species analysis from Clearcut plots at Camp Lejeune.

Camp Lejeune - Clearcut	Block 1		Block 2		Block 3		Block 4		Block 5		Block 7		Block 8	
Species name	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value
Andropogon glaucopsis					80.0	0.0002								
Berchemia scandens			41.7	0.0018										
Bignonia capreolata			34.0	0.0198										
Carex glaucescens									34.7	0.0116				
Carya glabra									34.7	0.0104				
Conyza canadensis													37.1	0.0092
Dichanthelium acuminatum					42.7	0.0058							35.6	0.0136
Dichanthelium commutatum									48.0	0.0004	48.0	0.0006		
Dichanthelium sabulorum	44.4	0.0030												
Digitaria ischaemum									52.1	0.0002				
Euthamia caroliniana					39.7	0.0348								
Gaylussacia frondosa	42.9	0.0018												
Liriodendron tulipifera			37.1	0.0098			42.9	0.0072						
Osmunda cinnamomea					59.5	0.0002								
Osmunda regalis					40.0	0.0046								
Photinia pyrifolia					33.3	0.0060								
Polypremum procumbens			34.7	0.0106										
Prunus serotina			30.0	0.0216										
Pseudognaphalium obtusifolium									42.9	0.0012			40.8	0.0060
Quercus marilandica							37.5	0.0252	34.0	0.0202	41.7	0.0042		
Rhexia mariana					37.9	0.0042								
Rhynchospora glomerata					50.0	0.0004								
Rhynchospora inexpansa					58.3	0.0002								
Symphyotrichum dumosum					42.1	0.0280								
Symplocos tinctoria									34.8	0.0370				

A-3.5.34 (cont.). Significant species and associated Importance Values and p-values identified from indicator species analysis from Clearcut plots at Camp Lejeune.

Camp Lejeune - Clearcut	Block 1		Block 2		Block 3		Block 4		Block 5		Block 7		Block 8	
Species name	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value	IV	p-value
Vaccinium fuscatum					27.8	0.0364								
Viola lanceolata					34.7	0.0054								
Woodwardia areolata					26.7	0.0276								
Woodwardia virginica					25.0	0.0272								

A-3.5.35. Complete species list with functional group classifications from Fort Benning

Section	Family	Genus	species	Common name	Functional group
PTERIDOPHYTES					
	Dennstaedtiaceae	*Pteridium*	*aquilinum*	western brackenfern	fern/herb
	Lygodiaceae	*Lygodium*	*japonicum*	Japanese climbing fern	fern/herb
GYMNOSPERMS					
	Cupressaceae	*Juniperus*	*virginiana*	eastern redcedar	woody/woody
	Pinaceae	*Pinus*	*palustris*	longleaf pine	woody/woody
		Pinus	*taeda*	loblolly pine	woody/woody
ANGIOSPERMS					
DICOTS					
	Acanthaceae	*Ruellia*	*caroliniensis*	Carolina wild petunia	forb/ herb
	Aceraceae	*Acer*	*rubrum*	red maple	woody/woody
	Anacardiaceae	*Rhus*	*copallinum*	winged sumac	woody/woody
		Toxicodendron	*pubescens*	Atlantic poison oak	woody/woody
		Toxicodendron	*radicans*	eastern poison ivy	woody vine/woody
	Aquifoliaceae	*Ilex*	*glabra*	inkberry	woody/woody
		Ilex	*opaca*	American holly	woody/woody
	Asclepiadaceae	*Asclepias*	*amplexicaulis*	clasping milkweed	forb/ herb
		Asclepias	*obovata*	pineland milkweed	forb/ herb
		Asclepias	*tuberosa*	butterfly milkweed	forb/ herb
	Asteraceae	*Ageratina*	*altissima*	white snakeroot	forb/ herb
		Ageratina	*aromatica*	lesser snakeroot	forb/ herb
		Ambrosia	*artemisiifolia*	annual ragweed	forb/ herb
		Baccharis	*halimifolia*	eastern baccharis	forb/herb
		Boltonia	*asteroides*	white doll's daisy	forb/ herb

A-3.5.35 (cont). Complete species list with functional group classifications from Fort Benning

Section	Family	Genus	species	Common name	Functional group
DICOTS					
	Asteraceae	*Brickellia*	*eupatorioides*	false boneset	forb/herb
		Chrysopsis	*mariana*	Maryland goldnaster	forb/ herb
		Chrysopsis	*gossypina*	cottony goldnaster	forb/ herb
		Cirsium	*vulgare*	bull thistle	forb/ herb
		Conoclinium	*coelestinum*	blue mistflower	forb/ herb
		Conyza	*canadensis*	Canadian horseweed	forb/ herb
		Coreopsis	*major*	greater tickseed	forb/ herb
		Croptilon	*divaricatum*	slender scratchdaisy	forb/ herb
		Elephantopus	*nudatus*	smooth elephantsfoot	forb/ herb
		Elephantopus	*tomentosus*	devil's grandmother	forb/ herb
		Erechtites	*hieraciifolia*	American burnweed	forb/ herb
		Erigeron	*strigosus*	prairie fleabane	forb/ herb
		Eupatorium	*album*	white thoroughwort	forb/ herb
		Eupatorium	*capillifolium*	dogfennel	forb/ herb
		Eupatorium	*compositifolium*	yankeeweed	forb/ herb
		Eupatorium	*glaucescens*	waxy thoroughwort	forb/ herb
		Eupatorium	*hyssopifolium*	hyssopleaf thoroughwort	forb/ herb
		Eupatorium	*rotundifolium*	roundleaf thoroughwort	forb/ herb
		Eupatorium	*serotinum*	lateflowering thoroughwort	forb/ herb
		Gamochaeta	*purpurea*	spoonleaf purple everlasting	forb/ herb
		Helianthus	*angustifolius*	swamp sunflower	forb/ herb
		Helianthus	*hirsutus*	hairy sunflower	forb/ herb
		Helianthus	*longifolius*	longleaf sunflower	forb/ herb
		Helianthus	*resinosus*	resindot sunflower	forb/ herb
		Hieracium	*gronovii*	queendevil	forb/ herb
		Ionactis	*linariifolius*	flaxleaf whitetop aster	forb/ herb
		Lactuca	*canadensis*	Canada lettuce	forb/ herb

A-3.5.35 (cont). Complete species list with functional group classifications from Fort Benning

Section	Family	Genus	species	Common name	Functional group
DICOTS					
	Asteraceae	*Lactuca*	*graminifolia*	grassleaf lettuce	forb/ herb
		Liatris	*elegans*	pinkscale blazing star	forb/ herb
		Liatris	*pilosa*	shaggy blazing star	forb/ herb
		Liatris	*spp*	blazing star	forb/ herb
		Liatris	*tenuifolia*	shortleaf blazing star	forb/ herb
		Pachera	*tomentosa*	woolly ragwort	forb/ herb
		Pityopsis	*aspera*	pineland silkgrass	forb/ herb
		Pityopsis	*graminifolia*	narrowleaf silkgrass	forb/ herb
		Pluchea	*camphorata*	camphor pluchea	forb/ herb
		Pseudognaphalium	*obtusifolium*	rabbit-tobacco	forb/ herb
		Rudbeckia	*hirta*	blackeyed Susan	forb/ herb
		Sericocarpus	*asteroides*	toothed whitetop aster	forb/ herb
		Sericocarpus	*tortifolius*	Dixie whitetop aster	forb/ herb
		Silphium	*compositum*	kidneyleaf rosinweed	forb/ herb
		Solidago	*altissima*	Canada goldenrod	forb/ herb
		Solidago	*nemoralis*	gray goldenrod	forb/ herb
		Solidago	*odora*	anisescented goldenrod	forb/ herb
		Solidago	*rugosa*	wrinkleleaf goldenrod	forb/ herb
		Solidago	*spp.*	goldenrod	forb/ herb
		Symphyotrichum	*concolor*	eastern silver aster	forb/ herb
		Symphyotrichum	*dumosum*	rice button aster	forb/ herb
		Symphyotrichum	*patens*	late purple aster	forb/ herb
		Vernonia	*angustifolia*	tall ironweed	forb/ herb
		Vernonia	*gigantea*	giant ironweed	forb/ herb
	Bignoniaceae	*Campsis*	*radicans*	trumpet creeper	woody vine/woody

A-3.5.35 (cont). Complete species list with functional group classifications from Fort Benning

Section	Family	Genus	species	Common name	Functional group
DICOTS					
	Buddlejaceae	*Polypremum*	*procumbens*	juniper leaf	forb/ herb
	Cactaceae	*Opuntia*	*humifusa*	devil's-tongue	woody/woody
	Campanulaceae	*Lobelia*	*puberula*	downy lobelia	forb/ herb
		Wahlenbergia	*marginata*	southern rockbell	forb/ herb
	Caprifoliaceae	*Lonicera*	*japonica*	Japanese honeysuckle	woody vine/woody
	Cistaceae	*Lechea*	*minor*	thymeleaf pinweed	forb/ herb
		Lechea	*mucronata*	hairy pinweed	forb/ herb
		Lechea	*sessiliflora*	pineland pinweed	forb/ herb
	Clusiaceae	*Hypericum*	*crux-andreae*	St. Peterswort	forb/ herb
		Hypericum	*hypericoides*	St. Andrew's cross	forb/ herb
		Hypericum	*gentianoides*	orangegrass	forb/ herb
	Convolvulaceae	*Ipomoea*	*pandurata*	man of the earth	forb/herb
		Jacquemontia	*tamnifolia*	hairy cluservine	forb/herb
		Stylisma	*patens*	coastal plain dawnflower	forb/herb
	Cornaceae	*Cornus*	*florida*	flowering dogwood	woody/woody
		Nyssa	*sylvatica*	blackgum	woody/woody
	Ebenaceae	*Diospyros*	*virginiana*	common persimmon	woody/woody

A-3.5.35 (cont). Complete species list with functional group classifications from Fort Benning

Section	Family	Genus	species	Common name	Functional group
DICOTS					
	Ericaceae	*Gaylussacia*	*dumosa*	dwarf huckleberry	woody/woody
		Vaccinium	*arboreum*	farkleberry	woody/woody
		Vaccinium	*myrsinites*	shiny blueberry	woody/woody
		Vaccinium	*spp.*	blueberry	woody/woody
		Vaccinium	*stamineum*	deerberry	woody/woody
		Vaccinium	*tenellum*	small black blueberry	woody/woody
	Euphorbiaceae	*Acalypha*	*gracilens*	slender threeseed mercury	forb/ herb
		Chamaesyce	*nutans*	eyebane	forb/ herb
		Cnidoscolus	*stimulosus*	finger rot	forb/ herb
		Croton	*glandulosus*	vente conmigo	forb/ herb
		Euphorbia	*pubentissima*	false flowering spurge	forb/ herb
		Tragia	*urens*	wavyleaf noseburn	forb/ herb
		Tragia	*urticifolia*	nettleleaf noseburn	forb/ herb
	Fabaceae	*Albizia*	*julibrissin*	silktree	woody/woody
		Centrosema	*virginiana*	spurred butterfly pea	forb/ herb
		Chamaecrista	*fasciculata*	partridge pea	forb/ herb
		Chamaecrista	*nictitans*	sensitive partridge pea	forb/ herb
		Clitoria	*mariana*	Atlantic pigeonwings	forb/ herb
		Crotalaria	*rotundifolia*	rabbitbells	forb/ herb
		Crotalaria	*purshii*	Pursh's rattlebox	forb/ herb
		Dalea	*carnea*	whitetassels	forb/ herb
		Dalea	*pinnata*	summer farewell	forb/ herb
		Desmodium	*obtusum*	stiff ticktrefoil	forb/ herb
		Desmodium	*ciliare*	hairy small-leaf ticktrefoil	forb/ herb
		Desmodium	*laevigatum*	smooth tricktrefoil	forb/ herb

A-3.5.35 (cont). Complete species list with functional group classifications from Fort Benning

Section	Family	Genus	species	Common name	Functional group
DICOTS					
	Fabaceae	*Desmodium*	*lineatum*	sand ticktrefoil	forb/ herb
		Desmodium	*marilandicum*	smooth small leaf ticktrefoil	forb/ herb
		Desmodium	*nuttallii*	Nuttail's ticktrefoil	forb/ herb
		Desmodium	*paniculatum*	panicledleaf ticktrefoil	forb/ herb
		Desmodium	*rotundifolium*	prostrate ticktrefoil	forb/ herb
		Desmodium	*spp.*	ticktrefoil	forb/ herb
		Desmodium	*strictum*	pine barren ticktrefoil	forb/ herb
		Desmodium	*viridiflorum*	velvetleaf ticktrefoil	forb/ herb
		Desmodium	*glabellum*	Dillenius' ticktrefoil	forb/ herb
		Galactia	*regularis*	eastern milkpea	forb/ herb
		Galactia	*volubilis*	downy milkpea	forb/ herb
		Kummerowia	*striata*	Japanese clover	forb/ herb
		Lespedeza	*angustifolia*	narrowleaf lespedeza	forb/ herb
		Lespedeza	*bicolor*	shrub lespedeza	forb/ herb
		Lespedeza	*capitata*	roundhead lespedeza	forb/ herb
		Lespedeza	*cuneata*	sericea lespedeza	forb/ herb
		Lespedeza	*hirta*	hairy lespedeza	forb/ herb
		Lespedeza	*procumbens*	trailing lespedeza	forb/ herb
		Lespedeza	*repens*	creeping lespedeza	forb/ herb
		Lespedeza	*stuevei*	tall lespedeza	forb/ herb
		Lespedeza	*virginica*	slender lespedeza	forb/ herb
		Mimosa	*quadrivalvis*	fourvalve mimosa	forb/ herb
		Phaseolus	*polystachois*	thicket bean	forb/ herb
		Pueraria	*montana*	kudzu	forb/ herb
		Rhynchosia	*reniformis*	dollarleaf	forb/ herb
		Rhynchosia	*tomentosa*	twining snoutbean	forb/ herb
		Strophostyles	*umbellata*	pink fuzzybean	forb/ herb

A-3.5.35 (cont). Complete species list with functional group classifications from Fort Benning

Section	Family	Genus	species	Common name	Functional group
<u>DICOTS</u>					
	Fabaceae	*Stylosanthes*	*biflora*	sidebeak pencilflower	forb/ herb
		Tephrosia	*florida*	Florida hoarypea	forb/ herb
		Tephrosia	*spicata*	spiked hoarypea	forb/ herb
		Tephrosia	*virginiana*	Virginia tephrosia	forb/ herb
	Fagaceae	*Quercus*	*falcata*	southern red oak	woody/woody
		Quercus	*hemisphaerica*	laural oak	woody/woody
		Quercus	*laevis*	turkey oak	woody/woody
		Quercus	*marilandica*	blackjack oak	woody/woody
		Quercus	*nigra*	water oak	woody/woody
		Quercus	*phellos*	willow oak	woody/woody
		Quercus	*spp.*	oak	woody/woody
		Quercus	*velutina*	black oak	woody/woody
		Quercus	*stellata*	post oak	woody/woody
	Hamamelidaceae	*Liquidambar*	*styraciflua*	sweetgum	woody/woody
	Hippocastanaceae	*Aesculus*	*pavia*	red buckeye	woody/woody
	Juglandaceae	*Carya*	*alba*	mockernut hickory	woody/woody
		Carya	*cordiformis*	butternut hickory	woody/woody
		Carya	*glabra*	pignut hickory	woody/woody
		Carya	*illinoinensis*	pecan	woody/woody
		Carya	*ovata*	shagbark hickory	woody/woody
	Lamiaceae	*Pycnanthemum*	*loomisii*	Loomis' mountainmint	forb/ herb
		Scutellaria	*elliptica*	hairy skullcap	forb/ herb

A-3.5.35 (cont). Complete species list with functional group classifications from Fort Benning

Section	Family	Genus	species	Common name	Functional group
<u>DICOTS</u>					
	Lamiaceae	*Scutellaria*	*integrifolia*	helmet flower	forb/ herb
		Trichostema	*dichotomum*	forked bluecurls	forb/ herb
		Trichostema	*setaceum*	narrowleaf bluecurls	forb/ herb
	Lauraceae	*Sassafras*	*albidum*	sassafras	woody/woody
	Linaceae	*Linum*	*medium*	stiff yellow flax	forb/ herb
	Loganiaceae	*Gelsemium*	*sempervirens*	evening trumpetflower	woody vine/woody
	Malvaceae	*Sida*	*elliottii*	Elliott's fanpetals	forb/ herb
	Melastomataceae	*Rhexia*	*mariana*	Maryland meadowbeauty	forb/ herb
	Meliaceae	*Melia*	*azedarach*	Chinaberrytree	woody/woody
	Myricaceae	*Morella*	*cerifera*	wax myrtle	woody/woody
	Onagraceae	*Gaura*	*filipes*	slenderstalk beeblossom	forb/ herb
		Oenothera	*biennis*	common evening primrose	forb/ herb
	Oxalidaceae	*Oxalis*	*spp.*	woodsorrel	
		Oxalis	*stricta*	common yellow oxalis	forb/ herb
	Passifloraceae	*Passiflora*	*incarnata*	purple passionflower	forb/ herb
	Polygalaceae	*Polygala*	*mariana*	Maryland milkwort	forb/ herb

A-3.5.35 (cont). Complete species list with functional group classifications from Fort Benning

Section	Family	Genus	species	Common name	Functional group
DICOTS					
	Polygalaceae	*Polygala*	*nana*	candyroot	forb/ herb
		Eriogonum	*tomentosum*	dogtongue buckwheat	forb/ herb
	Rosaceae	*Crataegus*	*flava*	yellowleaf hawthorn	woody/woody
		Crataegus	*spathulata*	Littlehip hawthorn	woody/woody
		Crataegus	*spp.*	hawthorn	woody/woody
		Prunus	*angustifolia*	Chickasaw plum	woody/woody
		Prunus	*serotina*	black cherry	woody/woody
		Rubus	*argutus*	sawtooth blackberry	woody/woody
		Rubus	*cuneifolius*	sand blackberry	woody/woody
		Rubus	*flagellaris*	northern dewberry	woody/woody
		Rubus	*trivialis*	southern dewberry	woody/woody
	Rubiaceae	*Diodia*	*teres*	poorjoe	forb/ herb
		Galium	*hispidulum*	coastal bedstraw	forb/herb
		Galium	*pilosum*	hairy bedstraw	forb/ herb
		Galium	*uniflorum*	oneflower bedstraw	forb/ herb
		Mitchella	*repens*	partridgeberry	forb/ herb
	Scrophulariaceae	*Agalinis*	*fasciculata*	beach false foxglove	forb/ herb
		Agalinis	*purpurea*	purple false foxglove	forb/ herb
		Aureolaris	*virginica*	downy yellow false foxglove	forb/ herb
		Nuttallanthus	*canadensis*	Canada toadflax	forb/ herb
		Penstemon	*australis*	Eustis Lake beardtongue	forb/ herb
		Seymeria	*cassioides*	yaupon blacksenna	forb/ herb

A-3.5.35 (cont). Complete species list with functional group classifications from Fort Benning

Section	Family	Genus	species	Common name	Functional group
DICOTS					
	Solanaceae	*Solanum*	*carolinense*	Carolina horsenettle	forb/ herb
	Ulmaceae	*Celtis*	*laevigata*	sugarberry	woody/woody
		Ulmus	*alata*	winged elm	woody/woody
		Ulmus	*rubra*	slippery elm	woody/woody
	Verbenaceae	*Callicarpa*	*americana*	American beautyberry	forb/ herb
		Verbena	*brasiliensis*	Brazilian vervain	forb/ herb
	Violaceae	*Viola*	*pedata*	birdfoot violet	forb/ herb
	Vitaceae	*Ampelopsis*	*arborea*	peppervine	woody vine/woody
		Parthenocissus	*quinquefolia*	Virginia creeper	woody vine/woody
		Vitis	*rotundifolia*	muscadine	woody vine/woody
ANGIOSPERMS	Agavaceae	*Manfreda*	*virginica*	false aloe	forb/herb
MONOCOTS		*Yucca*	*filamentosa*	Adam's needle	forb/herb
	Cyperaceae	*Bulbostylis*	*capillaris*	densetuft hairsedge	graminoid
		Bulbostylis	*ciliatifolia*	capillary hairsedge	graminoid
		Cyperus	*odoratus*	fragrant flatsedge	graminoid
		Cyperus	*plukenetii*	Plukenet's flatsedge	graminoid
		Cyperus	*spp.*	flatsedge	
		Cyperus	*strigosus*	strawcolored flatsedge	graminoid
		Rhynchospora	*harveyi*	Harvey's beaksedge	graminoid

A-3.5.35 (cont). Complete species list with functional group classifications from Fort Benning

Section	Family	Genus	species	Common name	Functional group
MONOCOTS					
	Cyperaceae	*Rhynchospora*	*rariflora*	fewflower beaksedge	graminoid
		Rhynchospora	*spp.*	beaksedge	
		Scleria	*ciliata*	fringed nutrush	graminoid
		Scleria	*pauciflora*	fewflower nutrush	graminoid
		Scleria	*spp.*	nutrush	
		Scleria	*triglomerata*	whip nutrush	graminoid
	Juncaceae	*Juncus*	*spp.*	rush	graminoid
	Liliaceae	*Aletris*	*farinosa*	white colicroot	forb/ herb
	Orchidaceae	*Spiranthes*	*praecox*	greenvein lady's tresses	forb/ herb
	Poaceae	*Andropogon*	*glomeratus*	bushy bluestem	graminoid/herb
		Andropogon	*ternarius*	splitbeard bluestem	graminoid/herb
		Andropogon	*virginicus*	broomsedge bluestem	graminoid/herb
		Aristida	*dichotoma*	churchmouse threeawn	graminoid/herb
		Aristida	*gyrans*	corkscrew threeawn	graminoid/herb
		Aristida	*lanosa*	woolysheath threeawn	graminoid/herb
		Aristida	*longespica*	slimspike threeawn	graminoid/herb
		Aristida	*oligantha*	prairie threeawn	graminoid/herb
		Aristida	*purpurascens*	arrowfeather threeawn	graminoid/herb
		Aristida	*spp.*		graminoid/herb
		Chasmanthium	*laxum*	slender woodoats	graminoid/herb
		Chasmanthium	*sessiliflorum*	longleaf woodoats	graminoid/herb
		Danthonia	*sericea*	downy danthonia	graminoid/herb
		Dichanthelium	*dichotomum*	cypress panicgrass	graminoid/herb

A-3.5.35 (cont). Complete species list with functional group classifications from Fort Benning

Section	Family	Genus	species	Common name	Functional group
<u>MONOCOTS</u>					
	Poaceae	*Dichanthelium*	*aciculare*	needleleaf rosette grass	graminoid/herb
		Dichanthelium	*acuminatum*	tapered rosette grass	graminoid/herb
		Dichanthelium	*boscii*	Bosc’s panicgrass	graminoid/herb
		Dichanthelium	*laxiflorum*	openflower rosette grass	graminoid/herb
		Dichanthelium	*oligosanthes*	Heller's rosette grass	graminoid/herb
		Dichanthelium	*ravenelii*	Ravenel's rosette grass	graminoid/herb
		Dichanthelium	*scoparium*	velvet panicum	graminoid/herb
		Dichanthelium	*sphaerocarpon*	roundseed panicgrass	graminoid/herb
		Dichanthelium	*spp.*	rosette grass	graminoid/herb
		Dichanthelium	*strigosum*	roughair rosette grass	graminoid/herb
		Digitaria	*violascens*	violet crabgrass	graminoid/herb
		Digitaria	*ciliaris*	southern crabgrass	graminoid/herb
		Digitaria	*spp.*	crabgrass	graminoid/herb
		Digitaria	*villosa*	shaggy crabgrass	graminoid/herb
		Eragrostis	*curvula*	weeping lovegrass	graminoid/herb
		Eragrostis	*hirsuta*	bigtop lovegrass	graminoid/herb
		Eragrostis	*spectabilis*	purple lovegrass	graminoid/herb
		Eragrostis	*spp.*	lovegrass	graminoid/herb
		Gymnopogon	*ambiguus*	bearded skeletongrass	graminoid/herb
		Gymnopogon	*spp.*	skeletongrass	graminoid/herb
		Panicum	*anceps*	beaked panicgrass	graminoid/herb
		Panicum	*verrucosum*	warty panicgrass	graminoid/herb
		Paspalum	*laeve*	field paspalum	graminoid/herb
		Paspalum	*notatum*	bahiagrass	graminoid/herb
		Paspalum	*setaceum*	thin paspalum	graminoid/herb
		Paspalum	*urvillei*	Vasey's grass	graminoid/herb
		Saccharum	*alopecuroides*	silver plumegrass	graminoid/herb

A-3.5.35 (cont). Complete species list with functional group classifications from Fort Benning

Section	Family	Genus	species	Common name	Functional group
<u>MONOCOTS</u>					
	Poaceae	*Saccharum*	*giganteium*	sugercane plumegrass	graminoid/herb
		Saccharum	*spp.*	sugercane	graminoid/herb
		Schizachyrium	*scoparium*	little bluestem	graminoid/herb
		Setaria	*parviflora*	marsh bristlegrass	graminoid/herb
		Setaria	*pumila*	yellow foxtail	graminoid/herb
		Sorghastrum	*elliottii*	slender Indiangrass	graminoid/herb
		Sorghastrum	*nutans*	Indiangrass	graminoid/herb
		Sorghastrum	*secundum*	lopsided Indiangrass	graminoid/herb
		Sorghum	*halepense*	Johnsongrass	graminoid/herb
		Tridens	*flavus*	purpletop tridens	graminoid/herb
	Smilacaceae	*Smilax*	*bona-nox*	saw greenbrier	woody vine/woody
		Smilax	*glauca*	cat greenbrier	woody vine/woody
		Smilax	*laurifolia*	laurel greenbrier	woody vine/woody
		Smilax	*rotundifolia*	roundleaf greenbrier	woody vine/woody

A-3.5.36. Complete species list with functional group classifications from Camp Lejeune

Section	Family	Genus	species	Common name	Functional group
PTERIDOPHYTES					
	Blechnaceae	*Woodwardia*	*virginica*	Virginia chainfern	fern/herb
	Dennstaedtiaceae	*Pteridium*	*aquilinum*	western brackenfern	fern/herb
	Osmundaceae	*Osmunda*	*cinnamomea*	cinnamon fern	fern/herb
		Osmunda	*regalis*	royal fern	fern/herb
GYMNOSPERMS					
	Cupressaceae	*Juniperus*	*virginiana*	eastern redcedar	woody/woody
	Pinaceae	*Pinus*	*palustris*	longleaf pine	woody/woody
		Pinus	*taeda*	loblolly pine	woody/woody
ANGIOSPERMS DICOTS					
	Aceraceae	Acer	rubrum	red maple	woody/woody
	Anacardiaceae	*Rhus*	*copallinum*	winged sumac	woody/woody
		Toxicodendron	*radicans*	eastern poison ivy	woody vine/woody
	Apiaceae	*Centella*	*erecta*	erect centella	forb/herb
	Aquifoliaceae	*Ilex*	*opaca*	American holly	woody/woody
	Araliaceae	*Aralia*	*spinosa*	devil's walkingstick	woody/woody
	Asteraceae	Ageratina	aromatica	lesser snakeroot	forb/herb

A-3.5.36 (cont). Complete species list with functional group classifications from Camp Lejeune

Section	Family	Genus	species	Common name	Functional group
DICOTS					
	Asteraceae	*Baccharis*	*halimifolia*	eastern baccharis	forb/herb
		Cirsium	*horridulum*	yellow thistle	forb/herb
		Conyza	*canadensis*	Canadian horseweed	forb/herb
		Elephantopus	*carolinianus*	Carolina elephantsfoot	forb/herb
		Elephantopus	*tomentosus*	devil's grandmother	forb/herb
		Erechtites	*hieracifolia*	eastern fireweed	forb/herb
		Eupatorium	*album*	white thoroughwort	forb/herb
		Eupatorium	*capillifolium*	dogfennel	forb/herb
		Eupatorium	*hyssopifolium*	hyssopleaf thoroughwort	forb/herb
		Eupatorium	*leucolepis*	justiceweed	forb/herb
		Eupatorium	*mohrii*	Mohr's thoroughwort	forb/herb
		Eupatorium	*pilosum*	rough boneset	forb/herb
		Eupatorium	*rotundifolium*	roundleaf thoroughwort	forb/herb
		Euthamia	*caroliniana*	slender goldentop	forb/herb
		Hieracium	*gronovii*	queendevil	forb/herb
		Lactuca	*graminifolia*	grassleaf lettuce	forb/herb
		Packera	*anonyma*	Small's ragwort	forb/herb
		Pityopsis	*graminifolia*	narrowleaf silkgrass	forb/herb
		Pluchea	*foetida var. foetida*	stinking camphorweed	forb/herb
		Pseudognaphalium	*obtusifolium*	rabbit-tobacco	forb/herb
		Solidago	*arguta var. caroliniana*	Atlantic goldennod	forb/herb
		Solidago	*canadensis*	Canada goldenrod	forb/herb
		Solidago	*fistulosa*	pine barren goldenrod	forb/herb
		Solidago	*odora*	anisescented goldenrod	forb/herb
		Solidago	*puberula var. pulverulenta*	downy goldenrod	forb/herb
		Solidago	*rugosa*	wrinkleleaf goldenrod	forb/herb
		Solidago	*ulmifolia*	elmleaf goldenrod	forb/herb

A-3.5.36 (cont). Complete species list with functional group classifications from Camp Lejeune

Section	Family	Genus	species	Common name	Functional group
DICOTS					
	Asteraceae	*Symphyotrichum*	*dumosum var. dumosum*	rice button aster	forb/herb
	Bignoniaceae	*Bignonia*	*capreolata*	crossvine	woody vine/woody
		Campsis	*radicans*	trumpet creeper	woody vine/woody
	Buddlejaceae	*Polypremum*	*procumbens*	juniper leaf	forb/herb
	Campanulaceae	*Lobelia*	*nuttallii*	Nuttall's lobelia	forb/herb
		Lobelia	*puberula*	blue lobelia	forb/herb
	Caprifoliaceae	*Lonicera*	*sempervirens*	trumpet honeysuckle	woody vine/woody
	Cistaceae	*Lechea*	*mucronata*	hairy pinweed	forb/herb
	Clethraceae	*Clethra*	*alnifolia*	coastal sweetpepperbush	woody/woody
	Clusiaceae	*Hypericum*	*gentianoides*	orangegrass	forb/herb
		Hypericum	*hypericoides*	St. Andrew's-cross	woody/woody
	Convolvulaceae	*Ipomoea*	*pandurata*	man of the earth	forb/herb
	Cornaceae	*Cornus*	*florida*	flowering dogwood	woody/woody
		Nyssa	*sylvatica*	blackgum	woody/woody
	Ebenaceae	*Diospyros*	*virginiana*	common persimmon	woody/woody
	Ericaceae	*Gaylussacia*	*dumosa*	dwarf huckleberry	woody/woody

A-3.5.36 (cont). Complete species list with functional group classifications from Camp Lejeune

Section	Family	Genus	species	Common name	Functional group
<u>DICOTS</u>					
	Ericaceae	*Gaylussacia*	*frondosa*	blue huckleberry	woody/woody
		Lyonia	*ligustrina*	maleberry	woody/woody
		Lyonia	*lucida*	fetterbush lyonia	woody/woody
		Oxydendrum	*arboreum*	sourwood	woody/woody
		Rhododendron	*periclymenoides*	pink azalea	woody/woody
		Vaccinium	*arboreum*	farkleberry	woody/woody
		Vaccinium	*fuscatum*	black highbush blueberry	woody/woody
		Vaccinium	*pallidum*	Blue Ridge blueberry	woody/woody
		Vaccinium	*stamineum*	deerberry	woody/woody
		Vaccinium	*tenellum*	small black blueberry	woody/woody
	Euphorbiaceae	Acalypha	gracilens	slender copperleaf	forb/herb
		Chamaesyce	*maculata*	spotted sandmat	forb/herb
		Cnidoscolus	*urens var. stimulosus*	finger rot	forb/herb
		Tragia	*urens*	wavyleaf noseburn	forb/herb
	Fabaceae	*Centrosema*	*virginianum*	spurred butterfly pea	forb/herb
		Chamaecrista	*nictitans*	sensitive partridge pea	forb/herb
		Desmodium	*ciliare*	hairy small-leaf ticktrefoil	forb/herb
		Desmodium	*laevigatum*	smooth tichtrefoil	forb/herb
		Desmodium	*lineatum*	sand ticktrefoil	forb/herb
		Desmodium	*nuttallii*	Nuttall's ticktrefoil	forb/herb
		Desmodium	*paniculatum*	panicledleaf ticktrefoil	forb/herb
		Lespedeza	*capitata*	roundhead lespedeza	forb/herb
		Lespedeza	*cuneata*	sericea lespedeza	forb/herb
		Lespedeza	*frutescens*	shrubby lespedeza	forb/herb
		Lespedeza	*hirta*	hairy lespedeza	forb/herb

A-3.5.36 (cont). Complete species list with functional group classifications from Camp Lejeune

Section	Family	Genus	species	Common name	Functional group
DICOTS					
	Fabaceae	*Lespedeza*	*repens*	creeping lespedeza	forb/herb
		Lespedeza	*virginica*	slender lespedeza	forb/herb
		Mimosa	*microphylla*	littleleaf sensitive-briar	forb/herb
	Fagaceae	*Quercus*	*alba*	white oak	woody/woody
		Quercus	*hemisphaerica*	Darlington oak	woody/woody
		Quercus	*margarettae*	runner oak	woody/woody
		Quercus	*marilandica*	blackjack oak	woody/woody
		Quercus	*michauxii*	swamp chestnut oak	woody/woody
		Quercus	*nigra*	water oak	woody/woody
		Quercus	*virginiana*	live oak	woody/woody
	Grossulariaceae	*Itea*	*virginica*	Virginia sweetspire	woody/woody
	Hamamelidaceae	*Liquidambar*	*styraciflua*	sweetgum	woody/woody
	Juglandaceae	*Carya*	*glabra*	pignut hickory	woody/woody
		Carya	*pallida*	sand hickory	woody/woody
	Lamiaceae	*Pycnanthemum*	*flexuosum*	Appalachian mountainmint	forb/herb
		Scutellaria	*integrifolia*	helmet flower	forb/herb
	Lauraceae	*Persea*	*borbonia*	red bay	woody/woody
		Sassafras	*albidum*	sassafras	woody/woody
	Loganiaceae	*Gelsemium*	*sempervirens*	Carolina jessamine	woody vine/woody
		Mitreola	*sessilifolia*	swamp hornpod	forb/herb

A-3.5.36 (cont). Complete species list with functional group classifications from Camp Lejeune

Section	Family	Genus	species	Common name	Functional group
DICOTS					
	Lythraceae	*Cuphea*	*carthagenensis*	Colombian waxweed	forb/herb
	Magnoliaceae	*Liriodendron*	*tulipifera*	yellow-popar	woody/woody
		Magnolia	*virginiana*	sweetbay	woody/woody
	Melastomataceae	*Rhexia*	*mariana*	Maryland meadowbeauty	forb/herb
	Myricaceae	*Morella*	*caroliniensis*	southern bayberry	woody/woody
		Morella	*cerifera*	waxmytle	woody/woody
	Onagraceae	*Ludwigia*	*alternifolia*	seedbox	forb/herb
		Ludwigia	*maritima*	seaside primrose-willow	forb/herb
		Ludwigia	*virgata*	savannah primrose-willow	forb/herb
	Oxalidaceae	*Oxalis*	*stricta*	yellow woodsorrel	forb/herb
	Passifloraceae	*Passiflora*	*incarnata*	purple passionflower	forb/herb
		Passiflora	*lutea*	yellow passionflower	forb/herb
	Phytolaccaceae	*Phytolacca*	*americana*	American pokeweed	forb/herb
	Rhamnaceae	*Berchemia*	*scandens*	Alabama supplejack	woody vine/woody
	Rosaceae	*Photinia*	*pyrifolia*	red chokeberry	woody/woody
		Prunus	*serotina*	black cherry	woody/woody
		Rubus	*spp.*	blackberry	woody/woody

A-3.5.36 (cont). Complete species list with functional group classifications from Camp Lejeune

Section	Family	Genus	species	Common name	Functional group
DICOTS					
	Rubiaceae	*Diodia*	*teres*	poorjoe	forb/herb
		Mitchella	*repens*	partridgeberry	forb/herb
		Oldenlandia	*uniflora*	clustered mille graines	forb/herb
	Scrophulariaceae	*Gratiola*	*pilosa*	shaggy hedgehyssop	forb/herb
	Symplocaceae	*Symplocos*	*tinctoria*	common sweetleaf	woody/woody
	Verbenaceae	*Callicarpa*	*americana*	American beautyberry	woody/woody
	Violaceae	*Viola*	*lanceolata*	bog white violet	forb/herb
	Vitaceae	*Parthenocissus*	*quinquefolia*	Virginia creeper	woody vine/woody
		Vitis	*aestivalis*	summer grape	woody vine/woody
		Vitis	*cinerea var. baileyana*	graybark grape	woody vine/woody
		Vitis	*rotundifolia*	muscadine grape	woody vine/woody
MONOCOTS					
	Cyperaceae	*Bulbostylis*	*stenophylla*	sandy field hairsedge	graminoid/herb
		Carex	*glaucescens*	southern waxy sedge	graminoid/herb
		Cyperus	*grayi*	Gray's flatsedge	graminoid/herb
		Cyperus	*plukenetii*	Plukenet's flatsedge	graminoid/herb
		Rhynchospora	*glomerata*	clustered beaksedge	graminoid/herb
		Rhynchospora	*inexpansa*	nodding beaksedge	graminoid/herb
		Rhynchospora	*microcephala*	smallhead beaksedge	graminoid/herb
	Iridaceae	*Iris*	*verna*	dwarf violet iris	forb/herb

A-3.5.36 (cont). Complete species list with functional group classifications from Camp Lejeune

Section	Family	Genus	species	Common name	Functional group
MONOCOTS					
	Juncaceae	*Juncus*	*dichotomus*	forked rush	graminoid/herb
		Juncus	*marginatus*	grassleaf rush	graminoid/herb
	Poaceae	*Andropogon*	*capillipes*	chalky bluestem	graminoid/herb
		Andropogon	*glaucopsis*	purple bluestem	graminoid/herb
		Andropogon	*virginicus*	broomsedge bluestem	graminoid/herb
		Aristida	*palustris*	longleaf threeawn	graminoid/herb
		Arthraxon	*hispidus*	small carpgrass	graminoid/herb
		Arundinaria	*gigantea*	giant cane	graminoid/herb
		Chasmanthium	*sessiliflorum*	longleaf woodoats	graminoid/herb
		Danthonia	*sericea*	downy danthonia	graminoid/herb
		Dichanthelium	*aciculare*	needleleaf rosette grass	graminoid/herb
		Dichanthelium	*acuminatum*	tapered rosette grass	graminoid/herb
		Dichanthelium	*commutatum*	variable panicgrass	graminoid/herb
		Dichanthelium	*consanguineum*	blood panicgrass	graminoid/herb
		Dichanthelium	*laxiflorum*	openflower rosette grass	graminoid/herb
		Dichanthelium	*ovale var. ovale*	eggleaf rosette grass	graminoid/herb
		Dichanthelium	*sabulorum var. patulum*	hemlock rosette grass	graminoid/herb
		Dichanthelium	*scoparium*	velvet panicum	graminoid/herb
		Dichanthelium	*sphaerocarpon*	roundseed panicgrass	graminoid/herb
		Digitaria	*ciliaris*	southern crabgrass	graminoid/herb
		Digitaria	*ischaemum*	smooth crabgrass	graminoid/herb
		Digitaria	*sanguinalis*	hairy crabgrass	graminoid/herb
		Eragrostis	*refracta*	coastal lovegrass	graminoid/herb
		Gymnopogon	*ambiguus*	bearded skeletongrass	graminoid/herb
		Panicum	*anceps*	beaked panicgrass	graminoid/herb
		Panicum	*verrucosum*	warty panicgrass	graminoid/herb

A-3.5.36 (cont). Complete species list with functional group classifications from Camp Lejeune

Section	Family	Genus	species	Common name	Functional group
MONOCOTS					
	Poaceae	*Paspalum*	*setaceum*	thin paspalum	graminoid/herb
		Paspalum	*urvillei*	Vasey's grass	graminoid/herb
		Saccharum	*giganteum*	sugarcane plumegrass	graminoid/herb
		Sorghum	*halepense*	johnsongrass	graminoid/herb
		Tridens	*flavus*	purpletop tridens	graminoid/herb
	Smilacaceae	*Smilax*	*bona-nox*	saw greenbrier	woody vine/woody
		Smilax	*glauca*	cat greenbrier	woody vine/woody
		Smilax	*laurifolia*	laurel greenbrier	woody vine/woody
		Smilax	*rotundifolia*	roundleaf greenbrier	woody vine/woody

A-3.8.1. Foliar nutrient concentrations of longleaf pine seedlings by main-plot and split-plot treatment in 2009 at Fort Benning and Camp Lejeune. Different letters indicate significant treatment differences for each nutrient and treatment

2009

Site	Effect	Treatment	Ca (%)	Mg (%)	S (%)	Zn (ppm)	Cu (ppm)	Mn (ppm)	Fe (ppm)	Na (ppm)
Fort Benning	Main plot	Control	0.121^{b}	0.090^{a}	0.076	34.2^{b}	3.3	347.1	46.1	35.1
		MedBA	0.131^{b}	0.082^{b}	0.077	38.1^{ab}	3.6	374.7	45.6	31.5
		LowBA	0.134^{b}	0.078^{b}	0.072	40.2^{a}	3.7	289.4	58.5	27.8
		Clearcut	0.172^{a}	0.081^{b}	0.083	41.2^{a}	3.6	386.8	39.8	30.1
		p-value	**0.0017**	**0.0036**	**0.0775**	**0.0488**	**0.2837**	**0.1881**	**0.3427**	**0.3470**
	Sub plot	NT	0.142	0.085	0.075	37.8	3.4	355.6	40.1	31.7
		H	0.140	0.083	0.080	39.9	3.6	329.4	51.8	30.5
		H+F	0.136	0.080	0.076	37.5	3.5	363.5	50.5	31.2
		p-value	**0.5917**	**0.0613**	**0.2166**	**0.2689**	**0.5318**	**0.4832**	**0.2317**	**0.8693**
Camp Lejeune	Main plot	Control	0.100^{a}	0.082	0.069	37.1^{b}	3.7	160.3^{b}	28.0	92.7^{a}
		MedBA	0.103^{b}	0.084	0.072	38.9b	3.8	155.6^{b}	26.7	72.0^{ab}
		LowBA	0.117^{ab}	0.089	0.072	41.7^{ab}	3.8	160.6^{b}	25.3	84.3^{ab}
		Clearcut	0.132^{a}	0.090	0.073	44.2^{a}	3.9	221.9^{a}	27.2	63.5^{b}
		p-value	**<0.0001**	**0.0586**	**0.4382**	**0.0033**	**0.3891**	**0.0143**	**0.3710**	**0.0203**
	Sub plot	NT	0.110	0.086	0.069^{b}	38.8	3.5^{b}	165.3	27.6	83.7
		H	0.114	0.085	0.071^{ab}	42.3	3.8^{ab}	178.4	25.7	72.6
		H+F	0.115	0.088	0.074^{a}	40.3	4.0^{a}	180.1	27.1	78.0
		p-value	**0.7060**	**0.5338**	**0.0316**	**0.1297**	**0.0261**	**0.5225**	**0.3283**	**0.0820**

A-3.8.2. Foliar nutrient concentrations of longleaf pine seedlings by main-plot and split-plot treatment in 2010 at Fort Benning and Camp Lejeune. Different letters indicate significant treatment differences for each nutrient and treatment

2010

Site	Effect	Treatment	Ca (%)	Mg (%)	S (%)	Zn (ppm)	Cu (ppm)	Mn (ppm)	Fe (ppm)	Na (ppm)
Fort Benning	Main plot	Control	0.148[b]	0.102	0.084	29.9	2.3[b]	323.8	47.1	23.5
		MedBA	0.164[ab]	0.098	0.086	35.8	2.8[b]	376.2	49.0	20.1
		LowBA	0.169[ab]	0.094	0.081	35.7	2.6[b]	242.1	45.1	22.5
		Clearcut	0.197[a]	0.088	0.088	37.8	3.9[a]	315.6	41.6	24.1
		p-value	**0.0122**	**0.0655**	**0.5607**	**0.1066**	**0.0003**	**0.0688**	**0.5490**	**0.6680**
	Sub plot	NT	0.166	0.095	0.087	33.3[b]	2.8	321.3	44.3	22.2
		H	0.175	0.100	0.084	37.2[a]	3.0	311.0	48.4	23.8
		H+F	0.166	0.093	0.083	33.4[ab]	2.9	315.2	44.4	21.1
		p-value	**0.4651**	**0.3532**	**0.2210**	**0.0302**	**0.7945**	**0.9250**	**0.4230**	**0.4585**
Camp Lejeune	Main plot	Control	0.147[b]	0.110	0.079[a]	45.4	3.3	219.3	33.2	71.9[a]
		MedBA	0.161[ab]	0.112	0.072[ab]	45.8	3.3	218.8	30.8	66.8[ab]
		LowBA	0.156[ab]	0.119	0.073[ab]	50.9	3.7	187.9	27.9	58.1[ab]
		Clearcut	0.185[a]	0.118	0.070[b]	51.8	3.5	239.4	28.3	48.0[b]
		p-value	**0.0152**	**0.2098**	**0.0146**	**0.1664**	**0.1166**	**0.3312**	**0.3608**	**0.0224**
	Sub plot	NT	0.166	0.117	0.073	48.6	3.4	218.4	29.8	67.6[a]
		H	0.162	0.113	0.075	49.2	3.6	217.3	29.8	59.8[ab]
		H+F	0.159	0.113	0.073	46.7	3.3	214.2	30.5	56.5[b]
		p-value	**0.7024**	**0.3983**	**0.5315**	**0.5081**	**0.1353**	**0.9855**	**0.6542**	**0.0355**

A-3.8.3. Foliar nutrient concentrations of longleaf pine seedlings by gap position and gap direction in 2009 at Fort Benning and Camp Lejeune. Different letters indicate significant treatment differences for each nutrient and treatment

2009

Site	Position	Treatment	Ca (%)	Mg (%)	S (%)	Zn (ppm)	Cu (ppm)	Mn (ppm)	Fe (ppm)	Na (ppm)
Fort	South	-10	0.135	0.092	0.073	39.2	3.2	366.7	46.8	47.8
Benning	Forest edge	0	0.130	0.082	0.070	38.0	3.3	373.7	44.3	28.7
		20	0.155	0.080	0.075	40.2	3.0	499.3	42.7	36.2
	Gap center	40	0.155	0.083	0.078	39.5	3.2	432.2	43.8	25.5
		20	0.163	0.087	0.078	47.7	3.7	417.0	55.0	31.2
	Forest edge	0	0.152	0.087	0.075	40.7	2.8	416.8	42.0	25.3
	North	-10	0.146	0.084	0.076	38.0	3.2	471.8	40.0	38.6
		p-value	**0.2242**	**0.7732**	**0.8454**	**0.1090**	**0.2616**	**0.3175**	**0.8402**	**0.1976**
	Direction	South	0.140	0.084	0.073	39.1	3.2	413.2	44.6	37.6
		North	0.154	0.086	0.076	42.4	3.2	433.1	46.0	31.3
		p-value	**0.1332**	**0.6326**	**0.3403**	**0.1972**	**0.8354**	**0.7957**	**0.6663**	**0.3159**
Camp	South	-10	0.105	0.085	0.073	38.5	3.5	137.2	26.3	115.3[a]
Lejeune	Forest edge	0	0.110	0.088	0.070	39.7	3.7	145.7	27.5	103.3[ab]
		20	0.122	0.098	0.075	46.3	3.8	169.3	26.7	63.2[ab]
	Gap center	40	0.123	0.087	0.067	43.3	3.5	150.8	26.7	53.5[b]
		20	0.113	0.083	0.068	41.2	3.3	156.8	24.7	53.5[b]
	Forest edge	0	0.113	0.083	0.073	36.0	3.3	147.8	23.5	72.3[ab]
	North	-10	0.097	0.083	0.068	35.2	3.3	114.3	25.3	87.8[ab]
		p-value	**0.3641**	**0.3393**	**0.4531**	**0.4559**	**0.7550**	**0.7020**	**0.9102**	**0.0072**
	Direction	South	0.112	0.091[a]	0.073	41.5	3.7	150.7	26.8	93.9
		North	0.108	0.083[b]	0.070	37.4	3.3	139.7	24.5	71.2
		p-value	**0.5372**	**0.0700**	**0.2963**	**0.1265**	**0.0510**	**0.5272**	**0.2399**	**0.0877**

A-3.8.4. Foliar nutrient concentrations of longleaf pine seedlings by gap position and gap direction in 2010 at Fort Benning and Camp Lejeune. Different letters indicate significant treatment differences for each nutrient and treatment

2010

Site	Effect	Treatment	Ca (%)	Mg (%)	S (%)	Zn (ppm)	Cu (ppm)	Mn (ppm)	Fe (ppm)	Na (ppm)
Fort	South	-10	0.156[ab]	0.114	0.088	41.2	3.0	433.8	39.6	18.8
Benning	Forest edge	0	0.158[ab]	0.088	0.076	45.0	4.4	466.0	36.6	18.8
		20	0.184[ab]	0.088	0.078	33.8	3.0	400.8	30.6	20.0
	Gap center	40	0.182[ab]	0.086	0.086	38.8	2.8	404.4	35.4	25.8
		20	0.210[a]	0.098	0.084	39.2	3.4	515.0	31.6	19.2
	Forest edge	0	0.170[ab]	0.100	0.086	31.8	3.0	423.4	38.8	19.2
	North	-10	0.154[b]	0.092	0.084	31.6	2.8	471.8	39.8	22.2
		p-value	**0.0376**	**0.4466**	**0.6624**	**0.5284**	**0.6451**	**0.8281**	**0.1726**	**0.8245**
	Direction	South	0.166	0.097	0.081	40.0	3.5	433.5	35.6	19.2
		North	0.178	0.097	0.085	34.2	3.1	470.1	36.7	20.2
		p-value	**0.3403**	**1.0000**	**0.3787**	**0.1885**	**0.4603**	**0.4655**	**0.6762**	**0.5567**
Camp	South	-10	0.166	0.114	0.086[a]	45.2	3.8	198.4	32.0	85.6
Lejeune	Forest edge	0	0.162	0.112	0.08[ab]	47.2	4.0	170.2	29.6	66.4
		20	0.156	0.120	0.064[b]	51.2	3.0	164.8	27.4	50.8
	Gap center	40	0.160	0.110	0.068[ab]	46.2	3.2	201.6	31.0	50.4
		20	0.156	0.112	0.066[b]	53.2	3.6	149.6	27.0	45.0
	Forest edge	0	0.166	0.118	0.078[ab]	46.2	3.6	182.2	35.2	89.0
	North	-10	0.172	0.112	0.082[ab]	50.4	3.4	185.2	38.2	151.2
		p-value	**0.9592**	**0.9577**	**0.0039**	**0.7116**	**0.1287**	**0.8101**	**0.7939**	**0.3976**
	Direction	South	0.161	0.115	0.077	47.9	3.6	177.8	29.7	67.6
		North	0.165	0.114	0.075	49.9	3.5	172.3	33.5	95.1
		p-value	**0.7406**	**0.8066**	**0.7706**	**0.5147**	**0.7775**	**0.7856**	**0.4387**	**0.3920**

A-3.9.1. Pre-fire (first line) and fuel consumption (second line) measurements (mean|*SE*) for main and split-plots treatments at Fort Benning, GA. Different letters within a row indicate significant treatment differences at α = 0.05. Note: fuel consumption measured as pre-fire - post-fire.

	Main Plot Treatment								**ANOVA**		**Sub-Plot Treatment**						**ANOVA**		**Main*Sub ANOVA**	
Fuel	Clearcut		LowBA		MedBA		Control		F-value	p-value	H+F		H		NT		F-value	p-value	F-value	p-value
1-hour (Mgha^{-1})	0.090	*0.025*	0.105	*0.034*	0.147	*0.029*	0.234	*0.099*	2.12	0.1399	0.150	*0.044*	0.154	*0.035*	0.128	*0.033*	1.47	0.2415	1.02	0.4292
	-0.085	*0.043*	-0.006	*0.053*	-0.024	*0.065*	0.022	*0.106*	0.53	0.6660	-0.015	*0.053*	-0.015	*0.054*	-0.041	*0.040*	0.45	0.6400	1.81	0.1211
10-hour (Mgha^{-1})	1.325	*0.421*	1.973	*0.578*	1.504	*0.333*	1.573	*0.238*	0.98	0.4303	1.801	*0.391*	1.594	*0.310*	1.387	*0.262*	0.75	0.4971	0.47	0.8233
	-0.152	*0.227*	0.110	*0.500*	0.166	*0.325*	0.207	*0.287*	0.42	0.7421	0.393	*0.314*	-0.083	*0.261*	-0.062	*0.127*	2.53	0.1017	0.96	0.4742
100-hour (Mgha^{-1})	5.186	*1.241*	5.022	*1.528*	5.841	*1.044*	3.712	*0.512*	0.33	0.8053	4.217	*0.521*	6.141	*1.086*	4.463	*0.757*	2.84	0.0704	1.30	0.2776
	1.310	*1.032*	-0.218	*0.453*	1.692	*0.924*	0.928	*0.582*	1.24	0.3298	0.573	*0.563*	0.942	*0.543*	1.269	*0.481*	0.42	0.6602	0.29	0.9366
Total FWD (Mgha^{-1})	6.601	*1.296*	7.100	*1.535*	7.492	*1.002*	5.518	*0.490*	0.59	0.6289	6.168	*0.456*	7.889	*1.131*	5.977	*0.875*	0.19	0.1247	1.64	0.1607
	1.073	*1.154*	-0.114	*0.759*	1.834	*0.994*	1.157	*0.828*	0.90	0.4643	0.952	*0.770*	0.844	*0.760*	1.167	*0.529*	0.07	0.9332	0.30	0.9331
1000-hour (Mgha^{-1})	66.334	*8.704*	130.510	*40.328*	147.553	*43.794*	118.832	*42.985*	1.91	0.1408	121.714	*61.913*	143.535	*31.516*	82.172	*11.858*	1.03	0.3922	0.75	0.6132
	-8.584	*10.394*	6.473	*19.945*	14.088	*29.088*	42.726	*26.189*	1.24	0.3214	26.262	*22.940*	24.222	*11.041*	-9.458	*10.189*	0.51	0.6021	1.05	0.4105
Litter (cm)	2.0^{b}	*0.3*	2.4^{ab}	*0.3*	2.4^{ab}	*0.5*	3.3^{a}	*0.4*	4.42	0.0205	2.6	*0.3*	2.4	*0.3*	2.6	*0.3*	0.52	0.5974	1.74	0.1375
	1.6	*0.4*	1.9	*0.3*	1.7	*0.5*	2.7	*0.4*	2.72	0.0813	2.0	*0.3*	1.8	*0.3*	2.1	*0.4*	0.93	0.4012	0.74	0.6201
Duff (cm)	0.1^{b}	*0.0*	0.1^{ab}	*0.0*	0.2^{ab}	*0.0*	0.20^{a}	*0.1*	3.47	0.0429	0.1	*0.0*	0.1	*0.0*	0.1	*0.0*	0.57	0.5808	3.59	0.0084
	0.0	*0.0*	0.0	*0.0*	0.1	*0.0*	0.1	*0.0*	3.30	0.0495	0.1	*0.0*	0.1	*0.0*	0.1	*0.0*	0.93	0.4250	1.19	0.3384
Fuel Depth (cm)	3.9	*0.9*	5.2	*0.6*	6.1	*1.0*	6.3	*0.7*	1.93	0.0538	5.8	*0.4*	5.4	*0.6*	4.9	*0.6*	0.87	0.5012	0.66	0.7861
	1.0	*0.8*	1.1	*0.8*	2.5	*1.2*	3.4	*1.0*	2.26	0.1234	2.4	*0.7*	1.6	*0.4*	2.0	*0.7*	0.59	0.5583	0.54	0.7747
Grass Cover (%)	36.1^{a}	*8.3*	19.2^{b}	*3.6*	18.3^{b}	*2.1*	14.4^{b}	*3.3*	6.70	0.0044	23.3	*3.4*	18.8	*4.7*	23.9	*4.3*	1.76	0.2206	1.25	0.3077
	29.6^{a}	*8.9*	16.4^{b}	*3.8*	16.4^{b}	*1.7*	12.1^{b}	*3.5*	3.99	0.0283	19.8	*3.8*	15.4	*4.9*	20.8	*4.5*	1.63	0.2448	1.36	0.2618
Forb Cover (%)	12.1^{a}	*2.7*	11.7^{a}	*1.3*	9.8^{a}	*1.5*	4.63^{b}	*1.1*	3.79	0.0265	10.5^{b}	*1.0*	7.7^{a}	*0.9*	10.6^{b}	*1.1*	3.77	0.0317	0.92	0.4883
	9.5	*2.5*	10.8	*1.4*	9.0	*1.6*	4.2	*1.1*	2.12	0.1293	9.1^{a}	*0.8*	6.3^{b}	*0.8*	9.7^{a}	*1.0*	8.13	0.0011	0.61	0.7227
Woody Cover (%)	13.4^{a}	*2.3*	14.6^{a}	*3.8*	10.1^{a}	*1.2*	3.4^{b}	*0.8*	6.93	0.0038	11.6	*2.5*	9.1	*1.4*	10.4	*1.2*	0.73	0.4878	0.79	0.5841
	7.7	*2.2*	10.8	*3.6*	7.5	*1.1*	2.7	*0.8*	0.94	0.4442	8.7	*2.3*	6.0	*1.6*	6.8	*1.2*	2.49	0.0960	1.05	0.4077
Hardwood Litter Cover (%)	8.6	*2.5*	13.4	*5.4*	6.6	*1.4*	6.6	*4.7*	1.55	0.2325	10.7	*3.0*	7.1	*2.2*	8.6	*1.7*	0.60	0.5672	1.44	0.2343
	3.9	*1.5*	11.7	*4.4*	6.4	*1.4*	5.8	*4.8*	0.97	0.4278	9.2	*3.2*	4.8	*1.4*	6.9	*1.2*	1.30	0.2849	0.83	0.5536
Pine Needle (%)	0.1^{c}	*0.0*	20.9^{b}	*5.0*	55.4^{a}	*4.4*	69.6^{a}	*5.1*	97.87	<0.0001	31.7	*2.8*	41.4	*2.6*	36.4	*1.5*	2.65	0.0830	1.43	0.2290
	0.1^{c}	*0.0*	18.4^{b}	*4.8*	50.6^{a}	*4.0*	61.1^{a}	*5.2*	41.31	<0.0001	28.1	*2.7*	36.1	*3.7*	33.4	*1.2*	0.80	0.4749	0.60	0.7290
Woody Litter Cover (%)	2.6	*0.8*	3.3	*0.8*	4.5	*0.9*	2.6	*0.3*	1.68	0.2028	3.1	*0.6*	3.5	*0.3*	3.1	*0.6*	0.42	0.6593	0.90	0.5069
	-0.8	*1.2*	1.0	*0.2*	1.6	*1.2*	-0.2	*0.6*	1.88	0.1740	0.3	*0.8*	0.0	*0.7*	0.8	*0.6*	0.54	0.5866	0.42	0.8601
Bare Ground (%)	11.5^{a}	*4.3*	4.6^{ab}	*1.7*	4.3^{b}	*1.7*	2.3^{b}	*1.0*	6.31	0.0055	6.5	*2.2*	5.8	*2.0*	4.7	*1.4*	1.22	0.3057	0.40	0.8773
	-2.6	*2.4*	-5.0	*2.6*	-5.9	*1.6*	-2.0	*0.8*	1.24	0.3315	-4.3	*2.2*	-3.5	*1.2*	-3.7	*1.4*	0.12	0.8880	0.60	0.7250
Burned (%)	59.1^{b}	*10.1*	70.4^{ab}	*8.3*	82.7^{a}	*3.9*	82.8^{a}	*5.3*	3.62	0.0380	73.3^{ab}	*5.1*	68.6^{b}	*6.6*	79.3^{a}	*4.3*	3.87	0.0290	0.60	0.7313

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A-3.9.2. Pre-fire (first line) and fuel consumption (second line) measurements (mean|*SE*) for direction and position effects in the large gap treatments at Fort Benning, GA. Different letters within a row indicate significant treatment differences at $\alpha = 0.05$. Note: fuel consumption measured as pre-fire - post-fire; position is distance from gap center in meters.

	Direction								**ANOVA**		**Position**										**ANOVA**		**Dir*Pos ANOVA**	
Fuel	East		North		South		West		F-value	p-value	10		20		30		40		50		F-value	p-value	F-value	p-value
1-hour (Mgha^{-1})	0.150	*0.005*	0.110	*0.015*	0.072	*0.009*	0.166	*0.016*	2.38	0.1038	0.075[b]	*0.018*	0.068[b]	*0.014*	0.110[ab]	*0.042*	0.143[ab]	*0.014*	0.228[a]	*0.058*	3.62	0.0207	1.49	0.1545
	-0.162	*0.079*	-0.074	*0.040*	-0.172	*0.101*	-0.130	*0.108*	0.50	0.6900	-0.165	*0.090*	-0.208	*0.108*	-0.168	*0.078*	-0.070	*0.073*	-0.063	*0.043*	1.50	0.2391	2.50	0.0098
10-hour (Mgha^{-1})	2.342[a]	*0.426*	1.190[b]	*0.288*	0.576[b]	*0.143*	1.497[ab]	*0.464*	7.94	0.0011	0.960	*0.231*	1.440	*0.258*	1.727	*0.393*	1.104	*0.310*	1.775	*0.336*	1.07	0.3766	1.09	0.3794
	0.576[a]	*0.411*	−0.384[ab]	*0.243*	−0.730[b]	*0.262*	0.384[a]	*0.270*	3.86	0.0117	0.000	*0.105*	-0.192	*0.265*	0.192	*0.398*	0.000	*0.268*	-0.192	*0.398*	0.21	0.9339	1.14	0.3388
100-hour (Mgha^{-1})	5.923	*1.709*	4.860	*1.145*	2.886	*1.360*	2.582	*0.548*	1.71	0.1976	3.607	*1.117*	6.645	*2.004*	5.506	*0.457*	1.519	*0.700*	3.038	*1.087*	2.73	0.0530	0.31	0.9856
	0.456	*1.819*	-1.063	*0.862*	-0.911	*0.780*	-0.152	*0.548*	0.43	0.7308	-0.380	*0.563*	0.000	*0.658*	-0.190	*1.227*	-2.088	*1.568*	0.570	*0.389*	0.88	0.4797	0.81	0.6391
Total FWD (Mgha^{-1})	8.416[a]	*1.894*	6.161[ab]	*1.090*	3.534[b]	*1.456*	4.246[ab]	*0.906*	3.27	0.0433	4.642	*1.163*	8.152	*1.964*	7.344	*0.457*	2.765	*0.942*	5.041	*1.331*	2.73	0.0533	0.55	0.8713
	0.869	*1.622*	-1.521	*0.766*	-1.813	*0.845*	0.102	*0.482*	2.36	0.0786	-0.545	*0.693*	-0.400	*0.769*	-0.166	*1.195*	-2.159	*1.670*	0.315	*0.497*	0.62	0.6513	0.57	0.8568
Litter (cm)	3.2	*0.4*	3.6	*0.7*	3.6	*0.6*	3.6	*0.7*	0.37	0.7764	3.7	*0.9*	3.1	*0.4*	3.3	*0.5*	4.1	*0.7*	3.5	*0.5*	1.65	0.1694	0.78	0.6684
	2.6	*0.3*	3.2	*0.7*	2.9	*0.5*	3.0	*0.6*	0.54	0.6594	3.3	*0.8*	2.5	*0.4*	2.6	*0.4*	3.5	*0.6*	2.8	*0.4*	2.34	0.0624	0.54	0.8854
Duff (cm)	0.0	*0.0*	0.1	*0.0*	0.1	*0.0*	0.1	*0.1*	0.65	0.5973	0.0	*0.0*	0.0	*0.0*	0.1	*0.0*	0.1	*0.0*	0.1	*0.0*	1.01	0.4048	1.45	0.1629
	0.0	*0.0*	0.1	*0.0*	0.0	*0.0*	0.1	*0.0*	0.39	0.7646	0.0	*0.0*	0.0	*0.0*	0.0	*0.0*	0.1	*0.0*	0.1	*0.0*	1.14	0.3443	1.46	0.1574
Fuel Depth (cm)	5.2	*0.8*	5.9	*1.3*	3.1	*0.7*	5.6	*1.1*	1.54	0.2104	1.7[b]	*0.5*	3.7[ab]	*0.8*	6.2[a]	*1.8*	5.7[a]	*0.8*	7.6[a]	*1.4*	4.53	0.0022	0.82	0.6255
	1.9	*1.0*	1.9	*1.4*	0.5	*0.7*	3.4	*1.4*	1.81	0.1511	-0.1	*0.6*	1.0	*0.7*	2.8	*1.6*	1.9	*1.1*	4.1	*1.5*	2.26	0.0686	0.63	0.8156
Grass Cover (%)	35.6	*5.7*	35.8	*8.6*	40.5	*10.4*	43.7	*10.2*	1.17	0.3541	45.7[a]	*8.8*	48.3[a]	*8.4*	37.2[ab]	*12.1*	40.0[ab]	*9.8*	23.3[b]	*6.1*	4.65	0.0081	0.99	0.4700
	32.8	*5.4*	32.7	*8.1*	34.2	*7.5*	39.7	*8.5*	0.88	0.4561	40.6[a]	*7.3*	44.0[a]	*7.7*	32.3[ab]	*9.4*	36.6[ab]	*8.2*	20.8[b]	*5.3*	5.18	0.0050	0.96	0.4982
Forb Cover (%)	15.6	*2.8*	16.6	*3.5*	19.0	*5.9*	13.0	*3.1*	0.81	0.5087	17.8	*5.4*	17.2	*4.2*	16.2	*3.8*	16.3	*3.3*	12.7	*3.9*	0.65	0.6337	0.94	0.5124
	14.2	*2.9*	15.7	*3.4*	17.0	*5.6*	12.3	*3.0*	0.18	0.9079	16.2	*5.0*	16.0	*4.1*	14.7	*3.6*	15.4	*3.2*	11.8	*3.8*	0.48	0.7524	1.04	0.4290
Woody Cover (%)	16.0	*1.5*	12.5	*2.3*	13.5	*3.6*	14.4	*2.8*	0.86	0.4669	15.3	*4.2*	15.7	*1.8*	19.2	*4.3*	12.7	*3.9*	7.6	*2.1*	2.01	0.1312	1.07	0.3976
	11.2	*1.8*	9.8	*2.3*	10.1	*3.6*	10.9	*3.2*	0.27	0.8493	11.8	*4.2*	10.7	*2.3*	14.1	*4.3*	10.1	*3.6*	5.8	*1.8*	0.49	0.7453	0.64	0.7990
Hardwood Litter Cover (%)	19.8	*5.1*	11.2	*2.6*	14.4	*3.6*	14.2	*2.5*	2.02	0.1548	16.1	*6.0*	16.1	*4.2*	20.8	*5.0*	10.9	*3.9*	10.6	*4.2*	1.02	0.4213	1.20	0.3075
	17.5	*4.8*	9.7	*2.9*	12.2	*3.4*	12.1	*2.2*	0.61	0.6197	12.6	*5.4*	13.4	*3.9*	18.3	*4.7*	10.3	*3.8*	9.6	*4.2*	0.67	0.6215	1.08	0.3962
Pine Needle (%)	9.2	*2.6*	22.6	*3.2*	15.5	*4.8*	15.7	*3.6*	2.44	0.1049	0.1[d]	*0.0*	0.5[cd]	*0.2*	3.7[c]	*1.6*	25.1[b]	*5.0*	49.4[a]	*6.5*	112.95	<0.0001	2.95	0.0027
	8.5	*2.5*	20.3	*2.9*	12.4	*5.1*	13.4	*4.0*	1.45	0.2678	0.0[b]	*0.0*	0.4[b]	*0.2*	3.3[b]	*1.6*	23.4[a]	*5.0*	41.1[a]	*6.1*	42.41	<0.0001	1.76	0.0755
Woody Litter Cover (%)	2.9	*1.2*	2.6	*0.9*	1.9	*0.9*	3.1	*0.8*	0.40	0.7579	1.9	*0.6*	3.7	*0.9*	2.7	*0.5*	2.8	*0.8*	2.2	*0.4*	0.81	0.5242	1.51	0.1387
	-3.3	*3.1*	-3.5	*2.5*	-3.6	*2.8*	-3.9	*4.6*	0.35	0.7877	-2.1	*1.9*	-4.6	*3.8*	-4.0	*3.2*	-3.5	*3.6*	-3.7	*3.8*	0.35	0.8422	0.72	0.7262
Bare Ground (%)	4.0	*1.0*	3.3	*0.7*	3.6	*1.1*	5.5	*3.0*	0.04	0.9876	7.6[a]	*2.7*	3.3[ab]	*1.1*	4.6[ab]	*2.0*	2.0[a]	*0.7*	3.0[a]	*1.2*	3.19	0.0174	0.50	0.9091
	-7.2	*5.6*	-8.4	*4.1*	-1.7	*1.9*	-5.3	*3.0*	1.22	0.3380	-7.2	*4.2*	-7.4	*4.3*	-4.6	*1.9*	-6.4	*3.2*	-2.7	*2.2*	0.62	0.6500	0.63	0.8129
Burned (%)	74.0	*9.0*	84.3	*3.5*	74.4	*7.6*	76.3	*8.3*	1.55	0.2436	67.2[b]	*8.5*	73.0[ab]	*9.6*	76.9[ab]	*8.4*	84.3[ab]	*6.0*	84.8[a]	*4.3*	3.09	0.0390	1.21	0.2955

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A-3.9.3. Pre-fire (first line) and fuel consumption (second line) measurements (mean|*SE*) for direction and position effects in the medium gap treatments at Fort Benning, GA. Different letters within a row indicate significant treatment differences at α = 0.05. Note: fuel consumption measured as pre-fire - post-fire; position is distance from gap center in meters.

	Direction								ANOVA		Position								ANOVA		Dir*Pos ANOVA	
Fuel	East		North		South		West		F-value	p-value	10		20		30		40		F-value	p-value	F-value	p-value
1-hour (Mgha^{-1})	0.133	*0.055*	0.233	*0.091*	0.160	*0.038*	0.211	*0.057*	1.59	0.2019	0.211	*0.095*	0.120	*0.032*	0.223	*0.077*	0.183	*0.053*	0.91	0.4604	0.72	0.6855
	−0.095^{b}	*0.060*	−0.095^{b}	*0.039*	−0.108^{b}	*0.048*	0.000^{a}	*0.051*	4.03	0.0112	-0.095	*0.052*	-0.098	*0.064*	-0.050	*0.066*	-0.055	*0.048*	0.39	0.7629	2.41	0.0207
10-hour (Mgha^{-1})	1.679	*0.568*	1.823	*0.523*	1.775	*0.272*	2.207	*0.545*	0.88	0.4552	2.111	*0.692*	1.440	*0.379*	2.399	*0.700*	1.536	*0.206*	0.37	0.7772	0.86	0.5686
	0.624	*0.517*	-0.048	*0.429*	0.288	*0.622*	0.864	*0.414*	1.62	0.1940	0.192	*0.664*	0.144	*0.438*	1.056	*0.369*	0.336	*0.455*	0.30	0.8231	1.14	0.3501
100-hour (Mgha^{-1})	5.506	*2.068*	6.835	*0.975*	5.126	*1.521*	6.075	*1.829*	0.59	0.6277	8.923^{a}	*2.486*	8.164^{a}	*1.117*	3.797^{ab}	*0.914*	2.658^{b}	*0.635*	5.21	0.0092	2.47	0.0228
	1.139	*2.121*	0.949	*0.993*	-0.380	*1.087*	2.658	*2.272*	2.51	0.0979	1.329	*2.248*	1.329	*1.361*	0.759	*1.126*	0.949	*0.903*	0.31	0.8172	1.27	0.2721
Total FWD (Mgha^{-1})	7.318	*2.585*	8.891	*1.066*	7.062	*1.740*	8.493	*2.347*	0.43	0.7344	11.245	*2.909*	9.724	*1.425*	6.419	*1.410*	4.376	*0.787*	2.99	0.0612	1.90	0.0766
	1.668	*2.527*	0.806	*1.171*	-0.200	*1.469*	3.522	*2.507*	1.18	0.3522	1.426	*2.771*	1.375	*1.553*	1.765	*1.301*	1.230	*1.194*	0.04	0.9882	1.66	0.1180
Litter (cm)	2.2	*0.3*	2.5	*0.6*	2.7	*0.4*	2.5	*0.4*	0.56	0.6491	2.2^{b}	*0.3*	2.0^{b}	*0.3*	2.3^{b}	*0.4*	3.4^{a}	*0.6*	9.46	0.0009	0.82	0.6044
	1.7	*0.3*	2.2	*0.6*	1.9	*0.3*	1.9	*0.4*	0.41	0.7506	1.7^{b}	*0.3*	1.4^{b}	*0.3*	1.7^{b}	*0.4*	2.9^{a}	*0.5*	9.23	0.0011	0.93	0.5125
Duff (cm)	0.0	*0.0*	0.0	*0.0*	0.1	*0.0*	0.2	*0.1*	2.84	0.0438	0.1	*0.1*	0.1	*0.1*	0.1	*0.0*	0.1	*0.0*	0.36	0.7826	0.82	0.6012
	0.0	*0.0*	0.0	*0.0*	0.1	*0.0*	0.1	*0.1*	1.53	0.2468	0.1	*0.0*	0.1	*0.0*	0.1	*0.0*	0.1	*0.0*	0.08	0.9684	1.43	0.1957
Fuel Depth (cm)	3.6	*1.3*	5.0	*1.1*	4.6	*0.8*	6.2	*0.9*	1.04	0.3982	5.9	*1.2*	5.3	*0.8*	3.5	*0.8*	4.7	*0.9*	1.08	0.3654	1.77	0.0934
	0.9^{a}	*0.9*	−0.6^{b}	*1.8*	1.3^{a}	*0.8*	3.9^{a}	*1.0*	3.34	0.0480	0.4^{a}	*1.4*	2.1^{a}	*1.0*	0.2^{b}	*1.0*	2.9^{a}	*1.1*	3.5	0.0420	1.61	0.1418
Grass Cover (%)	33.3	*6.3*	37.3	*6.1*	29.8	*7.7*	19.0	*3.5*	2.68	0.0847	34.8^{a}	*5.5*	33.5^{ab}	*6.8*	32.5^{ab}	*6.8*	18.5^{b}	*5.4*	4.13	0.0254	1.47	0.1867
	30.0	*6.6*	34.0	*6.6*	24.1	*7.5*	15.5	*4.2*	2.41	0.1080	30.2	*5.8*	30.0	*7.2*	28.0	*6.6*	15.5	*4.7*	2.87	0.0439	1.54	0.1553
Forb Cover (%)	14.8	*1.1*	15.5	*2.8*	11.6	*1.6*	14.6	*4.2*	0.53	0.6698	15.3^{a}	*2.3*	18.4^{a}	*3.4*	14.5^{ab}	*1.1*	8.3^{b}	*1.2*	5.73	0.0016	0.96	0.4843
	14.0	*1.1*	14.3	*2.7*	10.2	*1.7*	14.0	*4.2*	0.89	0.4688	13.8	*2.5*	17.0	*3.5*	13.7	*1.1*	7.9	*1.3*	1.31	0.3088	1.00	0.4510
Woody Cover (%)	11.2	*2.8*	12.0	*1.9*	11.0	*2.3*	12.2	*2.7*	0.26	0.8544	17.9^{a}	*4.3*	16.1^{a}	*3.9*	7.1^{ab}	*0.9*	5.3^{b}	*1.7*	8.48	0.0016	0.98	0.4688
	8.4	*3.0*	9.5	*2.4*	8.6	*2.3*	10.0	*2.9*	0.33	0.8039	13.1	*3.9*	13.1	*4.1*	5.4	*1.1*	4.8	*1.8*	2.14	0.1378	0.64	0.7588
Hardwood Litter Cover (%)	14.7	*3.5*	16.7	*3.1*	16.3	*4.7*	22.2	*1.3*	1.42	0.2455	25.4	*6.9*	17.8	*4.4*	13.2	*2.6*	13.4	*9.0*	1.27	0.3113	0.62	0.7756
	11.9	*3.1*	15.7	*3.2*	12.5	*3.5*	21.1	*1.1*	1.76	0.1956	21.7	*5.3*	14.2	*2.5*	12.1	*2.5*	13.2	*8.8*	0.71	0.5575	0.62	0.7728
Pine Needle (%)	25.0	*5.5*	17.0	*3.9*	26.3	*3.3*	29.6	*3.2*	2.22	0.1277	0.7^{c}	*0.2*	3.2^{c}	*0.6*	28.4^{b}	*6.1*	65.7^{a}	*7.8*	82.39	<0.0001	1.39	0.2194
	22.6	*4.8*	15.5	*3.9*	23.5	*2.6*	27.5	*3.4*	1.78	0.1938	0.6^{c}	*0.2*	2.7^{c}	*0.6*	24.8^{b}	*5.1*	61.0^{a}	*7.7*	49.33	<0.0001	1.37	0.2315
Woody Litter Cover (%)	3.5	*1.0*	2.7	*0.6*	2.8	*0.6*	3.1	*0.3*	0.06	0.9819	3.8	*1.6*	2.3	*0.3*	2.7	*0.2*	3.2	*0.4*	0.41	0.7452	0.64	0.7608
	1.6	*0.8*	0.4	*0.9*	-0.6	*1.0*	-0.5	*1.3*	1.00	0.4213	0.7	*0.6*	-0.3	*1.0*	-0.3	*1.1*	0.7	*0.7*	0.76	0.5196	0.61	0.7819
Bare Ground (%)	6.3	*2.2*	8.9	*1.9*	6.6	*2.9*	9.3	*3.0*	0.71	0.5493	11.7^{a}	*3.8*	11.5^{a}	*4.0*	6.5ab	*2.0*	1.4^{b}	*0.7*	6.81	0.0041	0.19	0.9946
	-6.8	*2.9*	-16.9	*8.5*	-4.7	*3.4*	-6.7	*3.3*	1.6	0.2302	-12.1	*7.1*	-7.0	*3.5*	-8.2	*3.2*	-7.7	*4.0*	0.38	0.7707	1.77	0.1012
Burned (%)	77.1	*8.5*	71.0	*7.6*	64.8	*10.4*	71.6	*10.1*	1.16	0.3559	56.0^{b}	*14.8*	64.9^{ab}	*12.8*	73.2^{ab}	*6.0*	90.4^{a}	*2.1*	3.53	0.0410	0.91	0.5213

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A-3.9.4. Pre-fire (first line) and fuel consumption (second line) measurements (mean|*SE*) for direction and position effects in the small gap treatments at Fort Benning, GA. Different letters within a row indicate significant treatment differences at α = 0.05. Note: Note: fuel consumption measured as pre-fire - post-fire; position is distance from gap center in meters.

	Direction								ANOVA		Position						ANOVA		Dir*Pos ANOVA	
Fuel	East		North		South		West		F-value	p-value	10		20		30		F-value	p-value	F-value	p-value
1-hour (Mgha-1)	0.197	*0.076*	0.107	*0.043*	0.100	*0.024*	0.160	*0.042*	0.89	0.4704	0.095	*0.025*	0.198	*0.074*	0.130	*0.011*	2.25	0.1559	0.27	0.9445
	-0.090	*0.097*	-0.050	*0.037*	-0.147	*0.039*	-0.077	*0.071*	0.57	0.6414	-0.150	*0.083*	-0.015	*0.030*	-0.108	*0.060*	1.99	0.1870	0.29	0.9386
10-hour (Mgha-1)	1.791	*0.575*	0.960	*0.293*	1.280	*0.162*	0.896	*0.308*	1.49	0.2276	1.056	*0.142*	1.344	*0.377*	1.296	*0.304*	0.16	0.8859	0.34	0.9146
	0.768	*0.586*	0.448	*0.335*	0.064	*0.251*	0.000	*0.222*	0.97	0.4152	0.048	*0.202*	0.576	*0.386*	0.336	*0.410*	0.02	0.9843	0.21	0.9716
100-hour (Mgha-1)	3.291	*2.163*	2.784	*1.138*	3.797	*1.743*	4.303	*1.898*	0.07	0.9754	4.177	*1.575*	3.797	*1.369*	2.658	*1.047*	0.02	0.9777	0.56	0.7568
	-1.772	*0.993*	-1.519	*0.555*	1.013	*1.013*	2.025	*1.339*	2.62	0.0793	0.949	*0.994*	-0.570	*1.050*	-0.570	*0.389*	0.93	0.4044	0.73	0.6316
Total FWD (Mgha-1)	5.279	*2.633*	3.851	*1.281*	5.177	*1.841*	5.360	*2.143*	0.31	0.8208	5.328	*1.716*	5.339	*1.597*	4.084	*1.203*	0.12	0.8883	0.59	0.7371
	-1.094	*1.300*	-1.121	*0.724*	0.929	*1.014*	1.948	*1.263*	1.46	0.2654	0.847	*1.005*	-0.009	*0.893*	-0.341	*0.243*	0.89	0.4183	0.87	0.5242
Litter (cm)	3.4	*0.3*	3.2	*0.5*	2.8	*0.3*	2.8	*0.6*	1.50	0.2251	2.7	*0.6*	3.1	*0.4*	3.4	*0.3*	2.57	0.1256	0.70	0.6490
	2.9	*0.4*	2.8	*0.5*	2.0	*0.3*	2.3	*0.5*	2.10	0.1141	2.1	*0.6*	2.5	*0.4*	2.9	*0.3*	2.65	0.1192	1.20	0.3227
Duff (cm)	0.0	*0.0*	0.1	*0.1*	0.3	*0.2*	0.2	*0.1*	0.91	0.4615	0.2	*0.1*	0.1	*0.1*	0.1	*0.0*	0.57	0.5728	1.36	0.2556
	0.0	*0.0*	0.1	*0.1*	0.1	*0.2*	0.1	*0.1*	0.21	0.8857	0.1	*0.1*	0.1	*0.1*	0.1	*0.0*	0.84	0.4384	0.88	0.5187
Fuel Depth (cm)	7.6	*2.6*	6.3	*2.0*	5.9	*1.2*	4.7	*1.7*	0.79	0.5063	5.4	*2.4*	6.5	*1.9*	6.5	*1.0*	0.28	0.7606	1.47	0.2604
	5.3	*2.6*	2.5	*1.1*	2.1	*1.8*	3.2	*1.4*	0.53	0.6619	3.4	*1.9*	2.2	*2.0*	4.2	*0.9*	1.71	0.1907	1.68	0.1437
Grass Cover (%)	17.2	*4.3*	19.6	*5.4*	15.1	*6.2*	16.0	*3.7*	0.88	0.4583	24.7[a]	*7.3*	14.9[b]	*3.3*	11.4[b]	*3.6*	9.52	0.0003	1.74	0.1296
	15.0	*4.0*	15.8	*5.5*	11.6	*6.2*	14.1	*4.4*	1.33	0.3007	20.7	*7.7*	12.3	*3.2*	9.4	*2.9*	2.89	0.0672	1.39	0.2422
Forb Cover (%)	14.1	*4.3*	13.2	*3.9*	11.1	*2.7*	10.2	*2.3*	0.49	0.6931	15.2[a]	*2.6*	13.7[a]	*3.6*	7.6[b]	*3.3*	6.80	0.0029	0.49	0.8128
	13.1	*4.1*	12.6	*3.9*	9.3	*2.7*	8.6	*2.4*	1.20	0.3451	12.3	*1.8*	13.0	*3.5*	7.4	*3.3*	1.96	0.1537	0.42	0.8594
Woody Cover (%)	12.2	*2.9*	11.8	*3.3*	9.1	*2.6*	6.6	*2.1*	1.18	0.3508	16.4a	*4.1*	8.6b	*2.1*	4.7b	*1.2*	17.21	<0.0001	2.43	0.0452
	9.9	*2.9*	10.5	*3.1*	7.3	*2.8*	5.8	*2.0*	1.27	0.2925	13.5a	*4.0*	7.5a	*2.3*	4.1b	*1.3*	6.71	0.0025	1.44	0.2181
Hardwood Litter Cover (%)	11.2	*3.5*	7.8	*4.2*	9.1	*3.4*	6.0	*2.1*	0.90	0.4484	12.6	*4.4*	7.5	*2.7*	5.5	*3.2*	2.70	0.1155	2.93	0.0169
	9.0	*3.0*	7.4	*4.2*	6.6	*3.2*	5.8	*2.1*	0.13	0.9437	9.2	*4.4*	7.2	*2.6*	5.2	*3.2*	0.27	0.7712	1.81	0.1188
Pine Needle (%)	35.0	*6.1*	29.3	*6.4*	28.3	*4.9*	32.7	*3.8*	0.70	0.5672	1.8[c]	*0.2*	27.5[b]	*4.2*	64.7[a]	*9.1*	87.19	<0.0001	0.93	0.4873
	28.5	*7.5*	24.2	*5.1*	24.1	*4.8*	22.9	*8.0*	0.58	0.6362	1.3[b]	*0.3*	23.0[a]	*4.8*	50.5[a]	*11.8*	12.93	0.0017	2.59	0.0381
Woody Litter Cover (%)	5.2	*1.6*	3.8	*0.9*	3.7	*1.5*	3.8	*1.6*	0.58	0.6386	3.5	*0.9*	4.8	*1.5*	4.1	*1.4*	1.12	0.3351	1.46	0.2154
	-5.3	*4.3*	-3.1	*4.5*	-5.6	*4.0*	-0.9	*3.3*	1.87	0.1489	-2.3	*2.0*	-3.4	*4.7*	-5.4	*5.3*	0.57	0.5827	0.74	0.6177
Bare Ground (%)	4.5	*2.5*	7.9	*4.0*	7.0	*3.4*	8.5	*5.8*	0.91	0.4590	11.6[a]	*5.8*	6.5[ab]	*4.0*	2.8[b]	*2.3*	4.51	0.0402	0.38	0.8839
	-5.4	*3.7*	-6.0	*3.1*	-1.6	*1.2*	-6.1	*2.7*	0.96	0.4373	-2.8	*2.7*	-6.3	*3.4*	-5.2	*2.2*	0.86	0.4525	1.50	0.2106
Burned (%)	83.6	*4.3*	85.3	*3.7*	69.7	*7.2*	85.3	*5.4*	3.06	0.0604	65.2[b]	*7.8*	84.2[a]	*3.4*	93.6[a]	*2.7*	8.52	0.0069	1.65	0.1676

A-3.9.5. Pre-fire (first line) and fuel consumption (second line) measurements for 1000-hour fuels (mean|*SE*) for gap size and direction effects in the gap treatments at Fort Benning, GA. Different letters within a row indicate significant treatment differences at α = 0.05. Note: fuel consumption measured as pre-fire - post-fire.

	Gap Size						ANOVA		Direction								ANOVA		Main*Sub ANOVA	
Fuel	LG		MG		SG		F-value	p-value	E		N		S		W		F-value	p-value	F-value	p-value
1000-hour ($Mgha^{-1}$)	34.916	*13.173*	55.695	*11.753*	34.883	*19.400*	1.11	0.3676	30.880	*6.393*	34.606	*10.992*	69.309	*29.559*	32.531	*11.256*	1.94	0.1360	1.28	0.2864
	1.234	*3.891*	-1.083	*6.608*	3.026	*4.737*	0.40	0.6749	-2.150	*1.763*	2.196	*4.305*	5.556	*6.556*	-1.367	*5.087*	0.76	0.5231	1.76	0.1288

A-3.9.6. Pre-fire (first line) and fuel consumption (second line) measurements (mean|*SE*) for main and sub-plots treatments at Camp Lejeune, NC. Different letters within a row indicate significant treatment differences at α = 0.05. Note: fuel consumption measured as pre-fire - post-fire.

	Main Plot Treatment								ANOVA		Sub-Plot Treatment						ANOVA		Main*Sub ANOVA	
Fuel	Clearcut		LowBA		MedBA		Control		F-value	p-value	H+F		H		NT		F-value	p-value	F-value	p-value
1-hour (Mgha^{-1})	0.437	*0.066*	0.405	*0.079*	0.428	*0.071*	0.387	*0.042*	0.15	0.9258	0.469^{a}	*0.057*	0.453^{a}	*0.057*	0.320^{b}	*0.038*	6.37	0.0130	1.36	0.2574
	0.058	*0.063*	0.043	*0.072*	0.020	*0.084*	0.071	*0.040*	0.18	0.9098	0.100	*0.064*	0.044	*0.059*	0.001	*0.048*	1.97	0.1821	0.80	0.5758
10-hour (Mgha^{-1})	2.413	*0.277*	2.022	*0.219*	2.093	*0.384*	1.845	*0.277*	1.10	0.3860	2.173	*0.257*	2.102	*0.231*	2.005	*0.240*	0.20	0.8340	0.58	0.7470
	0.662	*0.413*	0.225	*0.260*	0.402	*0.304*	0.071	*0.356*	0.73	0.5499	0.328	*0.296*	0.408	*0.229*	0.284	*0.242*	0.09	0.9152	0.86	0.5277
100-hour (Mgha^{-1})	5.568	*0.967*	5.662	*0.575*	5.428	*0.811*	3.229	*0.778*	2.70	0.0570	5.825	*0.577*	5.580	*0.973*	3.509	*0.522*	2.30	0.1410	1.82	0.1118
	0.936	*0.804*	0.655	*1.050*	0.702	*0.683*	-0.702	*0.476*	1.21	0.3335	0.561	*0.758*	1.018	*0.803*	-0.386	*0.467*	1.63	0.2364	1.19	0.3361
Total FWD (Mgha^{-1})	8.417^{a}	*1.054*	8.089^{a}	*0.690*	7.949^{a}	*1.069*	5.460^{b}	*0.920*	3.20	0.0310	8.467	*0.812*	8.135	*1.150*	5.834	*0.743*	3.00	0.0890	1.02	0.4235
	1.656	*0.760*	0.922	*1.242*	1.124	*0.871*	-0.560	*0.467*	1.92	0.1622	0.989	*0.889*	1.469	*0.988*	-0.101	*0.538*	1.64	0.2343	0.72	0.6325
1000-hour (Mgha^{-1})	108.254	*30.731*	69.342	*15.690*	67.378	*12.395*	88.732	*29.235*	0.71	0.5613	88.765	*24.336*	81.774	*22.852*	79.740	*10.662*	0.03	0.9684	0.50	0.8058
	-22.935	*40.825*	11.611	*7.632*	11.696	*6.565*	-4.185	*27.471*	1.42	0.2696	10.329	*17.132*	-0.474	*11.794*	-12.714	*24.261*	0.22	0.8054	1.27	0.2960
Litter (cm)	2.0^{b}	*0.2*	2.8^{a}	*0.3*	2.8^{a}	*0.3*	3.1^{a}	*0.2*	11.63	<0.0001	2.4^{b}	*0.2*	2.5^{b}	*0.3*	3.2^{a}	*0.2*	10.92	<0.0001	0.66	0.6840
	0.6^{b}	*0.3*	1.0^{ab}	*0.2*	1.5^{a}	*0.2*	1.8^{a}	*0.2*	6.17	0.0045	0.9^{b}	*0.2*	1.2^{ab}	*0.3*	1.5^{a}	*0.1*	4.15	0.0218	0.65	0.6906
Duff (cm)	0.3^{b}	*0.1*	0.6^{ab}	*0.2*	0.7^{a}	*0.2*	0.7^{a}	*0.2*	6.29	0.0041	0.6	*0.2*	0.6	*0.2*	0.5	*0.1*	0.02	0.9833	0.52	0.7894
	0.2	*0.1*	0.4	*0.1*	0.5	*0.2*	0.6	*0.2*	3.15	0.0504	0.5	*0.2*	0.4	*0.2*	0.4	*0.1*	0.07	0.9288	1.61	0.1720
Fuel Depth (cm)	4.5	*0.5*	5.3	*1.0*	4.9	*0.6*	5.5	*0.5*	0.92	0.4507	4.9	*0.6*	5.2	*0.7*	5.0	*0.5*	0.16	0.8510	0.70	0.6518
	0^{b}	*0.5*	1.2^{b}	*0.7*	0.7^{b}	*0.5*	2.1^{a}	*0.4*	6.60	0.0034	0.9	*0.5*	1.1	*0.4*	1.0	*0.5*	0.11	0.9004	1.05	0.4076
Grass Cover (%)	21.7^{a}	*6.0*	11.7^{ab}	*3.0*	7.5^{b}	*1.7*	5.6^{b}	*1.0*	7.72	0.0016	12.5	*2.7*	10.5	*2.4*	11.9	*2.1*	0.68	0.5240	0.57	0.7500
	1.2	*3.7*	1.0	*4.0*	-0.1	*3.0*	2.4	*0.9*	0.32	0.8079	2.6	*2.7*	0.8	*2.3*	-0.1	*1.7*	0.69	0.5204	0.83	0.5538
Forb Cover (%)	1.8	*0.8*	2.1	*0.9*	1.4	*0.6*	1.5	*0.8*	0.29	0.8331	0.8	*0.8*	1.8^{a}	*0.8*	1.0^{b}	*0.5*	6.83	0.0025	1.39	0.2387
	-0.2	*1.3*	-0.7	*0.6*	-0.4	*0.4*	-0.3	*0.3*	0.24	0.8667	-0.1	*0.6*	0.2	*0.5*	-1.3	*0.5*	1.32	0.2767	1.06	0.4000
Woody Cover (%)	21.8^{a}	*4.8*	19.7^{a}	*3.2*	15.6^{a}	*3.6*	8.3^{b}	*2.9*	15.85	<0.0001	15.8	*3.7*	16.2	*3.4*	17.1	*0.3*	1.06	0.3540	0.40	0.8723
	3.1	*4.3*	5.5	*3.4*	7.3	*2.8*	4.1	*1.8*	1.20	0.3391	4.1	*2.7*	5.7	*2.5*	5.2	*3.9*	0.37	0.6964	0.57	0.7490
Hardwood Litter Cover (%)	10.4^{a}	*3.2*	10.7^{a}	*2.9*	6.0^{ab}	*1.9*	2.7^{b}	*0.5*	5.47	0.0075	4.3^{b}	*1.6*	3.7^{b}	*1.4*	14.4^{a}	*2.9*	47.83	<0.0001	0.54	0.7729
	0.7	*4.1*	-0.7	*3.2*	0.4	*2.0*	-0.7	*1.0*	0.42	0.7439	−2.9^{b}	*2.3*	−0.9^{b}	*1.4*	3.6^{a}	*3.9*	8.67	0.0047	0.62	0.7137
Pine Needle (%)	4.6^{d}	*1.8*	18.5^{c}	*4.1*	29.2^{b}	*4.1*	58.0^{a}	*6.1*	78.83	<0.0001	28.2	*3.9*	30.4	*4.3*	24.1	*2.8*	2.8	0.1003	1.39	0.2438
	0.0	*2.2*	3.3	*7.0*	9.8	*4.0*	15.5	*7.9*	1.35	0.2904	8.5	*4.4*	7.9	*4.1*	5.2	*4.3*	1.25	0.3214	0.24	0.9601
Woody Litter Cover (%)	5.5	*2.5*	3.5	*2.4*	3.5	*2.1*	2.0	*1.0*	1.15	0.3556	4.2^{a}	*2.0*	4.2^{a}	*2.2*	2.4^{b}	*1.1*	3.71	0.0318	0.67	0.6762
	-7.7	*2.5*	-6.1	*3.3*	-11.7	*5.0*	-10.1	*3.2*	1.50	0.2479	-7.7	*3.2*	-11.0	*4.5*	-7.9	*2.1*	1.42	0.2801	0.72	0.6324
Bare Ground (%)	3.5^{a}	*1.4*	2.0^{ab}	*1.1*	0.6^{ab}	*0.2*	0.2^{b}	*0.1*	3.36	0.0417	1.9	*0.7*	1.7	*0.7*	1.0	*0.4*	1.84	0.2012	2.09	0.0787
	-2.2	*1.3*	-1.4	*1.8*	-1.8	*0.8*	-0.9	*0.4*	0.07	0.9736	-1.4	*1.0*	-1.2	*1.2*	-2.1	*1.0*	1.97	0.1827	1.02	0.4285
Burned (%)	55.8^{ab}	*9.1*	37.1^{b}	*10.7*	68.0^{a}	*7.3*	78.3^{a}	*5.7*	5.13	0.0097	57.6	*6.6*	58.5	*5.5*	63.3	*4.7*	0.79	0.4581	0.24	0.9602

A-3.9.7. Pre-fire (first line) and fuel consumption (second line) measurements (mean|*SE*) for direction and position effects in the large gap treatments at Camp Lejeune, NC. Different letters within a row indicate significant treatment differences at $\alpha = 0.05$. Note:fuel consumption measured as pre-fire - post-fire; position is distance from gap center in meters.

	Direction								ANOVA		Position										ANOVA		Dir*Pos ANOVA	
Fuel	East		North		South		West		F-value	p-value	10		20		30		40		50		F-value	p-value	F-value	p-value
1-hour (Mgha^{-1})	0.521	*0.147*	0.598	*0.172*	0.550	*0.118*	0.423	*0.097*	1.16	0.3280	0.524	*0.163*	0.459	*0.139*	0.539	*0.133*	0.557	*0.158*	0.537	*0.084*	0.79	0.5341	0.51	0.9026
	0.185	*0.170*	0.096	*0.145*	0.144	*0.133*	0.050	*0.101*	0.21	0.8899	0.133	*0.149*	0.085	*0.107*	0.153	*0.116*	0.130	*0.181*	0.093	*0.110*	0.20	0.9337	0.61	0.8243
10-hour (Mgha^{-1})	2.879	*0.432*	3.455	*0.589*	3.340	*0.634*	2.342	*0.092*	1.19	0.3392	3.311	*0.712*	2.783	*0.545*	2.975	*0.338*	3.023	*0.535*	2.927	*0.403*	0.18	0.9488	0.76	0.6907
	1.420	*0.378*	1.228	*0.703*	1.574	*0.344*	0.345	*0.365*	1.32	0.2976	1.344	*0.757*	1.727	*0.487*	0.960	*0.192*	1.152	*0.551*	0.528	*0.695*	0.60	0.6687	1.00	0.4602
100-hour (Mgha^{-1})	6.531	*1.114*	9.265	*2.097*	7.138	*2.798*	4.708	*1.603*	1.14	0.3649	6.455	*2.310*	9.113	*2.278*	6.265	*0.641*	9.493	*2.009*	3.228	*1.192*	2.33	0.0911	0.79	0.6613
	1.671	*1.477*	0.304	*2.190*	0.608	*1.658*	0.911	*1.289*	0.14	0.9345	-1.139	*1.410*	3.228	*1.775*	0.380	*1.005*	3.228	*2.305*	-1.329	*0.745*	2.24	0.1013	0.93	0.5261
Total FWD (Mgha^{-1})	9.932	*1.041*	13.317	*2.703*	11.028	*3.420*	7.473	*1.600*	1.46	0.2648	10.290	*3.069*	12.355	*2.347*	9.779	*0.647*	13.072	*2.061*	6.691	*1.229*	1.35	0.2572	0.76	0.6841
	3.276	*1.619*	1.628	*2.903*	2.326	*1.760*	1.307	*1.451*	0.38	0.7716	0.337^{b}	*2.109*	5.040^{a}	*1.599*	1.49^{abc}	*1.092*	4.510^{abc}	*2.373*	−0.708^{c}	*0.983*	3.71	0.0080	0.54	0.8856
Litter (cm)	2.6	*0.5*	2.5	*0.5*	2.3	*0.2*	3.3	*0.4*	2.75	0.0794	1.9^{b}	*0.4*	2.9^{a}	*0.4*	2.4^{ab}	*0.4*	3.0^{a}	*0.4*	3.1^{a}	*0.3*	5.44	0.0006	0.40	0.9599
	1.1	*0.7*	0.9	*0.4*	0.6	*0.3*	1.7	*0.5*	1.67	0.2169	0.6^{b}	*0.4*	1.0^{b}	*0.6*	0.9^{b}	*0.4*	1.1^{b}	*0.3*	1.8^{a}	*0.4*	3.07	0.0209	0.53	0.8923
Duff (cm)	1.9	*1.4*	0.7	*0.3*	0.7	*0.3*	0.5	*0.1*	0.37	0.7741	0.5	*0.2*	0.7	*0.3*	0.7	*0.2*	0.8	*0.2*	2.1	*1.6*	1.22	0.3319	0.91	0.5403
	1.7	*1.3*	0.5	*0.2*	0.5	*0.3*	0.4	*0.1*	0.56	0.6495	0.4	*0.2*	0.6	*0.2*	0.5	*0.2*	0.6	*0.2*	1.9	*1.6*	0.70	0.6031	1.21	0.2998
Fuel Depth (cm)	4.5	*0.5*	4.8	*0.2*	5.4	*0.4*	4.7	*0.5*	1.14	0.3389	4.4	*0.9*	4.9	*0.2*	4.1	*0.4*	5.5	*1.0*	5.4	*0.9*	0.69	0.6045	1.25	0.2670
	1.5	*0.5*	0.6	*0.9*	1.4	*0.8*	-0.9	*1.9*	0.85	0.4836	0.8	*0.5*	0.4	*0.6*	-0.5	*1.1*	0.5	*1.6*	2.1	*1.1*	1.00	0.4299	0.55	0.8705
Grass Cover (%)	17.2	*5.4*	14.8	*4.7*	15.6	*2.3*	23.2	*4.9*	2.76	0.0784	23.7^{a}	*7.0*	21.6^{ab}	*5.5*	19.9^{ab}	*4.5*	10.9^{b}	*5.1*	12.3^{b}	*3.8*	2.99	0.0436	1.26	0.2685
	2.6	*8.7*	-1.3	*7.2*	-6.1	*7.4*	3.3	*8.5*	1.18	0.3511	4.6	*10.3*	-2.1	*9.2*	-2.5	*8.9*	-3.5	*6.3*	1.6	*5.2*	0.60	0.6649	0.93	0.5230
Forb Cover (%)	0.6	*0.3*	1.4	*0.8*	1.7	*0.7*	0.9	*0.5*	1.53	0.2124	1.5	*0.6*	0.5	*0.2*	0.6	*0.2*	2.5	*1.5*	0.6	*0.4*	1.75	0.1786	1.66	0.0935
	-0.9	*0.5*	0.0	*0.2*	-0.9	*1.8*	-4.0	*2.8*	1.08	0.3879	-0.1	*0.4*	-3.2	*2.0*	-2.1	*1.9*	-1.5	*2.4*	-0.4	*0.6*	0.67	0.6232	0.53	0.8846
Woody Cover (%)	18.3	*4.0*	17.9	*3.4*	20.9	*6.7*	20.3	*4.1*	0.25	0.8634	23.9^{a}	*5.1*	24.4^{a}	*5.3*	22.4^{a}	*5.0*	14.6^{b}	*2.7*	11.6^{b}	*3.4*	6.58	0.0015	1.16	0.3306
	3.8	*5.3*	1.4	*3.6*	3.0	*4.7*	5.4	*6.3*	0.38	0.7711	5.3	*4.0*	1.5	*6.3*	3.1	*5.9*	1.8	*3.7*	5.2	*3.2*	0.74	0.5708	1.27	0.2513
Hardwood Litter Cover (%)	15.1^{a}	*5.3*	4.9^{b}	*2.3*	5.3^{b}	*1.6*	12.3^{ab}	*4.3*	5.64	0.0086	5.4	*1.8*	9.0	*3.8*	9.8	*3.8*	10.9	*2.4*	11.9	*3.9*	1.67	0.1968	1.34	0.2205
	6.0^{a}	*4.8*	−2.4^{b}	*2.6*	−0.4^{ab}	*3.3*	2.7^{ab}	*5.0*	3.52	0.0414	0.4^{b}	*2.5*	−2.3^{b}	*2.9*	−0.5^{b}	*4.2*	2.7^{ab}	*5.0*	7.1^{a}	*4.0*	7.07	<0.0001	1.36	0.2015
Pine Needle (%)	11.8^{b}	*3.8*	16.2^{ab}	*4.7*	18.9^{a}	*3.7*	14.7^{ab}	*4.5*	3.74	0.0347	4.0^{b}	*1.6*	4.6^{b}	*2.5*	7.6^{bc}	*3.2*	24.0^{a}	*5.5*	36.7^{a}	*8.3*	22.99	<0.0001	0.79	0.6565
	0.0	*6.0*	6.6	*6.4*	-1.6	*5.9*	-1.5	*5.6*	2.78	0.0775	-2.6	*3.3*	-4.6	*2.3*	-1.9	*5.9*	5.1	*7.2*	8.4	*11.7*	2.31	0.0935	0.85	0.5982
Woody Litter Cover (%)	4.1	*1.7*	8.2	*4.7*	5.7	*2.9*	4.8	*2.7*	0.75	0.5366	5.6	*2.8*	5.9	*3.2*	6.2	*3.2*	5.8	*2.9*	5.2	*2.9*	0.10	0.9806	0.79	0.6572
	-7.0	*3.7*	-5.2	*6.4*	-7.5	*3.9*	-4.5	*1.8*	0.21	0.8863	-6.4	*3.1*	-3.1	*2.7*	-2.6	*3.6*	-9.2	*5.7*	-8.8	*4.5*	1.45	0.2543	1.42	0.1824
Bare Ground (%)	1.0	*0.4*	2.1	*1.0*	2.1	*1.4*	0.7	*0.3*	1.12	0.3718	2.2^{a}	*0.7*	2.0^{a}	*0.6*	1.4^{ab}	*1.0*	1.4^{ab}	*0.7*	0.4^{b}	*0.2*	4.37	0.0030	0.87	0.5836
	-1.9	*1.4*	0.3	*1.1*	1.1	*1.6*	-1.6	*1.0*	1.64	0.2225	-0.3	*1.2*	0.8	*0.8*	-1.1	*1.7*	-0.6	*1.4*	-1.3	*0.7*	2.33	0.0911	0.73	0.7128
Burned (%)	59.9	*10.0*	59.0	*7.0*	41.3	*6.6*	54.3	*8.1*	1.98	0.1598	56.6^{ab}	*3.6*	41.2^{b}	*10.0*	48.2^{b}	*5.3*	48.9^{b}	*8.2*	73.1^{a}	*7.4*	4.05	0.0048	1.22	0.2845

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A-3.9.8. Pre-fire (first line) and fuel consumption (second line) measurements (mean|*SE*) for direction and position effects in the medium gap treatments at Camp Lejeune, NC. Different letters within a row indicate significant treatment differences at $\alpha = 0.05$. Note: fuel consumption measured as pre-fire - post-fire; position is distance from gap center in meters.

	Direction								ANOVA		Position								ANOVA		Dir*Pos ANOVA	
Fuel	East		North		South		West		F-value	p-value	10		20		30		40		F-value	p-value	F-value	p-value
1-hour (Mgha^{-1})	0.391	*0.087*	0.331	*0.092*	0.451	*0.178*	0.421	*0.054*	0.69	0.5758	0.572	*0.174*	0.376	*0.074*	0.328	*0.046*	0.319	*0.102*	1.68	0.2233	1.30	0.2703
	0.108	*0.088*	0.000	*0.067*	0.126	*0.192*	0.090	*0.124*	0.45	0.7208	0.271^{a}	*0.140*	0.114^{ab}	*0.108*	0.033^{b}	*0.098*	−0.093^{bc}	*0.081*	9.82	<0.0001	0.42	0.9170
10-hour (Mgha^{-1})	2.246	*0.477*	2.361	*0.459*	2.994	*0.413*	2.418	*0.608*	1.04	0.3840	2.822	*0.861*	1.843	*0.520*	3.109	*0.620*	2.246	*0.440*	1.24	0.3386	1.56	0.1545
	0.864	*0.417*	0.576	*0.473*	1.612	*0.310*	0.633	*0.775*	0.97	0.4132	1.497	*0.526*	0.461	*0.495*	1.382	*0.620*	0.345	*0.230*	1.54	0.2126	1.91	0.0675
100-hour (Mgha^{-1})	5.012	*1.056*	5.923	*1.587*	9.569	*3.613*	4.784	*1.503*	1.17	0.3626	8.657^{a}	*0.925*	5.240^{ab}	*0.925*	7.746^{ab}	*2.557*	3.645^{b}	*1.367*	4.25	0.0096	1.38	0.2251
	1.139	*0.882*	0.228	*1.216*	3.190	*3.368*	0.228	*1.268*	0.52	0.6750	2.506^{ab}	*0.664*	1.139^{ab}	*1.081*	3.417^{a}	*2.100*	−2.278^{b}	*1.570*	3.81	0.0373	1.19	0.3338
Total FWD (Mgha^{-1})	7.649	*1.084*	8.615	*1.911*	13.014	*3.718*	7.624	*1.596*	1.88	0.1868	12.050^{a}	*1.620*	7.459^{ab}	*1.013*	11.183^{ab}	*2.867*	6.210^{b}	*1.744*	4.23	0.0099	1.64	0.1297
	2.111	*1.041*	0.804	*1.339*	4.928	*3.281*	0.951	*1.508*	0.94	0.4470	4.274^{ab}	*0.730*	1.714^{ab}	*1.170*	4.832^{a}	*2.014*	−2.026^{b}	*1.724*	5.58	0.0111	1.06	0.4145
Litter (cm)	2.9	*0.4*	2.4	*0.6*	2.5	*0.6*	2.8	*0.5*	0.45	0.7238	2.7	*0.4*	2.9	*0.4*	2.5	*0.4*	2.5	*0.5*	1.22	0.3114	0.63	0.7647
	0.5	*1.0*	1.1	*0.6*	0.6	*0.4*	1.3	*0.4*	0.37	0.7794	0.8	*0.4*	1.0	*0.5*	0.7	*0.4*	1.0	*0.7*	0.13	0.9395	1.69	0.1287
Duff (cm)	0.6	*0.2*	0.6	*0.2*	0.6	*0.2*	0.5	*0.1*	0.15	0.9296	0.6	*0.1*	0.5	*0.1*	0.5	*0.1*	0.7	*0.3*	0.17	0.9137	1.09	0.3952
	0.4	*0.2*	0.4	*0.2*	0.4	*0.1*	0.4	*0.1*	0.03	0.9943	0.4	*0.1*	0.3	*0.2*	0.3	*0.1*	0.6	*0.2*	0.35	0.7913	1.13	0.3578
Fuel Depth (cm)	3.8	*0.7*	4.8	*0.8*	5.0	*1.4*	4.7	*1.0*	0.55	0.6486	4.6	*1.3*	4.1	*0.9*	5.1	*1.2*	4.5	*0.9*	0.12	0.9459	1.06	0.4116
	-1.1	*0.9*	0.7	*1.2*	0.3	*1.2*	0.8	*0.9*	0.84	0.4769	-0.2	*1.4*	-0.1	*0.9*	0.1	*1.5*	0.8	*0.9*	0.19	0.9031	0.81	0.6107
Grass Cover (%)	17.2	*7.2*	21.4	*8.1*	24.6	*9.1*	14.3	*4.2*	0.82	0.5057	22.3	*8.3*	25.2	*11.5*	21.0	*7.8*	8.9	*3.5*	1.62	0.2362	1.02	0.4426
	-4.7	*8.3*	2.9	*6.5*	-3.8	*6.8*	-5.1	*6.4*	0.99	0.4288	-7.2	*7.2*	-1.4	*12.0*	-2.4	*6.3*	0.3	*1.6*	0.38	0.7709	1.31	0.2654
Forb Cover (%)	1.4^{b}	*1.0*	4.5a	*2.7*	1.6^{b}	*1.1*	2.0^{ab}	*1.4*	4.01	0.0126	4.6	*2.8*	1.8	*1.4*	2.2	*1.8*	0.8	*0.4*	2.40	0.1187	0.71	0.6935
	-1.6	*0.9*	-0.9	*0.7*	-3.8	*4.8*	-0.8	*2.3*	0.20	0.8977	-1.0	*2.9*	-5.1	*3.3*	-0.6	*1.0*	-0.2	*0.3*	1.17	0.3614	0.96	0.4890
Woody Cover (%)	21.0	*6.4*	19.5	*6.4*	17.9	*5.1*	16.4	*3.0*	0.28	0.8417	23.2	*4.7*	23.2	*6.5*	15.2	*4.3*	13.2	*3.5*	4.32	0.0277	0.82	0.5981
	3.1	*7.2*	8.7	*4.9*	1.3	*7.4*	-3.6	*10.3*	1.04	0.4113	3.0	*1.2*	2.4	*0.5*	1.8	*0.9*	2.4	*0.7*	0.02	0.9958	0.84	0.5853
Hardwood Litter Cover (%)	18.2	*8.1*	12.9	*6.0*	9.4	*3.6*	12.0	*4.1*	1.11	0.3831	14.8^{ab}	*6.3*	16.5^{a}	*5.4*	13.3^{ab}	*5.2*	7.9^{b}	*3.2*	3.54	0.0483	1.61	0.1480
	-0.1	*6.2*	2.5	*7.6*	-1.9	*5.5*	-7.6	*9.5*	1.00	0.4270	-1.7	*9.0*	-6.2	*6.5*	-0.8	*7.2*	1.7	*3.9*	1.20	0.3521	2.03	0.0638
Pine Needle (%)	14.3	*5.1*	10.8	*4.1*	21.9	*6.4*	20.6	*4.3*	2.15	0.1470	2.7^{c}	*2.0*	4.5^{c}	*2.4*	20.7^{b}	*7.1*	39.7^{a}	*7.5*	25.15	<0.0001	1.47	0.1981
	3.1	*2.3*	-1.8	*4.1*	5.6	*6.6*	7.0	*4.9*	2.25	0.0941	0.4	*1.9*	1.1	*2.1*	4.1	*6.1*	8.5	*7.8*	1.66	0.2279	2.39	0.0249
Woody Litter Cover (%)	2.2	*1.3*	3.6	*2.5*	3.7	*2.7*	4.0	*3.0*	0.63	0.6124	3.8	*2.6*	3.6	*2.7*	2.7	*1.7*	3.3	*2.3*	0.45	0.7164	2.00	0.0602
	-2.7	*1.1*	-5.1	*5.8*	-2.3	*3.8*	-2.0	*3.6*	0.09	0.9620	-0.6	*2.8*	-1.2	*2.8*	-3.9	*3.2*	-6.4	*4.8*	2.11	0.1529	1.06	0.4113
Bare Ground (%)	0.6	*0.3*	2.4	*1.8*	1.6	*0.8*	3.4	*3.0*	0.62	0.6161	3.4	*1.8*	1.9	*1.5*	1.2	*0.8*	1.4	*0.9*	2.19	0.1418	1.50	0.1845
	-0.3	*0.5*	-2.9	*4.9*	0.5	*1.3*	1.4	*3.5*	0.55	0.6591	2.6^{a}	*1.9*	0.0^{ab}	*2.5*	-0.3^{ab}	*1.4*	-3.6^{b}	*3.4*	5.87	0.0105	3.01	0.0088
Burned (%)	37.1	*11.7*	48.3	*11.9*	35.5	*12.5*	39.5	*11.3*	1.28	0.3268	27.0	*15.5*	34.7	*15.5*	37.7	*15.2*	60.9	*11.5*	1.77	0.2054	0.97	0.4775

A-3.9.9. Pre-fire (first line) and fuel consumption (second line) measurements (mean|*SE*) for direction and position effects in the small gap treatments at Camp Lejeune, NC. Different letters within a row indicate significant treatment differences at α = 0.05. Note: fuel consumption measured as pre-fire - post-fire; position is distance from gap center in meters.

	Direction								ANOVA		Position						ANOVA		Dir*Pos ANOVA	
Fuel	East		North		South		West		F-value	p-value	10		20		30		F-value	p-value	F-value	p-value
1-hour (Mgha[-1])	0.374	*0.063*	0.391	*0.099*	0.532	*0.184*	0.401	*0.091*	0.32	0.8135	0.416[ab]	*0.096*	0.343[b]	*0.091*	0.514[a]	*0.073*	3.36	0.0448	0.68	0.6632
	-0.050	*0.090*	0.003	*0.104*	0.107	*0.172*	-0.017	*0.091*	0.19	0.8992	0.053	*0.094*	-0.053	*0.091*	0.033	*0.078*	1.22	0.3058	1.77	0.1299
10-hour (Mgha[-1])	2.495	*0.663*	2.111	*0.633*	2.815	*1.024*	2.623	*0.718*	0.32	0.8076	2.255	*0.592*	2.399	*0.412*	2.879	*0.920*	0.47	0.6304	0.66	0.6818
	0.320	*0.598*	0.064	*0.480*	1.024	*1.047*	0.064	*0.697*	0.28	0.8396	0.000	*0.278*	0.144	*0.593*	0.960	*0.869*	0.80	0.4555	0.72	0.6347
100-hour (Mgha[-1])	4.810	*1.728*	3.038	*1.240*	5.063	*1.450*	5.063	*1.739*	0.31	0.8199	4.556	*0.883*	4.936	*0.914*	3.987	*0.964*	0.47	0.6408	0.86	0.5354
	-0.253	*0.824*	0.506	*0.847*	0.253	*1.203*	-0.506	*0.086*	0.78	0.5104	1.139	*1.315*	-0.380	*0.914*	-0.759	*0.635*	0.09	0.9137	0.93	0.4812
Total FWD (Mgha[-1])	7.679	*2.347*	5.540	*1.856*	8.409	*2.422*	8.087	*2.295*	0.38	0.7720	7.228	*2.330*	7.679	*1.275*	7.380	*1.816*	0.31	0.7388	0.93	0.4816
	0.017	*0.801*	0.574	*1.118*	1.384	*1.281*	-0.459	*1.456*	0.34	0.7952	1.192	*1.346*	-0.288	*1.046*	0.233	*0.938*	0.18	0.8361	0.77	0.5947
Litter (cm)	3.4[ab]	*0.7*	2.4[b]	*0.4*	3.4[ab]	*0.5*	4.3[a]	*0.6*	5.67	0.0022	3.1	*0.6*	3.7	*0.8*	3.4	*0.3*	0.92	0.4298	0.76	0.6074
	1.9	*0.8*	0.9	*0.5*	1.6	*0.6*	2.1	*0.9*	2.14	0.1083	1.0	*0.7*	1.9	*1.0*	2.0	*0.4*	1.78	0.2186	0.46	0.8312
Duff (cm)	0.5	*0.2*	0.8	*0.3*	0.8	*0.4*	1.1	*0.3*	1.91	0.1721	0.5	*0.1*	0.9	*0.3*	1.0	*0.3*	2.46	0.0986	0.78	0.5909
	0.3	*0.1*	0.6	*0.3*	0.5	*0.4*	0.9	*0.3*	2.17	0.1343	0.4	*0.1*	0.7	*0.2*	0.7	*0.2*	0.52	0.5978	2.10	0.0749
Fuel Depth (cm)	6.0	*1.2*	3.7	*0.7*	6.1	*1.3*	6.1	*1.1*	1.41	0.2794	4.2	*0.5*	5.9	*1.0*	6.4	*0.9*	2.08	0.1379	0.25	0.9572
	2.7	*0.8*	0.6	*0.6*	1.3	*0.7*	2.5	*0.9*	1.63	0.1924	1.5	*0.6*	1.3	*0.5*	2.5	*0.9*	0.83	0.4429	0.35	0.9089
Grass Cover (%)	18.4[a]	*3.9*	10.9[ab]	*4.5*	13.4[ab]	*7.9*	6.0[b]	*2.2*	3.99	0.0283	17.0[a]	*6.6*	13.6[ab]	*4.9*	5.9[b]	*2.3*	6.67	0.0145	1.05	0.4129
	0.0	*5.1*	-4.6	*2.8*	1.7	*4.6*	-1.0	*2.3*	2.03	0.1524	-5.5	*3.8*	1.9	*3.5*	0.7	*3.1*	3.00	0.0954	0.81	0.5714
Forb Cover (%)	1.2	*0.7*	1.6	*0.7*	1.8	*0.8*	0.8	*0.5*	1.27	0.3190	1.5	*0.8*	1.7	*0.6*	0.9	*0.3*	0.39	0.6796	0.87	0.5245
	1.1	*0.6*	1.2	*0.5*	-1.6	*2.1*	0.5	*0.4*	1.46	0.2551	-0.2	*0.5*	0.2	*1.2*	0.8	*0.3*	1.31	0.2808	1.55	0.1866
Woody Cover (%)	9.8[b]	*1.3*	15.1[ab]	*1.9*	17.3[a]	*3.3*	15.7[ab]	*3.7*	2.96	0.0421	20.1[a]	*4.2*	12.4[ab]	*2.2*	10.9[b]	*2.0*	4.91	0.0326	0.69	0.6565
	3.3	*2.1*	1.3	*4.2*	3.7	*3.6*	5.8	*3.8*	1.24	0.3080	6.0	*5.1*	0.8	*3.6*	3.7	*1.7*	1.42	0.2873	2.20	0.0603
Hardwood Litter Cover (%)	14.5[ab]	*2.9*	10.4[b]	*3.8*	10.7[b]	*4.2*	24.7[a]	*3.8*	5.62	0.0087	15.8	*5.6*	14.2	*2.3*	15.2	*3.8*	0.04	0.9575	0.80	0.5800
	8.8[ab]	*2.7*	3.7[b]	*2.4*	4.2[ab]	*3.8*	11.8[a]	*4.6*	4.01	0.0279	4.4	*3.1*	6.8	*3.3*	10.2	*4.3*	2.88	0.1026	1.34	0.2701
Pine Needle (%)	33.4	*4.6*	33.3	*9.8*	31.0	*5.3*	37.8	*4.7*	0.23	0.8727	12.5[c]	*5.2*	33.4[b]	*5.3*	55.7[a]	*2.7*	56.00	<0.0001	1.08	0.3926
	10.9	*5.0*	11.2	*4.1*	3.8	*4.6*	4.3	*5.3*	0.95	0.4428	-1.1[b]	*4.3*	5.8[ab]	*3.1*	18.0[a]	*4.5*	5.47	0.0248	0.74	0.6225
Woody Litter Cover (%)	3.9	*2.9*	4.2	*2.6*	4.9	*2.4*	3.1	*1.4*	0.73	0.5502	2.6[b]	*1.7*	3.9[ab]	*1.9*	5.5[a]	*3.0*	4.22	0.0218	0.97	0.4593
	-9.1	*4.2*	-8.1	*4.8*	-4.4	*4.1*	-7.8	*2.8*	0.91	0.4594	−0.9[a]	*2.2*	−7.0[ab]	*3.1*	−14.0[b]	*4.9*	11.44	0.0001	1.36	0.2531
Bare Ground (%)	0.5	*0.3*	0.6	*0.3*	0.9	*0.7*	0.3	*0.2*	0.2	0.8991	0.6	*0.3*	0.9	*0.6*	0.3	*0.1*	1.41	0.2892	1.35	0.2549
	-2.8	*2.0*	-4.4	*2.8*	-1.1	*1.5*	-1.0	*0.6*	0.43	0.7336	-0.8	*1.0*	-2.7	*1.4*	-3.4	*2.0*	1.56	0.2577	1.17	0.3489
Burned (%)	59.1	*9.6*	55.3	*10.7*	37.9	*12.5*	47.4	*13.8*	1.41	0.2786	35.6	*12.7*	49.0	*10.7*	65.3	*7.9*	6.98	0.0127	0.82	0.5606

A-3.9.10. Pre-fire (first line) and fuel consumption (second line) measurements for 1000-hour fuels (mean|*SE*) for gap size and direction effects in the gap treatments at Camp Lejeune, NC. Different letters within a row indicate significant treatment differences at α = 0.05. Note: fuel consumption measured as pre-fire - post-fire.

	Gap Size						ANOVA		Direction								ANOVA		Main*Sub ANOVA	
Fuel	LG		MG		SG		F-value	p-value	E		N		S		W		F-value	p-value	F-value	p-value
1000-hour (Mgha[-1])	49.842	*17.781*	72.630	*34.995*	19.257	*17.175*	1.31	0.3027	50.758	*30.650*	36.806	*9.044*	78.470	*25.826*	21.075	*5.233*	1.37	0.2842	0.60	0.7262
	13.380	*8.842*	22.927	*12.736*	5.756	*5.079*	0.66	0.5333	9.728	*10.321*	11.162	*3.786*	29.811	*9.118*	5.360	*5.183*	0.54	0.6557	1.21	0.3180

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Technical Publications and Presentations

Referreed journals

Knapp, B.O., Wang, G.G., and Walker, J.L. 2013. Effects of canopy structure and cultural treatments on the survival and growth of *Pinus palustris* Mill. seedlings underplanted in *Pinus taeda* L. stands. Ecological Engineering 57: 46-56.

Hu, H., G.G. Wang, J.L. Walker, and B.O. Knapp. 2012. Silvicultural treatments for converting loblolly pine to longleaf pine dominance: effects on resource availability and their relationships with planted longleaf pine seedlings. Forest Ecology and Management 282: 115-123.

Hu, H., G.G. Wang, J.L. Walker, and B.O. Knapp. 2012. Silvicultural treatments for converting loblolly pine to longleaf pine dominance: effects on planted longleaf pine seedlings. Forest Ecology and Management 276: 209-216.

Knapp, B.O., G.G. Wang, H. Hu, J.L. Walker, and C. Tennant. 2011. Restoring longleaf pine (*Pinus palustris* Mill.) in loblolly pine (*Pinus taeda* L.) stands: effects of restoration treatments on natural loblolly pine regeneration. Forest Ecology and Management 262(7): 1157-1167.

Proceedings publications

Hu, H., B.O. Knapp, G.G. Wang, and J.L. Walker. 2013. Effects of canopy treatments on first year growth of planted longleaf pine seedlings: a preliminary study. In: Guldin, J.M. (ed.) Proceedings of the 15th Biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SRS-175. USDA Forest Service, Southern Research Station. 157-161.

Technical oral presentations

Knapp, B.O., Wang, G.G., Walker, J.L., and Hu, H. 2013. From loblolly to longleaf: five-year results of a longleaf pine restoration study at two ecologically distinct sites. 17th Biennial Southern Silvicultural Research Conference. March 5-7, 2013. Shreveport, LA.

Knapp, B.O., J.L. Walker, and G.G. Wang. 2011. Effects of longleaf pine restoration management on ground layer vegetation in existing lobolly pine forests of the southeastern United States. 96th Ecological Society of America Annual Meeting. August 7-12, 2011. Austin, TX.

Knapp, B.O., G.G. Wang, H. Hu, J.L. Walker, and C. Tennant. 2011. Developing silvicultural protocols for longleaf pine (*Pinus palustris* Mill.) ecosystem restoration in loblolly pine (*Pinus taeda* L.) forests at Fort Benning, GA. 16th Biennial Southern Silvicultural Research Conference. February 15-17, 2011. Charleston, SC.

Knapp, B.O., G.G. Wang, and J.L. Walker. 2010. Resource availability and planted longleaf pine (*Pinus palustris*) seedling response across canopy gaps in a loblolly pine (*Pinus taeda*) forest. 95th Ecological Society of America Annual Meeting. August 1 – 6, 2010. Pittsburgh, PA.

Knapp, B.O., H. Hu, J.L. Walker, G.G. Wang. 2010. Restoration of native grass species following harvesting treatments at Camp Lejeune, NC and Fort Benning, GA. 71st Annual Meeting of the Association of Southeastern Biologists. April 8-10, 2010. Asheville, NC.

Knapp, B.O., J.L. Walker, H. Hu, G.G. Wang. 2009. Longleaf pine restoration with non-traditional silviculture: early effects of harvesting treatments on ground layer vegetation at two military installations. Annual Symposium and Membership Meeting of the Southeastern Chapter of the Society for Ecological Restoration.March 24-26, 2009. Auburn, AL.

Hu, H., G.G. Wang, J.L. Walker, and B.O. Knapp. 2008. Effects of canopy treatments on first year growth of planted longleaf pine seedlings: preliminary results. 15th Biennial Southern Silvicultural Research Conference. November 17-20, 2008. Hot Springs AR.

<u>Technical poster presentations</u>

Hu, H., G.G. Wang, B.O. Knapp, and J.L. Walker. 2011. Effects of silvicultural treatments on longleaf pine seedlings and ground layer vegetation at Camp Lejeune, NC. 16th Biennial Southern Silvicultural Research Conference. February 15-17, 2011. Charleston, SC.

Knapp, B.O., H. Hu, J.L. Walker, and G.G. Wang. 2010. Evaluating effects of restoration management on longleaf pine ecosystem establishment at Fort Benning, GA and Camp Lejeune, NC. The Partners in Environmental Technology Technical Symposium and Workshop. November 30 – December 2, 2010. Washington, DC.

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Knapp, B.O., S.R. Ryu, H. Hu, J.L. Walker, and G.G. Wang. 2008. From loblolly to longleaf: determining loblolly pine stand susceptibility to decline and silvicultural protocols for longleaf pine restoration. The Partners in Environmental Technology Technical Symposium and Workshop. December 2-4, 2008. Washington, DC.

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Ryu, S.R., G.G. Wang, J.L. Walker, and B.O. Knapp. 2008. A preliminary assessment on the health of loblolly pine stands at Fort Benning, GA. 15th Biennial Southern Silvicultural Research Conference. November 17-20, 2008. Hot Springs, AR.

Ryu, S.R., G.G. Wang, J.L. Walker, B.O. Knapp, and S. Wangen. 2007. Predicting the occurrence of loblolly pine decline in potential red-cockaded woodpecker habitat at Fort

Benning, Georgia. 14th Biennial Southern Silvicultural Research Conference. February 26-March 1. Athens, GA