

Final Report Addendum

Integrated Control and Assessment of Knapweed and
Cheatgrass on Department of Defense Installations

SERDP Project SI-1145

FEBRUARY 2008

Mark W. Paschke (Project Leader)
Edward F. Redente
Department of Forest Rangeland and Watershed
Stewardship
Donald A. Klein
Department of Microbiology, Immunology and
Pathology
Colorado State University

Lincoln Smith
Western Regional Research Center
Exotic and Invasive Weeds Research Unit
USDA - Agricultural Research Service



Strategic Environmental Research and
Development Program

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE 01 FEB 2008		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Integrated Control and Assessment of Knapweed and Cheatgrass on Department of Defense Installations				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Department of Defense Strategic Environmental Research and Development Program (SERDP)				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

This report was prepared under contract to the Department of Defense Strategic Environmental Research and Development Program (SERDP). The publication of this report does not indicate endorsement by the Department of Defense, nor should the contents be construed as reflecting the official policy or position of the Department of Defense. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Department of Defense.

TABLE OF CONTENTS

Table of Contents	2
Executive summary	3
Objective.....	4
Project background.....	4
Technical approach.....	4
Control of non-indigenous invasive plant species.....	4
Reduction of pest plant population	5
<i>Biological control</i>	5
<i>Fire</i>	5
Control of N availability	6
Seeding.....	6
Restoration of the soil community.....	6
Remote sensing of non-indigenous plant populations.....	7
Ecological Modelling	7
Project Accomplishments	9
Study sites	9
Field plot design	9
Control of non-indigenous invasive plant species.....	9
Reduction of pest plant population	9
<i>Biological control of knapweed</i>	9
<i>Fire (annual brome only)</i>	10
Control of N availability	10
Seeding.....	11
Restoration of the soil community.....	11
2006-2007 Field Tasks	12
Insect Biocontrol Agents.....	12
Soil community structure and function.....	12
Plant community biomass	12
2006-2007 Results	13
Biological control agents at Fort McCoy, WI.....	13
Soil community	15
Plant community	16
<i>Yakima Training Center Annual Brome Site – 2006 and 2007</i>	16
<i>Yakima Training Center Knapweed Site – 2006 and 2007</i>	16
Concluding Summary	17
List of technical publications.....	18
Literature Cited.....	19

EXECUTIVE SUMMARY

SERDP project SI-1145 has explored alternative control and assessment strategies for knapweeds and annual brome, two non-indigenous plant taxa, on US military installations. These plant taxa infest large areas of the Western United States and they are a major concern for military bases. Heavy maneuvering of troops and equipment causes large disturbances where native vegetation is stressed, soil is lost, and invasive noxious plants often take hold. Replacing stands of noxious weeds with native plant communities on military training grounds will reduce soil erosion and create more sustainable ecological systems. Non-indigenous invasive plants can also reduce and destroy forage for livestock and wildlife, displace native plant species, increase fire frequency, reduce recreational opportunities, and can poison domestic animals. It is imperative to find economical, ecologically sound methods to control these weeds to minimize control costs and degradation of military training grounds.

The objective of SI-1145 was to develop a general strategy for the control, monitoring and prediction of knapweed and annual brome infestations on Department of Defense installations in the Western U.S. The driving hypothesis of this research was that the control of invasive exotic plants is best achieved through multiple ecological factors acting in synergy to reduce the target population rather than single factors

Biological control, fire, manipulation of soil nitrogen availability, seeding with native late-seral species, and restoration of the soil community were combined in field studies on disturbed weed-infested sites at Yakima Training Center (YTC), WA and Fort Carson (FC), CO. The effects of these manipulations on plant community composition were originally monitored over a 4-year period (2000 - 2003) on the ground and by using multispectral remote sensing techniques. Data from the field study was incorporated into an ecosystems dynamics simulation (EDYS) model. The EDYS model was calibrated to each of the field study sites to assess the direct and indirect effects of treatments on ecosystem dynamics at multiple spatial scales and to project the potential effects of treatments on long-term successional dynamics. The project received additional funding in 2006 in order to monitor treatment effects on research plots at YTC during 2006 and 2007. This additional field data has allowed for treatment evaluation over a more ecologically-relevant time frame. This report summarizes these 2006-2007 results from YTC and discusses long-term trends in plant community dynamics during the course of the CS1145 study.

Knapweed biological control agents that were released became well established. The biocontrol agents attacked knapweed in high numbers and were likely responsible for much of the knapweed decline observed during this study, although the effects of drought on knapweed decline could not be experimentally separated from biocontrol effects. Soil N availability was significantly reduced with soil carbon amendments resulting in significant reductions in weed abundance. Soil microbial community analyses has indicated plot-level differences and molecular approaches have shown potential for discerning fungal taxa that can be used as markers of restoration success.

During 2006 and 2007 research plots at YTC were evaluated for plant and soil community responses to the treatments that were applied in 2000 and 2001. Results from 2006 and 2007 indicate that there continued to be significant differences in the resulting plant communities from the treatments. Research plots that received a combination of multiple treatments contained fewer weeds and more desirable native vegetation. These recent results, when compared to previous results, indicate that the plant communities in the various treatment plots continue to undergo successional development and that some treatments have changed the rate of that development. It appears at this time that the successional trajectory of these weed-infested plant communities can be altered and set on a more desirable course via management actions that seek to stress weeds while at the same time promoting desirable native species. This finding challenges the existing management paradigm, where resources are directed primarily at controlling weed populations with less emphasis on restoring native species.

OBJECTIVE

The objective of this research was to develop a general strategy for the control, monitoring and prediction of knapweed and annual brome infestations on Department of Defense installations in the Western U.S. The driving hypothesis of this research was that the control of invasive exotic plants can best be achieved through multiple ecological factors acting in synergy to reduce the target population rather than single factors. Project SI-1145 was originally funded for the period 2000 to 2004. An extension of funding was provided for 2006 and 2007 to monitor longer-term treatment effects on test plots at Yakima Training Center.

PROJECT BACKGROUND

SERDP project SI-1145 has explored alternative control and assessment strategies for knapweeds and annual brome, two non-indigenous plant taxa, on US military installations. Large areas of the Western United States are infested by these plant taxa and they are a major concern for military bases. Heavy maneuvering of troops and equipment causes large disturbances where native vegetation is stressed, soil is lost, and invasive noxious plants often take hold. Replacing stands of noxious weeds with native plant communities on military training grounds will reduce soil erosion and create more sustainable ecological systems. Non-indigenous invasive plants can also reduce and destroy forage for livestock and wildlife, displace native plant species, increase fire frequency, reduce recreational opportunities, and can poison domestic animals. It is imperative to find economical, ecologically sound methods to control these weeds to minimize control costs and degradation of military training grounds.

TECHNICAL APPROACH

Single method approaches to non-indigenous invasive plant management rarely are successful. In natural plant communities, populations of plant species are kept in check by multiple factors acting synergistically. Therefore, we have examined the control of non-indigenous invasive plant species by using a combination of manipulations that accelerate natural secondary succession. We tested combinations of four types of manipulations for controlling non-indigenous plant populations: 1) reduction of the pest plant population using biological control or burning, 2) reducing soil N availability, 3) reseeding with desirable mid- and late-seral plant species, and 4) reintroduction of a native late-seral soil microbial community. We tested the general usefulness of this approach by applying different combinations of these treatments to established communities of non-indigenous knapweed and annual brome at Fort Carson, Colorado and Yakima Training Center, Washington. We monitored our research plots using remote sensing techniques in order to develop methods for assessing the status of weed populations and monitoring large-scale effectiveness of control methodologies. We have extrapolated our results to larger spatial and temporal scales using an ecosystem dynamics model in order to gain insight into ecological mechanisms of control methods so that we can project the likely effectiveness of single and combined control methodologies. Our goal has been to develop a general strategy for managing these non-indigenous species on DOD lands in the Western U.S. During 2006 and 2007 our efforts were limited to monitoring treatment effects in test plots at YTC. This report serves as an addendum to the final project report submitted in May of 2005.

Control of non-indigenous invasive plant species

Large areas of the Western United States are infested by exotic plant species, particularly knapweeds (*Centaurea maculosa*, *C. diffusa*) (Roché 1994, Hirsch and Leitch 1996, Sheley et al. 1998) and annual bromes (*Bromus tectorum*, *B. japonicus*) (DiTomasso 2000). Noxious weeds are a major concern for military bases. Heavy maneuvering of troops and equipment cause large disturbances where native vegetation is stressed, soil is compacted or lost and invasive non-indigenous plants often take hold (Goran et al. 1983, Shaw and Diersing 1990). Replacing stands of non-indigenous plants with native plant communities on military training grounds may reduce soil erosion (Lacey et al. 1989) and create more sustainable ecological systems. Non-indigenous plants can also reduce and destroy forage for

livestock and wildlife (Bedunah and Carpenter 1989, Spoon et al. 1983), displace native plant species (Sheley and Jacobs 1997), reduce land use opportunities, and can poison domestic animals or people. It is imperative to find economical, ecologically sound methods to control these weeds to minimize control costs and to minimize degradation of military training grounds.

The natural process of recovery of disturbed lands (secondary succession) can take decades or even centuries depending on the nature of the disturbance. This process can be arrested by the invasion and dominance of non-indigenous species. The processes that control the rate of recovery of disturbed lands to late-seral native plant communities are poorly understood. Nitrogen (N) availability has been found to be a control mechanism of succession in several ecosystems. The rate of natural recovery of disturbed lands can also be hindered by a lack of propagules of appropriate flora and fauna, as well as by the lack of a proper balance of plants and insect herbivores. Long-term disturbance to a site can destroy the soil seed bank as well as the rich community of soil organisms and insect herbivores that are vital to ecosystem functioning.

Reduction of pest plant population

Biological control

Biological control can play a key role in noxious weed management because it can permanently reduce weed populations, does not require expensive technology, and is ecologically non-disruptive (Harris and Cranston 1979, Maddox 1979, Story 1992, Radosevich et al. 1997). Twelve species of insects have been approved for introduction into the United States for biological control of spotted and diffuse knapweed (Rees et al. 1996). Most of these attack both weed species, but some of the insects are established in restricted habitats or only in a few sites. Although several of these agents have become well established and can be collected in large numbers, there is very little quantitative data on efficacy of weed control. Two flies, *Urophora affinis* and *U. quadrifasciata*, that form galls in seedheads have spread widely and have reduced knapweed seed production by 75% to 94% in British Columbia (Harris and Cranston 1979, Harris 1980). The root-feeding beetle, *Sphenoptera jugoslavica*, has become widely established in British Columbia and Washington State (Powell and Myers 1988, Lang et al. 1996), and it has reduced seedling and rosette survival, delayed flowering and reduced seed production (Powell 1990). A root-boring weevil, *Cyphocleonus achates*, which has reduced plant size in controlled experiments has multiplied prolifically in British Columbia and is also promising for application in states such as Oregon, Washington and Montana. The root-mining tortricid moth *Agapeta zoegana*, which has been introduced to western Canada (Harris and Myers 1984) and the northwestern USA (Maddox 1982), is spreading well but may have less impact on knapweed. *Larinus minutus*, a weevil whose larvae feed on developing seeds, was first released in the U.S. in 1991. It is multiplying rapidly and has decimated isolated patches of diffuse knapweed in Montana (Lang et al. 1996).

The effectiveness of biological control agents is also affected by other vegetation (interspecific plant competition; shading of soil), soil fertility, local climate, and site orientation (slope and aspect). For example, the root boring beetle, *Sphenoptera jugoslavica*, is more successful on diffuse knapweed when the plant is growing among determinate grasses that largely cease growing after flowering in the spring or early summer (Harris and Clapperton 1997). Arbuscular mycorrhizal (AM) fungi that transfer nutrients between plant species are thought to play an important role in this interaction. The root boring weevil, *Cyphocleonus achates*, reduced shoot growth of spotted knapweed twice as much under poor N conditions as under high N (Steinger and Muller 1992).

Fire

Cheatgrass and other exotic annual plant species are good competitors with native species because their fast growth allows them to mature earlier than natives. The easily ignited fuel of a cheatgrass stand increases the likelihood of repeated fires that may eliminate native species and perpetuate dominance by cheatgrass (Pellant 1990). Seeding with desirable species after cheatgrass canopy removal by fire can be an effective restoration practice (Anderson et al. 1990, McArthur et al. 1990). However, the success of reseeding can be diminished by recolonization of the site by cheatgrass.

The large build-up of plant litter associated with a cheatgrass stand (Paschke et al. 2000) may also hinder the germination and growth of native plant species. We tested the feasibility of an initial burn to remove the annual brome canopy and prepare the site for additional treatments, such as seeding, control of soil N availability, and soil community restoration.

Control of N availability

Nitrogen availability is inversely related to the abundance of native late-seral plant species in a number of ecosystems. In European heathlands, shrub dominance decreases and perennial grasses become more abundant as available N increases (Heil and Diemont 1983, Berendse et al. 1987, Heil and Bruggink 1987, Aerts and Berendse 1988). Huenneke and coworkers (1990) found that N additions to Californian serpentine grassland led to the invasion and dominance of exotic annual grasses in patches originally dominated by native annual forbs. Shifts from late-seral to mid- or early-seral stages in forests are correlated with increases in available N (Aber et al. 1989, Cherfas 1991). Increased N availability has been shown to affect the seral process in semiarid ecosystems, slowing the replacement of weedy annuals by native herbaceous perennials (McLendon and Redente 1991 and 1992, Trent et al. 1992). Conversely, decreased N availability has been correlated with the replacement of early-seral species by mid-seral species in prairie and shrubland systems (Wedin and Tilman 1990, Tilman and Wedin 1991, McLendon and Redente 1992), and competitive success of shrubs over grasses is increased by lower N availability in semiarid (van Auken and Bush 1989) and arid ecosystems (Ettershank et al. 1978). Our research has shown that cheatgrass biomass can be reduced through reduction of soil N availability in sagebrush shrublands (McLendon and Redente 1991) and on abandoned agricultural fields in shortgrass steppe (Paschke et al. 2000). The effects of reducing soil N availability on knapweeds have not been established.

Seeding

Seeding is a common practice in ecological restorations. The composition of the restored plant community can be controlled, and when used in combination with other treatments, seeding with native species may hinder development of a non-native plant community (Redente and DePuit 1988, DePuit and Redente 1988, Sheley et al. 1998). Seeding with native species is an important restoration method for establishing plant communities that effectively control erosion, are self sustaining, require only minimal management, and provide excellent wildlife habitat (Redente and Keammerer 1999). Seeding can also lead to communities with greater plant diversity that contributes to greater stability and more effectively meet the demands of multiple land uses (Munshower 1994).

Restoration of the soil community

Soil is a habitat for numerous and diverse organisms including bacteria, fungi, algae, lichens, protozoa, nematodes, microarthropods, macroarthropods, annelids, and molluscs. The soil community is an intricate part of the functionality of most terrestrial ecosystems. When soil habitats are severely degraded, their physical and biological attributes are compromised, resulting in far-reaching effects on the soil community.

The reestablishment of soil functionality following disturbance is dependent on assuring that the assemblage of soil organisms and vegetation with their respective influences on the soil environment and the plant-soil system. In some instances, the introduction of a single genus of a particular organism to a site can have profound effects on the structure and function of an ecosystem. An example is the practice of introducing symbiotic organisms such as mycorrhizae (improvement of plant responses to stress, as well as access to nutrients and soil moisture), or the diazotrophs *Rhizobia* and *Frankia*, to facilitate nitrogen accumulation by the plant community. Introduction of these microbes is often used successfully to enhance survival and growth of plants used in reclamation efforts. Unfortunately, commercial sources of these and other beneficial organisms are limited (Torrey 1992). The reintroduction of these endophytes and other beneficial organisms could be achieved by reintroducing healthy native soil to the restoration site. This technique may prove to be a low-cost and effective alternative to the inoculation of plants with select exotic microsymbionts.

A critical aspect of the exotic/native plant dynamic, that has been given lesser emphasis, is mycogenic; the structure of the filamentous fungal community, including the mycorrhizal extraradical hyphae and saprophytic fungi, reflects the nutritional and functional status of the fungal community (Klein and Paschke, 2005). The environment in which the fungi are functioning is suggested to be closely linked to the environment in which the plant community is functioning and competing. Information on filamentous fungal community structure may assist in better predicting the outcome of such competition, particularly in the context of management of such complex systems to minimize/preclude invasion by knapweeds, and other exotic invasive species.

In this context, the structure of the filamentous fungal community may be able to be related to specific soil conditions that will promote native perennial plant species maintenance and development. Among factors that may influence filamentous fungi, as well as plant community development, are nitrogen availability (Johnson et al., 2003), the C:N ratio and nutrient content/composition of plants undergoing decomposition (Klein et al., 1989), and the soil microbial community that is present or which can be added. In addition, nutrient pool shifts involving changes such as substrate lignification (Klein et al., 1995) and substrate heterogeneity (Holland and Coleman, 1987; Davidson, 1998; Rayner et al., 1999) may reflect common factors influencing both filamentous fungi and the invasive plant-native perennial grass interaction. The dynamics of root infection, including mycorrhizal (Allen et al., 2003) and non-mycorrhizal fungi (Mozafar et al., 2000) also are critical aspects of these interactions.

Stimulating the redevelopment of the soil community, both directly and indirectly, may accelerate the restoration of sites dominated by non-indigenous invasive plants. Military training grounds provide an excellent opportunity for exploring this approach because they usually contain intact areas of relatively undisturbed native plant and soil communities adjacent to degraded sites dominated by non-indigenous plants. These undisturbed soil communities could serve as unique sustainable sources of organisms for use in restoring adjacent disturbed lands dominated by non-indigenous plant species.

Remote sensing of non-indigenous plant populations

The development of comprehensive integrated weed management strategies requires timely and accurate information concerning the extent and distribution of weed populations. The field component of this project provided a unique opportunity to develop and test methods for monitoring populations of knapweed and cheatgrass from remote platforms. Thorough monitoring of plant populations in test plots through time, as done here, provided excellent sites for testing more cost-effective monitoring tools. The test plots in this study were monitored annually using high resolution multispectral airborne imagery. These data will be used with the detailed ground-collected plant community data to develop methods for assessing knapweed and cheatgrass populations on a larger spatial scale.

The Department of Energy Remote Sensing Laboratory (RSL) has shown that significant relationships exist between biological parameters related to plant conditions and spectral data. Utilizing laboratory-measured characteristics, we have been able to identify significant regressions between plant biomass and spectral data, as well as derived spectral indices (Blohm and Best 1995).

Assessing the relationships between spectral data and general plant characteristics was accomplished by using radiometric and geometric rectification of acquired Daedalus 1268 multispectral scanner digital imagery, simultaneous collection of aerial photography, and acquisition of ground-based imagery. Effectiveness of treatments on vegetation test sites was qualitatively and quantitatively monitored with airborne multispectral scanner imagery as well as from aerial and ground photography.

Further details of the approach used in the remote sensing portion of this project are available in the SI-1145 2004 Final Technical Report:

Ecological Modelling

The simulation modeling for this project was conducted using the EDYS ecological model. EDYS is a PC-based, mechanistic model that provides a powerful tool for evaluating ecological responses to a wide variety of natural and anthropogenic stressors over time, on spatial scales ranging from small plots to large landscapes and watersheds. EDYS has been applied to over 40 ecological communities

within deserts, forests, grasslands, shrublands, wetlands, and highly disturbed areas. The objective of this EDYS application was to evaluate long-term ecological responses to a set of management options experimentally tested at YTC and FC to control invasive species and to project rates and patterns of vegetation recovery through secondary succession.

Our first step was to validate the EDYS model for these sites. This was done by parameterizing the model for the initial conditions at the beginning of the field experiments, simulating the changes in the vegetation over the four-year experimental period, and then comparing these simulation results to data from the field experiments. Following this validation procedure, 50-year simulation runs were conducted to evaluate long-term responses to the control methods. Effects of variations in environmental and management factors were then simulated to estimate how these factors might impact the control of cheatgrass and knapweed and the recovery of the native vegetation.

The field experiments were applied to two sites at YTC and FC, and EDYS was applied to these same four sites. One site at each base was dominated by annual brome and the other was a community that had been invaded by knapweed. Each site consisted of a 4000 m² treatment area, divided into 40 10 m x 10 m treatment plots. The EDYS footprint consisted of 40 cells at each of the four sites, each cell corresponding to a treatment plot. Twenty plant species were included in this application at YTC and thirty at FC, along with the four treatments (prescribed fire/biological control, seeding to native perennial species, application of sugar, and microbial application). The four treatments were modeled as single factors and each of the combinations used in the experimental study. A control (no treatment applied) was included for each site. In addition to the treatments, natural ecological stressors (precipitation fluctuations, natural fire, intra- and inter-specific competition, ecological succession, natural herbivory by insects and rabbits, and livestock grazing) and military training (tracked and wheeled vehicles) were also included as environmental factors.

Further details on the approach used in the ecological modelling portion of this project and results are described in the 2004 SI-1145 Final Technical Report.

PROJECT ACCOMPLISHMENTS

Study sites

Originally, two US Army installations participated in this research. Yakima Training Center (YTC) in Washington and Fort Carson (FC) in Colorado each contain problem populations of the non-indigenous invasive plants knapweed (spotted knapweed at FC and diffuse knapweed at YTC) and annual brome (downy brome at YTC and Japanese brome at FC). Site personnel recommended several infestation sites for the project and these were evaluated by the PIs in April 2000. Site selection was based on accessibility, level of infestation, presence of biocontrol agents, and suitability for remote sensing work.

At FC, a suitable knapweed study site was established along Little Turkey Creek adjacent to the Turkey Creek Recreation Area. A population of spotted knapweed (*Centaurea maculosa*) at this site was identified by base personnel as a high priority for control. The area is regularly impacted by light vehicles. A large tract of annual brome within the Turkey Creek Recreation Area was also identified as a high priority for control. The area is currently not used for military training so it affords easy access for this study. The area has been used as a hay meadow and pasture in the past for Army cavalry units. Base personnel had mapped this community as an infestation of *Bromus tectorum* L. However, during our plant biomass sampling in the summer of 2000 we determined that the major cheatgrass species in this community was *Bromus japonicus* Thunb. ex Murr. These two species are easily confused and both are often grouped under the colloquial “cheatgrass” term. Both are annual exotic grasses in the Bromus genus and have very similar life histories and ecological characteristics (Hulbert 1955). Both study sites at FC contain numerous additional species of introduced weedy plants.

Very large expanses of cheatgrass (*Bromus tectorum* L.) are present at YTC, and with the assistance of base personnel, we located a suitable study site at the eastern edge of Training Area 4, on an upper terrace of the Columbia River floodplain. The area is used as a troop assembly area or camp during training exercises. A suitable knapweed site was located in Assembly Area 1. This site contains a problematic population of diffuse knapweed (*Centaurea diffusa* Lam.). Some biological control agents of knapweed were already present at this site, so a suitable control site was located some distance away near Badger Gap. SYBOR stakes were installed around all of the experimental plots at YTC to minimize troop damage to the research plots during the course of the study.

Field plot design

Immediately after the study sites were identified in April 2000, we established grids of 10- x 10-m study plots that would later contain a factorial arrangement of the four treatments (biocontrol for knapweed and burning for annual brome, sucrose amendment, seeding with native plant species and, soil community restoration) plus controls. Each treatment combination and control plot was replicated 5 times. Plots were arranged on the sites to avoid obvious discontinuities in the landscape and to maximize evenness in the experimental plant communities. Since the biological control agents of knapweed are mobile, and because the burning of annual brome was to be applied to a single area at each installation, additional control plots were located at sufficient distance from study plots to allow analysis of biological control and burning effectiveness.

Control of non-indigenous invasive plant species

Reduction of pest plant population

Biological control of knapweed

Initial assessments of knapweed biocontrol agents at our research sites in spring 2000 revealed that the root beetle, *Sphenoptera jugoslavica*, was already well established at the YTC research sites. One larva of the root weevil, *Cyphocleonus achates*, and no root moths, *Agapeta zoegana*, were observed at the FC site. The seedhead gall flies, *Urophora affinis* and *U. quadrifasciata*, were well established at all

sites at both locations. Based on these results, we decided to release only *Larinus minutus* at the YTC knapweed release site. By fall 2001, it became clear that the insect biological control agents were dispersing much better than anticipated. Infestation rates at the control site (treatment 1) at YTC had become as high as at the release site, so we decided to use a systemic insecticide to suppress the insects at the control site. In 2002, we applied insecticide (0.16 oz acephate [75% active ingredient] per gallon) to individual knapweed plants in treatment 1 in June and August. This treatment was repeated in May and July of 2003. No insecticide applications were made in 2004. The insecticide may have reduced the flower weevil population in fall 2003, but the seedhead flies were still abundant (see Final Technical Report). In spring 2004, the root beetle population decreased twice as much at the check site (treatment 1) as at the release site (treatments 2-8), which may have been due to the insecticide applications in 2003 effectively reducing the beetle population. The beetles have only one generation per year, but the flies have two or more generations, so their populations may have been able to recover as insecticide concentrations declined.

We planned on continued monitoring of insect biological control populations and effects on knapweed at YTC during the project extension (2006-2007) but our efforts to do so were severely limited by the decline of spotted knapweed plants at YTC. Therefore, in 2006 we established similar insect studies within a spotted knapweed infestation at Fort McCoy, WI where our efforts have continued. This will allow us to test hypotheses regarding biological controls in collaboration with SERDP project SI1388.

The presence of biological control agents in spotted knapweed seedheads and roots at Fort McCoy was assessed in Spring and Fall of 2006 and 2007 following procedures used previously at YTC. In addition, we measured impacts of the insects by counting seeds and carefully monitoring weed abundance in plots treated with systemic insecticides compared to untreated plots. In addition, root collections were made of leafy spurge (a species under study in SI-1388) and dissected to determine presence and quantity of biological control agents feeding on roots. In order to ensure an adequate population of insects to study at Fort McCoy, releases of *Larinus minutus*, *Cyphocleonus achates*, *Agapeta zoegana*, were made adjacent to the study site at Ft. McCoy during 2006.

Fire (annual brome only)

The unusually dry conditions in the western US during the spring and summer of 2000 created dangerous fire conditions. Fire bans were in effect in Colorado and Washington during our targeted spring burn dates due to large wildfires near the military bases. As a result, we were not able to burn the YTC cheatgrass site until July 21 and the FC burn was delayed until October 20, 2000. At the time of the burns, conditions were dry and the late season burns were hot enough to destroy a major portion of the annual brome seed on the soil surface, and the hot burns also provided ideal conditions for fall seeding.

Control of N availability

Nitrogen availability in the study plots was reduced by applying a carbon source to immobilize soil N beginning in the summer of 2000 and continuing through the spring of 2003. Treatment plots received sucrose at a rate of 1600 kg C ha⁻¹ yr⁻¹. The sucrose was hand broadcast in increments throughout the year in order to provide a more temporally uniform reduction in available N through immobilization. Our objective was to time the applications with periods of weed growth (and N uptake) to be more effective. This sucrose application rate and method has been effective at reducing soil N availability in a number of ecosystems (McLendon and Redente 1992, McLendon and Redente 1994, Horn and Redente 1998, Paschke et al. 2000). We monitored the effectiveness of sucrose for reducing soil N availability using standard *in situ* ion-exchange resin bags during 2000, 2001 and 2002 (Binkley and Matson 1983). Results from the resin bags indicated that sucrose treatments were having the desired effect on soil N availability on annual brome sites (Figure 1). Resin bag results from the knapweed sites indicate a trend toward available soil N reduction, but the effect is not as discernable as in brome plots. This is likely due to less soil N mineralization and availability in these perennial dominated plant communities (Paschke et al. 2000).

Seeding

During the autumn of 2000 study plots were seeded with mixtures of plant species appropriate for each study site. Seed was hand broadcast on the plots and the plots were then raked by hand. Seeding rates and mixtures were based on standard practices employed by resource management personnel at the installations (Table 1). The FC plots were seeded on November 3, 2000 using 240 g of seed per plot. The YTC plots were seeded on September 26, 2000 using 227 g of seed per plot. Preliminary analysis of 2001 data and ground surveys made in the autumn of 2001 indicated that seeded species had not yet established at either military base. Base personnel indicated that similar results were observed for other seeding efforts on the bases during this dry year (Figures 2 and 3). While this lack of results during the first year is not unusual (personal communication with base personnel), especially in dry years, it was decided to augment the seeding with a second application of seed. This second seeding was conducted on December 1, 2001 at YTC and April 2, 2002 at FC.

Table 1. Seed mixtures used in the study.

Installation	Common name	Genus species	Purity
Fort Carson	Western wheatgrass	<i>Pascopyrum smithii</i>	35.79
	Sideoats grama	<i>Bouteloua curtipendula</i>	24.91
	Crested wheatgrass	<i>Agropyron cristatum</i>	10.59
	Alfalfa	<i>Medicago sativa</i>	5.01
	Alkali sacaton	<i>Sporobolus airoides</i>	1.09
	Sand dropseed	<i>Sporobolus cryptandrus</i>	1.06
Yakima Training Center	Siberian wheatgrass	<i>Agropyron fragile</i>	32.31
	Bluebunch wheatgrass	<i>Pseudoroegneria spicata</i>	20.91
	Beardless wheatgrass	<i>P. spicata ssp. inermis</i>	16.16
	Intermediate wheatgrass	<i>Agropyron intermedium</i>	8.24
	Indian ricegrass	<i>Achnatherum hymenoides</i>	7.49
	White yarrow	<i>Achillea millefolium</i>	7.45
	Canby bluegrass	<i>Poa secunda</i>	3.44

Restoration of the soil community

At the time of plot establishment, an undisturbed late-successional plant community was identified adjacent to each experiment site. These late-successional native plant communities were used as a source of donor soil for the experimental sites infested with the invasive plant species. Soil inoculum was collected from these sites by shovel (rocky soils precluded the use of other methods) on September 26, 2000 at YTC and November 3, 2000 at FC. The soil was immediately transported to the research plots where it was hand broadcast on the plots at a rate of 400 grams (dry weight basis) per plot. This treatment was repeated in the spring of 2002 at both military bases.

2006-2007 Field Tasks

Insect Biocontrol Agents

We planned on continued monitoring of insect biological control populations and effects on knapweed at YTC during the project extension (2006-2007) but our efforts to do so were severely limited by the decline of spotted knapweed plants at YTC. Therefore, in 2006 we established similar insect studies within a spotted knapweed infestation at Fort McCoy, WI where our efforts have continued. This has allowed us to test hypotheses regarding biological controls in collaboration with SERDP project SI-1388. The presence of biological control agents in spotted knapweed seedheads and roots at Fort McCoy was assessed in Spring and Fall of 2006 and 2007 following procedures used previously at YTC. In addition, we measured impacts of the insects by counting seeds and carefully monitoring weed abundance in plots treated with systemic insecticides compared to untreated plots. In addition, root collections were made of leafy spurge (a species under study in SI-1388) and dissected to determine presence and quantity of biological control agents feeding on roots.

Soil community structure and function

In 2006 and 2007, soil samples were collected from each plot at the YTC (at the time of plant community biomass sampling) for microbial community analysis. Ten soil samples were collected in each study plot using a 1.5 x 15-cm soil corer at random locations. These ten soil samples were composited to yield one soil sample per research plot. Samples were processed in the field by gently sieving through a 2.0 mm-mesh screen and then transported under cooled (5° C) conditions and processed at Colorado State University, Department of Microbiology for microscopy-based assessment of microbial community structure.

Microscopic analyses were completed within 48 h of the time of sampling. Total and active fungal biomass was determined by measuring the length and diameter of all hyphae in agar-film soil suspensions using FDA and a combination of epifluorescent and phase contrast/DIC microscopy (Ingham and Klein 1984a, b, Stamatiadis et al. 1990, Lodge and Ingham 1991).

Plant community biomass

Plant community biomass composition of the research plots was assessed in June of 2006 and 2007 at YTC by clipping six randomly located 0.5 m² quadrats in each study plot. Plants were clipped to ground level, separated by species, and then transported to the lab where they were dried to constant mass and weighed. Voucher specimens of all plant taxa were collected for positive identification and deposition in the Restoration Ecology Herbarium at CSU.

2006-2007 Results

Biological control agents at Fort McCoy, WI

The root-feeding weevil, *Cyphocleonus achates*, occurred at very low densities in 2006 and 2007 at the Fort McCoy study plots (Fig. 1). Insecticide treatment did not affect infestation rate of roots in spring 2007 (samples in 2006 preceded application of insecticides). The root-feeding moth, *Agapeta zoegana*, was not observed either year. Infestation of seedheads by introduced insects continued to increase, damaging 94% of unsprayed plants in 2007 (Fig. 2).

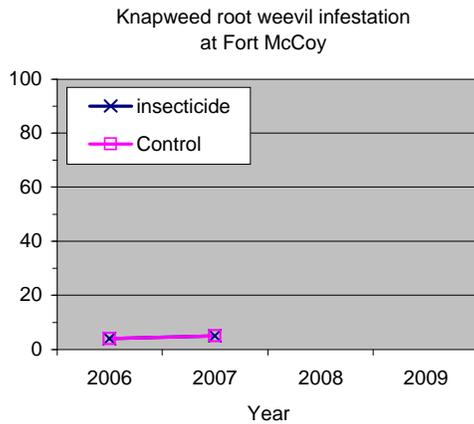


Figure 1. Infestation of insects on spotted knapweed roots in six pairs of plots, half of which received insecticide.

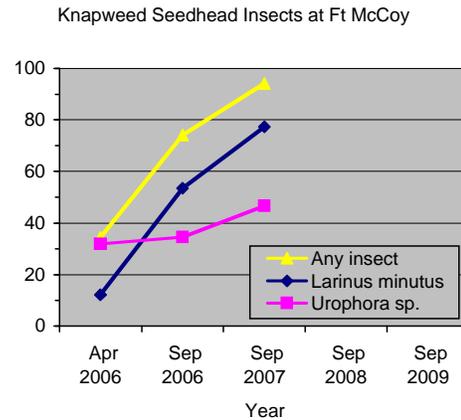


Figure 2. Infestation of spotted knapweed seedheads on unsprayed plants.

Based on dissections of seedheads collected in Sept. 2007 in six pairs of plots, insecticide treatments reduced attack by the *Urophora* flies (infesting 13% of insecticide and 69% of control seedheads) (Table 5). However, attack rates by the weevil *Larinus minutus* were actually higher on sprayed plants, as was observed last year (infesting 88% of insecticide and 72% of control seedheads). The insecticide treatments did not significantly affect mortality of *Larinus minutus* developing within seedheads (Table 6); however, it did kill more *Urophora* flies (65% in insecticide vs. 23% in control). These patterns were also observed in the regular experimental plots (Tables 7 and 8; Figs. 3 and 4). The insecticide treatments did not appear to have any effects on spotted knapweed population in the field (Table 9). Based on these results, either frequency of insecticide treatments should be increased in 2008 and/or we should switch to using a pyrethroid in 2008, which should have a stronger repellency effect.

Table 5. Effect of insecticide treatment on insects attacking spotted knapweed seedheads in September 2007 at Fort McCoy, WI (6 control plots and 6 treatment plots).

Insect species	No. seedheads	Seedheads infested		Seedheads with live insect	
		Insecticide	Control	Insecticide	Control
<i>Larinus minutus</i>	120	88.3% *	72.5%	56.7%	52.5%
<i>Urophora</i> species	120	13.3% *	69.2%	2.5% *	56.7%
Any insect	120	90.8%	91.7%	57.5% *	87.5%

* control and insecticide treatments are significantly different (ANOVA, P < 0.05).

Table 6. Effect of insecticide treatment on survival of insects attacking spotted knapweed seedheads in September 2007 (6 control plots and 6 treatment plots).

Insect species	Number of insects	Insects killed	
		Insecticide	Control
Larinus minutus	196	24.8%	16.1%
Urophora species	255	65.0% *	23.4%
Any insect	451	31.0% *	21.4%

* control and insecticide treatments are significantly different (chi square, $P < 0.05$).

Table 7. Effect of insecticide treatment on insects attacking spotted knapweed seedheads in September 2007 (100 SI-1388 experimental plots).

Insect species	No. seedheads ¹	Seedheads infested		Seedhead with live insect	
		Insecticide	Control	Insecticide	Control
Larinus minutus	1960	79.5% *	77.3%	43.2%	49.7%
Urophora species	1960	22.9% *	46.6%	11.4% *	27.7%
Any insect	1960	86.6% *	94.1%	51.5% *	71.8%

¹ No seedheads were collected in plots 41 and 44.

* control and insecticide treatments are significantly different (ANOVA, $P < 0.05$).

Table 8. Effect of insecticide treatment on survival of insects attacking spotted knapweed seedheads in September 2007 (100 SI-1388 experimental plots).

Insect species	Number of insects	Insects killed	
		Insecticide	Control
Larinus minutus	1935	36.5%*	25.2%
Urophora species	2019	42.3%	41.5%
Any insect	3954	40.3% *	30.7%

* control and insecticide treatments are significantly different (chi square, $P < 0.05$).

Table 9. Density of target weed species by insecticide treatment in experimental plots at Fort McCoy, WI in 2007. Density of target weed species (spotted knapweed or leafy spurge; number/m²) in plots receiving insecticide treatment ($n = 40$) versus those that were not sprayed ($n = 40$). Data is presented for both rosettes and bolts of spotted knapweed, and stem counts for leafy spurge. No significant treatment effect detected. Means are reported \pm standard error.

Target species	No Insecticide	Insecticide
Spotted knapweed: Rosettes	10.73 \pm 2.38	9.00 \pm 1.57
Spotted knapweed: Bolts	15.57 \pm 1.78	15.10 \pm 2.00
Leafy spurge: Stems	34.97 \pm 4.83	34.23 \pm 6.01

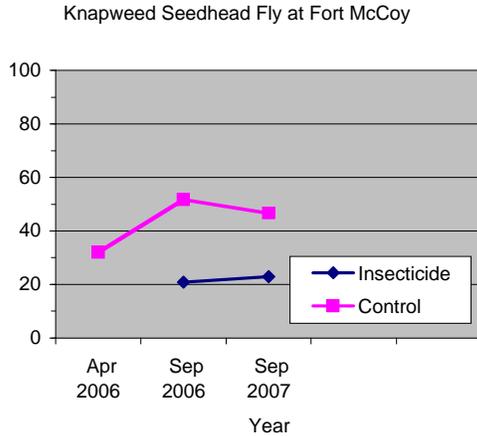


Figure 3. Infestation of spotted knapweed seedheads by *Urophora* gall flies on sprayed and unsprayed plants in the 100 experimental plots.

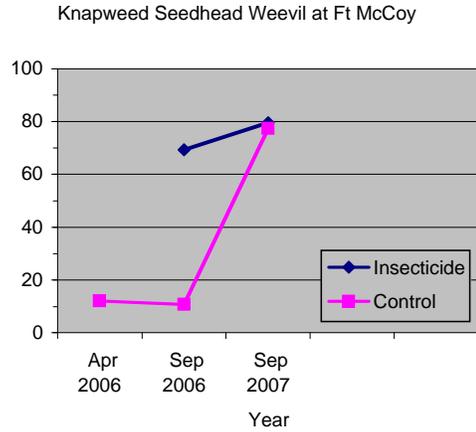


Figure 4. Infestation of spotted knapweed seedheads by the weevil, *Larinus minutus*, on sprayed and unsprayed plants in the 100 experimental plots.

Soil community

Extraradical filamentous fungal responses for the YTC plots in 2006 and 2007 are shown in Table 4. Total and active hyphal lengths were similar between control and treated plots except for total fungi at the cheatgrass site where some differences were detected in 2006. At this early point of plant community development it does not appear that hyphal lengths differ greatly among the plots.

Table 4. Mean hyphal lengths (m/g soil) of active and total soil fungi in treatment plots at the cheatgrass and knapweed study site at Yakima Training Center in 2006 and 2007 (n = 4). Means within a column followed by the same letter are not significantly different (t-test, alpha = 0.05). Treatments are: 1 = control, 2 = biocontrol, 3 = biocontrol + seeded, 4 = biocontrol + N reduction, 5 = biocontrol + seeded + N reduction, 6 = biocontrol + seeded + soil inoculation, 7 = biocontrol + N reduction + soil inoculation, 8 = biocontrol + seeding + N reduction + soil inoculation.

Study Site	Treatment	Active Fungi		Total Fungi		Percent Active	
		2006	2007	2006	2007	2006	2007
Cheatgrass	1	24.61	20.78	237.86 ab	114.31	10.33	15.83
	2	13.67	0.00	174.98 ab	77.94	10.30	0.00
	3	16.40	25.98	142.17 b	119.51	13.72	12.50
	4	5.47	15.59	300.74 a	166.36	5.87	4.61
	5	24.61	0.00	199.58 ab	67.51	9.52	0.00
	6	41.01	41.57	183.18 ab	161.08	12.57	19.83
	7	21.87	5.20	215.99 ab	140.29	11.65	1.47
	8	16.40	25.98	210.52 ab	161.08	6.56	16.19
Knapweed	1	0.00	10.39	125.76	124.71	0.00	6.50
	2	10.94	10.39	92.96	187.06	25.00	3.89
	3	19.14	0.00	123.04	88.33	13.33	0.00
	4	8.20	5.20	51.95	109.12	13.40	2.94
	5	16.40	25.98	106.63	166.27	7.06	13.33
	6	2.73	10.39	164.04	119.51	1.82	4.17
	7	16.40	10.39	133.97	62.35	7.62	15.28
	8	21.87	20.78	103.89	197.46	14.17	7.68

Plant community

Plant community biomass composition of the research plots at YTC was assessed prior to treatments in the early summer of 2000 to provide baseline data. The plant community was sampled again in 2001, 2002, 2003, 2006 and 2007. Results from the 2001 sampling indicated that significant desirable treatment effects had already occurred in many of the test plots. The biomass of invasive species had been reduced by treatment combinations and in some cases treatments had increased the biomass of desirable species. These observations were also evident from the remote sensing data.

Yakima Training Center Annual Brome Site – 2006 and 2007

The YTC annual brome site continued to be dominated by cheatgrass in 2007 (Table 2). Although, cheatgrass appeared to be declining based upon differences between 2003 and 2006, there was a rebound in cheatgrass dominance in 2007. The reduction in relative dominance in cheatgrass at this site during 2006 was due to a flush of exotic annual forbs during this year. In 2006 and 2007 it appears that treatment 5 (burn, seed and reduce soil N) is trending toward having significantly more native and desirable plant biomass than other treatments. However, given the still very-early seral nature of this site, it may be too soon to draw meaningful conclusions. These observations of long-term persistence of cheatgrass followed by gradual establishment and increasing presence of natives is consistent with EDYS model predictions that were made based on earlier trends (Mata-Gonzalez et al., 2006). The decline in cheatgrass appears to be occurring due to increased relative abundance of annual forbs and perennial grasses, so the site appears to be undergoing the natural secondary successional pathways predicted by the EDYS model.

Table 2. Mean relative biomass (% of total biomass) of cheatgrass, native plant species, and desirable plant species (native, late-successional plus seeded species) in treatment plots at the cheatgrass study site at Yakima Training Center in 2003, 2006 and 2007 (n = 4). Means within a column followed by the same letter are not significantly different (t-test, alpha = 0.05). Treatments are: 1 = control, 2 = burn, 3 = burn + seeded, 4 = burn + N reduction, 5 = burn + seeded + N reduction, 6 = burn + seeded + soil inoculation, 7 = burn + N reduction + soil inoculation, 8 = burn + seeding + N reduction + soil inoculation.

Treatment #	Cheatgrass			Native			Desirable		
	2003	2006	2007	2003	2006	2007	2003	2006	2007
1	81.33 ab	37.72	77.08a	0.01	0.04 b	0.16	0.01	0.04 b	0.16
2	77.62 b	54.55	86.06ab	0.00	0.36 ab	0.27	0.12	0.16 b	0.21
3	80.16 ab	43.11	85.34ab	0.00	0.37 ab	0.00	1.74	0.00 b	0.00
4	79.32 b	37.57	86.85ab	0.00	1.11 a	1.31	0.00	0.00 b	1.14
5	84.05 ab	52.96	90.04ab	0.10	0.11 ab	2.08	0.10	1.99 a	2.08
6	80.85 ab	38.65	89.39ab	0.00	0.17 ab	0.00	0.02	0.00 b	0.00
7	92.32 a	52.88	95.80b	0.00	0.07 b	0.00	0.00	0.00 b	0.00
8	77.27 b	43.18	80.76ab	0.00	0.52 ab	0.09	2.95	0.00 b	0.00

Yakima Training Center Knapweed Site – 2006 and 2007

Significant and desirable treatment effects continue to be evident in treated plots at the YTC knapweed study site (Table 3). Treated plots are characterized by an increased abundance of native species. The relative ranking of the various treatments (3-8) in 2007 is still unclear depending on which variables one chooses to compare. Also, at this early point in time of successional development of the plant communities, treatments have not have a long enough time to result in very many statistical differences in plant variables. However, within treated plots, the relative abundance of native plant species appears to be increasing with time. In the insect control plots (treatment 1) where insects were not released, the trend is the opposite, with native species declining as diffuse knapweed increases. Whether this resurgence of knapweed in treatment 1 is due to insecticide treatments in 2003 and 2004 is

unclear at this point. Further monitoring of the plots at a later date would indicate if knapweed resurgence is unique to treatment 1, or perhaps all treatments will eventually see increases in knapweed. However, the good establishment of native and desirable species in treatments 3 through 8 with the reduction of knapweed biomass indicates that the long-term momentum of the plant community has been shifted in favor of native late-seral vegetation. Whether this vegetation can resist re-invasion of knapweed will need to be evaluated at a later date.

Table 3. Mean relative biomass (%) of diffuse knapweed, native species, and desirable species (native, late-successional plus seeded species) in treatment plots at the knapweed study site at Yakima Training Center in 2003, 2006 and 2007 (n = 4). Means within a column followed by the same letter are not significantly different (t-test, alpha = 0.05). Treatments are: 1 = control, 2 = biocontrol, 3 = biocontrol + seeded, 4 = biocontrol + N reduction, 5 = biocontrol + seeded + N reduction, 6 = biocontrol + seeded + soil inoculation, 7 = biocontrol + N reduction + soil inoculation, 8 = biocontrol + seeding + N reduction + soil inoculation.

Treatment #	Diffuse knapweed			Native			Desirable		
	2003	2006	2007	2003	2006	2007	2003	2006	2007
1	3.99	3.91a	32.22a	59.09	50.98bc	47.75a	31.48b	25.58c	26.51a
2	0.18	2.08ab	7.96b	43.18	41.66c	62.87ab	42.68ab	45.60abc	53.45ab
3	0.27	0.09b	0.76b	47.96	79.78a	91.62c	43.89ab	59.70ab	63.43b
4	1.62	0.35b	0.00b	62.31	78.27a	91.56c	48.94ab	67.38ab	69.70b
5	1.09	0.00b	2.45b	52.48	67.97ab	75.95bc	39.34ab	48.22abc	67.93b
6	0.88	1.17ab	4.56b	48.81	51.56bc	71.76abc	36.92ab	42.40bc	63.97b
7	3.82	0.53b	0.84b	57.28	82.42a	79.07bc	48.16ab	73.13a	42.42ab
8	1.14	0.11b	0.32b	66.13	70.90ab	82.04bc	61.75a	69.75ab	62.53b

CONCLUDING SUMMARY

During 2006 and 2007, SI-1145 research plots at Yakima Training Center were evaluated for plant and soil community responses to the treatments that were applied in 2000 and 2001. Results from 2006 and 2007 indicate that there continues to be significant differences in the resulting plant communities from the treatments. Research plots that received a combination of multiple treatments continue to contain fewer weeds and more desirable native vegetation. This is more evident at the knapweed test site whereas the cheatgrass test site continues to be dominated by cheatgrass in all treatments. These recent results, when compared to previous results, indicate that the plant communities in the various treatment plots continue to undergo successional development and that some treatments have favorably changed the rate of that development. At this point in time, it appears that treatments that reduce weed abundance combined with treatments that promote desirable species will yield the best results. Our results suggest that management that focuses only on weed control may simply obtain temporary solutions. In the absence of competition from native plant species, weeds may simply rebound as we have observed in this study in the knapweed control plots. However, given the dynamic nature of plant communities, the long-term outcome of the treatments on plant community dynamics will need to be evaluated at a later date to confirm this finding.

LIST OF TECHNICAL PUBLICATIONS

- Klein, D.A. 2007. Biodiversity of chytrids. Chpt 9. *In: Biodiversity in Agricultural Production Systems*, G. Benckiser and S. Sylvia Eds., CRC Taylor & Francis, Boca Raton, FL.
- Mata-Gonzalez, R., R.G. Hunter, C.L. Coldren, T. McLendon, and M.W. Paschke. 2006. Modeling plant growth dynamics on *Bromus tectorum* communities affected by fire. *J. Arid Environments* 69:144-157.
- Klein, D.A., M.W. Paschke and T.L. Heskett. 2006. Comparative fungal responses in managed spotted knapweed (*Centaurea maculosa* Lam.), and diffuse knapweed (*C. diffusa* Lam.) - infested plant communities. *Applied Soil Ecology* 32:89-97.
- Meiman, P.J., E.F. Redente and M.W. Paschke. 2006. The role of the native soil community in the invasion ecology of spotted (*Centaurea maculosa* auct. non Lam.) and diffuse (*C. diffusa* Lam.) knapweed. *Applied Soil Ecology* 32:77-88.
- Klein, D.A. and M.W. Paschke. 2004. Filamentous fungi: the indeterminate lifestyle and microbial ecology. *Microbial Ecology*. 47: 224-235.
- Klein, D.A. and M.W. Paschke. 2000. A soil microbial community structural functional index: the microscopy-based total/active: fungal/bacterial (TA/AFB) biovolumes ratio. *Appl. Soil Ecol.* 14:257-268.
- Szili-Kovács, T, K. Török, Zs Hayek, M. Halassy, T. Tóth, T., M.W. Paschke, L.J. Wardell. 2000. Immobilisation of soil nitrogen as a possible method for the restoration of sandy grassland. *Applied Vegetation Science* 3: 7-14.
- Meiman, P.J. 2003. Invasion ecology of knapweed (*Centaurea* spp. L): Competition, establishment and interactions with soil biota. PhD dissertation. Colorado State University, Dept. of Forest, Rangeland and Watershed Stewardship. Fort Collins, CO.
- Smith, L. and J. M. Story. 2003. Plant size preference of *Agapeta zoegana* L. (Lepidoptera: Tortricidae), a root-feeding biological control agent of spotted knapweed. *Biological Control*. 26: 270-278.
- Al-Qarawi, A.A. 2002. Relationships among nitrogen availability, vesicular-arbuscular mycorrhizae, and *Bromus tectorum* in disturbed rangeland sites in Colorado. PhD Dissertation. Colorado State University, Dept. of Rangeland Ecosystem Science. Fort Collins, CO.
- Smith, L. (ed.). 2001. Proceedings of the First International Knapweed Symposium of the Twenty-First Century, March 15-16, 2001, Coeur d'Alene, Idaho. USDA-ARS, Albany, CA. 103 p.
- Smith, L. 2001. Considerations for Resuming Foreign Exploration for Natural Enemies of Spotted Knapweed, pp. 18-26. In L. Smith (ed.), Proceedings of the First International Knapweed Symposium of the Twenty-First Century, March 15-16, 2001, Coeur d'Alene, Idaho. USDA-ARS, Albany, CA.
- Smith, L., J. M. Story, and J. M. DiTomaso. 2001. Bibliography of Spotted Knapweed, Yellow Starthistle and Other Weedy Knapweeds. In L. Smith (ed.), Proceedings of the First International Knapweed Symposium of the Twenty-First Century, March 15-16, 2001, Coeur d'Alene, Idaho. USDA-ARS, Albany, CA. 62 p.

LITERATURE CITED

- Aber, J.D., K.J. Nadelhoffer, P. Steudler, and J.M. Melillo. 1989. Nitrogen saturation in northern forest ecosystems. *Bioscience* 39:378-386.
- Aerts, R. and F. Berendse. 1988. The effect of increased nutrient availability on vegetation dynamics in wet heathlands. *Vegetatio* 76:63-69.
- Allen, M.F., Swenson, W., Querejeta, J. I., Egerton-Warburton, L. M., Treseder, K. K., 2003. Ecology of mycorrhizae: a conceptual framework for complex interactions among plants and animals. *Annu. Rev. Phytopathol.* 41, 271-303.
- Anderson, M.R., E.J. DePuit, R.H. Abernethy and L.H. Kleinman. 1990. Suppression of annual brome grass by mountain rye on semiarid mined lands. p.47-55. *In: E.D. McArthur et al. (eds.) Proceedings of a Symposium on cheatgrass invasion, shrub die-off, and other aspects of shrub biology and management. US For. Serv., Int. Res. Sta., Gen. Tech. Rep. INT-276. Ogden, UT.*
- Barrow, J. R., Havstad, K. M., McCaslin, B. D., 1997. Fungal root endophytes in fourwing saltbrush, *Atriplex canescens*, on arid rangelands of southwestern USA. *Arid Soil Res. Rehab.* 11, 177-185.
- Bedunah, D. & J. Carpenter. 1989. Plant community response following spotted knapweed (*Centaurea maculosa*) control on three elk winter ranges in western Montana, pp. 205-212. *In P.K. Ray and J.R. Lacey (editors), Proceedings of the 1989 Knapweed Symposium, April 4-5, 1989, Bozeman, Mt. Plant and Soil Department and Extension Service, Montana State University, Bozeman, Montana.*
- Berendse, F., H. Oudhof, and J. Bol. 1987. A comparative study on nutrient cycling in wet heathland ecosystems. I. Litter production and nutrient loss from the plant. *Oecologia* 74:174-184.
- Binkley, D., and P. Matson. 1983. Ion exchange resin bag method for assessing available forest soil nitrogen. *Soil Science Society of America Journal* 47:1050-1052.
- Blohm, J.D. and R.G. Best. 1995. SNAPP acquisition and analysis final report, EG&G/EM letter report. EG&G/EM, Las Vegas, NV.
- Cherfas, J. 1991. Disappearing mushrooms: another mass extinction? *Science* 254:1458.
- Childress, W.M., T. McLendon, and D.L. Price. 1999. A multi-scale ecological model for allocation of training activities on U.S. Army installations. Pages 80-108 in J.M. Klopatek and R.H. Gardner (eds.), *Landscape Ecological Analysis*. Springer-Verlag, New York.
- DePuit, E. J. and E. F. Redente. 1988. Ecosystem dynamics on reconstructed semiarid lands, pp. 162-204. *In: Allen, E. (ed.) Reclamation of Disturbed Arid Ecosystems*. Westview Press. Boulder, CO.
- Ettershank, G., J.A. Ettershank, M. Bryant, and W.G. Whitford. 1978. Effects of nitrogen fertilization on primary production in a Chihuahuan Desert ecosystem. *J. Arid Environments* 1:135-139.
- Goran, W. D., L. L. Radke and W. D. Severinghaus. 1983. An overview of the ecological effects of tracked vehicles on major U.S. Army installations. US. Army Corps of Eng. Const Eng Res Lab. Tech. Report N-142.
- Harris, P. 1980. Effects of *Urophora affinis* Frfld, and *U. quadrifasciata* (Meig.) (Diptera: Tephritidae) on *Centaurea diffusa* Lam. and *C. maculosa* Lam. (Compositae). *Zeitschrift fur Angewandte Entomologie* 90: 190-201.
- Harris, P. and J. H. Myers. 1984. *Centaurea diffusa* Lam. *C. maculosa* Lam. diffuse and spotted knapweed (Compositae), pp. 127-137. *In: Kelleher, J.S. and M.A. Hulme (eds) Biological Control Programmes Against Insects and Weeds In Canada 1969-1980. London: Commonwealth Agricultural Bureaux.*
- Harris, P. and M. J. Clapperton. 1997. An exploratory study on the influence of vesicular-arbuscular mycorrhizal fungi on the success of weed biological control with insects. *Biocontrol Sci. Tech.* 7: 193-201.
- Harris, P. and R. Cranston. 1979. An economic evaluation of control methods for diffuse and spotted knapweed in western Canada. *Can. J. Plant Sci.* 59: 375-382.
- Heil, G.W. and M. Bruggink. 1987. Competition for nutrients between *Calluna vulgaris* (L.) Hull and *Molinia caerulea* (L.) Moench. *Oecologia* 73:105-107.

- Heil, G.W. and W.H. Diemont. 1983. Raised nutrient levels change heathland into grassland. *Vegetatio* 53:113-120.
- Hirsch, S. A. & J. A. Leitch. 1996. The impact of knapweed on Montana's economy. North Dakota State University, Fargo. Agricultural Econ. Rep. No. 355. 43 p.
- Horn, B. E., and E. F. Redente. 1998. Soil nitrogen and plant cover of an old-field on the shortgrass steppe in southeastern Colorado. *Arid Soil Research & Rehabilitation* 12:193-206.
- Huenneke LF, Hamburg SP, Koide R, Mooney HA, Vitousek PM. 1990. Effects of soil resources on plant invasion and community structure in California serpentine grassland. *Ecology* 71:478-491
- Hulbert, L. C. 1955. Ecological Studies of *Bromus-Tectorum* and Other Annual Bromegrasses. *Ecological Monographs* 25:181-213.
- Ingham, E. R., and D. A. Klein. 1984a. Soil fungi: measurement of hyphal length. *Soil Biol. Biochem.* 16:279-280.
- Ingham, E. R., and D. A. Klein. 1984b. Soil fungi: relationships between hyphal activity and staining with fluorescein diacetate. *Soil Biol. Biochem.* 16:273-278.
- Lacey, J. R., C. B. Marlow, and J. R. Lane. 1989. Influence of spotted knapweed (*Centaurea maculosa*) on surface runoff and sediment yield. *Weed Technol.* 3: 627-631.
- Lang, R. F., J. M. Story and G. L. Piper. 1996. Establishment of *Larinus minutus* Gyllenhal (Coleoptera: Curculionidae) for biological control of diffuse and spotted knapweed in the western United States. *Pan-Pacific Entomologist* 72: 209-212.
- Lass, L., 2002, Integrating Remote Sensing and Topographic Indices to Detect the Impact of Invasive Species, Cheatgrass and Yellow Starthistle, on Critical Winter Elk Forage Areas in the Umatilla Subbasin, Bonneville Power Administration FY 2002 Innovative Project Proposal # 34024.
- Lodge, D. J., and E. R. Ingham. 1991. A Comparison of Agar Film Techniques for Estimating Fungal Biovolumes in Litter and Soil. *Agriculture Ecosystems & Environment* 34:131-144.
- Maddox, D. M. 1982. Biological control of diffuse knapweed (*Centaurea diffusa*) and spotted knapweed (*Centaurea maculosa*). *Weed Sci.* 30: 76-82.
- Maddox, D.M. 1979. The knapweeds: Their economics and biological control in the western states, U.S.A.. *Rangelands* 1: 139-143.
- Mata-Gonzalez, R., R.G. Hunter, C.L. Coldren, T. McLendon, and M.W. Paschke. 2006. Modeling plant growth dynamics on *Bromus tectorum* communities affected by fire. *J. Arid Environments* 69:144-157.
- McArthur, E.D., A.C. Blauer and R. Stevens. 1990. Forage kochia competition with cheatgrass in central Utah. p.56-65. In: E.D. McArthur et al. (eds.) Proceedings of a Symposium on cheatgrass invasion, shrub die-off, and other aspects of shrub biology and management. US For. Serv., Int. Res. Sta., Gen. Tech. Rep. INT-276. Ogden, UT.
- McLendon, T. and E.F. Redente. 1991. Nitrogen and phosphorus effects on secondary succession dynamics on a semi-arid sagebrush site. *Ecology* 72:2016-2024.
- McLendon, T., and E. F. Redente. 1992. Effects of nitrogen limitation on species replacement dynamics during early secondary succession on a semiarid sagebrush site. *Oecologia* 91:312-317.
- McLendon, T., and E. F. Redente. 1994. Role of nitrogen availability in the transition from annual-dominated to perennial dominated seral communities. Pages 352-362 in S. B. Monsen and S. G. Kitchen, editors. Proceedings -- Ecology and management of annual rangelands. USDA Forest Service, GTR INT-313.
- Munshower, F.F. 1994. Practical Handbook of Disturbed Land Revegetation. CRC Press, Inc. Boca Raton, FL.
- Paschke, M. W., T. McLendon, and E. F. Redente. 2000. Nitrogen availability and old-field succession in a shortgrass steppe. *Ecosystems* 3:144-158.
- Pellant, M. 1990. The cheatgrass-wildfire cycle -- Are there any solutions? p.11-18. In: E.D. McArthur et al. (eds.) Proceedings of a Symposium on cheatgrass invasion, shrub die-off, and other aspects of shrub biology and management. US For. Serv., Int. Res. Sta., Gen. Tech. Rep. INT-276. Ogden, UT.

- Powell, R. D. 1990. The functional forms of density-dependent birth and death rates in diffuse knapweed (*Centaurea diffusa*) explain why it has not been controlled by *Urophora affinis*, *U. quadrifasciata* and *Sphenoptera jugoslavica*. Proc. VII Int. Symp. on Biol. Control of Weeds 195-202
- Powell, R. D. and J. H. Myers. 1988. The effect of *Sphenoptera jugoslavica* Obenb. (Col., Buprestidae) on its host plant *Centaurea diffusa* Lam. (Compositae). J. Appl. Entomology 106: 25-45.
- Radosevich, S. R., J. S. Holt and C. Ghera. 1997. Weed Ecology: Implications for Management. 2nd edition. John Wiley and Sons.
- Redente, E. F. and E. J. DePuit 1988. Reclamation of drastically disturbed rangelands, pp. 559-584. In: Tueller, P. T. (ed) Vegetation Science Applications for Rangelands Analysis and Management. Kluwer Academic Pub.
- Redente, E. F. and W. R. Keammerer. 1999. Use of native plants for mined land reclamation. VI International Rangeland Congress, July 1999. Townsville, Australia.
- Rees, N.E., P.C. Quimby Jr., G.L. Piper, E.M. Coombs, C.E. Turner, N.R. Spencer and L.V. Knutson (eds.). 1996. Biological Control of Weeds of the West. West. Soc. Weed Sci., Bozeman, Montana.
- Remote Sensing Laboratory, 2000, Remote Sensing Progress Report, SERDP, Yakima, Washington, 20 p.
- Remote Sensing Laboratory, 2001, Remote Sensing Progress Report, SERDP, Yakima, Washington, BN-RSL-02-0024, 61 p.
- Research Systems Inc., 2001, ENVI Users Guide
- Roché, B. F., Jr. 1994. Status of knapweeds in Washington. Wash. State Univ. Coop. Ext. Serv. Knapweed Newsletter 8: 2-4.
- Shaw, R. B. and V. E. Diersing. 1990. Tracked vehicle impacts on vegetation at the Pinon Canyon Maneuver Site, Colorado. J. Environ. Qual. 19: 234-243.
- Sheley, R. L. and J. S. Jacobs. 1997. "Acceptable" levels of spotted knapweed (*Centaurea maculosa*) control. Weed Technology. 11: 363-368.
- Sheley, R.L., J.S. Jacobs & M.F. Carpinelli. 1998. Distribution, biology, and management of diffuse (*Centaurea diffusa*) and spotted knapweed (*Centaurea maculosa*). Weed Tech. 12: 353-362.
- Spoon, C.W., H.R. Bowles & A. Kulla. 1983. Noxious weeds on the Lolo National Forest. A situation analysis staff paper. US Dep. Agric. For. Serv., Northern Region, Missoula, MT. 6 p.
- Stamatiadis, S., J. W. Doran, and E. R. Ingham. 1990. Use of Staining and Inhibitors to Separate Fungal and Bacterial-Activity in Soil. Soil Biology & Biochemistry 22:81-88.
- Steinger, T. and H. Muller. 1992. Physiological and growth responses of *Centaurea maculosa* (Asteraceae) to root herbivory under varying levels of intraspecific plant competition and soil nitrogen availability. Oecologia 91: 141-149.
- Story, J. M. 1992. Biological control of weeds: selective, economical and safe. West. Wildlands 18: 18-23.
- Tilman, D. and D.A. Wedin. 1991. Dynamics of nitrogen competition between successional grasses. Ecology 72:685-700.
- Torrey, J.G. 1992. Can plant productivity be increased by inoculation of tree roots with soil microorganisms? Can. J. For. Res. 22, 1815-1823.
- Trent, J.D., J.A. Young and R.R. Blank. 1992. Potential role of soil microorganisms in medusahead invasion. p.140-142. In: S.B. Monson and S.G. Kitchen (eds.) Proceedings of a Symposium on the Ecology, Management, and Restoration of Intermountain Annual Rangelands. US For. Serv., Intermountain Res. Sta., Gen. Tech. Rep. INT-GTR-313. Ogden, UT.
- Tucker, C.J., 1979, Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing of the Environment, 8:127-150.
- USDA, NRCS. 2003. The PLANTS Database, Version 3.5 (<http://plants.usda.gov>). National Plant Data Center, Baton Rouge, LA 70874-4490 USA.
- van Auken, O.W. and J.K. Bush. 1989. *Prosopis glandulosa* growth: influence of nutrients and simulated grazing of *Bouteloua curtipendula*. Ecology 70:512-516.
- Wedin, D.A. and D. Tilman. 1990. Species effects on nitrogen cycling: a test with perennial grasses. Oecologia 84:433-441.