TECHNICAL REPORT

67-41-ES

FIRE IN TROPICAL FORESTS AND GRASSLANDS

by
Robert B. Batchelder, Ph.D.
and
Howard F. Hirt, Ph.D.

Boston University
Boston, Massachusetts

Contract No. DA19-129-AMC-229(N)

June 1966

UNITED STATES ARMY
NATICK LABORATORIES
Natick, Massachusetts

Earth Sciences Division
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FOREWORD

Centuries of clearing and burning in tropical forests and grasslands have produced profound changes in physical and cultural environments. The frequent and widespread occurrence of fire poses a major hazard to the successful operation of men and equipment. Accordingly, there is need for information of a comprehensive and detailed character on the myriad aspects of fire in the tropics. This report contributes to the fulfillment of the U.S. Army's requirements for knowledge of world physical and cultural environments. Prepared in two sections, text and classified bibliography, this report is an evaluation of a vast and diverse literature. Emphasis is on the frequency, season of occurrence and geographic distribution of fire. Wherever possible, the interrelations between fire and the total environment, its possible influence on military operations and practices and methods for controlling fire have been stressed. The study, begun in February 1964 (Project No. 1V025001A129) was conducted in the Department of Geography, Boston University, under contract No. DA-19-129-AMC-229(N) over a period of nearly two and one-half years

Dr. Robert B. Batchelder directed the project as Principal Investigator, assisted by Dr. Howard F. Hirt as Research Associate. Dr. George K. Lewis assisted as consultant on African material Messrs. Roberts Mednis and Robert Easton assisted in library research and compilation of bibliography Mr. Mednis directed the cartographic work, assisted by Mr. John George and Mrs. Uttara Bose. Mrs. Lillian Funk typed the drafts and final copy; proof reading and editorial assistance was provided by Mrs. Ruth Batchelder; bibliographical assistance by Miss Linda Morrissey.

Robert B. Batchelder

Boston University
June 1966

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ACKNOWLEDGMENTS

A study such as this owes much to the work of numerous government officials and scholars in many parts of the world, who have diligently labored to clarify the physical and cultural role of fire in the tropical forests and grasslands. The authors wish to express their appreciation for the assistance that they have received.

Particular gratitude is expressed to: W. E. Aitken, Dr. Simon Baker, Dr. A. S. Boughey, Dr. Gerardo Budowski, Dr. Harold C. Conklin, Dr. Raymond E. Crist, Dr. William Denevan, Henri Dessens, R. Devred, Dr. J. L. D'Hoore, Dr. Wolfram U Drewes, Dr. F R. Fosberg, Dr. Robert Fuson, Q. Ghani, P L. Giffard, Dr B. L. Gordon, H. D. Gross, Dr. Theo L. Hills, Mr. E. V. Komarek, A. G. McArthur, Dr. Th. Monod, Dr. John Phillips, Dr. Hugh Popenoe, Dr. J. M. Rattray, Dr W. E. Reifsnyder, Dr P. W. Richards, Francisco Tamayo, and Dr. R F. Watters.

Thanks are due to the following for special assistance and facilities provided to the project: Boston University Libraries and African Documents Center; Committee on Fire Research, N A.S.- N.R.C., Washington, D.C.; Harvard University--Gray Library, Forestry Library, Human Relations Area Files, and Harvard Forest; Interamerican Institute of Agricultural Sciences, Turrialba, Costa Rica; Joint Fire Research Organization, Fire Research Station, Boreham Wood, Herefordshire, England; Library of Congress, especially the Map Division, McGill University, Savanna Research Project; New York Public Library; Pan American Union, Dept. of Economic Affairs, the Natural Resources Division; The Tall Timbers Research Station, Tallahassee, Florida; University of Florida Library, Latin American Collection; University of Michigan Botanical Library; Yale University Libraries.

ABSTRACT

Fire in the tropics has a long history in which frequent widespread burning has profoundly altered physical and cultural environments. A vast and diverse literature pertaining to fire and its effects in tropical forests and grasslands has been evaluated, classified and presented in a selected bibliography. Fire behavior in the field is at present unpredictable. In this report, the numerous variables interacting with fire are analyzed. Emphasis is on the relation of fire to climate, natural vegetation, soils, cultural origins, technological level and way of life and other significant factors of the total environment. The incidence and frequency of occurrence of fire are examined in terms of the geographic distribution of passive and active environmental characteristics. The relationship of burning to climate and natural vegetation is shown on maps which represent a first attempt to depict the geographic distribution of fire in the tropics. Potential combustibility and the implications of fire to military operations are discussed.

CHAPTER 1

FIRE IN THE TROPICS

A. Introduction

Fire has a long history of occurrence in the tropical world, and its effects upon the physical and cultural environment have been profound. The causes of fires and the trends in use by various peoples, however, have changed greatly within historic times Prior to the advent of use of fire by man, the effects of natural fire are assumed to have been much more limited than natural fire today It is reasoned that the geographic distribution of humid tropical forests was much wider during the early Pleistocene than at present. In the forest microclimate combustibility would have been low, limiting the period in which fire, once ignited, could be sustained As a result, the geographic area subject to possible widespread fires is presumed to have been limited to areas climatically transitional from moist to semiarid Pleistocene climates. A general assumption is that natural fires were caused principally by lightning and volcanic activity, of which the latter must have been of more importance in regions clothed with humid forests.

The advent of man's use of fire is of great importance because a new cycle was introduced marked by cultural practices fostering widespread distribution of fire and an increased frequency of occurrence. Various lines of evidence suggest that the control of fire by man may not be more than 12,000 years old, even though as noted by Stewart (1956), man may have guarded and transported fire for thousands of years earlier Authorities believe that no evidence suggests that man in Africa knew how to make or use fire before the end of the Early Stone Age. One of the earliest records of fire, noted by Busse (1908), was by Hanno, the Carthaginian, who sailed along the West Coast of Africa circa 500 B C , and noted the burning of vegetation. Palynological data for the Llanos Orientales of Colombia and the Rupununi Savanas of Guyana (British Guiana) suggest that human influence was probably an important factor 3.000 years B.P. (Wymstra and van der Hammen 1965)

More recently, fire has been used widely throughout the tropics to drive game, collect honey, ease travel through densely vegetated areas, provide new succulent forage for grazing animals, clear land for cultivation, and make war on neighboring peoples. Use of fire is so deeply ingrained in certain cultures, that it has become an essential part of religious beliefs and taboos Numerous authors also suggest that pyromania is widespread in which fires are set but the reasons for doing so, in many cases, are long since forgotten by the people

That certain parts of the tropics are experiencing more extensive and intensive alteration of the natural landscape by fire is well documented Use of fire and its effects appear to have declined in Oceania and parts of South and Southeast Asia, notably India. The agricultural populations have become sedentary, while primitive cultivators using fire in clearing forest represent an unimportant minority located in remote geographic areas. On the other hand, cultural use of fire is increasing in much of Africa and parts of tropical and subtropical Latin America. The rate of population increase is high particularly among rural people Consequently, new lands are being sought for clearing by expanding populations. In already settled areas, population increase has disastrously shortened the period of forest fallow among shifting cultivators.

Although no one generalization can be applied to the entire tropics, it is clear that the effects of fire on the natural and cultural environment are increasing at an increasing rate. Numerous scholars and administrators, noting the change accompanying widespread use of fire, have appealed for more intensive and wider study

B. Scope and Purpose of Study

1. Scope of the Literature

For more than two centuries, observers and investigators have reported on the history of burning of vegetation in the tropics. Much of the literature reflects both concern for and interest in the long-range effect of burning, the objectives of those who burn as a part of a way of life, and the effects of fire upon plants, soils, animals and other phenomena. During this period the character of references has varied. Early works frequently are narrative accounts written by missionaries, explorers, and administrators traveling in little-known areas. These accounts are of inestimable value, particularly for establishing the historical evolution of the natural and cultural landscapes in relation to the effects of fire. Contemporary research on fire is vast, representing a wide spectrum of academic disciplines as well as private and government agencies, personnel and laboratories Intensive research extends from laboratory experimentation on behavior of fire under controlled conditions, to field studies on fire behavior under natural conditions in which the large number of variables are instrumentally measured. Numerous intensive studies also have been conducted in small areas, and include analyses of environmental and cultural milieus of tribal peoples, ecological vegetation studies, experimentation on fires' effects on soils, plant succession in relation to time of burning, best burning policies in relation to commercial range and forest management and many others.

Furthermore, ideas and attitudes towards fire and its effects in the tropical environment, as expressed in the literature, have in many instances changed significantly For example, references dated prior to the early 20th century frequently contain alarming predictions of soil deterioration and erosion, loss of vegetative cover and destruction of landscape. No doubt exists that widespread destruction of forests has occurred in parts of the tropics However, other effects and predictions have not been verified for all locations for which predictions were made. Early literature often reflected essentially the authors' experience with fire in temperate latitudes, which largely demanded total fire prevention for preservation of the existing environment. More recent studies recognize fire as an indispensible tool in the agricultural economy, and in forest and range management in most tropical areas. Nearly all authorities agree that widespread, indiscriminate, uncontrolled burning is disastrous but that fire properly used is an effective low-cost measure, and the only economical means by which certain tropical environments can be managed for maximum resource use.

2. Purpose of the Study

The number of ramifications of the role played by fire is nearly infinite penetrating all aspects of the tropical environment. Recognizing a need for a preliminary study of fire in the tropics, a necessary precursor to subsequent investigation, the U. S. Army Natick Laboratories sponsored a search of the literature, to include sources in all major languages, to be conducted over a period of two years. Particular stress was to be laid on ascertaining the influence of the physical and cultural environment in tropical forests and grasslands on the occurrence and frequency of fire, as well as the effect of fire upon the natural and cultural environment. Significant contributions found in the literature were extracted for incorporation in this report.

In this study, fire is considered to be a phenomenon operating under physical laws and processes and acting as a physical agent in modifying the physical and cultural environment. In turn, fire-altered landscapes are presumed to trend toward conditions favorable for an increasing occurrence and frequency of fire. Because the number of possible interrelationships among fire, man, and environment are nearly infinite, no one condition or set of conditions can be assumed to be dominant for all parts of the tropics. Consequently, many researchers support an ecological or holistic view, in which fire is only one component of the total environment. Although the immediate effects of fire are easily perceived and are frequently catastrophic, there are, according to this view, no valid reasons for ascribing to fire a role uniquely different or in some way "separate" from the environment. Recognizing the emotional aspects of fire, Reifsnyder (1965) commented at the Tenth Pacific Science Congress, University of Hawaii, August, 1961:

> Deep-rooted psychological attitudes towards fire have ... distorted man's approach to the use of fire in wild-land management. Traditions for or against use of fire have often prevented rational research on effects and use of fire. Of particular importance ... is the role of fire in agricultural practices in the tropics and subtropics. There is perhaps no other subject in fire so circumscribed with emotional bias as the use of fire in shifting agriculture. Much more objective research is needed in this important area.

Currently the most widespread and accepted view on fire is an ecological one, and such a view is supported in this study.

This report is divided into two sections, text and classified bibliography. For several reasons, the bibliography assumes a more important role than it might otherwise and should be considered of value equal to that of the text The text stresses the following: 1) fire as a natural phenomenon, particularly its characteristics and behavior under natural environmental conditions; 2) the interaction of fire with the physical environment, notably climate, aperiodic patterns of weather, natural vegetation, soils, and other aspects of the environment; 3) the interaction of fire with the cultural environment, particularly those cultural aspects determining the use of fire, selection of sites for burning, techniques employed in burning, and time of burning as determined by agricultural calendars, religious or other beliefs; and 4) the geographic distribution of the occurrence of fire and probable period of burning correlated to climatically determined ecologically dry months and natural vegetation. In various sections of the total report, aspects of the total environment which are due to fire's effect on living conditions and mobility of people have been noted.

The bibliography is arranged in two separate sections and organized for maximum flexibility in its use. References contained in the first section are grouped according to large sections of the various continental areas, such as Western Africa, Southeast Asia, and Middle America, and arranged alphabetically by author under each section. Each reference is further identified according to its contents by a code system which indicates the various topics covered in the reference. The code also identifies the country or countries either in which the study was conducted or to which the study refers The second section of the bibliography is classified as is the first section, and contains references known to be valuable to study of fire in the tropics However, the references are not classified topically according to contents since they represent the later additions to the general bibliography which was kept current up to the preparation of this report.

Preview of existing bibliographies preceded establishing the criteria to be employed in selecting references for inclusion in the bibliography accompanying the text. The three-volume annotated bibliography, compiled by the late H.H. Bartlett (1955. 1957, 1961), and the selected bibliography compiled by H C. Conklin (1963), containing more than 1,300 references pertaining to shifting cultivation in the tropics, were evaluated.[1] There appeared to be no valid reason for repeating the excellent work accomplished by these men. Certain significant references making substantial contributions to the literature pertaining to fire and appearing in the bibliographies mentioned above, are reproduced in the bibliography accompanying this report. Wherever possible, however, duplication was avoided.

Readily available general works and textbooks were not included in the bibliography. Similarly, references which by their titles appeared promising but contained only brief and casual reference to fire were omitted. In addition, relatively few references were included that were dated before 1920 It was quickly established that earlier signif-

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[1]The following sources contain references to research on fire in the tropics but references to fire in extra-tropical areas are more numerous:

Berl. Walter G. (ed.) Fire Research Abstract and Reviews. National Acad. of Sci.-National Res Coun. Wash., D.C.

This publication. printed three times annually, contains abstracts of papers published in scientific journals, progress reports of sponsored research, and reports of technical laboratories.

References to Scientific Literature on Fire. Dept. of Scientific and Indust Res. and Fire Officer's Committee Joint Fire Res. Organ.. Forest Res. Sta., Boreham Wood, Hertfordshire. England.

An annual mimeographed publication listing all published materials appearing that year and topically arranged under subheadings. such as, occurrence of fire, ignition and combustion studies. fire precaution. fire resistance, fire fighting organization and general works.

icant references were invariably cited in full in more contemporary literature. Exceptions were made for references to fire in geographic locations for which information was scanty. No other restrictions, either geographical or topical were intended; however, gaps undoubtedly exist. References to works in non-European languages are few. Every effort has been made to produce a bibliography representing the wide diversity of fields of interest as revealed by the vast literature.

C. Delimiting the Tropics

Initially, the tropics were to be determined solely by climatic criteria. A first approximation was made by limiting the tropics to the Af (tropical rainy), Am (tropical monsoon), and Aw (tropical wet-and-dry) types of climate as determined by the Koeppen Classification. Comparisons were made of the areas thus delimited with the geographic distribution of climates determined by other classification systems and with major formations of natural vegetation (Chambers, Dalrymple and Jones, 1957). It was concluded that climatic criteria were too restrictive because fire was also significant in areas experiencing semiarid climates and cool highland climates. Fire is important in all types of natural vegetation where fuel quantities and spacing are sufficient to sustain combustion.

In many parts of the tropics, similarities were noted in the time of burning regardless of whether it occurred in lowlands or uplands. Conversely, numerous sharp differences were discovered in which the period of burning was closely related to cultural practices regardless of similarity of the physical environment. For these reasons, the investigation was extended to all land located between the Tropics of Cancer and Capricorn, and including South Africa and parts of subtropical Australia. In order to present the comprehensive role and effects of fire, a diffuse delimitation of the tropics was found to be more realistic.

D. Sources and Methods Used in Study

Most of the information used in the preparation of this report was obtained from libraries in the United States. Significant references in unobtainable foreign journals invariably appeared in full in one or more other available publications. Visits were made to a number of libraries containing collections pertinent to the study.

A valuable supplement to the literature survey was an extensive correspondence with potential informants. Letters of inquiry were sent to individual scholars, university departments, government agencies, independent research centers and international business firms. The response from those best able to assist the study was excellent. The information thus acquired proved invaluable, particularly in terms of the insight and observations of persons and agencies who became known to us during their visits to the eastern portion of the United States.

Information extracted from all sources was recorded in triplicate and organized separately in a regional file, a topical file and a chronological file. Items in the regional file were organized by continental area and country. The contents of a given reference were classified topically by a code system and filed under the headings in the topical file. The chronological file contained copies of all references organized in numerical order, the number being assigned at the time the material was extracted The latter file was indispensable for cross-checking reference entries to avoid duplicating work, especially those references appearing in more than one publication Bibliography cards were made for each reference with a notation of its form number and the geographic location number. Retrieval of information recorded on some one thousand forms was greatly facilitated by this system. Not only could all topics on fire for a country be quickly assembled, but also the ease with which one could extract material on a single topic for the entire topical world exceeded expectations.

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Wijmstra, T. A. and T. van der Hammen (1965) Palynological data on the history of tropical savannas in northern South America, 30 p (in press)

Chapter II

FIRE BEHAVIOR AND CHARACTERISTICS

A. Introduction

Present knowledge concerning the characteristics and behavior of fire is largely empirically derived from observations as man has combatted uncontrolled fires or has successfully used fire as a tool Many of the characteristics of flame ignition, fire propagation and fire persistence are recognized only in qualitative terms, often without complete understanding of the processes involved. At the present time, it is impossible to predict the behavior and course of a fire While many factors such as wind, humidity, fuel type, and topography are recognized as important, no quantitative estimates can be made of flame height, the magnitude and direction of fire-induced wind velocity, the radiative energy loss and its effect on convection, and the drying and gasification of the fuel. I' ability to predict these characteristics renders difficult, if not impossible, meaningful prediction of behavior of the firefront and the persistence and spread of fire. The following qualitative description of a forest fire illustrates the complexity of fire and the number of interrelating factors involved in its behavior.

> "A forest fire has burned for some hours. There is a growing perimeter of active combustion. Flames and smoke cover the luminous solid remains of grass, brush, and trees Radiation from the luminous flames heats the fuel in and ahead of the fire front. The amount of heat thus received, together with convected heat by the rising convection column.

gasifies additional fuel. The non-uniform fuel distribution and details of the topography cause convection columns and flames which are here violent, there gentle By interaction with the general wind, these irregular columns help produce eddies, small whirlpools of gases and firebrands which help propagate the fire front. The rising convection column alters the local wind pattern and thus alters the manner in which air is brought into the fire for its maintenance and the manner in which hot gases and brands are moved for its spread."[1]

B. Behavior of Fire

1 Ignition and Sustained Combustion

For combustion to occur, the temperature of the fuel must reach a value, or threshhold, where volatile gases are emitted from the fuel which upon reacting with the oxygen of the air ignite. Solids and liquids do not burn directly, but rather the gases emitted from these fuels at various temperatures burn. Organic compounds making up wood and grass, resins and oils, have a wide range of boiling points. Water also is present in varying amounts, both as a liquid and as chemisorbed water vapor. When a fuel is exposed to heat, it warms to where the water vapor boils off and in that process steam distillation probably takes place, whereby organic chemicals with a boiling range similar to water vapor are carried along with the steam. Continued heating after removal of the water vapor results in volatilization of additional organic compounds, which upon reaction with oxygen of the air, burst into flame, and a self-sustaining combustion process is established

Once the fuel reaches a stage of sustained combustion, the flame propagates by having the heat generated by the initial combustion process transferred to adjacent unignited fuel by convective and radiative heat transfer.

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[1] A Proposed Fire Research Program. The Committee on Fire Research and The Fire Research Conference. Nat Acad. of Sci . Wash., D C. 1959, n.p.

If the above explanation is at all adequate, it becomes clear that ignition, persistence of continuous combustion, and propagation of fire largely depends on the type, quantity and moisture content of the fuel or fuels, and that the areal arrangement of the fuels is very important during the initial phase of development of a fire front.

Controlled experiments in burning grasslands and forests in the tropics reveal that relatively high ignition temperatures characterize many, if not most fuels, and that combustion is not as easily sustained as the parched appearance of a landscape during the dry season would suggest.

Vareschi (1962) conducted a number of burnings in the Sabana de Calabozo, Venezuela, in which the typical vegetative formation was savanna parkland. Pyranometers were used to measure temperatures at various levels during burnings, and the same instruments were used to determine ignition temperatures of Trachypogon montufari, the dominant grass, and of other grasses and trees. The marked increase in ignition temperature of the Trachypogon m., when the fuel is not completely cured, is evident from Table 1.

TABLE 1

IGNITION TEMPERATURES OF SELECTED GRASSES

Sabana de Calabozo, Venezuela

Grasses	Fuel condition	Month	Wind	Ignition Temp.	
Trachypogon montufari	dry stage	Feb.	no wind	129°C	(264°F)
Trachypogon montufari	dry stage	Feb.	wind 3 m/sec.	135°C	(275°F)
Trachypogon montufari	almost dry stage	Dec.	no wind	205°C	(401°F)
Axonopus (and other grasses)	dry stage	Feb.	no wind	130° to 160°	(266°F to 320°F)

Ignition temperatures of the wood and bark of the Chaparro (<u>Curatella</u>) and Chaparro Manteca (<u>Byrosonima</u>) in a dry state ranged from 290°C to 330°C (554°F to 626°F). On the other hand the ignition temperature of the same species climbed to 500°C (932°F) or more, if the bark contained sap. Considering the fuel types and arrangement typical of the vegetative formations of the Sabana de Calabozo, Vareschi concluded that marked dessication of vegetation must precede uncontrolled fire.

The variation of average ignition conditions of the savanna in the Calabozo area is compared against the distribution of monthly rainfall at Bancos de San Pedro (Fig. 1). Low ignition temperatures coincide with the end of the dry season and the danger of unmanageable fire begins in January. It also is apparent that from May to December, the savanna is almost impossible to set afire.

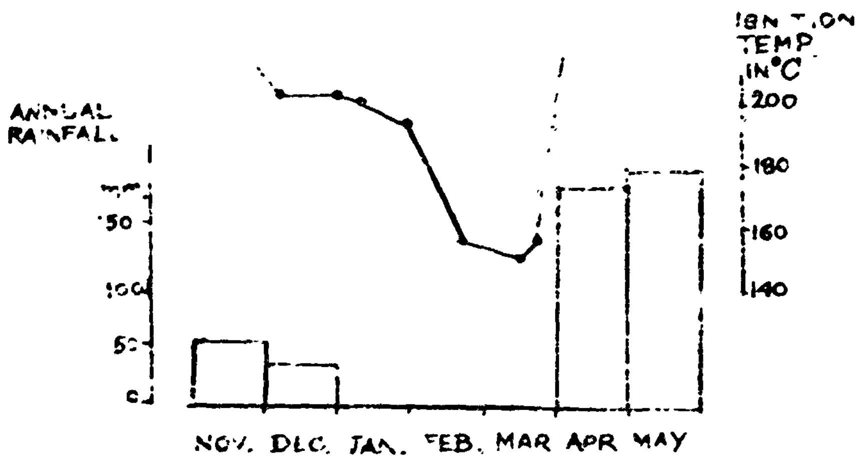


Fig 1. Variation of ignition temperature of <u>Trachypogon spp</u>. (grasses) with monthly precipitation recorded at Bancos de San Pedro, in the Sabana de Calabozo of Venezuela.

After Vareschi, 1962.

As revealed by many studies, fuel moisture content and water in various forms materially affect persistence of fire. Trapnell (1959) in discussing the effects and methods of early burning in a grass and low brush area near Ndola, Zambia, mentions that it is often difficult to initiate burning early in June (the beginning of the dry season) because fuels are not sufficiently dry. Therefore, burning was light and patchy, skipping more moist grass fuels and spreading with difficulty because the season's dry leaves had not yet fallen to provide a continuous carpet of fuel. Results of experimental burns reported by the Service des Eaux, Forêts et Chasses, Senegal, stress that for a relatively homogeneous grass cover, sustained combustion is also a function of grass height and spatial density, as well as fuel moisture. When hot, dry east winds blew for a few days in October over open savanna woodland near Ferlo, Senegal, grasses withered in less than two days and became highly inflammable. In brushy areas, many plants have aromatic oils rich in oxygen, such as menthol and thynol. Under high heat and within the brush zone, an almost explosive atmosphere can develop and once ignition takes place, intense fire occurs.

Characteristics of the fuel matrix (i.e., fuel size and spatial arrangement,) occurring under southern pine forest of the southeastern United States, permit burning shortly after dry conditions set in. The combination of wire grass and pine needles makes a fine fuel with a large percentage of surface exposure per unit area. Both fuel types are highly inflammable: thus it is possible to achieve sustained combustion in a year's growth only three to five hours following a summer shower.

At the savanna-semi-deciduous forest boundary it has been frequently observed that fire spreading into the forest from nearby grasslands burns out after penetrating less than 10 meters. Here, the presence of moisture under a forest micro-climate dampens the fire with amazing suddenness, since much of the heat generated at the ground is utilized in transforming water in the fuels to steam. There results a significant loss of oxygen to feed the flame, so that a lowering of fire temperature occurs to values too low to sustain combustion. Most cool surface fires typical of moist tropical forest environments are not self-sustaining without an accumulation and drying of slash.

2. Propagation of Fire and Rates of Fire Spread

Many factors of the natural environment relate directly to successful propagation of fire with forward movement of a fire front In addition to the factors of fuel inflammability, fuel size, and composition, it appears that dominant factors affecting rates of fire spread are fuel moisture content, fuel quantity, and wind velocity. McArthur (1963) in reporting the results of fire behavior in grasslands of Central Queensland conducted during spring months, presents the relationship between air temperature, relative humidity and the fuel moisture content of a standing grassland(Table 2).

TABLE 2

THE FUEL MOISTURE CONTENT OF FULLY CURED STANDING GRASSLAND RELATED TO AIR TEMPERATURE AND RELATIVE HUMIDITY

(fuel moisture content expressed as per cent of fuel weight)

Air Temp.		Relative Humidity							
°C	(°F)	5	10	15	20	30	40	50	60
10	(50)	-	-	-	-	12.0	13.5	15.0	16.5
16	(60)	-	-	8.5	9.0	10.5	12.0	13.5	15.0
21	(70)	-	6.0	7.0	8.0	9.5	11.0	12.0	13.5
28	(80)	4.0	5.0	6.0	6.5	8.5	10.0	11.0	-
32	(90)	3.0	4.0	5.0	5.5	7.5	9.0	-	-
38	(100)	2.0	3.0	4.0	5.0	6.5	-	-	-
43	(110)	1.5	2.5	3.0	4.0	-	-	-	-

After McArthur (1963)

Fuel moisture content is a very important factor in determining combustibility of green grasslands. The table indicates that for cured grasslands variation in fuel moisture content related to various air temperatures and relative humidities is rather modest. Rains, dew formation and the occurrance of other weather phenomena assume a more important role than fuel moisture content itself. In cured grasses, the rate of fire spread appeared to be almost directly proportional to fuel quantity and the wind velocity.

The relationship between fuel moisture content, wind velocity and rate of forward progress of a head fire in a fully cured grassland carrying 3 tons of fuel per acre and travelling over level to undulating ground, is shown in Table 3.

TABLE 3

RATE OF FORWARD PROGRESS OF HEADFIRE IN FEET/MIN. RELATED TO FUEL MOISTURE CONTENT AND WIND VELOCITY

(Fuel Quantity 3 tons/acre)

Fuel moisture content (Percent)	Wind Velocity in the Open (mph.)					
%	5	10	15	20	25	30
2.....	55.0	132.0	264.0	440.0	671.0	968.0
4.....	39.6	99.0	198.0	330.0	506.0	715.0
6	29.7	79.3	148.5	253.0	396.0	561.0
8.....	23.1	60.5	115.5	203.5	297.0	429.0
10....	18.7	47.3	93.5	154.0	236.5	330.0
15....	9.9	24.2	46.2	79.2	121.0	176.0
20....	5 5	13.4	24.2	44.0	66.0	88.0
25....	-	6.6	13 2	22.0	33.0	49.5
30 ...	-	-	6.6	13.2	18.7	26.4

After McArthur (1963)

The quantity of fuel in a grassland assumes an important role in fire spread. Three tons per acre is a heavy cover for much of the tropics, and particularly for Australia.

where it normally is about 1.5 tons per acre. Since the rate of fire spread is directly proportional to fuel quantity, then for a fuel quantity of 1.5 tons per acre the rates of spread in table 3 are halved. Experiments indicate that flame height and fire intensity also are directly proportional to fuel quantity. In drought years, fuel quantity in many tropical grasslands may not exceed 0.25 to 0.5 tons per acre. Under such conditions, a grass fire will not spread faster than 1 to 2 mph under the worst possible fire weather conditions, and flames are virtually invisible.

As noted, values for fire spread are based on observations made of burning on level to undulating terrain. Where perceptible slopes exist, marked variations in rates of fire spread occur. McArthur found that for the same fully-cured fuel quantity per acre, rates of fire spread up a 10° slope were double those indicated in the table; for a 20° slope, rates were increased fourfold. Under extreme fire weather and ample fuel conditions of homogeneous grass cover, maximum rates over steep terrain exceed 30-40 mph. Fortunately, steep slopes have modest lengths so that such rates of fire spread are usually over short distances.

Byram (1958) observed in studies of fire behavior in grass under southern pine in North Carolina the following rates under various wind conditions for both backing fires and head fires (Table 4)[1]. Unfortunately fuel quantity was not indicated, but fire spread was measured in grass cover over pine needles.

TABLE 4

FIRE SPREAD IN GRASS COVER UNDER SOUTHERN PINE

(North Carolina)

Type of fire	Backing fires				Head fires			
Wind vel (mph.)	Calm	2	4	6	Calm	2	4	6
Rate of Fire spread in feet min.	1.8	2.0	3.8	4.5	no value given	3.0	30.0	60.0

After Byram (1958)

[1] Head fires propagate downwind and back fires spread against the wind

Factors critical to rate of fire spread, also are important influences on the nature of the fire front. Commonly, grass fires are characterized by narrow burning zones, frequently continuous over considerable distances. The overall homogeneity of fuel type and low fuel quantities characteristic of tropical grasslands frequently result in low intensity fires. Single fire fronts not only are characteristic of savanna grassland and parkland, but also of open savanna woodland (or sparsely wooded campo cerrado), if the relative proportion of grass and sedge cover to woody herbaceous species and trees heavily favors the former. In such cases, a surface fire results, behaving primarily in response to conditions of ground cover and weather (PLATE 1).

Propagation of fire in brush and forest is very different than in a predominantly grass cover. The ignition line is carried forward by different patterns of burning at different heights above the ground. One pattern of flame occurs creeping through the refuse on the forest floor, while a different combustion pattern can be observed in the low, dense brush understory. Finally, in the case of fire in tree crowns, a third pattern is present often with flames extending skyward several times the height of the trees. One can only conclude that fire spread depends not only on the total fuel mass per acre and its total surface area, but it also depends on the distribution of this mass and surface area with height, including the randomness of placement of fuel at various levels.

Whereas radiative heat transfer is important in flame propagation in the forest litter, within the brushy understory much heating of unignited fuels occurs through convective action. At this level, the fine structure of the wind carries eddies of flame, or partially ignited gas mixture, that move forward a short distance to bathe a twig or branch. Flame propagation by convective processes increases immeasurably as the wind increases.

PLATE 1: A low intensity surface fire in the campo cerrado, central Brazilian Highlands, as observed from low altitude. Note single fire front, narrow burning zone, and thin smoke plumes (Photo by T. L. Hills).

PLATE 2: Brush fire in early dry season (July) preparatory to cultivation and planting, 25 miles inland from Dar es Salaam, Tanzania. Vegetation being invaded by fire is still green. Note flame height over stacked slash (Photo by I. J. Stolberg).

Another heat transport mechanism, one which varies greatly in importance depending on the gross physiognomic character of the vegetation and the various types of fuels, is that of ignition by fire brands ahead of the continuous burning zone. Fire spotting, by fire brands, has been mentioned as a significant contributor to fire spread in pine plantations of Tanzania, Zambia and Southern Rhodesia. The problem of fire brands is acute in fires under moderate winds in Australian Eucalypt forests, where incidents of spotting nine miles ahead of the fire front have been recorded. In fires started by persons clearing land in dense, moist, semi-deciduous forest, the likelihood of either spotting by fire brands or fire in crowns of trees is negligible. Fires in tall brush and low trees of the woodland and the semi-deciduous open forest, while not necessarily crown fires, do send up rather high flames, the radiation from which is a major contributor to fire spread.

Thus there emerges a picture not of a single fire front moving forward, but two or perhaps three, each of markedly different structure, each propagating forward as a result of the combustion of fuel in its own level of the forest or brush, and of the transfer into it of heat from other levels. In a fire which is advancing steadily through a forest or brush zone, these three regions of combustion move together without change of relative position, unless the physiognomic character of the vegetation changes. Commonly, such changes do occur which render complex any analyses of fire propagation. It hardly needs emphasizing that the basic fire problem is not one of determining the velocity of fire spread, but one of understanding why fire propagates (see PLATE 2).

Ignition and conditions favorable for sustained combustion in forest and brush differ markedly from those of relatively homogeneous, fine fuels found in grasslands. Under dry conditions grasses can be fired and combustion sustained within a brief period following dew or rains. This is not true for forest fuels.

The moisture content of woodland fuels--dead sticks, brush, grass, leaves on the ground or aloft--is an essential factor in determining flammability of forests. Partially counteracting the fairly large fuel quantities normally available, perhaps from 2 tons per acre to more than 30 tons/per acre, depending on type of forest, is the need for higher ignition temperatures than for grass. The forest microclimate usually retards evaporation and other forms of moisture loss. If the fuel moisture content of forest litter is 20 per cent or more, the more sensitive tinders are ignited only with great difficulty, and then will tend to only smolder. On the other hand, at five per cent or less fuel moisture content, rapid ignition occurs and active spread of flame ensues. These values of fuel moisture content represent equilibrium with atmospheric humidities of approximately 80 and 20 per cent respectively. In a forest, response of fuels to changes in atmospheric humidity is only minutes for leaves, but hours for twigs, and days for coarser fuels.

Few studies report the relationship between fuel moisture content, wind velocity and rate of fire spread. McArthur (1961) presents empirically-derived values based on experiments conducted in dry sclerophyll, low Eucalypt forest (E. marginata) of Western Australia. The high inflammability of Eucalypt forest has been noted. One may suppose, therefore, that the rates of fire spread may well represent maximum values and that for other types of forest or woodland, rates of fire spread would be much lower (Table 5). As in the case of fine, homogeneous fuels, the effect of fuel quantity on the rate of fire spread in low Eucalypt forest appears to be directly proportional. Under similar meteorological conditions, a fuel quantity of 5 tons per acre would support a rate of fire spread one-half that indicated in Table 5. Fire behavior in slash areas where fuels are stacked results in greatly intensified fires, and no generalization about fire spread can be made.

TABLE 5

RELATIONSHIP BETWEEN FUEL MOISTURE CONTENT, WIND VELOCITY AND RATE OF FORWARD SPREAD (FEET/MIN.) - FUEL QUANTITY 10 TONS PER ACRE, FUEL TYPE LOW SCLEROPHYLL EUCALYPT FOREST

Wind Velocity in Forest (mph)	Fuel Moisture content (as percent of estimated dry weight)					
	6	8	10	12	14	16
1	7.0	3.6	2.0	1.4	0.9	0.7
2	9.0	4.7	2.6	1.8	1.2	0.9
3	11.8	6.0	3.4	2.2	1.6	1.1
4	15.0	7.7	4.4	2.9	2.0	1.5
5	19.0	9.8	5.6	3.7	2.6	1.9
6	25.0	12.7	7.2	4.7	3.3	2.4

After McArthur (1961)

Biswell (1963) reported on 14 years of experience in using fire in southern California in which fire was used in three vegetation types, chaparral, woodland grass, and ponderosa pine. The first two vegetation types may be considered to have certain aspects in common with types of vegetation in the drier parts of the tropical world. "Chaparral" is derived from the Spanish word "chaparra" meaning scrub oak. It now has been applied to a low, shrubby, dominantly evergreen vegetation, the most important features of which are a deep root system, dense rigid branching and small, thick heavily-cutinized evergreen leaves. The various shrubs form almost a closed canopy so complete as to almost preclude much herbaceous vegetation as understory. Biswell noted that any time that the relative humidity was 25 to 30% and the wind calm, it was possible during the spring season to light a fire at the bottom of a slope and have

-ained combustion uphill, usually dying out at hill crest, -spite of rather high moisture content of grasses outside brush areas and budding growth on brush itself. In woodland grass areas composed of pines and oaks with an understory of considerable herbaceous vegetation, sustained burning had to be deferred to drier summer months in order to carry fire under the forest upperstory.

Controlled burning in wire grass and pine needle litter under southern pine in southeastern United States often is undertaken three to five hours following a summer shower. Here, again, the objective is to promote a surface fire of low intensity

The question of minimum fuel quantity necessary to sustain combustion in a forest cannot be answered with broad generalizations. Many comments on minimum fuel quantities are related to experience of persons using fire as a forest management practice to reduce the understory in forest plantations, thereby lessening wild fire hazards. Cooper (1963) in discussing the use of fire in southern pine plantations of Georgia, United States of America, where palmetto-gallberry undercover occurs, noted that at least a ton of fuel per acre distributed fairly evenly was necessary to sustain a surface fire. For low Eucalypt forest, only low intensity fires are possible even under the worst meteorological conditions when fuel quantities drop below 4 tons per acre. When less than 2 tons per acre occurs, sustained combustion is spotty and clean burns are nearly impossible. The changing characteristics of flame height and rate of fire spread under varying fuel quantity conditions have been determined for low Eucalypt forest of Western Australia (Table 6).

TABLE 6

RELATIONSHIP BETWEEN RATE OF SPREAD, FUEL QUANTITY AND FLAME HEIGHT (in feet)
(Low Eucalypt Forest, Western Australia)

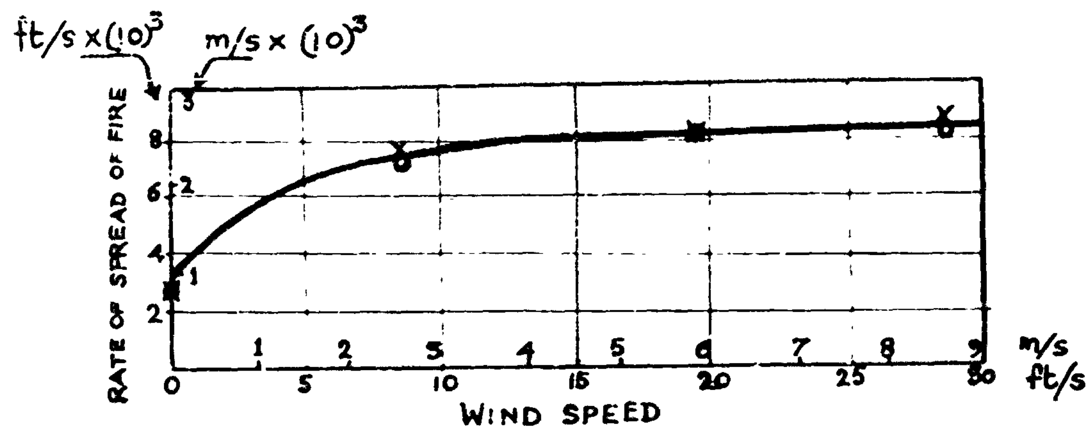
Rate of Spread (feet/min.)	Fuel Quantity (tons/acre) 2	4	6	8	10
		Flame Height in Feet			
1	1	1.5	2.0	2.5	3.0
2	1.5	2.5	3.5	4.5	5.5
3	2.0	3.5	5.0	6.5	8.0
4	2.5	4.5	6.5	8.5	10.0
5	3.5	6.0	8.0	10.0	12.0

After McArthur (1961)

3. Laboratory study of Fire Behavior

The number of variables involved in determining fire behavior has made study of fire an incredibly complex task. Experimentation with fire under controlled conditions in the laboratory reduces the number of variables and permits certain simplifying assumptions to be made concerning fire behavior. Many laboratory fires have been studied to determine fire behavior, particularly propagation and spread.

Thomas and Pickard (1961), in laboratory study of the spread of fire in forest and heathland materials. expressed graphically and quantitatively certain aspects of fire behavior. Initial investigation into the effect of wind speed on the rate of spread of fire was made in the laboratory using 10-feet long and one-foot wide wooden cribs made of Parana Pine conditioned at 18.3°C (65°F) and 65 per cent relative humidity. Rates of spread of the front and rear faces of the burning zone were measured over a range of wind speeds from 0 to 30 feet per second (Fig. 2).



X-Front face of burning zone; O-Rear face of burning zone.

Fig. 2 -- The Effect of Wind on the Rate of Spread of Fire.
After Thomas and Pickard (1961)

Plotting the results revealed that although increasing the wind speed increases the rate of fire spread, the effect becomes progressively less as the wind speed increases, while fuel quantity and quality remains constant. Note that the initial difference of rates of fire spread of the front and rear faces of the burning zone gradually coincide within the 10 foot length of the crib. At that point, about two-thirds the length of the crib, the fire becomes two-dimensional. A limited number of experiments with grass and heather gave fire spread rates 10 times larger than for wooden cribs -- probably due to the high surface-to-volume ratio of the natural vegetation.

Investigations were also made into the correlation between flame length and wind velocity, because of the direct effect of flame length on convective-radiative heat transfer ahead of the fire front on unburnt fuels. If such a relationship could be quantified, it would permit a first approximation of the amount of heat transferred ahead of the flame front. If L represents flame length, and D the length of the burning zone in the direction of the wind, statistical analyses of experimental burnings under differing wind velocities indicate that for a given rate of burning, the flame length decreases as the wind speed rises because the mixing rate of oxygen with fuel for combustion also rises leading to a reduced flame surface The ratio of L/D is so correlated with the rate of weight loss per unit ground area, wind speed, and length of burning zone in the direction of the wind, as to appear directly related to mass and specific gravity of fuel elements, moisture content, and matrix. Under natural conditions, these cannot be determined with a high degree of accuracy because there is no way to maintain or sustain a set rate of burning. However, laboratory results indicate that the rate of weight loss per unit ground area, and the length of the burning zone in the direction of the wind are related to the rate of fire spread in the form of;

$$m = \frac{WV}{D};$$

where W is the amount of fuel burnt per unit ground area; V is the rate of spread of fire; m is the weight loss per unit ground area; and D is the length of the burning zone in the direction of the wind.

It becomes obvious that these relationships are a first step toward quantification of fire behavior. Before application of laboratory results to field problems, the character of fuels must be quantitatively expressed, as well as the various factors controlling propagation of fire and the processes by which a fire front propagates. The development of fire models to determine the laws of fire behavior is well-rewarding, even though many simplifying assumptions must be made if one is to avoid intractable mathematical equations (see Appendix I). Therefore, attempts to define fire behavior are still at an initial stage. From a developed fire model, one can perform laboratory fires to determine the accuracy of equations as well as refine them. Likewise, the problem is not how to control fires in the laboratory, but rather how to meaningfully separate the complexities of fire behavior in a wide variety of physical situations into entities that can be studied.

4 Fire Intensity

There are relatively few studies of tropical experimental fires ignited under natural conditions where flame temperature at various levels, flame scorch heights and penetration of heat into soil have been measured. Part of the reason is that although fire has long been used as a tool in range and forest management in parts of the tropics, trial and error methods in fire use and protection have permitted application of knowledge gained to successful solution of problems. The need for quantitative data has been expressed by many: written reports reflect direct interest in the effect of flame front on plant conditions and ecological succession as well as the effect of heat on soils.

Temperatures recorded during fires cover a wide range of values as might be expected in experimental fires burned at different seasons, under varying weather conditions, and which included various types and quantities of fuel. Long recognized as among the hottest and most destructive are the heavy slash fires in the coniferous forests of the Pacific Northwest of the United States and Canada. In such fires in Douglas fir, cedar and hemlock temperatures above the ground reached 450°C (850°F) while below 1.9cm (0.75 inch) of duff, temperatures attained 48.4°C (120°F). Perhaps, more nearly analagous to what might be expected in parts of the subtropics, Heyward (1938) reported temperatures of surface fires in longleaf pine of southeastern United States as 65°C to 87°C (150° to 190°F) at the ground surface for a period of only two to four minutes. Bentley and Fenner, (1958) recorded temperatures between 93°C and 120°C (200°F and 250°F) at mineral soil surface when burning grasslands with light litter in western United States, and temperatures below 93°C (200°F) when the land was covered with heavy litter. Where brushland was burned, mineral soil surface temperatures rose to 175°C (350°F). Sampson, (1944) in his study of plant succession in Chaparral bush after burning gives figures for temperature about 1 inch below the mineral soil surface of 158°C to 285°C (320 to 550°F).

Comparison of studies of one area to studies conducted in other areas is unwise because of the number of variables involved. Nevertheless, such studies do indicate the general spectrum of temperatures associated with various fuels. Masson (1949) conducted a series of experimental burns in Senegal primarily to determine the effect of the fires on the soil. To check the instrumentation a small plot about 9 meters square was burnt where the cured grasses 40 to 60 cm (16 to 24 inches) high grew on stoney land. In the first test, wind velocity was high (no value given) and so the test was repeated under the same conditions the same day. The fire lasted 1 minute 20 seconds. In both cases, a maximum temperature at ground level of 105°C (221°F) was reached in the first six to eight minutes of the burns with a rate of cooling off of about 9°C to 16°C (40° to 60°F) in the next six to eight minutes and more gradually thereafter; it must be remembered that the ground was stoney. Repetition of his experiments under conditions of no wind gave maximum temperatures of 200°C (415°F) reached some 10 minutes after ignition. Extension of his experiments to taller grasses 50 to 60 cm (25 to 30 inches) high gave, as would be expected, higher values of maximum temperature at ground level which were reached more quickly (Fig. 3). Wind conditions were light averaging 2 to 3 m/sec.

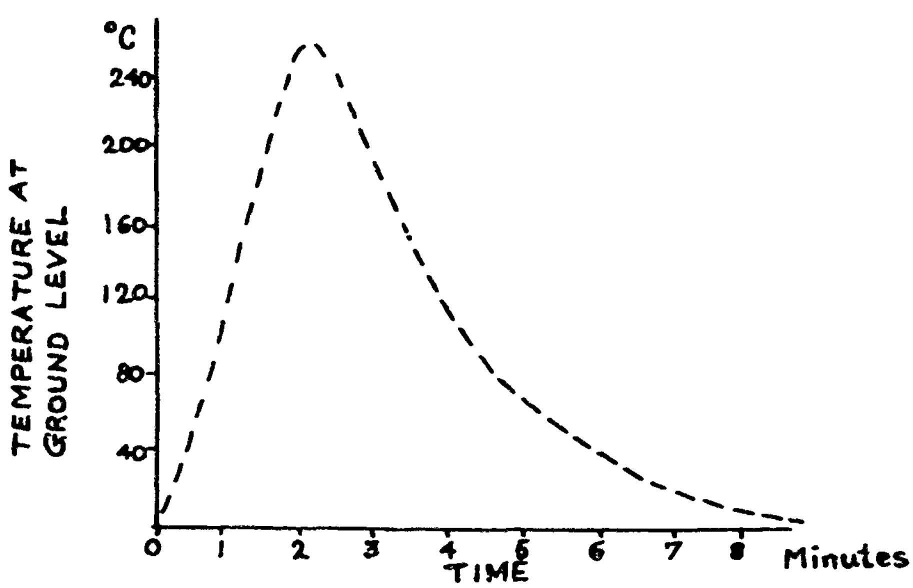


Fig. 3. Temperature profile recorded at ground level during fire passage in cured grass 50 to 60 c . high on sandy soil; wind, 2 to 3 m/sec. Senegal. (After Masson, 1949).

The final experiment was conducted in tufted grasses exceeding 100 cm (40 inches) in height (Fig. 4). Again temperature was recorded at ground level. The soil was sandy and rich in humus and wind variable at 2 to 3 m sec. A maximum temperature of 715°C (1319°F) was reached in one minute and 15 seconds, which returned to the ambient temperature in about ten minutes. Masson concluded that temperatures at the surface during a grass fire depend directly on fuel quantities provided they are in a cured state. In brush fires, the fuel was composed of communities of Gramineae in the Senegalese brush. Higher maximum temperatures at the soil surface in brush fires and an effect of the fire at ground level lasting a noticeable time, were noted, although no attempt was made to relate flame temperature to fuel characteristics and environmental conditions.

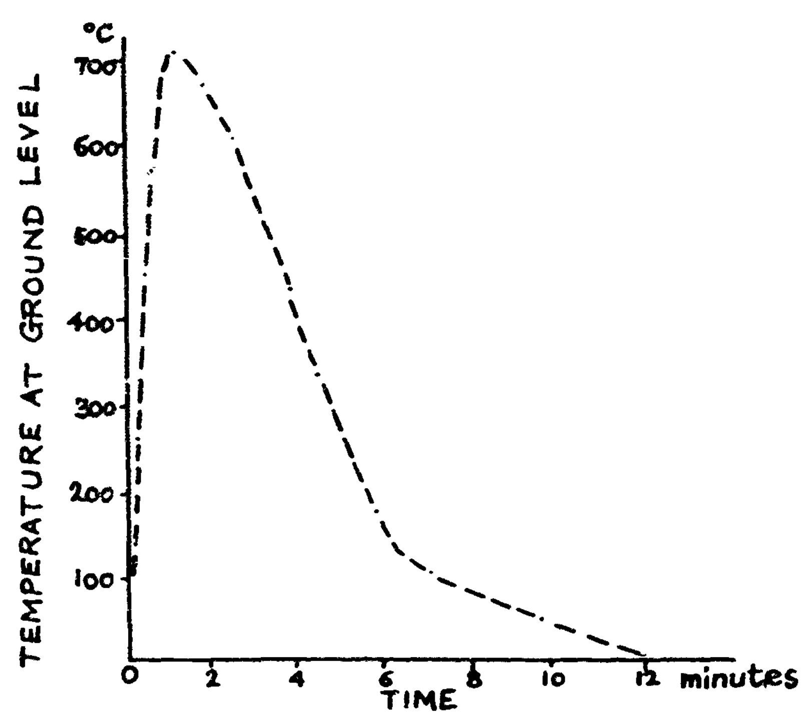


Fig. 4. Temperature profile recorded at ground level during fire passage in cured tufted grass more than 100 cm. high; sandy, humus-rich soil; wind 2 to 3 m sec. Senegal

(After Masson. 1949)

Vareschi (1962), in his study of experimental fire in the Llanos de Calabazo, Venezuela, came to the conclusion that temperatures during the burning stage sweeping over cured grass savanna (creeping Cynodon) without herbs, brush or trees, would be 297°C to 392°C (572 to 752 °F), with a possible absolute maximum of about 646°C (1260°F). Although he does not state the height of grasses fired nor the fuel quantity per unit area, it does appear that his observed temperature values are comparable to Masson's study.

Of much more significance, is Vareschi's composite graphic analysis of a typical flame front occurring during burning in the dry season in the Sabana de Calabozo (Fig. 5).

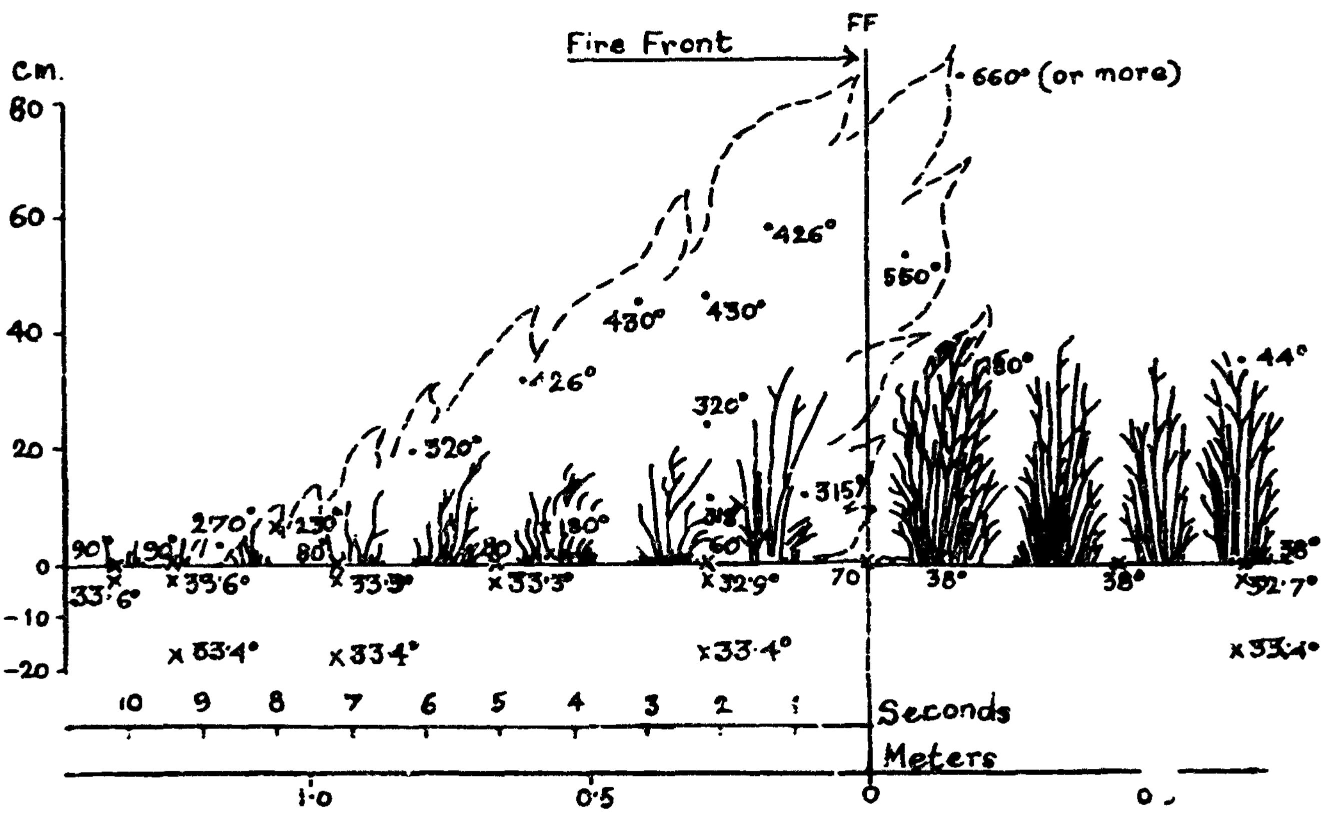


Fig. 5. Thermal structure at the fire front and in the burning zone of a typical fire in fully-cured savanna grass, Sabana de Calabozo, Venezuela.

(After Vareschi, 1962)

Since much of the Sabana is burnt annually, accumulation of fuel is modest It would appear from the graph that with tufted grasses about 40 cm (16 inches) high probably there s a cured fuel not exceeding 1.5 to 2.0 tons per acre. ote that flame height is about 36 inches with maximum temperatures recorded along the forward wall of the fire front increasing from the ground surface upward. Maximum temperature values are 320° to 426°C (608 to 800°F) at mid-flame height, whereas, the temperature gradient is a rapidly decreasing one near ground level.

Surprisingly low temperatures were recorded among the tuft clumps at ground level:80° to 90°C (176°F to 194°F), comparable to Masson's observations in grasses of similar height. The rather low surface temperatures beneath the flames are an important ecological factor in the survival of seed and new plant buds The depth of heat penetration into the soil is very shallow and the amount of temperature change is very modest. Absorption of solar radiation on bare ground during the dry season can raise surface temperatures to 60°C (140°F) or slightly more. Therefore, the difference between solar heating of bare soil and the rise of surface temperatures during the passage of a fire having a frontal zone about four or five feet wide is rather negligible.

The increase in soil temperature at 2 cm depth is only a fraction of a degree centigrade. Masson (1949), in 's study of experimental burns in Senegal, found that although surface temperatures at passage of fire in brush land may exceed 800°C (1472°F), and that high temperatures may persist for 10 minutes or more, depending on the soil, the penetration of heat below 2 cm depth was slight.

The relationship of fire intensity to fuels and fuel arrangement and rate of fire spread has been empirically determined from repeated experimental burns in Australian Eucalypt forest (McArthur, 1962). The simple empiric equation is,

$$I = Hwr;$$

where I, represents fire intensity in B.T.U. per second per foot of fire front; H, represents heat yield in B.T.U. per pound of fuel; w. represents the weight of available fuel in pounds per square foot; and r. is the rate of fire spread in feet per second. As the rate of fire spread is directly proportional to the fuel quantity, it follows according to this formula that as the fuel quantity doubles. the fire intensity will increase fourfold.

H, or heat yield in B.T.U. per pound of fuel is not readily determined, since the value of H depends on the heat properties of the fuels present, the various sizes of fuels, and their arrangement. Data derived for Eucalypt forests assume a shrub layer 2 to 3 feet high which contributes approximately 2 tons per acre of available fuel when consumed by fire. To produce a fire intensity of 100 B.T.U.'s per second per foot of fire front, in a fuel quantity of 4 tons per acre, the rate of fire spread would be about 5 feet per minute, whereas for 10 tons per acre, the rate would be only 2 feet per minute. McArthur (1962) notes that fires at I values of 100, are about the maximum which can be considered "two-dimensional" that is, where the depth of convective activity over the fire front is negligible and the width of the burning zone is three feet or less.

The high inflammability of Eucalypt fuels makes it difficult to translate the results of experimental burns in Australia to other types of vegetation in the tropics. However, the relationships between the following fire intensities and description of fire behavior may represent upper limits of combustibility (Table 7).

Martin and Davis (1961) test-burned a number of plots in which temperature profiles against time were recorded for both headfires and backfires under southern pine on the coastal plain of Georgia. The summer burns were in palmetto-gallberry fuels of varying quantity and composition, but all plots had a pine needle mat of varying thickness. Temperatures were recorded at the one-foot and four-foot level. It is unfortunate that winds were neither measured nor reported

TABLE 7

RELATIONSHIP BETWEEN FIRE INTENSITY AND FIRE BEHAVIOR IN EUCALYPT FOREST, WESTERN AUSTRALIA[1]

Fire intensity B.T.U. sec. ft. of fire front	Flame Height (in feet)	Scorch Height (in feet)	Fire Behavior[2]
5 - 12			fires self-extinguishing
13 - 50	1 - 3	6 - 15	surface fire easily controlled
51 - 70	3 - 5	16 - 30	spotting danger present, too severe for some forest species
70 - 100	6 - 12	30 - 45	spotting danger severe, damage to trees pronounced. Danger of damage to canopy.

After McArthur (1963)

[1]Data in table 7 is estimated from behavior of fire in a fuel type carrying a shrub layer 2 to 3 feet high which contributes 2 tons per acre of available fuel.

[2]Description of fire behavior is made in relation to controlled burning practices in Eucalypt forest with mature trees 60 - 100 feet high, and in which fire is used to reduce surface fuel build-up.

in their results; however, the effect of wind is discussed. Temperatures were obtained by iron-constantan thermocouples connected to galvanometers. Temperature profiles were graphed in which the change of temperature was plotted against time measured in seconds. In headfires, temperature rises rapidly to a peak, and as the fire front passes, drops rapidly at first and then at a decreasing rate. The temperature profile for Block 2 plot 3 represents a normal curve for both levels measured (See Fig. 6A, p. 36). Since peak temperatures at both levels are essentially in phase, it is assummed that winds were light permitting rapid build up to values of 820°C (1508°F) within approximately 45 seconds at the one-foot level, and values of 200°C (392°F) in less than 25 seconds at the 4-foot level. The decline in maximum temperature at the 4-foot level may be due to a number of causes, such as increased convection of air carrying heat away, or variation in wind velocity.

The profile of the burn of Block 3 plot 3 shows clearly the effect of a fast-moving head fire, moving before the wind (Fig. 6B). The wind inclines the flames and convection currents causing earlier peaking at the 4-foot level than at the one-foot level. The fire builds to an equilibrium condition of high fuel consumption rates. Such rapid burning produces high rates of heat yield resulting in high temperatures of nearly equal value at both levels. Such high temperatures permit a wide range of fuel sizes to be ignited simultaneously, which in turn, sustain the high temperatures and heat yields. Maximum temperatures are about 600°- 610°C (1112°- 1130°F) somewhat lower than temperatures recorded for Block 2 plot 3.

Temperature profiles of two back fires, in which the fire front advances into the wind, reflect a slow temperature rise peaking not once, but a number of times at rather low values (Fig. 7A and 7B). Furthermore, maximum temperatures in backfires are sustained longer than is the case in headfires before the temperature begins to fall off. The low rates of heat yield of backfires and attendant low maximum temperatures of 200°C to 260°C (360° - 500°F) are due to slow rates of ignition, in which ignition progresses from finer to coarser fuels under conditions of slower rate of oxygen supply, since convection is limited. Consequently, backfires reach dynamic equilibrium at a much lower temperature level than do headfires.

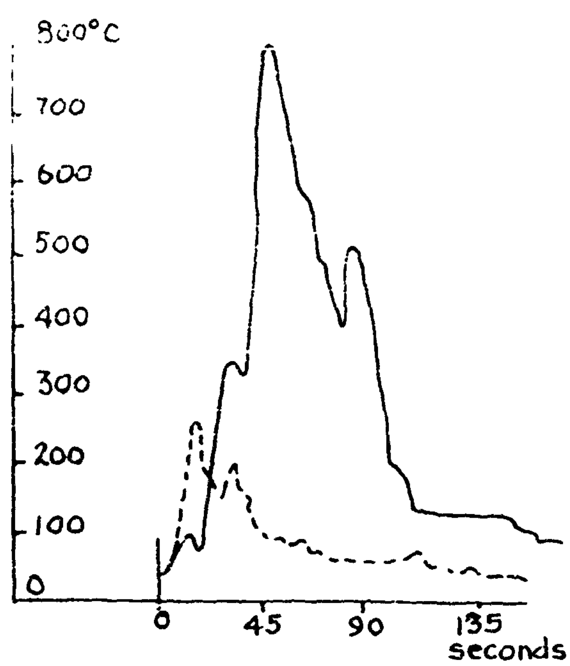


Fig. 6A. Normal headfire t° profile: light wind Block 2, plot 3.

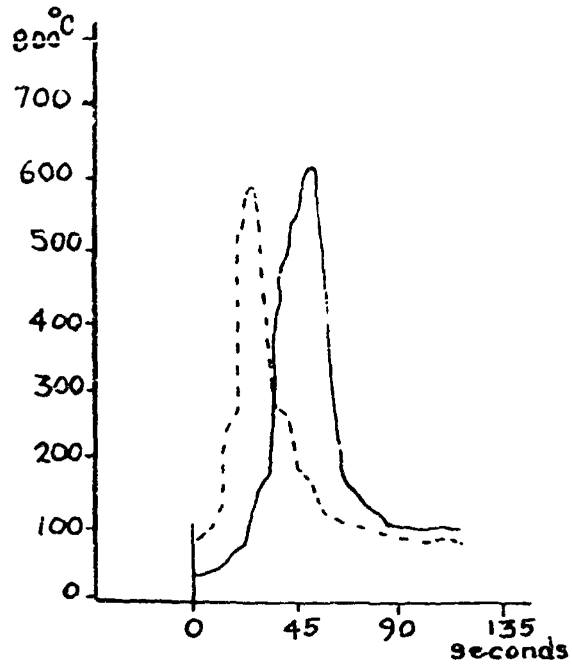


Fig. 6B. Wind-altered headfire t° profile, causing differences in t° values and peaking. Block 3. plot 3.

TEMPERATURE PROFILES OF SUMMER BURNS

PALMETTO-GALLBERRY FUELS
Alapaha. Georgia 1959

30.5 cm. (1 foot) level
121.9 cm. (4 foot) level

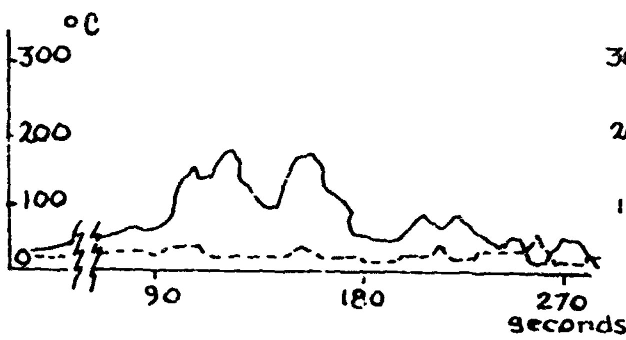


Fig. 7A. Backfire t° profile. Multiple peaking and low t° values, light wind. Block 1. plot 3.

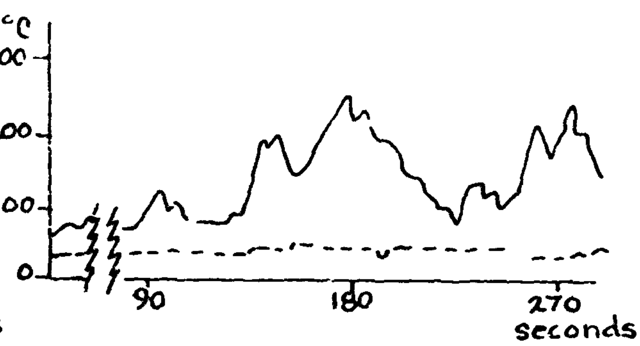


Fig. 7B. Complex backfire t° profile - wind altered. Block 2, plot 3.

(After Martin and Davis 1961)

Although results of test-plot burns in palmetto-gallberry fuels may not represent fuels typical of much of the tropics, it is noteworthy that the temperature profiles appear to agree in general with results obtained by other investigations of fire in the tropics. Most uncontrolled tropical fires are headfires, exceptions being the use of fire to prepare fire breaks, or fire used as a land management tool by competent persons. Since much burning occurs at the end of the dry season in the wet-and-dry tropics, fuels are fully cured. It appears that maximum temperatures obtained in headfire tests by Martin and Davis more nearly resemble those recorded for brush savannas rather than pure grasslands. The effect of a southern pine canopy may be rather modest because of the physical character of palmetto-gallberry fuels and the high combustibility. If this assumption is valid, then the temperatures of 400° to 800°C (752° to 1472°F) measured by investigators burning brush in African savanna woodland are too low. It has been suggested by a number of investigators that fire-resistant species can comprise a significant portion of this type of vegetation, and therefore, fuels available for combustion may actually be less than in the case of palmetto-gallberry fuels.

In moist, dense semi-deciduous forest and tropical rainforest, fires are all surface fires in which temperatures are low. Sustaining combustion often is difficult owing to the factors of widely variable fuel size and composition, varying rates of fuel moisture, and other local environmental conditions. Repeated burning of forest clearings preparatory to planting in order to produce enough ash and cleared land for cropping is widespread in tropical rainy climatic areas. Few climates are so wet as to preclude the use of fire. Burning requires the piling of slash and a varying period of drying, depending on climatic conditions, prior to firing the cleared plot. Under these conditions, the behavior of fire is not a serious problem, and if the fire front should enter the forest, it frequently is extinguished after penetrating only a few meters.

5. <u>Smoke and Visibility</u>

Few references among the many pertaining to fire in the tropics mention the color and behavior of smoke, or seasonal variation of visibility. This is not surprising since the number of variables which contribute to characteristics of smoke are exceedingly large. Some of the factors of known importance are fuel type and quantity, characteristics of fuel arrangement, fuel moisture content and condensed water in the fuel matrix and intensity of the fire. Important environmental conditions would be those factors contributing to combustibility, such as wind velocity and height of temperature inversion, and to fire spread, such as terrain and so forth. The number of possible interrelationships among the various factors is almost infinite.

Generally, low intensity fires are characterized by pale or white smoke; the opacity of the whiteness of the smoke is directly related to fuel and environmental conditions. Under low intensity fires, temperatures along the flame front are able to ignite only the finer fuels. If fuel moisture content is appreciable, or rains or dew formation are recent much of the heat at the fire front goes to generate steam which contributes to the whiteness and opacity of the smoke column. Most fires in the tropics are surface fires. "Cool" fires are more characteristic of open savanna which has a fairly homogeneous fuel matrix. Although rates of fire spread may be high as the relatively narrow burning zone proceeds downwind, generally the smoke column is pale or white in color, leaning downwind and rising to relatively modest altitudes (PLATE 3).

PLATE 3: Fire and smoke plumes in open park savanna of the Llanos, Apure State, Venezuela. Note gallery forest and second fire in center of photo near horizon (Photo by T. L. Hills).

PLATE 4: Poor visibility and destruction immediately following fire in the arid wooded savanna typical of parts of Southern Rhodesia (Photo by P. E. Glover).

Poor visibility due to smoke concentrated in low levels of the atmosphere has been noted in many places in the tropics. The customary burning of the fields in southern Sumatra around Palembang resulted in disrupted flight service to that city because of smoky haze as recently as September-October 1964. Numerous casual references relate poor visibility, viewed both from the air and on the ground, in central Brazil, Colombia and the Venezuela Llanos, to widespread burning at the end of the dry season. Smoke plumes rising to more than 10,000 feet elevation in Senegal and Tanzania have received comment in literature on fire. Unfortunately, very little information is available which would identify in more than general terms. the variables and combinations of variables that favor the onset of poor visibility due to smoke.

The relationship of the quantity, type and spatial distribution of fuel to single or multiple fire fronts and other characteristics of fire, has been examined above. Although grass fires may have narrow burning zones and low fuel quantities per unit area, a great deal of smoke may occur depending on the moisture content of the fuels and the area burned. Frequent references note grass fires sweeping uninterruptedly for miles (see PLATE 3).

In savanna woodland, multiple fire fronts and spotting ahead of the general fire area are likely, because there exists a wide range of fuel types and sizes. Grasses, herbaceous growths and low trees burn at different rates. Consequently a large area swept by fire would continue smoking for a considerable period of time due to smoking logs and isolated fires (see PLATE 4). Where fuel quantity is low, on the other hand, the fire may be two dimensional, producing a narrow burning zone and little smoke (see PLATE 1).

Fires in moist tropical forests are limited in areal extent, and rarely spread much beyond the zone cleared for planting (see PLATE 24, p. 145). The total amount of smoke contributed to the atmosphere would depend on the cultural practices and agricultural calendars employed by the people. The total number of fires in an area depends in part on the population density and the length of the forest-fallow period. Another important variable, is that no dry season occurs; thus rain showers during the drier period remove smoke from the atmosphere.

Smokiness also is related to meteorological conditions that limit dispersion of smoke to the lower layers of the atmosphere. Frequently during the dry season, air masses are highly stratified with marked vertical variations in temperature and moisture. Temperature lapse rates at low levels usually are fairly steep due primarily to surface heating. Smoke plumes rise rapidly for the first 3,000 to 6,000 feet of elevation, only to spread laterally along the base of a temperature inversion. The strength of the inversion and the mean height of its occurrence depend on many factors, such as air mass characteristics and air mass modification as it traverses a region. It has been observed that poor visibility frequently occurs for periods of a few days to a week or more. Presumably, persistent low level inversion, coinciding with widespread burning at the end of the dry season, does occur with significant frequency in many parts of the tropics.

Intense fires are more likely in the forest-savanna boundary and in savanna woodland. The relatively large fuel quantities present promote combustion and permit higher temperatures in the burning zone. Consequently, a wide range of fuel sizes is readily ignited, and carbonization of fuels under high heat results in darker tones in the color of smoke. Naturally convection is active and the smoke rises rapidly, often to great heights. That rather intense fires occur in Chad, Sudan and Senegal in savanna woodland and along the forest-savanna boundary is evident from accounts of well-defined convection columns carrying smoke skyward 3,600 feet in less than six minutes.

C. Conclusions

The number of variables involved in determining fire behavior is so large as to make it impossible at the present time to predict with any degree of certainty what will occur when an accidental fire is ignited. Generally, an empirical approach has been and is used in the study of fires in the tropics. Frequently, one idea and then another has been applied to see which one works best. The experience gained from repeated experimental fires has been satisfactory in solving some of the problems associated with fire, both as an enemy and as a servant.

The main variables affecting fire behavior are:

1. fuel size, quantity and spatial arrangement;
2. fuel moisture content, both chemisorbed and present as condensed water in the fuel matrix;
3. terrain, particularly slope;
4. wind velocity;
5. the transport of burning embers -- the spotting process; and
6. atmospheric conditions, especially the temperature and dew point lapse rates, particularly at ground level, but also within the first 5,000 feet.

This list of factors is by no means complete. Fortunately many of the variables assume importance only under extreme fire behavior conditions, especially those factors affecting the process of energy release and convection formation. In the tropics, burning in forested environments is generally limited to control burning policies or to clearing land for cultivation. In both cases, the goal is to obtain a low-intensity ground or surface fire. Fires in grasslands often are free-burning, but here the available fuels are less than those available in forested environments. Consequently, the general intensity of such fires is not high, even though their frequency of occurrence and the extent of area burned annually may be large.

Areas in which basic studies would contribute most significantly to an understanding of fires, actually are the same ones identified as being significant factors in fire behavior. Of utmost importance, however, are those factors pertaining to sustaining combustion and fire spread. Inadequate information is available on gas and flame emissivities as a function of frequency at high temperatures. Mathematical techniques also must be developed for prediction of the radiation emitted by distributed sources and transmitted through absorbing gases. These data and techniques are necessary in order quantitatively to determine the radiant heat transfer which has a large influence on the rate at which fuel becomes available to the fire.

The model laws for aerothermodynamic systems in which the fuel consumption rate is dependent on and is controlled by the heat evolution rate should be determined. Parameters to be studied include: effects of geometry, fuel type, radiation, and heating rates. Types of fire-front propagation should also be studied, e.g., continuous flame fronts or discontinuous sources of ignition distributed by aerodynamic forces.

Fundamental information on the aerodynamic properties of burning bodies in motion is needed. The available scanty information indicates that burning decreases drag. The magnitude of this effect and its connection with the aerodynamic pickup and transport of embers is unknown.

Consequently, it is impossible to predict with certainty the chances of fire spotting ahead of a flame front or the course of the fire.

The convection of air and hot gases associated with a liberation of heat has two aspects: 1) the general rising air currents; and 2) the local gas movements in and near the heat source. Convection currents are modified by interaction with winds, topography and turbulence. The local motions are the result of interaction of the broader scale convection with those currents due to gas expansion associated with combustion. The quantitative and in most cases, the qualitative features of these convection currents and their role with respect to burning are unknown.

Study of naturally occurring fires indicates that much information is needed. Factors to be measured in the atmosphere at all significant elevations might include: 1) wind speed and direction; 2) turbulence; 3) temperature, including lapse rates and dew point temperatures; 4) air moisture; and 5) cloud activity. Time-lapse photography would provide an excellent continuous record of convection column, smoke and fire behavior, particularly if the film were keyed to a time scale.

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CHAPTER III

FIRE AND THE PHYSICAL ENVIRONMENT

A. Introduction

The interaction of fire with the physical environment both modifies that environment and those conditions of the environment favoring occurrence of fire. Frequent fire in a given area alters its ecological balance, with progressive change toward environmental conditions which appear to favor more frequent and widespread fire. If this is true for most parts of the tropics, then fire, from both natural and cultural causes, is one of the more important physical agents able to initiate profound and lasting changes in the physical landscape. Whether the total effect of fire over long periods of time is degradational, causing deterioration of vegetative cover and soil-water relationships, depends on the degree to which accidental fire is reduced and prescribed burning is consistent with known facts concerning induced fire-changes.

It is recognized that repeated occurrence of fire in an area initiates successional change in the vegetative cover in which fire-resistant species become dominant. Likewise, vegetation changes are accompanied by micro- and topoclimatic changes, which in turn affect soil moisture, surface and ground water supplies and other variables. Thus one should conceive the presence of fire in the tropics as a physical agent in the same sense as one considers precipitation, lightning, or soil microorganisms. Furthermore, fire is an integral part of the total ecological system, which would include not only the myriad aspects of the physical environment, but the cultural environment as well. The role fire plays in this encompassing ecological view, and the magnitude and direction of its effects on the total environment, are identified only in the broadest terms. Appeals for detailed and quantitative information on the effects of fire are prevalent in the literature.

To simplify the problem of the interaction of fire with the environment, the physical environment has been separated from the cultural environment, each to be treated in some detail (see Chapter IV). The occurrence and frequency of fire in an area is more likely to be due to cultural rather than natural causes. The reader is cautioned, therefore, to recognize the interrelationship of two rather arbitrarily separated spheres of the total tropical environment.

A topical organization is employed here in presenting the interaction of fire with the physical environment. It is important to recognize that many of the effects of fire reported in the literature in one area cannot be extrapolated to other tropical areas. For example, soil water and ground water conditions and successional change in vegetation are phenomena restricted in area. Only the broadest generalizations are possible for the entire tropics. One should not assume, that the topics treated represent an implied order of significance or are the most dominant effects. Rather, they reflect the research interest and biases evident in the literature. Finally, exhaustive treatment of each topic is not attempted, but rather to indicate latest information and the direction and conclusions of the various sources used.

The interaction of fire with the physical environment is organized around the following topics: 1) fire and atmospheric conditions, including climate and aperiodic weather; 2) fire and natural vegetation, including ecological effects and successional change; and 3) fire and its effects on selected aspects of the environment, including soils, edaphic considerations. and biota.

B. Fire and Atmospheric Conditions

1. Atmospheric Influences on Fire

The most significant relationship between fire and atmospheric conditions is the occurrence of a number of variables that combine to produce highly inflammable fuels and an explosive atmosphere. Lack of precipitation, low absolute and relative humidity, high fuel and air temperature, moderate winds and a high rate of evaporation, all contribute to the conditioning of fuels to low ignition temperatures. Most fire danger rating systems employed in Australia, India and other parts of the world use the above criteria in various ways in order to predict fire. Nearly all systems are empirical and restricted in areal usefulness because the value for each criteria employed represents a regional application of climatic and meteorological data to fuel conditions in major types of natural vegetation (see Chapter II).

For many parts of the tropics, the incidence and danger of fire coincide with a definite climatic dry or drier season. Climatically, the recorded annual rainfall and overall seasonality are less significant than the occurrence of a dry period and its duration and intensity. What constitutes a dry season potentially high in fire danger depends on many factors and is not easily determined. On one hand, the climate must be characterized by rainfall sufficient to support fuel quantity. type and spacing adequate to permit sustained combustion and fire spread. On the other hand, a drier period must occur of sufficient intensity and duration to permit burning. As mentioned previously, fire is frequently an annual occurrence in semi-arid tropical climates where annual precipitation may be as low as 41 cm. (16 inches) and 6 to 8 months of severe drought occur. Even though tufted grasses, low herbaceous plants and widely scattered clumps of brush and trees are separated by considerable distances of bare ground, fire has been reported.

Perhumid tropical climates, in which fire is virtually impossible owing to excessive well-distributed rainfall and high atmospheric humidity, are limited areally. Typical sites would be mountain and plateau slopes transverse to prevailing onshore moist winds. An example is the Pacific coast of Colombia where at Andagoya, elevation 71 meters, annual precipitation is 7,089 mm. falling on 303 rainy days per year, and in which no month has fewer than 21 rainy days (West, 1957). Here, land is cleared by felling and piling brush, which under existing extreme conditions of moisture and humidity, is reduced by microbial activity in a few years. Along Caribbean Costa Rica, however, it has been recorded that certain tree species lose their leaves when monthly rainfall falls below 13 mm. even though annual precipitation varies from 3,700 - 5,800 mm. along the coast. Furthermore, in the humid and rainy parts of the Congo River Basin, slash and burn agriculture is practiced even though felled trees and piled limbs and brush are left to dry a month or slightly more prior to burning. In this case, the forest bioclimate is completely altered by opening the forest canopy. Consequently, piled slash will dry out even though the land may be cleared at any time. The slash is burned, on any clear day.

Numerous factors other than the seasonal march of temperature and precipitation are important in establishing the characteristics of the dry period. Soil texture and permeability and soil moisture storage capacity, as well as the mean depth of subsurface water are significant edaphic factors. Evaporation from surface soil has been measured at tropical experimental stations. In nearly all cases observed results can be extrapolated to other areas only with caution. Thus, in the absence of better information applicable to large areas, climatic data have been the primary source of empirical relationships established to determine the length and severity of a dry season. Since no one boundary coincides with onset of dryness, a fundamental problem is to establish the threshold through which water formerly freely available for plant growth is replaced by water need. Once a threshold has been established satisfactory to a meaningful interpretation of the observed response in natural vegetation, the date and duration of a dry period can be identified from climatic data. Since the severity of drought is accumulative and progressive, a second problem is to indicate by some means the magnitude of the water deficit. (see sec. 2 a).

2. The Climatic Dry Season

Two methods for determining climatic dry season, each very different from the other, have been selected for comparative analysis. The more complex and sophisticated water balance method employed by C. W. Thornthwaite Associates (1955) has the merit of quantitatively expressing water utilization, deficit and surplus for any location for which monthly temperature and precipitation data are available. Also widely used is the simple and easily applied criteria proposed by the noted French geobotanist H. Gaussen and evaluated by the German ecological botanist H. Walter (Bagnouls and Gaussen, 1953. 1957: Gaussen. 1954; and Walter, 1955, 1958). Both methods are applied to 13 climatic stations, four in Latin America, five in Africa, and four in tropical Asia. Care was taken to select stations representative of the expected types of tropical climate within the limitations imposed by available data.[1] For each tropical area, there-

[1] C. W. Thornthwaite Associates, Centerton, New Jersey, have published a series of volumes entitled Average Climatic Water Balance Data of the Continents. For stations listed, location, elevation and length of record are presented. Average monthly and annual totals, where applicable, of potential evapotranspiration, precipitation, soil moisture storage, actual evapotranspiration, water deficit and water surplus are given for each station, all values being expressed in millimeters.

Most of the data used for the preparation of the climographs utilizing the method of Bagnouls and Gaussen were from: F.L. Wernstedt. (1961) World Climatic Data, (Latin America and the Caribbean, Africa). Department of Geography, Pennsylvania State University.

tore, four or more stations roughly along a latitudinal traverse line were selected. Two climographs, illustrating the two methods, were constructed for each station (Figs. 8 through 14). It was not our purpose to evaluate the climates represented by the climographs, but to compare the ability of the two methods to identify and determine the characteristics of a dry season, if present, in relation to potential combustibility of natural fuels.

a. Dry Season as Determined by Climatic Water Balance.--Thornthwaite (1948) introduced the term potential evapotranspiration which was empirically derived from temperature data and expressed in units of water need. If the amount of water available in a climate was unlimited, potential evapotranspiration (PE) expressed as average monthly values of water need, represents potential moisture loss by the various physical processes as determined solely by the climate. When PE is plotted against recorded precipitation, the gross features of the seasonal water balance are identified. Actual evapotranspiration, however, varies constantly, and it is related to a number of variables, particularly soil moisture. Unable to determine the constantly varying water loss by vegetation as related to soil moisture, Thornthwaite developed a model which permitted the first 10 cm. depth of water in the root zone to be lost at the potential rate. Actual evapotranspiration would decline to zero after 10 cm. have been removed from the soil. A water surplus would occur whenever there was precipitation greater than the 10 cm. of soil moisture recharge, while water deficit would occur when water need (PE) exceeded precipitation following the exhaustion of 10 cm. of soil moisture. Using this essentially bookkeeping procedure, quantitative values of moisture balance could be obtained.

The solution of the problem of determining actual water loss by vegetation or actual evapotranspiration (AE) has remained elusive. Thornthwaite and Mather (1955) modified the system whereby: "a) the available soil moisture storage can vary, depending on the vegetation cover and the

(to p. 60)

THE CLIMATIC DRY SEASON

The determination of the dry period according to Bagnouls and Gaussen formula [$P_{(mm.)} \leq 2T_{(°C)}$], left, and Thornthwaite's Water Balance, right.

Bagnouls & Gaussen

- ——— Temperature
- - - - - Precipitation
- Humid period
- Dry period

Thornthwaite

- - - - - Precipitation
- —o—o— Potential evapotranspiration
- —x—x— Actual evapotranspiration
- Water surplus
- Water deficit
- Soil moisture utilization
- Soil moisture recharge

Note: In some climographs the vertical scale above 200 mm. has been adjusted.

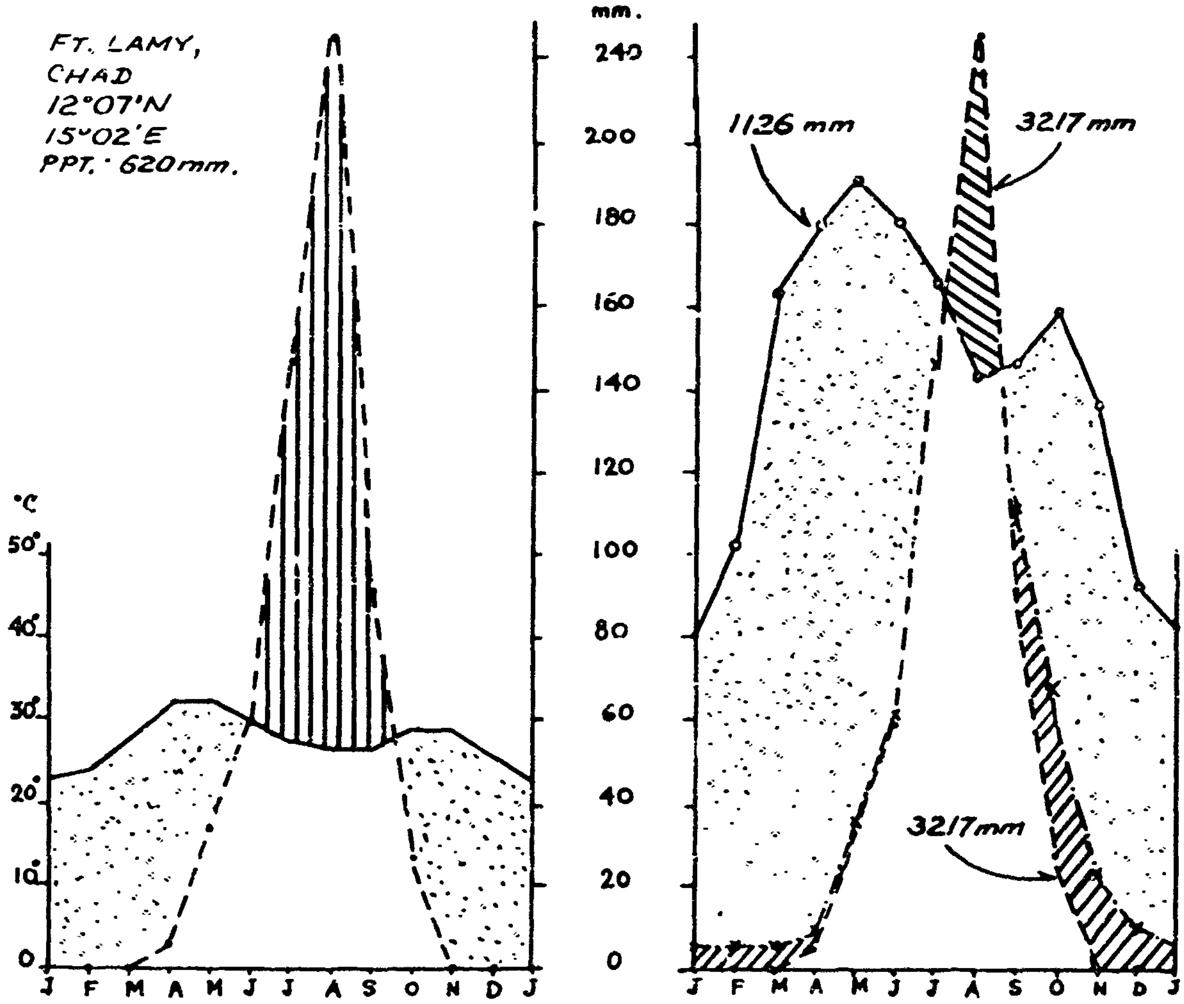


Fig. 8

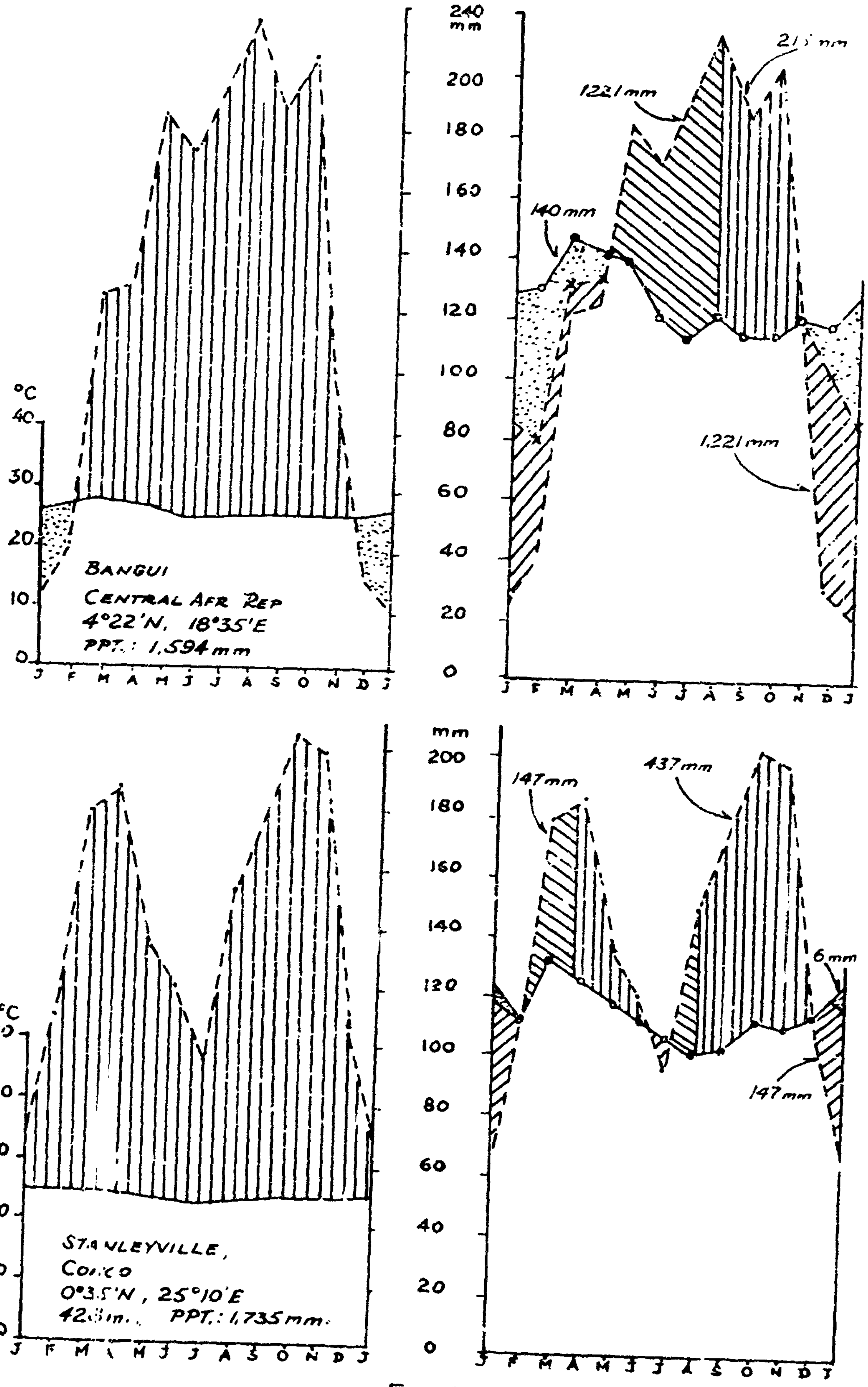

BANGUI
CENTRAL AFR REP
4°22'N, 18°35'E
PPT.: 1,594 mm
140 mm
1221 mm
1,221 mm
STANLEYVILLE,
0°35'N, 25°10'E
PPT.: 1,735 mm
147 mm
437 mm
6 mm
147 mm

Fig. 9

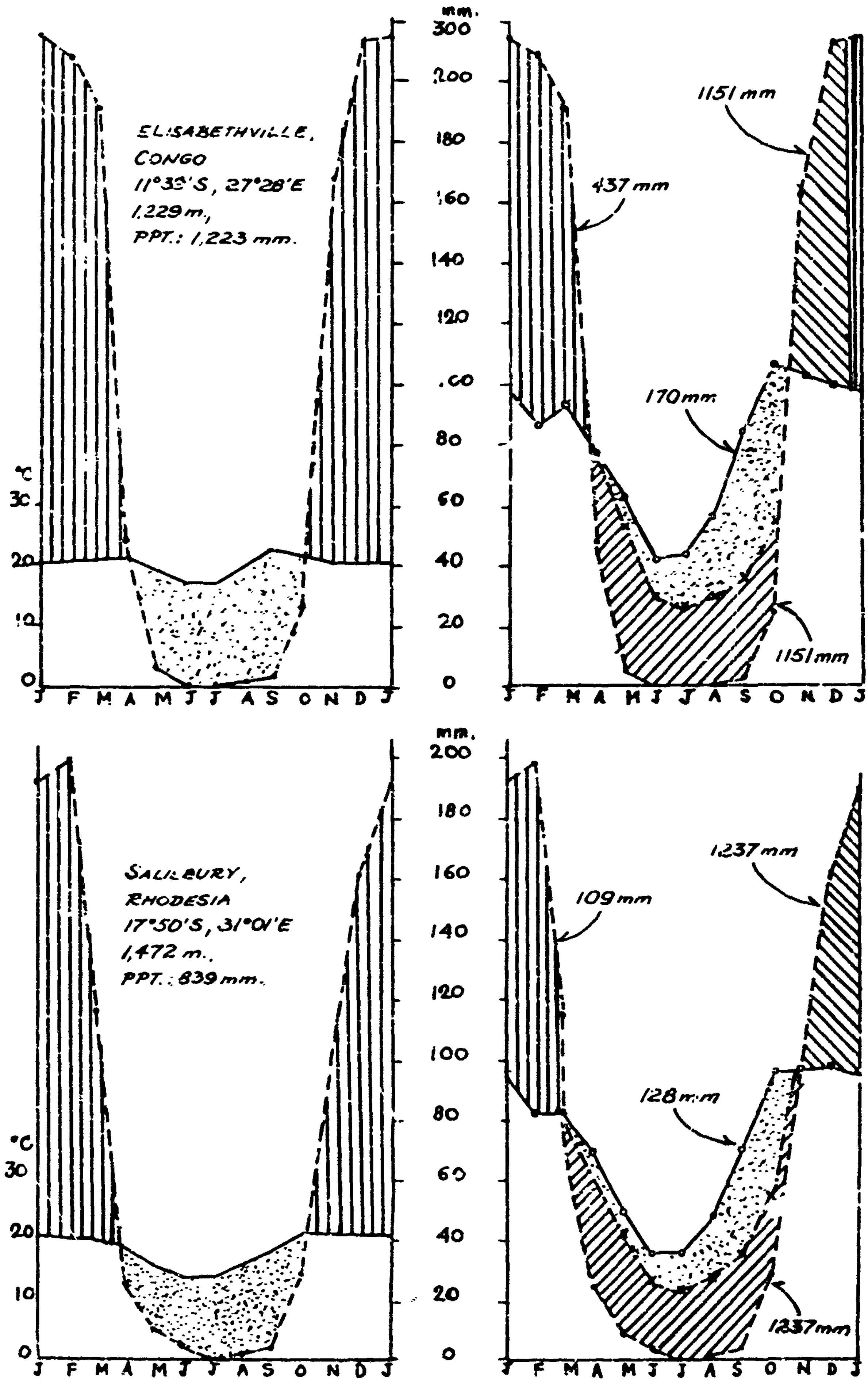

ELISABETHVILLE,
CONGO
1,229 m.,
PPT.: 1,223 mm.
437 mm
1151 mm
170 mm
1151 mm
SALISBURY,
RHODESIA
17°50'S, 31°01'E
1,472 m.,
PPT.: 839 mm.
109 mm
1,237 mm
128 mm
1237 mm

Fig. 10

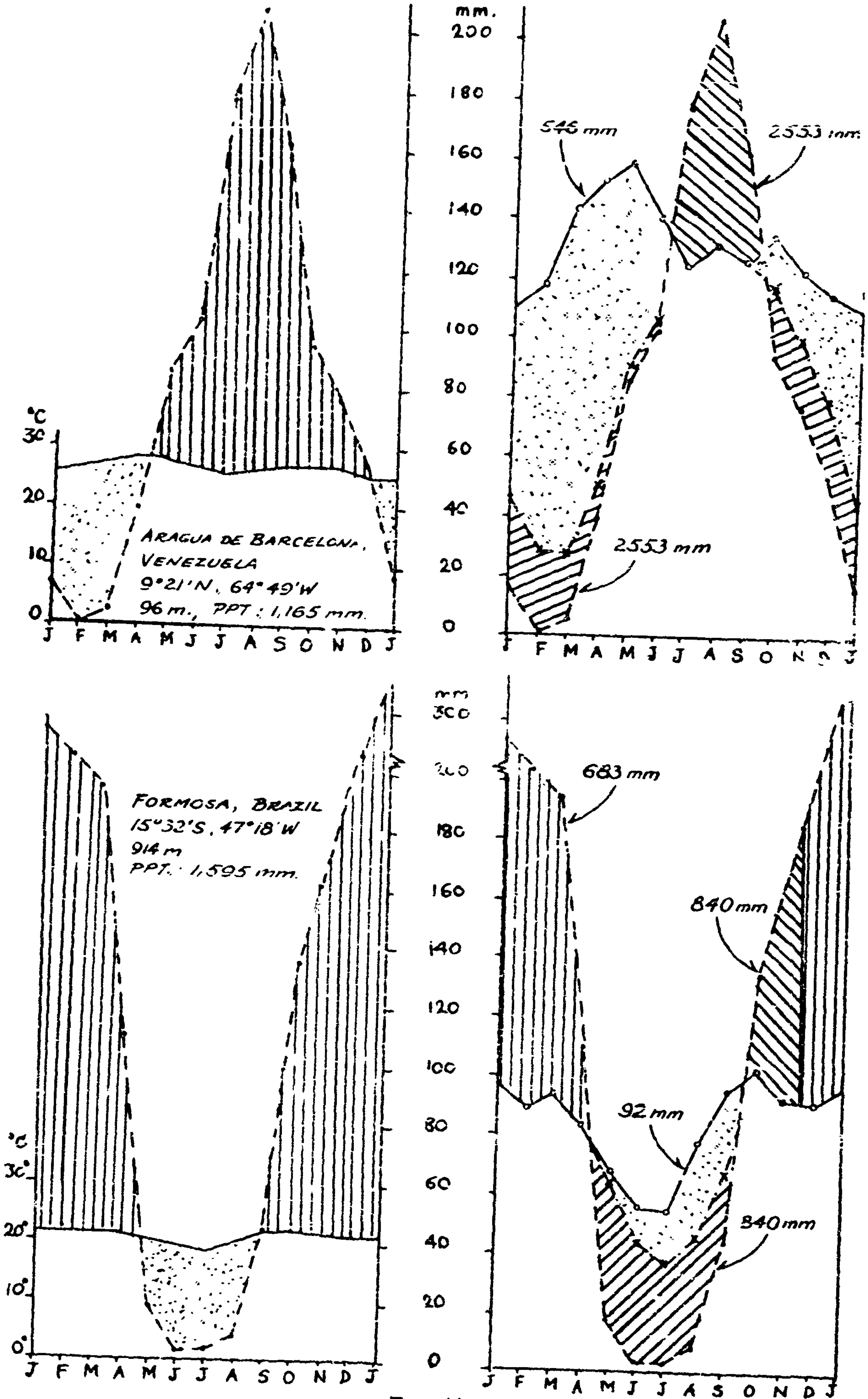
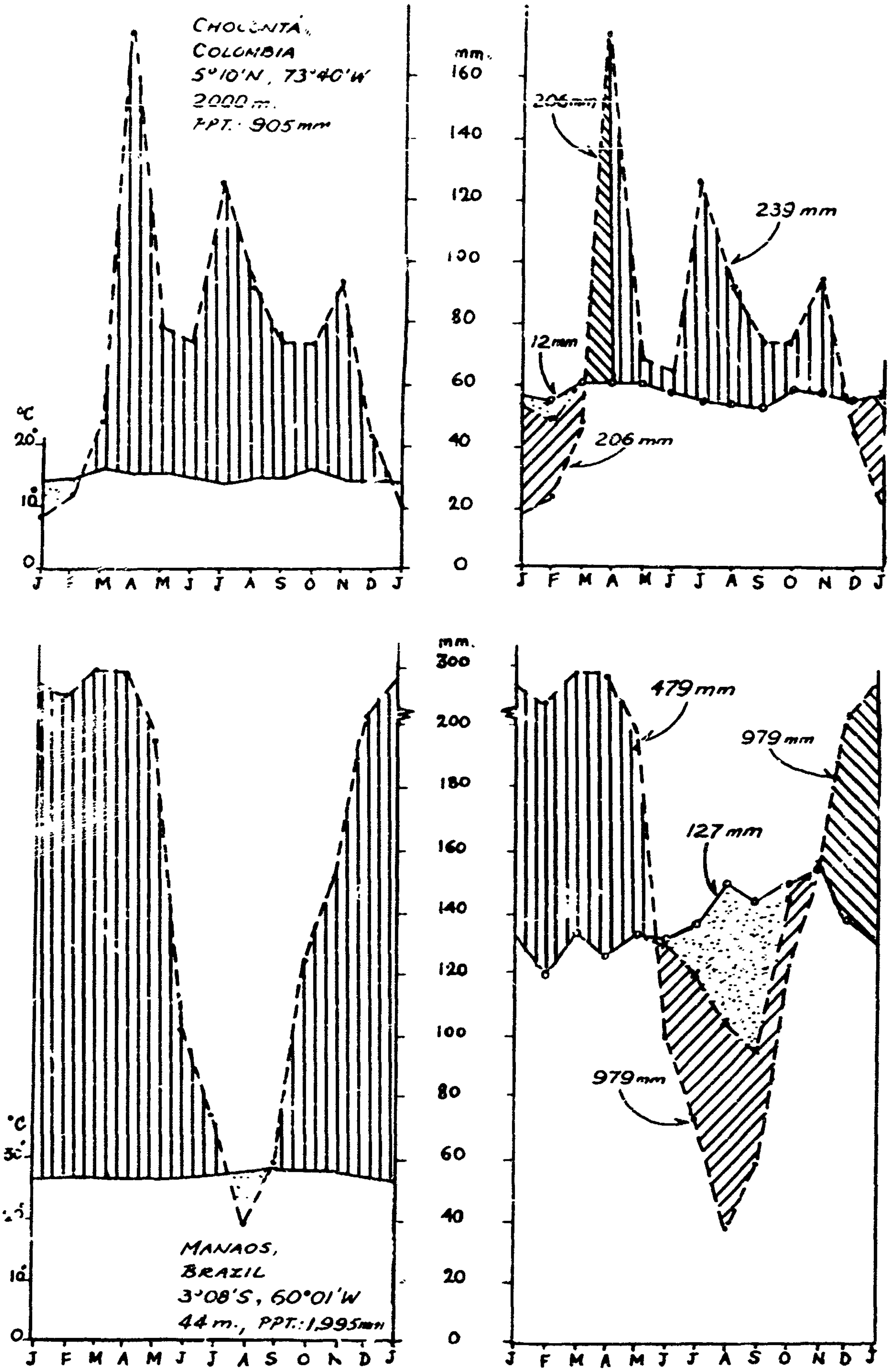

ARAGUA DE BARCELONA, VENEZUELA
9°21'N, 64°49'W
96 m., PPT: 1,165 mm.
FORMOSA, BRAZIL
15°32'S, 47°18'W
914 m
PPT: 1,595 mm.
546 mm
2553 mm
2553 mm
683 mm
840 mm
92 mm
840 mm
°C
mm.
J F M A M J J A S O N D J

Fig. 11



CHOCONTÁ,
COLOMBIA
5°10'N, 73°40'W
2000 m.
PPT.: 905 mm
°C
mm.
206 mm
239 mm
12 mm
206 mm
J F M A M J J A S O N D J
MANAOS,
BRAZIL
3°08'S, 60°01'W
44 m., PPT.: 1,995 mm
479 mm
979 mm
127 mm
979 mm

Fig. 12

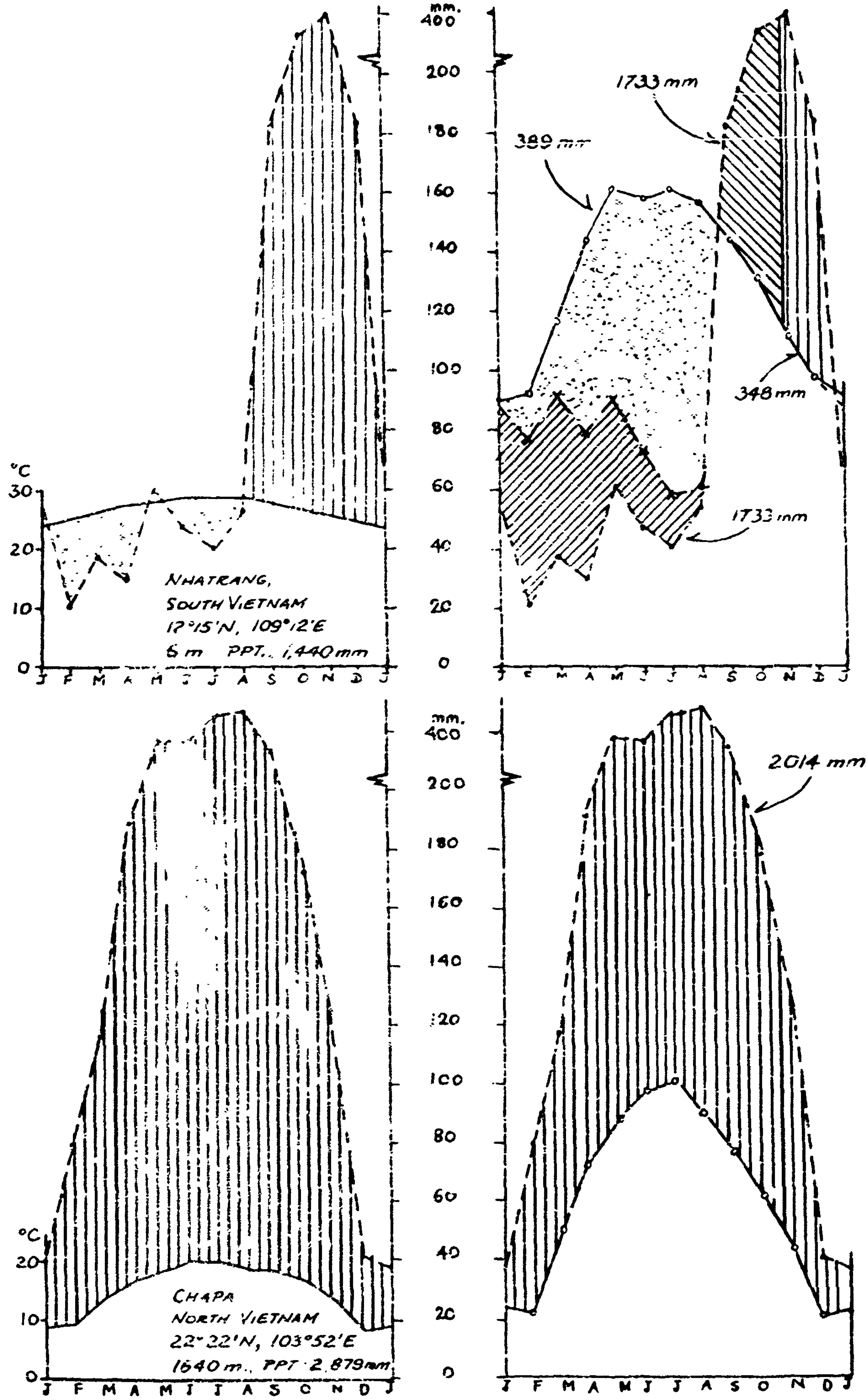

mm.
400
200
180
160
140
120
100
80
60
40
20
0
°C
30
20
10
0
NHATRANG,
SOUTH VIETNAM
12°15'N, 109°12'E
6 m PPT. 1,440 mm
1733 mm
389 mm
348 mm
1733 mm
°C
20
10
0
CHAPA
NORTH VIETNAM
22°22'N, 103°52'E
1640 m., PPT 2,879 mm
2014 mm
J F M A M J J A S O N D J

Fig. 13

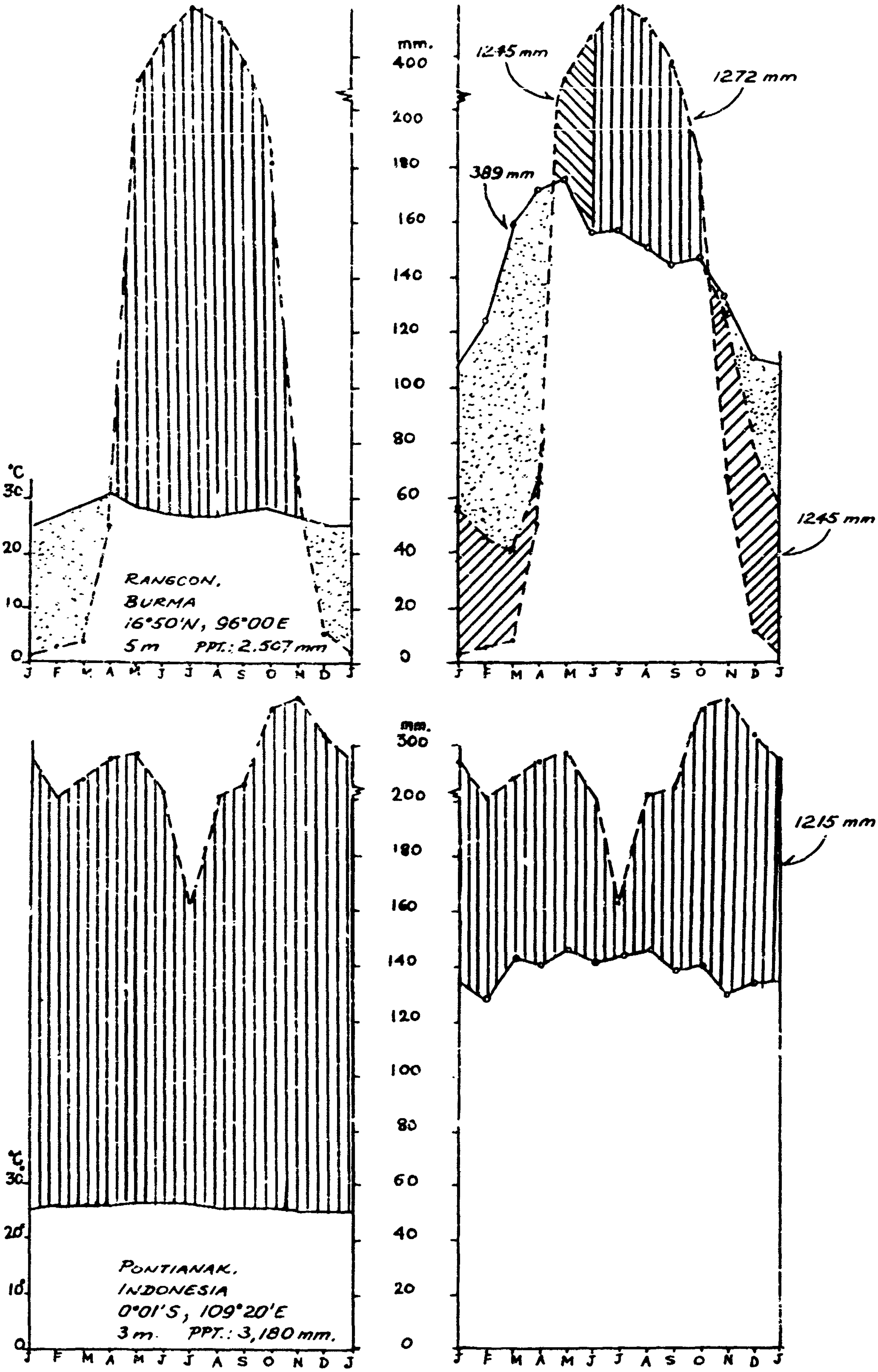
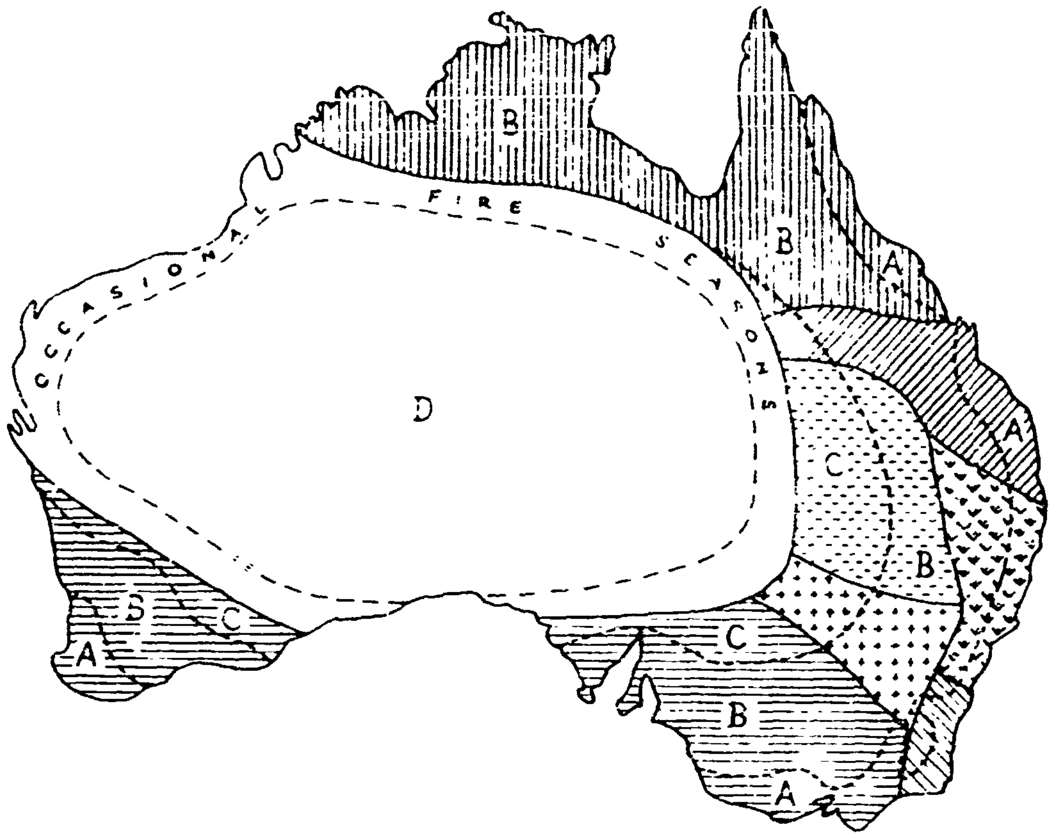

°C
30
20
10
0
RANGOON,
BURMA
16°50'N, 96°00E
5 m PPT.: 2,567 mm
J F M A M J J A S O N D J
mm.
400
200
180
160
140
120
100
80
60
40
20
0
1245 mm
1272 mm
389 mm
1245 mm
°C
30
20
10
0
PONTIANAK,
INDONESIA
0°01'S, 109°20'E
3 m. PPT.: 3,180 mm.
mm.
300
200
180
160
140
120
100
80
60
40
20
0
1215 mm

Fig. 14



MAP 1

DURATION OF FIRE SEASONS

ZONE	J	A	S	O	N	D	J	F	M	A	M	J
	●	●	●	●	0	-	-	-	-	-	0	●
	0	0	●	●	●	●	0	-	-	-	-	-
	-	0	0	●	●	●	●	0	-	-	-	-
	-	-	0	0	●	●	●	0	-	-	-	-
	-	-	-	0	●	●	●	●	0	-	-	-
	-	-	-	-	0	●	●	●	0	0	-	-
	-	-	-	-	0	●	●	●	●	0	-	-

Normal months of fire season .... ●
Occasional additional months 0
Fire occurrence very unusual .... -
Limits of fuel regions ----------------

FUEL REGIONS:

A - Predominantly forest fuels with some open grasslands. Sufficient fuel for fires every season.

B - Predominantly grass fuels but including large areas of savanna woodland. Sufficient fuel for fires in most seasons.

C - Sufficient grass fuels in occasional seasons following above average rainfall.

D - Arid. Insufficient fuel to support combustion in any season.

After McArthur, 1964

type of soil, from just a few millimeters to well over 300 mm. depth of water; and b) the rate of water loss from the vegetated soil surface depends on the existing soil moisture content. Thus, water is not equally available to the plant from field capacity to the wilting point. Some deficit will occur as soon as the soil moisture content drops below field capacity, and the water needs of plants will be increasingly difficult to meet as continued drying of the soil occurs." The data from which the climographs were prepared included computations for conditions of soil and plant cover which correspond to a soil moisture storage of 300 mm.

Three sets of curves are plotted on the climographs indicating the water balance at each station: potential evapotranspiration (PE), precipitation (P), and actual evapotranspiration (AE), which is the water loss from the soil. AE equals PE as long as soil moisture storage is at field capacity (300 mm. in this case), thus these curves frequently intersect as seasons progress. When soil moisture is less than field capacity, AE drops proportionally below PE. Water surplus occurs when P-PE values result after soil moisture is at full field capacity. Water deficit results whenever there is a P-AE value recorded.

b. Empirical Method of Bagnouls & Gaussen.--A simple empirical formula for distinguishing humid months from dry months, according to Bagnouls and Gaussen, is $P_{(mm)} \leq 2T_{(°C)}$, by which a period is dry if average precipitation recorded in millimeters is equal to or is less than twice the average temperature expressed in degrees centigrade. A graph so constructed in which the plotted vertical scales express this simple relationship, permits easy identification of the climatic dry period and its duration. The relationship of the two sets of curves is empirical and therefore there is no way to determine the intensity of the dry period. Thus, the stippled areas on the left-hand graphs do not have the same meaning as those showing the climatic water balance (see Figs. 8 through 14).

c. Evaluation of the Two Methods.--Thirteen stations were selected as a representative sample of major types of climates in each of the continental areas. Selected aspects of the graphs and the data from which they were drawn are arranged in Table 8 to facilitate comparison of the two methods. For each station and under the heading of site, the major type of natural vegetation is given.[1] The station climate is identified by letters of the Koeppen classification. Onset and duration of the climatic dry season is presented as well as an indication of the severity of the dry season. The latter is expressed as ecologically dry months (EDM), which are defined as months where recorded precipitation is 25 mm. or less (Phillips, 1965). (Table 8)

TABLE 8

ABILITY OF TWO CLIMATIC METHODS TO CHARACTERIZE A DRY SEASON

	$P_{(mm)} \leq 2T_{(°c)}$ (Bagnouls and Gaussen)	Climatic Water Balance (Thornthwaite and Mather, 1955)
	AFRICA	
Ft. Lamy, Chad		
Site:	Grass savanna and woody steppe (1) Subarid wooded savanna (2)	
Climate:	BSh No recorded precipitation: 4 mos.	
Dry Period:	Mid-Sept to June	Mid-Aug. to early July
Duration:	8 1/2 mos.	10 3/4 mos.
Severity:	EDM (ecologically dry months) = 7	Water deficit 1125 mm., or nearly twice annual precipitation

[1]For stations in Africa under the heading of site, vegetation and bioclimate is presented adapted from Aubréville et al. (1959), and Phillips (1965). The vegetative descriptions of Aubréville and Phillips are indicated by the numbers (1) and (2) respectively. The major types of vegetation indicated for stations in Latin America were adapted from various individual maps contained in the map collection, Library of Congress, Washington, D.C. For those in Asia, Library of Congress maps were used as well as the study by Chambers (1961).

TABLE 8 (continued)

	$P_{(mm)} \leq 2T_{(°C)}$ (Bagnouls and Gaussen)	Climatic Water Balance (Thornthwaite and Mather, 1955)
Elisabethville, Congo		
Site:	Woodlands and savannas with abundant *Brachystegia* and *Julbernardia* (1) Tropical subhumid wooded savanna (2)	
Climate:	Cwa. No recorded precipitation: 3 mos.	
Dry Period:	April to Sept.	Mid March to Mid-Oct.
Duration:	5 mos.	7 mos.
Severity:	EDM = 5	Water deficit 170 mm.
Salisbury, Southern Rhodesia		
Site:	Woodlands and savannas with abundant *Brachystegia* and *Julbernardia* (1) Mild, subarid wooded savanna (2)	
Climate:	Cwa. No recorded precipitation: zero mos.	
Dry Period:	Late March to early Oct.	Late Feb. to Nov.
Duration:	6 1/2 mos.	8 1/4 mos.
Severity:	EDM = 6	Water deficit 128 mm.
SOUTH AMERICA		
Aragua de Barcelona, Venezuela		
Site:	Low tree and shrub savanna	
Climate:	Awi. No recorded precipitation: zero mos.	
Dry Period:	Dec. to mid-April	Mid-Sept. to early July
Duration:	4 1/2 mos.	8 3/4 mos.
Severity:	EDM = 1	Water deficit 546 mm.
Choconta, Colombia		
Site:	Temperate montane forest and dense shrub	
Climate	Cwb. No recorded precipitation: zero mos.	
Dry Period:	Mid-Dec. to mid-Feb.	Late Nov. to March
Duration:	2 mos.	3 1/2 mos.
Severity:	EDM = 2	Water deficit 12 mm.
Manaos, Amazonas, Brazil		
Site:	Humid tropical forest (selva)	
Climate:	Ami. No recorded precipitation: zero mos.	
Dry Period:	Mid July to Sept.	Mid May to late Oct.
Duration:	1 1/2 mos.	5 1/4 mos.
Severity:	EDM = zero	Water deficit 127 mm.

TABLE 8 (continued)

	$P_{(mm)} \leq 2T_{(°c)}$ (Bagnouls and Gaussen)	Climatic Water Balance (Thornthwaite and Mather, 1955)
Formosa, Minas Gerais, Brazil		
Site:	Campo cerrado and semi-deciduous low forest	
Climate:	Awi. No recorded precipitation: zero mos.	
Dry Period:	Late April to Sept.	Mid-April to mid-Sept.
Duration:	4 1/4 mos.	5 mos.
Severity:	EDM = 4	Water deficit 92 mm.
TROPICAL ASIA		
Rangoon, Burma		
Site:	Humid tropical evergreen and deciduous forest	
Climate:	Ami. No recorded precipitation: zero mos.	
Dry Period:	Early Nov. to April	Mid- Oct. to mid-April
Duration:	4 3/4 mos.	6 mos.
Severity:	EDM = 4	Water deficit 389 mm.
Pontianak (Borneo), Indonesia		
Site:	Humid tropical evergreen forest	
Climate:	Afi. No recorded precipitation: zero mos.	
	No dry period	No dry period
Nhatrang, South Vietnam		
Site:	Semi-deciduous humid and subhumid forest	
Climate:	Aw. No recorded precipitation: zero mos.	
Dry Period:	Early Jan. to early August	Mid-Dec. to mid-August
Duration:	7 mos.	8 mos.
Severity:	EDM = 2	Water deficit 473 mm.
Chapa, North Vietnam		
Site:	Tropical and subtropical dense forest and shrub	
Climate:	Cwa. No recorded precipitation: zero mos.	
	No dry period	No dry period

Several points are clearly shown by the table concerning the ability of the two climatic methods to identify and characterize a dry season. Both methods effectively determine the existence of a dry season from standard climatic data. As might be expected, certain differences in the two methods occur for humid climates where abundant precipitation in one season nearly balances water losses by various physical processes during a period of lesser rainfall (see Figs. 9, Stanleyville, and 12, Manaos). The Thornthwaite method consistently indicated a longer, and therefore more severe dry period than did the method of Bagnouls and Gaussen. In most cases, the difference was one or two months, but for stations in South America, particularly, differences as great as three and four months occurred. If the tendency for the Thornthwaite method to identify a longer dry period is actually more realistic in terms of a period ecologically dry to vegetation and soil, then the difference in the two methods is significant. The rationale of the water balance method is not in question here, but rather to what extent the method correctly identifies vegetative dryness from climatic data meaningful to a study of combustibility. Until this can be done, the simple empirical equation of Bagnouls and Gaussen, and the definition of ecologically dry month (EDM) by Phillips, remain useful and are easily applied.

Few studies are available in which the complex interrelationships or microclimate, soil water conditions and natural vegetation have been studied in detail. Eden (1964), in reporting on the continuing research in the northern Rupununi Savanna, Guyana emphasizes the abrupt change that occurs in ecological conditions at the end of the rainy season. Whereas the relationships among rainfall, soil water conditions and runoff during the rainy season are direct, soil moisture content and water table levels are quickly affected at onset of the dry season. Basing his conclusions on detailed field instrument observations, Eden concluded that: 1) rates of potential evapotranspiration varied greatly from season to season; 2) measured rates of PE differed significantly from rates computed by the Thornthwaite method; and 3) that even though root depths to 180 cm.

for grasses were measured, the bioclimatic response to the dry season began shortly after cessation of rains (TABLE 9).

TABLE 9

MEAN DAILY POTENTIAL EVAPOTRANSPIRATION (PE), ST. IGNATIUS, GUYANA 1963-64 (in millimeters)

Seasons	Pan evap. (mm.)	Lysimeter (mm.)	Atmometer evap. (mm.)
Rainy May 4 - Aug. 21	4.2	N/A	N/A
Early Dry Sept. - Dec.	7.3	7.1	7.6
Late Dry Jan. to Mar.	9.2	9.2	9.2

After Eden, 1964

Measured PE values at St. Ignatius (1963-64), when compared with Thornthwaite values showed relatively close agreement for months of the rainy season. Monthly figures for mean daily PE during this period varied from 4.2 to 4.7 mm., and mean wind velocity measured at one-meter height above the ground was approximately 3 m.p.h. During the dry season (Sept. to Mar.), wind velocities varied from 4 to 8 m.p.h., the latter figure recorded in March, late in the dry season. Observed PE rose to a mean monthly total of 9.4 mm. per day for March, while computed PE values did not exceed 5.1 mm. per day for March, or for the period of record. Clearly, brisk winds sweeping over open grassland savanna increased the PE rate greatly. Actual evapotranspiration (AE) was much lower, being controlled in part by water supply. Values varied from 4 mm. per day in August near the end of the rainy season, to less than 0.2 mm. per day in March late in the dry season. Eden stated that, at that time, ground water supplies were at 4 to 6 meters depth. Obviously, surface moisture in the form of sporadic showers and possibly dew formation was quickly returned to the atmosphere during the dry season. Thus, plant response depended on soil water holding capacity and ground water levels in relation to the root zones of the various types of vegetation.

For much of the tropics, climates are characterized by well-defined seasonality of rainfall. The role of climate is, therefore, dominant during rains, when soils and water tables are recharged. Actual evapotranspiration (AE) may be greater during the period of rains than during the following dry season because of plentiful surface moisture. Once the dry season begins, factors other than climate assume a more significant role in the water balance of an environment. Primarily because of the ease with which it can be applied, and considering the limitations of climatic methods to express clearly specific relationships to the incidence of fire, the method of Bagnouls and Gaussen was used in the preparation of the various maps appearing in Chapter V.

3. Aperiodic Factors Important to Fire.

The various factors that aperiodically combine to produce _fire weather_ have long been identified and studied intensively. Any combination of wind, high temperature, and low atmospheric humidity preceded by a rainless period will quickly remove fuel moisture and increase combustibility. The severity of fire weather depends on a number of variables, including the persistence of desiccating conditions, or frequency of occurrence of brief dry spells. The characteristics and quantity of available fuel also contribute to the resulting fire danger.

The study of aperiodic atmospheric factors important to fire outbreak has as its primary purpose the identification of conditions associated with severe fire nazard in order that reliable prediction of fire can be made and proper precautionary measures taken. Consequently, support for such studies frequently is initiated and encouraged by governmental agencies, both local and national, where concern for preservation of natural resources and protection of life and property commonly resides.

The various factors which contribute to dangerous combustibility of natural vegetation have been discussed (see Chapter II). Included here is a brief examination of certain meteorological phenomena known, or suspected, to be either conducive or inimical to the occurrence of fire.

a. Synoptic Weather Patterns.--The study of synoptic weather patterns associated with the leading up to widespread and severe fire has been limited to a few subtropical countries. However, narrative descriptions of conditions accompanying fire outbreaks in tropical climates leave little doubt that spells of weather occur in which very rapid desiccation of the natural environment takes place. Most of the tropics experience the effects of prevailing trade easterlies, ITC (Intertropical Convergence Zone), or monsoon circulation during the year. These planetary wind belts extend poleward to approximately 25 degrees of latitude in either hemisphere. The most characteristic and widespread feature of tradewind and monsoon circulation is the presence of surface air, usually moist, which is overlain by dry air that gently subsides. The boundary separating these quite different types of air is termed the tradewind inversion, which is most persistent and widespread areally over subtropical oceans.

The function and role of the tradewind inversion in the planetary atmospheric circulation is discussed by Riehl (1954). He notes that even for low latitudes, the low level moist air is not of great vertical thickness, and that dry air is found at upper levels. Thus the seasonal and aperiodic fluctuation in height of the tradewind inversion controls in part the presence and vertical thickness of the moist air masses associated with the tropical westerlies.[1] Fluctuation in the movement of the zone of interaction between tropical westerlies and trade easterlies accounts for aperiodic, sporadic rains alternating with brief dry periods characteristic of seasonal transition in nearly all climates.

In Senegal, for example, dust carried on 20 m/sec. (45 mph.) NE winds, frequently heralds the end of the rainy season The relative humidity may drop as low as 7 per cent, and the combination of winds, dry air and high temperature yellows grass in two days or less. Most countries bordering the Sahara experience similar conditions at the retreat of the ITC and the establishment of anti-cyclonic circulation. Similarly, Africa south of the equator experiences oscillations in the mean height of the inversion. Protracted dry spells and drought due to large scale fluctuations in mean wind flow occur in nearly all tropical climates, even those normally considered to be rainy. For example, drought has been reported in coastal Guyana, South America, over much of the Congo Basin, and even in parts of insular Southeast Asia.

Rainbird (1958), in discussing the various ways in which wind affects fire, draws attention to the importance of forecasting new cyclonic developments in existing troughs over Australia which may suddenly alter broad-scale air flow during critical periods. At the height of the monsoon season over India, rains may suddenly cease or be sharply reduced for periods lasting from a few days to a few weeks owing to variations in the southwest monsoon. Similarly, the

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[1]To many meteorologists, the tropical westerlies, ITC (Intertropical Convergence) and doldrums are one and the same phenomena differing only in regional characteristics and vertical structure. The ITC also is considered to be the zone of dynamic interaction of air masses comprising the tropical westerlies on the one hand and tradewind air on the other.

unpredictability of rainfall for northeast Brazil is believed due to fluctuations in the mean position of the ITC, vigor of subsiding air aloft, and variations in the pattern of air flow above the tradewind inversion.

Fire weather occurring during periods normally considered part of the rainy season has been reported in the Congo and in various countries in Latin America. Even during massive onshore flow of very moist air, which characterizes the rainy season in the Amazon Basin and West Africa, periods of a few days to a week, depending upon location, experience little or no rain even though skies are overcast and cloud ceilings are low. It appears that layers or zones of moist air alternating with relatively dry zones frequently exist in the highly stratified lower air. Gentle subsidence of the entire lower level would be sufficient to inhibit rain. Consequently, it is possible for primitive cultivators to simply stack the slash, and, because of the opening in the forest canopy, sufficient drying occurs to permit firing during a brief rainless spell even though there is no climatic dry season.

The problem of relating synoptic patterns to fire danger in the tropics is no less complicated and frustrating than it is for temperate latitudes. Currently, efforts consist mainly of applying criteria and techniques proved useful in middle latitudes and modifications to fit regional and local conditions (Foley, 1947; Larkins, 1958; Mizon, 1958; Rainbird, 1958; Schroeder and Countryman, 1960; Reifsnyder, 1960, 1962; Stoddard, 1962). Most research has been limited to empirical considerations for various levels of fire hazard and danger rating systems. The criteria most often employed are temperature, relative humidity, wind speed and fuel state.

b. Local Topoclimatic Influences.--Atmospheric influences most critical to fire outbreak and behavior occur initially in the lower layers of air which is in intimate contact with the physical landscape. Whereas correct analysis of a synoptic weather pattern may indicate potentially severe fire danger for a period over a broad area, the probability of fire depends on local conditions.

The surface wind is both the most obvious and in many ways the most important influence on fire behavior. As noted, oxygen supply to burning fuels, rate of fire spread and fire spotting are directed by winds. Variability of wind direction and velocity is very significant, and it is influenced greatly by topography. Unfortunately, little success has occurred to date in attempts to abstract and simplify wind patterns and yet retain a necessary degree of usefulness. Rainbird (1958), in his discussion on winds and fire during the dry season ascribes to the seabreeze far-reaching effects on fire behavior in Australian coastal areas. Inasmuch as the seabreeze is nearly ubiquitous in the tropics. its role as a suppressor of fire danger brought about by decreased temperatures and increased relative humidity should be noted. A seabreeze may, on the other hand, aggravate fires in progress due to sudden wind shift turning a fire front, or a brisk increase in wind velocity causing fire to escape out of control. Rainbird noted that occasional explosive convective buildup of fire in progress has occurred with the onset of a seabreeze. Of unknown importance is the stratification of the lower atmosphere accompanied by the sharp alteration of pre-seabreeze temperature and dew point lapse rates, once a seabreeze sets in.

The relation of the thermal structure of the lower air to atmospheric stability and potential convection over fire has long been recognized. There is, of course, a relationship between temperature lapse rates and the wind pattern During typical fire weather, there is a strong diurnal fluctuation in the vertical temperature gradient that is reflected in surface wind structure. Intense solar heating of terrain during midday hours fosters development of superadiabatic lapse rates isolating surface winds from upper air flow; air motion is relatively non-turbulent and controlled largely by topography.

Similarly, the diurnal variation in the state of atmospheric moisture near ground level is especially important to fire behavior in the tropics. In most of the tropics, the formation of morning dew and mists may extend well into, or entirely through the dry season. The amount of precipitable water in the lower atmosphere is surprisingly high over and in forest and woodland vegetation formations. Depending on nocturnal air drainage, heavy mists may occupy bottomlands for two to four hours after sunrise. Numerous references cite the hours of 1000 to 1500 local time as the most propitious for burning slash. The establishment of ground-level dew point inversions is known to quickly suppress fire danger because of the rapidity with which relatively fine fuel types respond to the presence of moisture. Numerous writers have mentioned that untended fires in forest and woodland clearings quickly dampen down after sunset not only because the encircling tree growth is effective in preventing fire spread, but also because of the sharp increase in relative humidity. References to fires observed at night are few even for those areas characterized by open grasslands.

Fire whirlwinds or fire storms are reported most frequently as occurring in extratropical areas. Greatly feared, fires of this type may suddenly develop in which convective buildup over the burning zone may rise to an altitude of more than 10 km. (33,000 feet). Numerous studies of fire whirlwinds have been made. While no two fires occur under the same conditions, it is known that when pronounced atmospheric instability develops through a deep layer, surface fire, largely controlled by topoclimatic conditions, can in minutes become a raging inferno. Frequently the change in atmospheric equilibrium accompanies frontal passage or the movement into an area of an upper level disturbance. There is a notable scarcity of reports of fire whirlwinds in low latitudes. Severe fires of holocaust proportions have been reported in tropical Australia and south central Brazil. Although poor communications may account for the lack of reports of fire of this type, it should be noted that atmospheric conditions generally are not favorable. Strong wind shear at the tradewind inversion tends to shred cloud tops, while gentle subsidence prevailing in the dry upper air inhibits convection. However, fire cloud columns over extensive fires have been reported for many parts of Africa and Latin America. Cumulus and cumulonimbus produced by brush fires have been reported in Senegal, Sudan and Southern Rhodesia, as well as Matto Grosso, Brazil (Dessens, 1957; Tothill, 1948; Phillips, 1964).

The reciprocal of atmospheric influences on fire is fire-induced weather. Dessens in 1956-57 in a series of experiments attempted to form and build cummulus cloud by igniting brush fires in an effort to encourage rain during the dry season; first at Leopoldville and later at Bangui. Both localities experience the humid tropical climate of the Congo Basin. At Leopoldville, radiosonde observations indicate that on most days during the dry season, there is a three-layered structure in the atmosphere extending from the surface to 550 millibar pressure level. Warm and nearly saturated Atlantic Ocean air extends from the surface to 850 millibars, followed by a relatively dry layer with an inverted temperature lapse rate, above which occurs a deep and rather dry layer that is quasi-isothermal (Taljaard, 1955).

In one experiment Dessens reports the formation of cumulus that grew to a vertical development of 2.6 km. (8,600 feet) 6:22 minutes following ignition at 1603 hours of 30 m. tons of grass and brush which was spread over one hectare. Repeated experiments did not provide conclusive proof that intense fire can induce cloud formation. There appeared little doubt based on films taken during the experiment, that pre-existing cumulus of modest vertical thickness grew to appreciable proportions over the fire area.

Fire whirlwinds and severe fire-induced weather do not appear to be of the same order of significance in low latitudes as in middle latitudes. The less frequent and abrupt alternation of synoptic weather patterns characteristic of the tropics, as well as the prevailing thermal and moisture stratification of the lower atmosphere during the dry season are important.

c. Determining Fire Hazard.--Criteria used for determining fire hazard in most tropical areas are modifications of those long developed and tested in temperate latitudes, usually the United States. In most cases, the systems are empirical tables or charts developed from experience gained largely by foresters and game conservators. The factors evaluated are temperature, relative humidity or dewpoint, wind speed and direction, gross characteristics of fuels and fuel moisture content, time since last rains and seasonal weather patterns. These are assessed priorities or weights, or are transformed into index numbers. Various methods may be employed to arrive at an overall index of fire hazard. Generally, types of fuels and fuel conditions are highly important, so that multiple danger rating tables may be used, each table prepared for regional conditions, particularly, the dominant types of fuel present.

A useful aid in determining the occurrence and regional characteristics of fire danger is a fire season map. Climatic data, particularly seasonal rainfall, rainfall variability, temperature and dew point can be used to delimit seasons expected to be hazardous. These data, combined with qualitative data on the distribution of fuel types and quantities based on evaluation of vegetative formations, permit delimiting fire seasons. Past history of fires could be incorporated to refine the map. Australia has produced such a map which is extremely useful, (see Map 1, p. 59), (McArthur, 1964). Use of hazard sticks or other techniques to quantitatively measure dryness in vegetation is limited largely to commercial forestry on protected tropical tree plantations, and to range management in parts of Africa and Australia. The qualitative character of fire hazard rating is due to the large number of variables and more importantly, the rapidity with which these variables change in time and space. For this reason, determining fire hazard is more of an art than a science, largely dependent on the degree to which local personnel are familiar with their area, and on experience dirived from past fires.

4. Conclusions

Many specific needs for fire weather research have been expressed (Keetch, 1959; Reifsnyder, 1962; Whittingham, 1965; and Wilson, 1958a, 1958b). Some of the needs include: 1) development of procedures for predicting important weather conditions that have a severe impact on fire danger; 2) development of procedures for fine scale measurement and analysis of weather elements in mountainous terrain; 3) development of methods and techniques for interpreting long range synoptic forecasts in terms of local fireweather conditions; and 4) development of techniques for the use of data located at forecast centers in the preparation of essential guidance material for use by officers and workers of small agencies directly connected in various ways with fire

C. Fire and Natural Vegetation

The effects of fire on the floristic and gross physiognomic characteristics of tropical vegetation are both catastrophic and subtle. Clearing of forest and woodland by ax and fire abruptly changes the microclimate and biological environment. Regeneration in cleared areas is rapid, but plant succession on abandoned plots depends on a host of factors including the frequency and intensity of fire. Repeated fire in forests initiate subtle changes in the environment. Fire-sensitive species are gradually eliminated and the floristic composition of the forest becomes impoverished. Degradation of the ecological environment inevitably leads to the establishment of plant communities adapted to physiologically drier conditions. Degradation of forest and woodland also proceeds from an initial state of low potential combustibility to varying degrees of greater combustibility.

Similarly, fires' effects on the various types of savanna produce temporary and lasting change. The familiar scene of blackened earth, scorched tree and brush, and carbonized fragments littering the surface suggests total destruction. However, many plants are fire-resistant and respond quickly following fire with new growth. Repeated burning, however, attacks even the most fire-resistant species, so that gradual elimination of trees and brush occurs resulting in a landscape largely characterized by grasses, low herbaceous plants and fire-deformed shrubs.

1. Major Types of Tropical Vegetation

Nearly 15 million sq. km. (5.8 million sq. mi.) and 17.4 million sq. km. (6.7 million sq. mi.) of the earth's surface support tropical forests and savannas respectively. Numerous detailed studies identify, classify, and describe natural vegetation, largely floristically and physiognomically. Although studies of small areas may indicate dominant ecological relationships, no meaningful generalizations can be applied to broad areas. This is not surprising, considering the complexities involved in determining botanically and otherwise, the diverse character of tropical vegetation. There is an almost infinite number of variables contributing to specific aspects of site, location, floristic composition, gross physiognomic characteristics, and dominant ecological relationships. Poore (1963) in discussing problems in the classification of tropical rainforest noted that the "technical problems of description and identification are so great, and so little is known of the effects of climate, soil and other living organisms on the vegetation, that little progress has been made." Even selecting representative areas in tropical tall forest is difficult because dominant species so necessary to aid classification are few. Knowledge of the Malayan rainforest is more advanced than of many other equatorial regions, but even there basic data on its structure and pattern are inadequate Poore concludes that it is still too early to develop methods that are both satisfactory and economical to classify forest types and to investigate their relation to habitat.

The problem is no less complex for identifying and describing savanna vegetation. The literature is replete with descriptive names used to identify tropical grass and woodlands. A tabular presentation of descriptive terms for the vegetation types classified or mapped as savanna vegetation as well as a table indicating name-equivalents according to classifications of savanna vegetation appears as Appendix II (Hills, 1965). An extremely useful map, Major Bioclimatic Regions of Africa South of the Sahara, by Phillips (1965) combines floristic and physiognomic characteristics of natural vegetation with selected qualitative ecological values of climate and geographical location. Striking similarities exist between Phillips' map showing the distribution of his bioclimatic regions and the Vegetation Map of Africa, by Aubréville, _et al_. (1959), although each was produced independently. The categories appearing on these maps were ideal for relating fire and natural vegetation. Consequently, the categories were adapted for the preparation of maps showing the distribution of fire in the tropics and the relation of burning to climate and natural vegetation (see Chapter V).

To facilitate examination of a complex subject, the effects of fire on natural vegetation are discussed primarily on the basis of overall biological environments, including microclimate, major physiognomic characteristics of vegetation, and general characteristics of degradation and regeneration of the vegetation. Consequently, no attempt is made to analyze each of the types of vegetation appearing on the maps in Chapter V. Rather, the collective characteristics of vegetation and environment are grouped into the following three categories: 1) low elevation, humid tall forest and rainforest, and medium elevation, humid montane forest; 2) forest-savanna mosaic, that is, tall degraded forest coexisting in various proportions with savanna; and 3) wooded savanna and open grassland savanna. In the last category the effects of fire on grasses and woody growths are treated separately even though they appear together in a wide variety of vegetative landscapes. These forests are associated with tropical rainy (Af) and tropical monsoon (Am) climates, and there is abundant moisture in the ground to carry the humid forest through an ecologically dry period varying from one to two months. The microclimate is characterized by high humidity in which relative humidities are rarely below 75 per cent, and there is virtually no wind. Measurements of the effect of the forest on precipitation indicates that perhaps as much as 20 per cent is retained in the canopy and is lost by evaporation. The general distribution of that which passes downward is approximated by experiments conducted in the tropical rainforest of Brazil (Freise, 1936).

TABLE 10

PERCENTAGE DISTRIBUTION OF RAINFALL IN THE VEGETATION ZONE, TROPICAL RAINFOREST, BRAZIL[1]
(per cent of total rainfall)

Caught and evaporated in forest canopy	--- 20				
Caught in raingauge	--- 33				
Rain running down tree trunks	--- 46	Evaporated on trunk surface	--- 9		
		Absorbed by tree bark	--- 9		
		Reaching base of tree	--- 28	Reached water table	--- 7
				Absorbed by roots	--- 21
Totals	96		46		28

[1]Total rainfall recorded and the period of observation are not known.

After Freise, 1936.

2. <u>Humid, Tall Forests and Montane Forests</u>

a. <u>Characteristics of the Environment</u>.--A variety of forests are found in equatorial latitudes in climates experiencing 1600 to more than 6000 mm. of rainfall annually with no definite dry or drier season. Tropical rainforest, humid monsoon forest. mixed tropical evergreen forest, semi-evergreen forest and humid semi-deciduous forest are only a few among the confusing array of terms applied to forests noted for their floristic and physiognomic diversity. In an effort to avoid the problem of the ratio of evergreen to deciduous species occurring in a forest, the terms <u>mixed evergreen</u> and <u>semi-evergreen</u> have not been used. The term humid <u>semi-deciduous</u> forest has been applied to all forest types in which certain species respond to dry or drier periods by shedding leaves, but many tree species are also broadleaf evergreen. The term is also restricted to humid forests located below 600 m. (2,000 feet) elevation.

The floristic and physiognomic characteristics of these types of forest differ greatly from each other and differ within each type in different parts of the tropics. Generally, these forests are characterized by dense stands that vary in height from 18 to 60 m. (60 to 200 feet) or more, with few dominant species. A three-tiered leaf canopy frequently is present, and undergrowth is limited because of the interlocking leaf canopies. Horizontal visibility in a mature forest is 60 to 100 feet. Fairly abundant raw organic matter litters the forest floor, and the moist soil possesses more incorporated organic matter than as found in soils under dry semi-deciduous forest.

Humid montane forests may be broadleaf or needle leaf, evergreen or semi-deciduous occurring at moderate elevations (600 to 2100 m.; 2000 to 7000 feet), in plateau uplands and mountainous areas. Latitudinal location, elevation and exposure to prevailing winds are important environmental factors in determining the type of forest. Moderate to heavy precipitation may occur due to orographic uplift of moist air. Except for persistent cloud zones. the cool temperatures recorded are less a factor than one may suppose, because intense solar radiation that is typical of low latitudes. On the other hand, a modest increase in relief appears to be sufficient to cause differences between rainforest and submontane forest. This transitional type of forest is rarely more than 25 m. (82 feet) tall, and commonly has two stratified layers. At higher elevations, the true montane forest is only 10 to 15 m. (33 to 50 feet) high, and usually a single stratum of trees is present. A modest undergrowth is commonly present in both types of forest even though canopies are touching or closed. Stands are dense, and if undisturbed, the microclimate and biological environment is too humid to sustain fire.

In East Africa, Central and Caribbean America and Mexico, stands of conifers, notably pine and cedar, clothe upper mountain slopes. In Africa, pines are exotic species planted in forest reserves. Species of pine commonly grown are Pinus radiata, P. elliotti and P. patula. These commercial species are protected from fire by modern methods However, fires do sweep into forest plantations from adjacent areas. In Mexico, Central America and Hispaniola, pines and cedars occur at elevations higher than 1,000 meters (3,300 feet). The presence of pure stands of Pinus pseudostrobus in Guatemala is a positive indication of past burning.

b. Impact of Fire.--The impact of fire in humid, broadleaf montane and tall tropical forests is associated with clearing by shifting cultivators preparatory to planting crops. Practices employing the use of fire vary widely among various peoples: hence, the effect of fire on humid forests is directly related to cultural traditions (see Chapter IV). From a botanical and ecological viewpoint, once a clearing is made an abrupt change occurs in the environment. Trees are felled, girdled, or both, and the slash piled over a portion of land cleared to produce fertilizing ash when burnt. Even for tropical areas experiencing no well-defined drier season, the piled slash dries sufficiently in a short period of time to permit burning. Because the quantity of fuel per unit area is large, fires are intense. A successful burn is one in which all but the larger logs are consumed. Surface litter plus most of the soil humus is reduced to ash (see Chapter IV). A less intense burn results in rapid reclamation of the plot by seeds and bushy growths, because weeds and rhizomes are not killed.

c. Types of Regeneration.--Various types of vegetation reclaim abandoned clearings. One sequence is the establishment of a dense growth of light-loving brush and trees. These species, which are suppressed in the mature surrounding forest, quickly respond to the opening in the leaf canopy made by fire. In fact, abandonment of cultivated plots is due as much to encroachment of brush and weeds as it is to soil exhaustion. First year growth may be more than 4 m. (13 feet) tall and so dense that movement on foot is virtually impossible. Visibility is limited to a foot or two (see PLATE 5, p.88). The initial rank growth is gradually replaced by the less readily disseminated tree species, and a process of succession is begun which results in the re-establishment of a new forest.

In many parts of the tropics, grasses not trees occupy abandoned clearings and form a dense surface cover which preserves the forest opening. In certain parts of Africa, India and Southeast Asia, elephant grass (*Pennisetum spp.*) is quickly established, especially if soils are relatively fertile. On exhausted or badly eroded soils, perennial coarse grasses such as spear grass (*Imperata spp.*) and *Sorghum spontaneum* are found. These latter grasses are so widespread that they are known by many regional names. In Sumatra, Vietnam and other parts of Southeast Asia, *Imperata* and its associates are termed *lalang*; in Malaysia, *alang-alang*; and in the Philippine Islands, *cogon*. These grasses are also widely distributed in tropical Africa and America. Depending on frequency of fire and environmental conditions, the grass cover varies in height from 1 to 2 m. (3 to 6 feet). *Imperata spp.* will burn even when green and its' fire is intense. In Africa north of the Congo Basin, in plots protected from fire, *Imperata* is gradually replaced by other coarse perennial grasses, such as *Andropogon spp.*

Numerous clearings support jungle-like vegetation consisting of bamboos and a few quick-growing, soft-wooded trees. Bamboo represents a successional stage in forest regeneration in much of tropical Asia. Parts of Burma, Thailand, North and South Vietnam and India possess extensive areas of bamboo thicket or forest. Stamp (1925) noted seven different types of bamboo vegetation in Burma, and considered the prevalence of bamboo to be due to widespread deforestation. Burmese forests frequently have a bamboo understory, and even though clearing and burning of the forest takes place, enough bamboo sprouts apparently survive to quickly reclaim abandoned clearings. In his study of Tim and Kamuk people of northeastern Thailand, Credner (1935) noted that weeds reclaimed a clearing in the second year which were quickly succeeded by bamboo. The bamboo, however, did not give way to small trees until 10 years or more had passed. The transformation of humid evergreen forests located in the Chittagong and Arakan regions (Burma and East Pakistan) to bamboo forests by widespread clearing for shifting cultivation was the object of deep concern by Champion (1929). In both North and South Vietnam, lower hill lands and plains are in bamboo attesting to clearing of forest, while its persistence is due to its utilization as construction material. In areas where soil drainage is poor, bamboo and elephant grass occur together producing dense stands in which horizontal visibility is less than 2 m. (6 feet).

Forest clearings distant from grass seed sources more frequently revert to successional stages leading to forest than those located near savannas Where fire has fed on a fairly deep surface organic layer, the soil may have undergone significant change in bulk density, water storage capacity and aeration. Presumably the fire-altered soil now exposed to the weather is unable to immediately support tree seeds wafted into the clearing. Budowski (1956), on the other hand, states that there is "no evidence to believe that in tropical regions a soil may become too poor to support forest growth."

Cultural factors also are significant to rates of regeneration on cleared land as well as to the type of plant succession. Closely associated with soil degradation are the cultural practices which determine selection of site, the intensity of cultivation, and the length of time the plot is used before abandonment. Another important factor is the length of the forest-fallow period which is related to population pressure on the land and the type of shifting agriculture practiced (see Chapter IV).

A very useful set of generalizations for secondary succession in humid forest environments was derived from intensive study of 16 plots in Costa Rica and Western Panama. All were located in areas with temperatures ranging from 23.5°C-25.5°C. (74°F-78°F), annual rainfall varying from 2000-4000 mm. (80-160 inches) (Budowski, 1962). Each of the plots illustrated different successional seral stages in forest regrowth. Relatively good knowledge of past disturbances by man was available. Techniques used in making the study followed essentially the recommendations by Richards, Tansley and Watt (1940). The generalizations derived from the study are set forth below:

1) The floristic composition of pioneer communities is limited to a few species of wide natural distribution. There is little variation in the species represented in spite of different soil or climatic conditions.

2) The number of strata in a community is highly indicative of its successional status. Few and well-defined strata reveal an early seral stage whereas several strata, difficult to separate, reveal an advanced stage of succession.

3) The absence of large stem diameters is a characteristic of early stages of succession.

4) A dense undergrowth is characteristic of very early stages of development but not advanced stages of the climax.

5) The shape of the upper crowns is highly indicative. Early stages display uniform, thin light-green crowns. Older stages display many variations in crown forms and a darker green color.

6) Intolerance of the dominant species is characteristic of early stages and decreases towards the climax where most of the dominants are tolerant.

7) The evenaged condition is characteristic in early successional stages. There is a gradual change to an unevenaged condition with advance towards the climax.

8) Early pioneer species characteristically have small seeds that are dispersed by wind, birds and bats. Old secondary or climax species mostly have large fruits and seeds, many of which are dispersed by gravity.

9) Deciduousness is characteristic of many of the dominants in communities of intermediate status between the very early and the very advanced seral stages.

10) Seeds of early pioneer species may remain dormant in the forest soil until favorable conditions such as clearing and fire trigger their development.

11) Regeneration of the dominants is common in advanced stages but infrequent or absent in early pioneer stages.

12) Diameter and height growth is very rapid in early pioneer stages.

13) Rapid reestablishment of an advanced stage of the original forest is favored by proximity of such a forest to the disturbed area; redevelopment of the original forest is more rapid in small clearings than in large ones.

14) The presence of dominants having a very short life span is highly indicative of an early stage of succession.

15) The presence of a large proportion of species with leaves of the macrophyll size class, is indicative of an early pioneer stage. Climax species mostly have mesophyll leaves.

16) The hardness and weight of wood is highly indicative of successional position. The wood of trees representing early stages is soft and light whereas in species characteristic of advanced stages the wood is hard and heavy.

17) Climbers are highly indicative In early stages of successional development, there are few species but many individuals and they are mostly herbaceous, often forming a tangle In advanced stages of succession, they are large and woody with many species, but are not abundant.

18) An increasing number of species and variety in life forms of epiphytes is characteristic of progressive development towards the climax.

19) Certain species are highly indicative of the successional status of the community. Some can be correlated with past practices, notably exhaustive agricultural or fires. Others, notably palms, are indicative of long undisturbed conditions.

20) On lateritic soils the presence of a community with dominants typical of habitats much drier than the rainfall would indicate for the region, points to past soil degradation, mainly compaction through extensive use of fire.

c. Potential Combustibility.--A fundamental relationship between vegetation and fire is the role vegetation plays as a fuel in which widely different fuel types and quantities are spatially arranged in one or more levels. Inflammability of fuels depends not only on the composite physical character of the matrix, but also on the response of dominant species to increasing desiccation (see Chapter II). Potential combustibility is conceived to be a broad term encompassing that range of phenomena which contribute to the ability of an ecological environment to sustain fire without cutting and stacking fuels.

Potential combustibility in tropical rainforest is exceptionally low. The combination of high humidity beneath the upper canopy, absence of wind, and high moisture content of the forest litter produce an environment inimical to fire from natural causes. Consequently, fires started by lightning are rarely reported, even though low latitudes experience a high frequency of thunderstorms. The difficulties encountered by foresters deliberately igniting fuels in the Malayan rainforest illustrates the non-combustible character of humid forests (see Chapter IV, sec. B 3).

Fires can be started by shifting cultivators only because of the complete change that takes place in the microclimatic and biological environment. Very intense fires fed by piled slash that has dried only three days have been observed near Leopoldville (Phillips, 1965). The forest surrounding a burning plot, however, is an effective barrier to fire spread. Consequently, fires in clearings are usually untended at night. The sharp increase in atmospheric moisture beginning near sunset quickly dampens smoldering logs and embers.

Potential combustibility in humid broadleaf montane forests is very difficult to assess because of the influences of topography upon climate and other characteristics of the environment. The montane forest is composed of many types which, depending on terain, climate and soils, change abruptly from one type to another within short distances Lowest potential combustibility would occur in forests so located as to be persistently in cloud and rain caused by exposure to prevailing orographic uplift of moist air masses. Moderate to heavy precipitation in montane forest is offset by rapid surface runoff on steep slopes, high winds and the chimney effect of fire moving upslope. Although undisturbed forests are relatively impossible to ignite, areas that have been cleared slowly return to the original type of cover. Loss of exposed soil may prohibit tree growth so that the brush, regenerating on such area, represents an environment having a higher potential combustibility.

Potential combustibility in coniferous montane forests is high, particularly since they occur in areas experiencing a climatic dry season. In commercial pine forests, burning is often employed as a tool to reduce fuel accumulation to lower fire hazard. Mature pines are relatively fire resistant if flames do not seriously scorch tree crowns Seedlings are more susceptible to fire. Precautionary measures employed to suppress fire in commercial forests are modern in terms of techniques and equipment (see Chapter IV).

3. Forest-Savanna Mosaic

a. Characteristics of the Environment.--Centuries of clearing and burning in humid tropical forests have produced extensive geographic areas where forest and savanna coexist in complex patterns (see maps, Chapter V). The term forest-savanna mosaic is essentially morphological and designates the replacement of forest by seral stages of various types of savanna appearing in a dominantly forested landscape (Aubréville et al., 1959). The mosaic pattern occurs in degraded rainforest and montane forest located in humid climates where ecologically dry period rarely exceeds two months (see PLATE 6, p. 88).

In the tropical monsoon (Am) and wet and dry (Aw) climates where the well-defined dry season is short, tall forests co-mingle with less tall, mostly deciduous forests. These forests occupy upland sites, whereas the more humid types are found along rivers, in deep ravines and other protected areas. The drier forest is multistoried with leaf canopies that are closed or touching Undergrowth, if present, is dense brush; grass is not present in an undisturbed forest. The effects of fire upon this more open type of forest has been severe. After clearing, tall grasses reclaim the land. Retreat of the forest has been fairly rapid in many parts of the tropics, notably in south-central Africa, where forest relics appear as isolated remnants surrounded by open savanna (see PLATE 7, p. 89).

An infinite number of gradations occur in the ratio of forest to savanna in the mosaic pattern and no one term is adequate. The term derived savanna with its genetic connotation, also appears in the literature and refers to the forest-savanna vegetation complex (Keay, 1959; Phillips, 1965). This term applies especially well to the vegetation of Africa, where many excellent studies have documented the effects of fire on forest vegetation. Numerous experimental studies also indicate that when protection from fire and human activities is provided, grasses of the forest-savanna mosaic are quickly invaded by brush as a pioneer stage leading to forest (Aubréville, 1953; Richards, 1952; Budowski, 1962; Fuson, 1963; Denevan, 1965).

PLATE 5: First year regenerated growth behind field worker. Maize crop on second year cycle of shifting cultivation in rainforest; Lake Izabal, northern Guatemala (Photo by H. Popenoe).

PLATE 6: Brush and grass opening made by ax and maintained by fire in tropical rainforest located just north of the equator in the Republic of Congo (Brazzaville), (Photo by J. F. V. Phillips).

PLATE 7: Relict subtropical, humid, montane forest, East Griqualand, South Africa. Forest retreat due to axe, browsing and fire (Photo by J. F. V. Phillips).

PLATE 8: Abrupt forest-savanna boundary coinciding with physiographic border between lowland and mountain slopes. Fire has penetrated rugged hills in background. Northern Rupununi, Guyana (Photo by T. L. Hills).

b. The Forest-Savanna Boundary.--In order to identify and clarify the processes by which forests degrade, a number of studies have explored the forest-savanna boundary.[1] Basically two types of boundaries with many variants have been observed. In many areas a zone of varying width containing low trees and brush with a grass ground cover separates more open savanna from forest. Elsewhere, the boundary is abrupt in which the change from grassland to forest may take place within a distance of four meter, (13 feet) (PLATE 8). It is important to understand the action of fire in these two boundary situations, particularly with respect to the significance of changes that occur in ecological conditions in forest. Until these are clarified, constructive use of fire in grassland and forest management suffers.

In all probability, degradation and retreat of a forest boundary depends on frequent occurrence of fire attacking the forest edge from established savannas. Since the attack is on dense. rainforest, montane forest, or tall deciduous forest characterized by a close or nearly closed canopy. potential combustibility in these types of forest is low.[2] A basic question, therefore, is how degradation of an essentially non-combustible forest is initiated, and once begun, how it progresses.

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[1]The boundary between tropical forest and savanna grassland was the focus of an international symposium to which invited authorities from many countries presented papers which are to appear in a single volume I.G.U. Symposium on the Ecology of the Savanna-Forest Boundary, Venezuela, May 1964.

[2]The various types of subhumid and semiarid, semi-deciduous and deciduous forests which are significant components of savanna landscapes are not being considered.

In traversing the deep linear filaments of savanna invading the Gabon forest, Aubréville (1949) found that brush fires from the savanna actually penetrated many meters into the tall forest in some places. Where fire invaded the forest the farthest distance, it had fed on accumulated litter and a relatively deep humus layer. Fire did little direct damage to the lower tree trunks, but certain fire-sensitive species were killed by fire attacking the upper portions of their roots. Dead trees quickly succummbed to attack by insects and microbial activity and were easily toppled by wind. That humus fires are possible in dense humid forest and can be very intense, is made clear by the account of the disastrous fire in the virgin state forest, Vohibe-Autocha, Madagascar, November 1955 (Vignal, 1956) A surface fire, ignited for purposes of clearing during a period of extreme drought, became uncontrollable, destroying some 1,500 hectares (3,750 acres) of primary forest. The fire spread in the deep surface litter extending downward to a depth of 5 to 10 cm. below the surface. Mature trees were killed at upper root level and rapidly felled by winds and their own weight. The humus layer was completely destroyed leaving a mixture of sand and ashes overlying the lower horizon. It is doubtful that the original forest cover will ever be reestablished.

Puri (1960) in his two-volume comprehensive survey of vegetation on the subcontinent of India unequivocally states that savannas are derived from degraded forests. Fire protection in forests possessing commercial value results in heavy stands often characterized by dense understories. Consequently, such protected forests experience fire only in relation to forest management. Elsewhere, overgrazing and annual burning, collection of wood for fuel and construction material, have reduced forests to woodland savannas. Puri states that the presence of big trees, such as Shorea robusta, Adina cordifolia, or Lagerstroemia parviflora, in savannas indicate the existence of previous high forest.

The effects of fire on plant communities in northern Australia indicate that burning has a long history. Where annual precipitation exceeds 889 mm. (35 inches), the land in the north is fired annually. Southward toward the interior desert, the accumulation of fuels is slow so that fierce fires occur perhaps once in 10 years. Fires set by aboriginals are for hunting, food gathering, and to enable easy movement from place to place. Indiscriminate burning, however, is not practiced because of the scarcity of food supply for the nomads. The overall effect of centuries of burning both by aboriginals and later by European settlers, has been to produce a vegetation landscape in which many if not most vegetative formations have been altered by fire (Stocker. n.d.). Along the northern coast occur patches of semi-deciduous. tall forest densely festooned with vine. These remnants are located in areas possessing abundant soil moisture and high ground water tables (Specht, 1958). Stocker, after examining many of these relic communities, concluded that the availability of soil and ground water determined only the total height and complexity of the formation, and that existing rainfall was adequate to support this type of vegetation on many soils. Fire is the dominant agent restricting the area of forest. In many forest patches there was no significant penetration of fire into the undisturbed forest. The implication is that the boundary between relic forest and wooded savanna may well have been abrupt.

Fire is known to be a significant agent in maintaining sharp dividing lines between forest and savanna vegetation, but it is not clear how the boundary reaches dynamic equilibrium. (PLATE 9). Study of the northern Rupununi savanna. Guyana (British Guiana) indicates that the main forest vegetation is found on hills and mountains along the physiographic margin of the savanna which occupies a late Tertiary lowland (Eden, 1964). Locally, the savanna

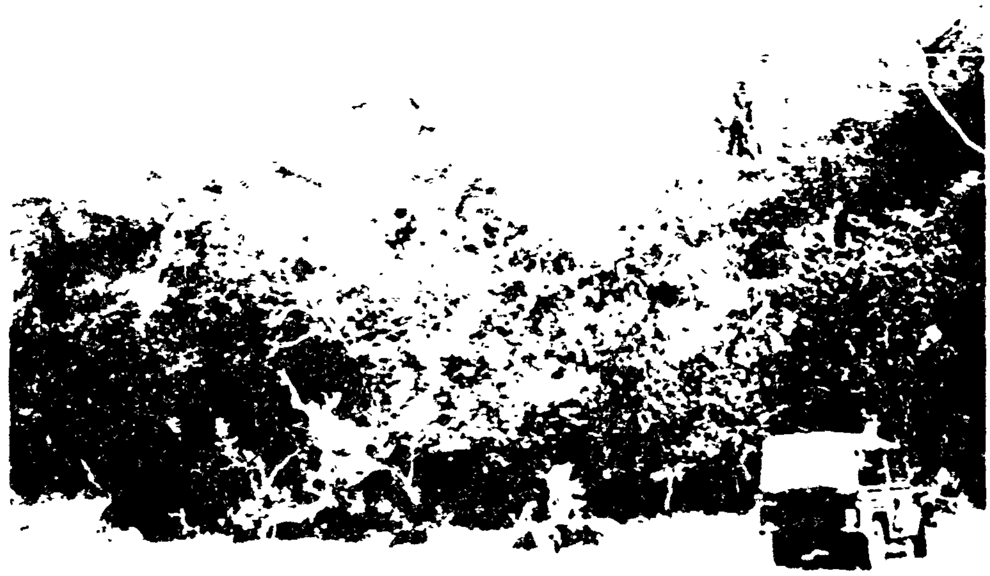


PLATE 9: Savanna abutting stony slopes clothed in dry, semi-deciduous forest. Boundary width is less than 4 meters and is maintained by fire. Northern Rupununi, Guyana (Photo by T. L. Hills).

PLATE 10: A few meters distance into the dry semi-deciduous forest (see Plate 9). Stoniness and lack of surface litter may account for inability of fire to penetrate forest from the savanna. Northern Rupununi, Guyana (Photo by T. L. Hills).

has transgressed into the hills, but there is a general coincidence of semi-deciduous forest grading into rain-forest at higher elevations on elevated terrain, and savanna with bush islands in the lowland (PLATE 8, p 89). Bush islands and galeria forest in the savanna, according to Eden, are distinct formations both floristically and physiognomically, and differ from the main forest associations. Soil water and ground water levels in the savanna differ markedly from those of the uplands. Annual fires in the savanna may well contribute to maintaining the sharpness of the boundary, but it appears that the respective environments are hostile to invasion by vegetation across the forest-savanna boundary. Savanna tree species are intolerant of shaded conditions that occur in the forest. Conversely, the forest trees are fire-susceptible, particularly in the sapling stage, and therefore, would not regenerate easily in the savanna. Furthermore, the abrupt change in fuel types and quantity across the vegetation boundary results in radical change in potential combustibility (PLATE 10).

Among the many physical aspects investigated in the forest-savanna mosaic, there is, at present, no clear understanding of the relative significance of the many differences noted in the two types of environment. Transitional boundaries may well occur where no great differences are present in geologic strata, soils, and topographic relief. In such cases, repeated burning will first selectively kill fire sensitive tree species at the forest edge. The dense upper canopy is thinned, permitting an increase in insolation reaching the ground which promotes rapid growth in the understory. Consequently there is a sharp increase in the quantity of finer-textured fuels which then respond quickly to onset of dry conditions. The more open nature of the forest also permits soils to dry out more rapidly, and there may be a fall in the local water table. Each new fire season fire penetrates more deeply into the forest. Adlard, (1961) states that in Southern Rhodesia, Katanga and Angola there have been reported lanes of fire-tolerant trees with a grass understory entering humid montane forest communities. The lanes into the forest are parallel to prevailing winds of the dry season.

Conversely, abrupt forest-savanna boundaries appear to be associated with strongly contrasting ecological environments. The influence of geologic strata, topographic relief, climatic dry season, geomorphic processes leading to formation of laterite crusts, and soil-water relationships, singly or in combination, have been advanced as causal factors able to maintain forest and savanna environments with abrupt boundaries. The role of fire as a maintaining factor is relatively clear. Regeneration of grass, and particularly, wooded savanna is well-documented in many parts of the tropics. It is possible that even where the forest-savanna boundary is sharp, absence of fire results in forest invading a physiographically distinctive savanna environment. Such may be the case in the sparsely occupied southern Rupununi savanna (Waddell, 1963).

c. Potential Combustibility.--The forest-savanna mosaic has many characteristics which favor high potential combustibility. Fuel quantities are large and arranged at different levels so that the entire fuel complex has a large surface exposure The tropical monsoon (Am), wetter margins of the tropical wet and dry (Aw), and drier margins of the tropical rainy (Af) climates all experience a drier or dry period extending from one to two or three months. Vegetative response to the ecologically dry season is a varying proportion of deciduous trees in evergreen forest communities, and the rapid desiccation of grass and brush vegetation of open areas. The tall, perennial grasses become woody as they mature and respond quickly to drier conditions. Thus a fine, homogeneous type fuel is present, and when ignited burns fiercely.

Although certain aspects of the forest-savanna mosaic suggest high potential combustibility, other aspects reduce the ability of fire to effect widespread devastation. The pattern of vegetation is one of disparate elements each possessing distinctive microclimate and biological environments. While annual burning may occur in savanna areas, the forest acts as a barrier to fire. Consequently, the overall combustibility of this type of vegetation landscape depends on the ratio of forest to savanna. Since the mosaic pattern is derived from degradation of humid tropical forests, it should be remembered, that clearing of the forest is the dominant factor, and fire is essentially a tool in the modification of the landscape.

4. Wooded and Open Savannas

a. Characteristics of the Environment.--Tropical savannas are very widespread and are found in a wide range of physical environment. Savannas are found along coasts and at elevations above 1000 m. (3300 feet). Certain savannas may owe their origin to edaphic, biotic, geologic or some other condition. It appears unlikely that climate alone is a factor in the distribution of savanna vegetation, even though the occurrence of a definite dry season is significant. Therefore, various types of savanna are found in tropical wet and dry (Aw) climate experiencing mean monthly temperatures ranging from 18°C (64°F) to above 23°C (74°F), and annual rainfalls varying from more than 1700 mm. (67 inches) to as little as 662 mm. (30 inches).

Dry types of wooded savanna, found particularly in Africa and Australia, are associated with low latitude semi-arid (BSh) climates where annual rainfall may be as low as 410 mm. (16 inches). Certain characteristics representative of all climates are common to savannas. These are the occurrence of a definite dry season in which the number of months that are ecologically dry may be as few as three or more than seven. Saturation deficit during the dry season is moderate to high. Most savanna areas experience a large variability in rainfall from year to year; occurrence of drought is fairly common.

Equally as important as the climatic dry season, are soil-moisture relationships. Soil textural classes may vary from coarse sands with layers of gravel to heavy, compact clays. Thus within an area, certain combinations of soils, topography and drainage combine to produce a moist biological environment able to support broadleaf evergreen forest, while an adjacent area may support only xerophylous shrub. Soils that are too freely drained will be physically dry, whereas soils that are too poorly drained will be physiologically dry. Thus, in savannas where climate, topography and parent material are the same, a change in vegetation indicates a change in soil or soil-water relationships.

Savanna is a woody-plant/grass complex where the areal density of woody species, generally trees, varies considerably in a well-developed grass cover. It is possible that the climate is sometimes sufficiently dry to maintain the more or less open nature of the savanna, but it seems more likely, that the frequency of fire acts as a greater deterrent to the encroachment of woody species than does climate. Perhaps it is more correct to say, that climate in combination with geologic strata, topography, soils and edaphic conditions provide a delicately balanced forest environment in most tropical areas. The occurrence and intensity of fire appears to have been sufficient to have degraded the forest and woodland cover in most areas, and to have eradicated nearly all woody species in open grasslands. Most savanna vegetation, therefore, is in a state of ecological disequilibrium with the environment. The diversity of vegetation types comprising savannas is such that occasionally all stages from essentially woodland to grass savanna, or even grass steppe, can be found in a few hectares. Selected examples of savanna types illustrate this diversity.

Wooded savanna in Africa covers extensive areas both north and south of the Congo Basin (see maps, Chapter V). In humid sites trees may be more than 20 meters high (66 feet), semi-deciduous, and form a leaf canopy that is thin enough for sufficient light to reach the ground to support a grass cover. Tree species are fire-tolerant, but are unable to withstand fierce fires. Climax vegetation is believed to be a closed woodland with little grass. When fire is excluded, a dense understory of brush quickly becomes established. However, most of this type of wooded savanna is thinned by annual fires which kill new saplings and promote grass understory. In areas where climate or site is dry, trees are mainly deciduous and vary in height from 4 m. to 10 m. (13 feet to 33 feet) high with density of stand depending on edaphic conditions and the nature and extent of human interferrence. Seldom is woodland continuous for more than a few kilometers, and open grassland surrounds the wooded area (PLATE 11).

In the Brazilian Highlands, the woodland transitional between forest and campo cerrado is termed cerradão. The cerradão of the Planalto Central is physiognomically like a luxuriant campo cerrado, Waibel (1948). The average height of trees is 10 to 15 m. (33 to 50 feet), and at the height of the dry season 20 to 30 per cent of the ground per unit area is estimated to receive the direct rays of the sun In the adjacent much taller semi-deciduous forest, Waibel stated that only 3 to 5 per cent of the ground is directly exposed to the sun and grasses are not present. In the campo cerrado on the other hand, trees average 4 to 8 m. high (13 to 26 feet), and 80 to 90 per cent of the ground is estimated to receive direct sunlight. Primarily on the basis of soil characteristics, Waibel classifies cerradão as a transitional type of forest, but the campo cerrado is an open wooded landscape composed of clumps of bush and trees densely scattered and interspersed by grass (PLATE 12) The term savanna does not fit well the distinctive vegetation of Central Brazil.

PLATE 11: Regenerating woody species in subhumid, wooded savanna protected from grazing and fire. South Africa (Photo by J. F. V. Phillips).

PLATE 12: Campo cerrado vegetation in the Planalto Central of Brazil (Photo courtesy of T. L. Hills).

The pine woods with a grass ground cover located in Coastal British Honduras, Honduras and Nicaragua are also termed savannas. Located on sandy soils, these savannas have widely spaced trees (Pinus caribaea) with a tall grass ground cover giving an overall appearance of a parkland which is definitely subclimax to a tall mesophytic forest. Pine savannas are definitely fire-maintained. The presence of a dense brush understory composed of hardwood saplings, (oak), thicket and vine is an indication that fire has not occurred for three or more years. Control burning reduces fuel accumulations which would feed fires too intense to be withstood by young pine trees. Methods employed in burning are patterned after the experience, supported by many studies, of foresters and others in the pine forests of southeastern United States

Open savannas are largely perennial mesophytic grasslands in which the various grass species form tussocks isolated from each other. The culms when fully grown form a more or less continuous layer dominating any lower stratum of plants The density of ground cover depends largely on edaphic conditions. In wet sites, sedges and reeds are dominant forms. Even though grasses may be the dominant vegetation, it is the type and distribution of trees which impart the distinctive characteristics to the various types of open savanna (see Appendix II). Since annual fires are common to grass savannas, all tree forms are phyrophilic and may appear widely scattered, in island-like patches, and as galeria filaments following stream courses. Palms, also fire-resistant, may dominate open savanna areas and occur in upland sites and along wet bottomlands (PLATE 13).

Many savanna trees are adapted to the occurrence of fire by having deep tap root systems, thick bark, the ability to quickly send out buds and new leaves, and to send up suckers or new shoots. In certain species roots are massive rather than branching (PLATE 14). Most of these

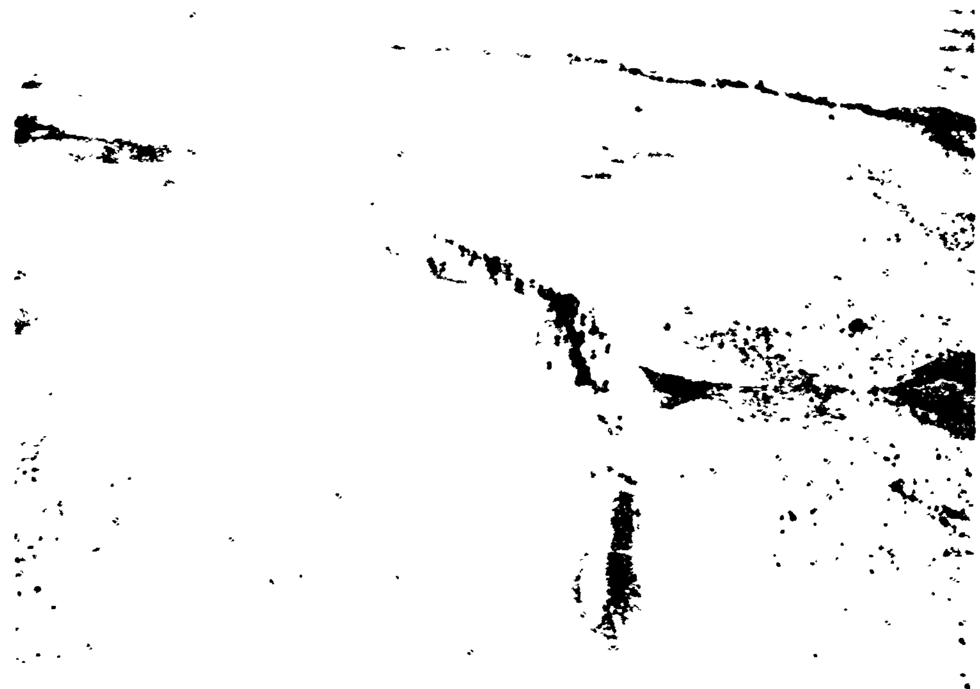


PLATE 13: Scattered bush savanna with galeria forest and palm marsh. Irregular dark patterns on the rolling terrain are recently burnt areas. Color believed due to reddish latosols. Rio Branco Savanna, Brazil (Photo by T. L. Hills).

PLATE 14: Massive root systems of Courbonia edulis (left) and another shrub. These are typical fire-resistant plants of the wooded savanna, Africa, and troublesome regeneration species in open grasslands (Photo by H. J. Van Rensburg).

pyrophiles belong to the legume family in Africa, notably Acacia spp , Brachystegia spp., Isoberlinia spp., and Julbernardia spp. In America, the most conspicuous savanna trees are Curatella americana, Byrsonima spp., Bowdichia virgilioides and Xylopia spp. (see PLATES 17 & 18 p. 111). In northern Australia, eucalyptus is found where fire is not too intense and in drier areas Acacia spp. are common. It is doubtful that natural savannas occur in South and Southeast Asia. Successional stages in clearings in the various types of forest may include grasses and/or bamboo or vine and low tree growth.

Savanna grasses include perennial and annual species which have been subjected to varying degrees of disturbance, such as grazing pressure by domestic animals, concentration of game and frequent fire. As a result of the interaction of all or some of these disturbing factors, much of the grass cover reflects many different stages of degradation and recovery which may persist for varying periods of time as secondary grasslands. Predominant grasses are coarse perennial species that vary in height from 40 cm. to more than 3 m. (16 inches to 10 feet) depending on climate and soil-water conditions. These grasses generally have flat basal and cauline leaves, and propagate from creeping roots or rhizomes. Bermuda grass (Cynodon dactylon) is widespread especially in the pine savannas of Central America. The genus Hyparrhenia characterizes the grass cover of a large part of all tropical savannas between latitudes 20°S and 8°N, and where rainfall is about 762 to 1525 mm. (30 to 60 inches) annually. In Africa, Hyparrhenia spp. are associated with the wooded savannas of Angola, parts of southern Rhodesia and with the broad wooded savanna belt extending from Sudan to Sénégal. When this type of cover occurs as an understory to an undisturbed woodland of Brachystegia or Isoberlinia, it is usually sparse and spindly. When the trees are more open, however, or where clearing and fire has taken place, the grasses thicken, and *Hyparrhenia* then becomes a significant member of the grass association, often reaching a height of 2 to 3 m. (6 to 10 feet) and forming dense thickets (Rattray, 1960).

Guinea grass (*Panicum maximum*) is widely distributed throughout savannas in Africa and America. It reaches its maximum development under warm, moist conditions on fertile soils, and is therefore, often associated with elephant grass (*Pennisetum purpureum*). Elephant grass is found in the degraded forests and wooded savanna in Nigeria, Ghana, Ivory Coast, Liberia and Sierra Leone. *Imperata cylindrica*, (sword grass) also is widespread in savannas, particularly in those north of the equator. Fires in both *Pennisetum* and *Imperata* are fierce; the latter grass carries fire even when green. The genus *Andropogon* has a very wide distribution in Africa, but reaches its maximum development north of the tropical evergreen forest; *Andropogon spp.* and *Hyparienia spp.* are frequently co-dominants in the various types of savanna characterized by a marked dry season, but with annual rainfall greater than 762 mm. (30 inches).

In northeastern Australia, wooded savanna grasses include *Heteropogon contortus* (black spear grass), *Themeda spp.* (kangaroo grass) and in parts of the Northern Territory, the annual, *Sorghum intrans* is widespread among the perennial grasses, *Themeda australis*, and *Sorghum plumosum*. Numerous grasses reclaim abandoned clearings in South and Southeast Asia, where on wetter sites elephant grass and bamboo often is combined in a dense thicket. *Imperata cylindrica* with various *Sorghum spp.* comprise a typical successional stage.

An important factor affecting the occurrence of fire in the coarse perennial savanna grasses is that they are nutritive and palatable only during early stages of growth. As the grasses mature during the rainy season, they become harsh and woody, and their protein value in proportion to their bulk is so low that the grasses provide a starvation diet for grazing animals. In most savannas, it is the presence of certain perennial and particularly annual grasses that determine the quality of pastures. Unlike the perennial grasses where translocation of nutrients to the stems and rhizones occurs at onset of the dry season leaving largely cellulose, certain perennial and annual grasses retain their nutrients in their aerial portions even when dry.

Pastures containing a relative large proportion of the latter grasses are termed sweetveld in southern Africa, whereas pastures dominated by the coarse grasses are termed sourveld. Sweetveld is associated with relative dry climates receiving 510 to 890 mm. (24 to 35 inches) of rainfall annually. whereas sourveld is found in wetter tropical and subtropical climates. Burning is an annual occurrence in the sourveld.

b. Impact of Fire.--The effect of fire on savanna depends on the ratio and spatial distribution of grass to tree in the savanna complex. It also depends on cultural activities (see Chapter IV). However, the response of the two physiognomic units, tree and grass, to fire, or to the absence of fire depends on a multiplicity of strictly regional factors.

In grassveld areas of Africa, fire is widely employed as a tool in pasture management. Sweetveld pastures are burned every three or four years, if at all, because the grasses are palatable to stock during the dry season. The coarser grasses of the sourveld are burned annually to remove dry vegetation and to prevent brush encroachment. It should be noted that for most grassvelds, absence of fire or grazing or both leads to the accumulation of old undecomposed grasses and subsequent deterioration of the sward by encroaching woody plants (PLATES 15 A and B and 16 A and B). Within a few years, the grass cover may die

PLATE 15A: Grassland subjected to annual August (spring) burning, but no mowing or grazing for 7 years. Highland Sourveld, Natal, South Africa (Photo by J. D. Scott).

PLATE 15B: Close-up of the grass sward. Highland sourveld, Natal, South Africa (Photo by J. D. Scott). Compare plates 15A and B with 16A and B.

PLATE 16A: Grassland protected for 7 years against mowing and burning. Note deterioration of grass sward. Highland Sourveld, Natal, South Africa (Photo by J. D. Scott).

PLATE 16B: Close-up of the deteriorated grass sward. Highland Sourveld, Natal, South Africa (Photo by J. D. Scott).

out to such an extent that the percentage of ground cover may be reduced as much as 60 to 70 per cent, resulting in the formation of large bare patches which are colonized by scrub and brush growth (Staples, 1945). The recommended time for burning the grasslands is late in the dry season, or preferably, shortly after first rains. Burning earlier in the dry season may destroy annual grasses before they seed, and weaken perennial grasses by removing their aerial portions before nutrients return to the roots. On the other hand, if burning takes place at onset of first rains, it means that highly inflammable dry grasses are exposed to accidental fire during dry months, and can feed disastrous fires. In addition, severe fire materially affects Themeda triandra, one of the most important grasses for stock in the sourveld and a dominant grass in East African savannas. Experiments conducted by Edwards (1942) on grass plots in Tanzania over a period of 5 to 10 years, indicated that light burning in fire protected plots maintained this valuable grass, but hot fires killed T. triandra, and the and the composition of the grass cover became almost a pure stand of Digitaria abyssinica, a much less valuable species. It should be noted that although the recommended time for burning is shortly after first rains, widespread occurrence of fires during the dry season takes place in non-commercial pastures and woodlands and are attributable to traditional practices among African native peoples.

In Africa north of the Congo Basin, the ecolgical effects of fire on savanna grasslands are such as to suggest that annual burning should be discouraged. For example, a sample area protected from fire in Sudan had perennial grass cover of Andropogon amplictus, A. gayanus, Hyparrhenia spp. and Cymbogon giganteum, (Letourneaux and Lechner as cited by Guilloteau, 1957). Each year the fire-protected, coarse, tufted grasses grew denser, and reached their maximum development in three years. Thereafter they became weakened since they were no longer prevented from fructifying. At the point of exhaustion of the perennial grasses, a shorter annual grass appeared, Pennisetum setosum, which became dominant by the sixth year of the experiment. This grass is excellent fodder, remains green well into the dry season, and is a poor combustible. It appears that for the Sudan area, protection of savanna perennial grasses from fire results in establishment of more nutritious grass insofar as the tree cover permits. Whether continued protection from fire would have resulted in establishment of brush, was not determined. However, the authors concluded that annual fires are detrimental to the natural improvement of tropical pastures in the area.

Nearly a century of burning in Queensland and Northern Territory of Australia by commercial graziers appears to have established a fire climax little changed. The wooded savannas are dominated by various species of Eucalyptus and Acacia. In Queensland, spear grass (Heteropogon contortus) is dominant because it is more fire resistant than the kangaroo grass (Themeda spp.) and blue grass (Dichanthium spp.). Stock selectively feed more heavily on the latter two grasses. In the Northern Territory Sorghum plumosum, Themeda spp. and in wetter climatic areas, the annual grass Sorghum intrans are dominants. All these grasses are fairly nutritive early in the rainy season, but like the sourveld of Africa, quickly lose their protein and are unable to provide more than a starvation diet for cattle. Consequently, widespread burning is practiced primarily to destroy the rank grass and to extend the grazing season as long as possible in order to reduce the period when stock lose weight (Davis, 1959). Burning is directly adjusted to establishing new growth as quickly as possible at onset of rains, or to extend grazing as long as possible into the dry season. Hence, two periods of burning are possible.

In tropical America, burning of open savanna grasslands occurs during or at the end of the dry season. As in the case of Australia, burning is directly related to providing a flush of new grass for stock, reducing brush encroachment and to killing pests. The effect of late season burning on savannas has been lamented in much of the literature, but there are few ecological studies on which to base a sound judgement of the effects of fire on these tropical grasslands.

Fire's' effects on tropical woody species is no less involved than its effects on savanna grasses. In West Africa, burning early in the dry season is prescribed from Sudan to Sénégal as a measure to reduce accumulation of fuels that would feed intense fires occurring later in the dry season. Early burning is a preventative measure, supported by foresters and conservators to maintain tree growth and to encourage forest regeneration. However, if burning is too early so that fuels are not effectively burned, the regrowth provides a severe fire hazard to the forest and woodland by the end of the dry season. In the grass velds of southern Africa, late burning is recommended as a measure to erradicate woody growth that infests pastures. The same late burns, as has been noted, may also do considerable harm to the quality of the pastures.

Many savanna trees and bushes are adapted to attack by fire. Most species have a great power of recovery in which new buds will begin development and new leaves will unfold at almost any time of the year after damage by fire. This new flush of growth is supported by food reserves stored either in the tree or its root system. Fires early in the dry season attack seedlings and saplings which have yet to establish a tap root system or other adaptations to drought and fire, so that cut-back by fire kills them. On the other hand, such fires cause little damage to mature woody species and therefore would not effect ecological change in the floristic and physiognomic character of the woodlands, bush islands and palm marshes. Frequent late season fires often lead to mortality of less tolerant canopy trees and reduce size and density of the trees so that gradual thinning may take place. Unless ecological conditions permit, degradation of even fire-resistant savanna species may continue until only isolated trees or small clumps remain (see PLATES 17 and 18).

Indiscriminate and widespread burning can initiate change in vegetation cover which is non-reversible. Few authors consider the campo cerrado of Brazil to have been derived from an extensive forest, but there is ample evidence that many areas now in low brush and grass were once forested. Hardy (n.d.) in studying the campo cerrado of south-east Brazil, concluded that burning contributed greatly to the rapid degeneration of soils after the forest had been felled. This was especially evident in areas where repeated burning took place. Not only was organic residue in the soil lost, but rapid mineralization and loss of nutrients by leaching was accompanied by soil erosion. Accordingly, the edaphic environment was completely altered and forest is prevented from regenerating. Hardy noted that soils supporting campo cerrado are extremely low in nutrients and have all the characteristics of senile soils in transition between kaolinite and the gibbsite-hematite stages of weathering. He concludes, therefore, that campo cerrado is a "deflected" climax, that is, the campo cerrado is an edaphic savanna, supporting low brush and grass as an edaphic climax produced by forest clearing and fire. Very low soil fertility and sub-soil drainage conditions have been offered as explanations for the occurrence of other savannas (Parsons, 1955; Schnell, 1945; Denevan, 1963).

Based on known ecological effects of fire on the various plant communities found in tropical savannas, it is evident that constructive use of fire must include the

PLATE 17: Bush island remnant thinned by frequent fires in the surrounding Trachypogon plumosus grassland. Note burned area in foreground. Northern Rupununi, Guyana (Photo by T. L. Hills).

PLATE 18: Flush of new growth (Trachypogon plumosus) following burn (to the right), and two years unburned growth (to the left) in which a jeep track acted as a fire break. Scattered brush is Curatella americana. Northern Rupununi, Guyana (Photo by T. L. Hills).

proper time of burning. In many cases, fire will favor either grass or trees. but not both. All authorities agree that indiscriminate burning, which is very widespread, is harmful to the total environment, cultural as well as natural.

Studies of the ecological effects of fire have been predicated upon commercial exploitation of either woodland, planted forests or grasslands for cattle and sheep. One should not construe that the widespread occurrence of fire in tropical savannas is determined by policies derived from conclusions obtained from these studies. The land area exploited in intensive commercial enterprises is very small in relation to the area subject to indiscriminate burning, and over vast areas, indiscriminant burning takes place.

c. Potential Combustibility.--High potential combustibility characterizes the various types of savannas. Although fire is possible nearly any season, the presence of a well-defined climatic dry season establishes the combustible period which may extend from three to more than seven months. On the other hand, annual rainfall is sufficently large in amount to produce fuel quantities exceeding 25 tons/acre. At the onset of the dry season, desiccation proceeds rapidly with sedges and grasses becoming harsh and dry within periods as short as three days depending on weather conditions. As the dry season advances, woody growths become tinder dry and are able to sustain fierce fires. The actual behavior of fire in tropical savannas depends on the proportion of woody species to grasses and their respective areal distribution. In open savannas, bush islands may be sufficiently large enough to escape the attack of fires sweeping over the grasslands. Likewise, galeria forests may act as barriers to unlimited sweep of grass fires. In wooded savanna areas, the heterogeneous mixture of types of fuel arranged at various levels may support very intense fires lasting for a considerable period of time. Since the various fuel sizes do not burn at equal rates, multiple fire fronts may occur. Grassland fires, on the other hand, are surface types, which although intense, have a narrow burning zone.

Paradoxically, semiarid tropical areas experience severe drought of long duration which is most favorable to high potential combustibility, but low annual rainfall and high rainfall variablility severely limits the quantity of fuel present. Protracted periods of rapid and severe desiccation of vegetation produces a condition of high inflammability. Furthermore, semiarid brush frequently comprises aromatic species that are high in inflammable oils and resins. On the other hand, ignition of the vegetation from natural causes is rarely mentioned in the literature. A frequent explanation given is that lightning is associated with shower activity heralding the onset of rains. At that time, much of the land, particularly in Africa, has already been burnt preparatory to clearing for cropping and grazing. During the protracted dry season, prevailing climatic conditions tend to be unfavorable for convective overturning of the lower atmosphere necessary to cloud buildup. Although fires burn fiercely in semiarid scrub and grass, and fuel spacing permits rapid fire spread, total fuel quantity per unit area is low, particularly in predominantly steppe regions subject to intensive nomadic and commercial grazing.

d. Long Term Effects of Fire.--No accurate assessment of the areal extent of fire-induced degradation of major vegetations formations is possible (Richards 1964). Aubréville (1947) doubted that much virgin tropical rainforest remains in West Africa. Richards believes that for Asia, undisturbed forests are probably limited to non-continuous areas of varying size located in rugged highlands and other inaccessible parts of Southeast Asia, Oceania and Northern Australia. Puri (1960), states that savanna grasslands are not natural to India, but represent degraded forest areas repeatedly burned. Numerous authors suggest that large portions of Latin America, once believed to possess virgin tropical rainforest and other types of humid forest, actually are not climax but mature stages of second growth (Budowski, 1956; Bartlett, 1956; Popenoe, (1963): Denevan, 1965; Dansereau, 1948; Gordon, 1957, and many others). Much if not most of the Caribbean Islands have little or no virgin vegetation. Fires and their effects on the vegetation in parts of Mexico and Central America have been reported by numerous writers (Budowski, 1958; Fuson, 1963; Johannessen, 1963).

The role fire plays in savannas of the tropical world is a dominant one. For most savanna areas annual burning occurs, and there is little doubt that frequent fire both transforms certain landscapes and maintains grassland in others. The role of fire in modifying and maintaining existing savannas is represented by a vast literature. On the other hand, the origin and spread or retreat of savanna vegetation are open questions. Hills (1965), in reviewing the problems of savanna research, assumes that in most places fire maintains or even may extend savanna vegetation. He also notes instances of forest encroachment on former savanna. He concludes, however, that among the many explanations offered for the origin of savanna, no one factor, be it climatic, edaphic, geomorphic, biotic or anthropic, has universal acceptance as a single convincing view point.

D. Fire and Selected Phenomena

1. Fire and Soils.--The effects of fire on soil are both direct and indirect, temporal and permanent. The most obvious direct effect of a burn is the exposure of the soil to the weather, the reduction of vegetation and soil humus to ash and the immediate availability of nutrients to crops. In many tropical areas, it is difficult to determine a permanent change occurring in forest soils, particularly if

the forest fallow cycle is long enough to permit regeneration of fairly mature tree growth. Elsewhere in the tropics, the removal of forest cover is believed to initiate permanent change as, for example, in parts of the campo cerrado of Brazil. Finally, numerous authors have referred to the sharp differences between savanna and forest soils. In many areas, savannas and forests occupy distinctive types of landforms, each differing in their geology, topography, and geomorphic evolution. The role of fire in the latter case may be tenuous, but in degraded forests, soil changes have been observed leading to characteristics similar to those observed for savanna soils. Somewhat arbitrarily then, the effects of fire are divided into those that are direct and temporal and those that appear to be indirect and more lasting.

a. Direct Effects.--Considerable research has been conducted on changes that occur when forest soils are subjected to burning. Of particular importance is whether significant change occurs in the chemical and physical properties of soils. Although piled slash feeds intense fire that may burn more than 24 hours, the penetration of heat is measurable to about 80 cm. depth. The downward movement of heat, however, may be significant to only about 20 cm. depth. In grasslands, the penetration of heat rarely exceeds 5 to 10 cm. There is sterilization of the upper soil leading first to a reduction or total destruction of microorganisms, and then reestablishment of microbial activity, often within a week following the burn. Shortly thereafter, microbial activity may rise above the level preceding fire due to increased rates of mineralization in the exposed soil, the presence of ash nutrients, and in some cases a rise in pH. Particularly in savanna grasslands, fire stimulates microbial activity because grasses, which suppress nitrification, are burnt, and microorganisms respond to the greater availability of nitrogen (Nye and Greenland, 1960).

Considerable attention has been focused on the effect of fire on organic material, availability of nutrients, pH and related factors in soils. There is no question that burning felled forest or grassland produces varying amounts of phosphorus, potassium, calcium and magnesium, while nitrogen and sulphur evolve as gases to the atmosphere. Nye (1959) lists estimated amounts of nutrients available in the aerial parts of a West African forest 40 years old and contrasts this with an area of tall grass (Andropogoneae) containing 48,000 pounds of woody plants per acre (Table 11). Shrub and tree growth in the Guinea savanna of Ghana is very slow, probably due to nitrogen deficiency induced by fixation by the grasses of the low amount of available nitrogen.

TABLE 11

ESTIMATED QUANTITIES OF NUTRIENTS IN AERIAL PORTIONS OF TROPICAL FOREST AND WOODED SAVANNA, GHANA, AFRICA

Nutrients released upon burning (pounds/acre)	P	K	Ca	Mg
Tropical forest 40 years old	112	731	2,254	309
Wooded savanna:				
Herb layer	7	41	31	23
Wood portion 48,000 lbs/acre	13	130	210	56

After Nye, 1959

Nutrients contained in the ash are water soluble and are absorbed by the clay fraction of the soil. Rapid loss of these nutrients occurs as leaching proceeds. However, abandonment of cultivated fields is as much due to weed and brush infestation and the amount of labor required to maintain the field, as it is to loss of soil fertility. Although nitrogen is normally lost to the atmosphere, tests following burning often show no loss or even an increase in available nitrogen. The explanation frequently offered is that for soils where the decomposed organic layer is not entirely consumed, the action of heat on the organic matter releases nitrogen to the soil.

Equally variable have been reports on the effect of fire on pH of the soil. Numerous studies indicate that a sharp increase in pH occurs as alkaline ash is incorporated in the soil. However the effect is temporary: about one half to two thirds of the increase is lost in the first year of crop production and by leaching due to heavy rains. Decline in pH is gradual thereafter returning to original values in 2.5 to 4 years. In wooded savannas and open grasslands, both an increase in pH and no change in pH following fire have been reported, but studies are inconclusive since so many variables determine soil response to fire.

Likewise there are mixed reports concerning the immediate effect of fire on the physical properties of soils. In parts of Africa, India and South America, it has been noted that incorporation of large amounts of ash tended to deflocculate the colloidal gels in clayey soils, but had little effect on sandy soils (Griffith, 1946; Renard, 1949; Freise, 1934). Heavy soils are frequently found in savannas occupying level to undulating sites. Although the presence of loam and clayey soils is due to geomorphic evolution of the landscape, the inferior porosity of the soils may be due in part to deflocculating of surface particles caused by ash from annual fires. Superficial induration of savanna soils has been noted by a number of researchers and has been attributed to the impact of heavy rains on bare ground, and capillary action in the dry season (Aubréville, 1947; Waibel, 1948; Eden, 1964).

Clearly, the number of factors which govern the immediate response of soil to fire depends not only on the pedogenetic characteristics of the soil, but on vegetation, site, edaphic conditions and other factors. Even though there have been cases where fire has been the direct cause of breakdown of soil structure and increase in bulk density of tropical soils, there is an equal number of studies where no deterioration occurs. Baldanzi (1959) concluded that the amount of heat transmitted to the soil from burning grass plots in Curitiba, Brazil was decidedly insufficient to damage the soil. The heat fosters dehydration and the coagulation of colloid and promotes aggregates in the soil. Studies conducted in Colombian coffee soils however indicated that the percentage of large soil aggregates in the upper horizon was materially increased by burning with resulting improvement in soil permeability (Suarez de Castro, 1953). Joachim and Kandiah (1948) carried out experiments over several years to find out whether or not shifting cultivation as practiced in Ceylon degraded the soils. The authors stated that chena (shifting) agriculture had no adverse effect on soil structure that would not occur as a result of the usual methods of preparation of a forest soil for any other type of rotational agriculture. Nye (1959), in discussing rainfall acceptance and percolation tests on some East African soils of fairly high clay content, concludes that the improvement in structure and other physical properties by protecting grass fallows from fire was obliterated in the first year of subsequent cultivation. The physical properties of most latosols are inherited from the soil itself, particularly its mineral compostion as established by pedogenetic processes. Consequently, the combination of iron oxide and kaolinite is very important to stable microaggregation. Most heavy red tropical soils possess remarkably stable physical properties, while light sandy soils tend to indurate easily and erode severly.

Analyses of soils from 30 fields in various stages in the shifting cultivation cycle in the Polochic River Valley, northern Guatemala, indicated a high porosity and low values for bulk density of all soils sampled (Popenoe, 1959). Consequently, the heavy rains were readily absorbed by the soils, and little surface erosion was observed on cultivated slopes. Popenoe noted that most of the erosion was by landslides.

b. Indirect Effects.--The action of fire in altering the microclimate and biological environment in tropical areas can initiate significant changes in soils. Particularly, the degradation of forest and establishment of savanna is believed to be accompanied by degradation of the forest soil. Such changes occur over considerable periods of time, hence knowledge of processes operative in degrading forest soils is derived largely from comparative studies of soils under different, but adjacent types of vegetation. More numerous are the studies investigating the effects of cultivation on forest soils, and the relationship between effects noted and cultural practices. Few studies have investigated the gradual changes occurring in soils once forested. However, a considerable literature has developed supporting the view that in addition to a lessening of fertility, degraded soils become more compact and develop impeded drainage. In turn, the effects of poor soil drainage and fluctuating ground water table contribute to the formation of indurated hardpan, widely observed in savanna areas.

Although the physical-chemical properties of tropical forest soils do not compare with temperate forest soils, they are superior to those associated with savannas. Generally, forest soils are favored over tropical grassland soils because they are easily cultivated due to their open structure and because they have a fair amount of organic material that can be reduced by fire to contribute to ash fertilizer. A tall forest may contribute 4 tons of dry litter and 2 tons of new roots per acre per year. The total supply of nutrients derived from organic matter is small because of an intense nutritive cycle that quickly returns bases to new vegetative growth. However, the same cycle maintains nutrients in the surface layer, particularly phosphorus.

Savanna soils commonly have less favorable characteristics. Frequently they are either derived from coarse colluvial materials and therefore are droughty, or they are heavy, fine-textured and possess inferior drainage characteristics. Savanna soils are low in surface organic matter. A regularly burned grassland contributes nutrients and organic matter primarily in the root zone, and may add less than 2 tons per acre per year. Grasses suppress exchangeable nutrients so that fertility is low. Degradation of savanna soils proceeds more rapidly than is the case for forest soils. Depending on cultural practices, the impact of shifting cultivation is negligible on forest soils if a fairly long forest fallow period ensues. On the other hand, cultivation of savanna soils, notably in Africa and Asia, requires removal of the sod and hoeing each year prior to planting. Compaction of soils with attendant loss of pore volume is likely to be more severe in grassland soils.

2. Fire and Biota

a. Vegetation and Macrofauna.--Certain aspects of the complex and subtle interrelationships between fauna and habitats are of significance to the study of fire. The use of fire in hunting, driving game, forest gathering and other activities is culturally controlled. Of importance to the physical habitat is the effect of large animals on vegetation considered as potential fuel. The trampling and browsing of elephants, for example, can reduce vegetation as effectively as fire.

The movement of macrofauna along well-defined routes quickly establishes trails that may act as fire breaks. Even for open grasslands, a criss-cross pattern often develops due to migration of wild animals and movement of domestic stock. In wooded savannas, where trees appear in isolated clumps, it has been reported that stock, particularly cattle, pulverize the ground cover as they seek shade during the midday. Consequently, fire cannot be sustained around the wooded areas with the effect that woodland patches are preserved as bush islands. Photos depicting the effects of drought in South African game preserves showed that trampling, grazing and browzing by game attracted to the few remaining water holes completely devastated the natural vegetation in roughly circular areas 3 km. in radius. Although this represents extreme conditions, it is clear that most areas close to water holes will support a sharply reduced vegetative cover.

The macrofauna of American savannas are noted for their poverty compared to the richness of the highly specialized fauna of the adjacent tall forests. Whereas the forest habitat has been stable for a long period of time, the savanna grasslands are probably not very old (Budowski, 1956). Deer, rabbits, quail and other species only slightly differentiated from North American types are the most numerous.

b. Vegetation and Termitaria.--The role of termites in molding savanna landscapes is well-documented. Of interest to the subject of fire is that abandoned termite mounds frequently provide microtopographic relief propitious to the establishment or maintenance of forest communities. The distribution of termite mounds definitely favors wooded savanna environments. Termite mounds are constructed by the termite worker filling its mouth with clay drawn from the subsoil, then it picks up a sand grain which it carries to a selected site and places into position. The saliva-wetted clay is squirted around the grain which is pressed into place (Hesse, 1955). Termite mounds have been excavated showing that in their need for clay, workers have dug down 4 m. to as much as 12 m. (13 to 40 ft.) and lateral galleries may run to a radius of 200-300 m. (660 to 990 ft.). Kellogg and Davol (1949) noted that in certain savannas in the Belgian Congo, termite mounds covered 15-30 per cent of the total area. Mounds often stand 4 m. (13 ft.) above ground level and are about 7 m. (23 ft.) broad. Termite mounds in the Sudan have been described as being 5 m. (16 ft.) high and 19 m. (63 ft.) across.

Termite mounds are remarkably persistent features of the landscape, even in climates receiving as much as 1200 mm. (47 in.) in a well-defined rainy season, and may vary in height from 3 m. to 10 m. More importantly, occupied mounds are bare of vegetation and hence are not affected by fire. Since about two-thirds or more of the number of mounds in a given area are abandoned, the vegetation that becomes established on the mound commonly is composed of woody species. Boughey (1963) states that large undisturbed mounds in Central Africa are clothed with vegetation resembling a dry deciduous forest. There is a dominant tree layer, below which is found a more or less dense thicket of small trees, shrubs and woody climbers. Many species are relatively fire-sensitive, indicating that annual fires of the savanna grasslands do not penetrate the center of mound vegetation. It is not clear but it is believed that the vegetation of these large mounds represent survival of what was a late Tertiary plant community (Boughey, 1963).

In many savannas abandoned mounds are micro-sites capturing woody species. In the Rupununi savannas, Guyana, even small mounds frequently have at their base a few pyrophilic species, commonly <u>Curatella americana</u> (PLATE 19). Whether bush islands or patches of woodland can start from the establishment of a few trees around a mound is not known. In the Ivory Coast in wooded savanna with vestiges of dense forest, patches of woodland are established which very often are on a termite mound. These patches are usually scorched, but are not often penetrated by fire. The resistant pyrophiles are fo[illegible] at the outer margins of the wooded patches, while less fire-tolerant species are found in the center (Bergeroo-Campagne, 1956). These in turn protect a larger

PLATE 19: Micro-topographic effect of termite mounds is to provide sites favorable to establishment of woody pyrophilic species in open savanna. Northern Rupununi, Guyana (Photo by T. L. Hills).

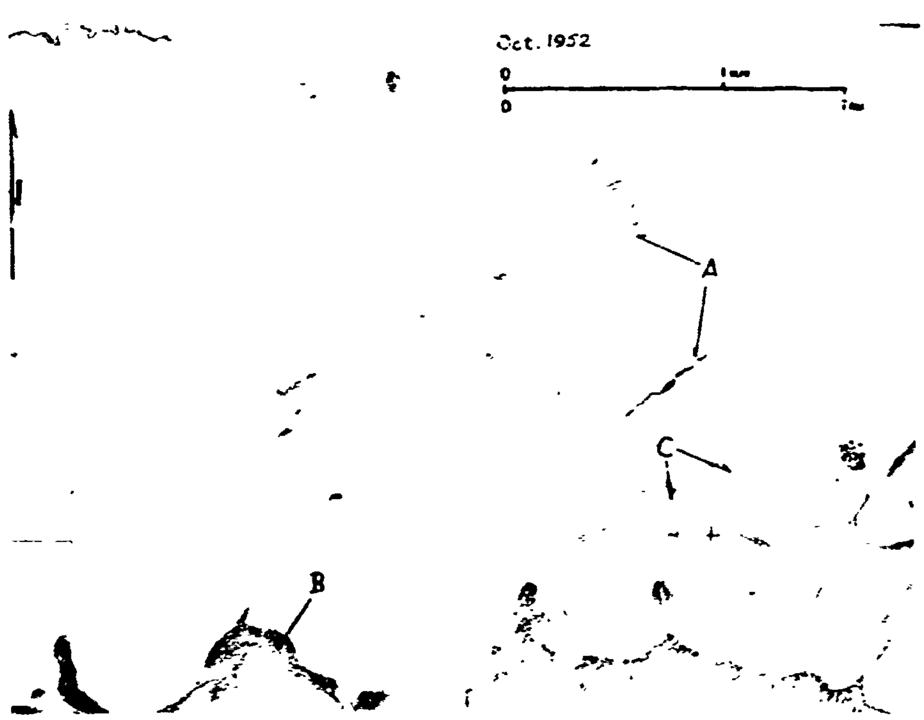


PLATE 20: Patterns of two wind-driven fires in progress (A) occurring on the flood plain of the Rupununi River. Dense evergreen and swamp forest communities (B) border a meandering tributary. Finely-textured white sands (C) rise 50 feet above the flats. Northern Rupununi, Guyana (Lat. 3°50'N, 59°20'W). (Photo by Hunting Aerosurveys, Ltd., courtesy of T. L. Hills).

zone from the invasion of grasses, allowing the establishment of new fire-resistant woody species on the periphery. In this way, the author believes forest communities can become established, and those possessing concentric differentiation in fire tolerance are old communities.

E. Areal Patterns of Burning

The fact that there is an infinite number of possible areal patterns of burning should not act as a deterrent to the search for useful generalizations based on subjectively relating environmental conditions to known characteristics of fire behavior. Surprisingly few observations concerning areal patterns of burning are recorded in the literature, considering the abundant opportunities to view fires in progress. Burning is neither a chaotic nor random phenomenon, but follows known processes controlled by various physical laws (see Chapter II and Appendix I). Among the more important factors influencing the pattern of burning would be the state and characteristics of the natural vegetation, the type of terrain, and wind direction and velocity.

The patterns of burning in tropical forests are determined largely by the cultural practices of shifting cultivators. Factors of selection of site, time of burning in the agricultural year, amount of area cleared each year and the forest fallow cycle are presented in Chapter IV. The time of burning in relation to climate and vegetation is presented cartographically and analyzed in the accompanying text (see Chapter V). Few useful generalizations concerning the pattern of burning can be made based solely on conditions in the physical environment.

The area of forest patches subject to burning rarely exceeds 2 hectares (5 acres), even though among certain peoples a larger area of forest is felled and the brush collected to the site to be planted (<u>chitemene</u>). The encircling forest limits fire spread. Consequently, the pattern of burning reflects the population pressure on the land, the forest fallow period and the site preferences of shifting agriculturalists. In many cases, clearing the forest takes place where forest and savanna meet. The opportunity for accidental fire in the neighboring grasslands is considerable. The pattern of clearing and especially the plots recently burned can be identified from aerial photographs (see PLATES 20 and 21).

Savanna grasslands have broad expanses of fine-textured fuels possessing large surface exposure to the air within the vegetation zone. Since grasses quickly dry following the beginning of a period of little or no rainfall, fire sweeps rapidly through the fuel matrix commonly in a single flame zone of narrow width. The pattern of burning varies according to a host of local environmental factors, but three important factors, in addition to combustibility of the grasses, are fuel quantity, prevailing wind direction, and mean velocity of the wind.

In open grassland savannas relief is frequently level to undulating, and obstructions to fire spread are limited to galeria forest and isolated wooded areas. Depending on the quantity of fuel present, fires move downwind, driven by tradewinds noted for their constancy of direction and high mean wind velocity. If fire occurs during brisk wind, a linear pattern of burning develops in which the flame advances as spearheads sometimes separating and then reuniting (PLATE 20). The constancy of wind direction also accounts for the linear pattern, and under such conditions fires have recently traveled distances in excess of 200 km. (124 mi.) in parts of Africa north of the Congo Basin. In 1960, a fire in the northern Rupununi savanna, Guyana, traveled uninterruptedly from Annai to south of Pirara for an estimated distance of 80 km. (50 mi.) (Waddell, 1963).

Where fuel quantities are modest and winds exceed 4.5 m/sec. (10 mph), there frequently results a linear striped pattern composed of a sequence of burned and unburned

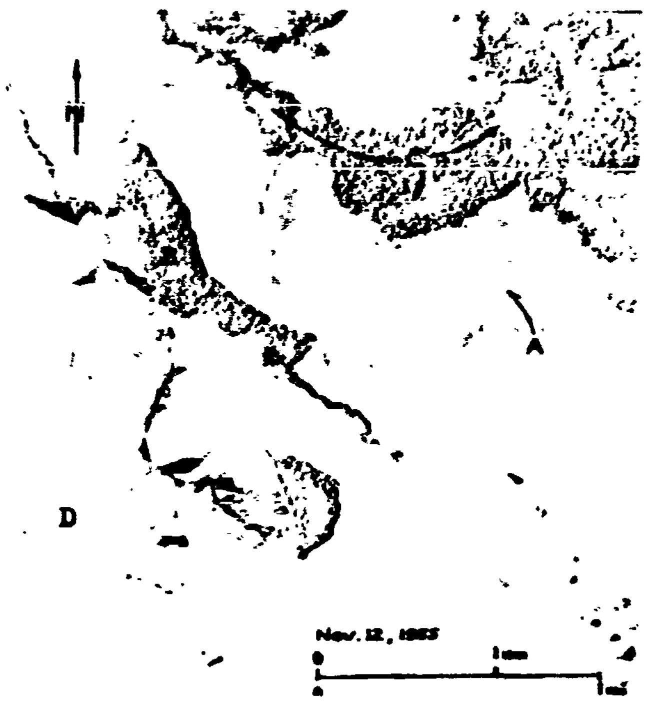


PLATE 21: Striped burn patterns (A) in open grassland of an alluvial lowland. Galeria forest (B) with an abrupt forest-savanna boundary. Abandoned clearings (C) in various stages of regeneration. Riverine, evergreen forest. Rupununi, Guyana (Lat. 3°28'N, 59°35'W) (Photo by Hunting Aerosurveys, Ltd., Courtesy of T. L. Hills).

PLATE 22: Alternating burned and unburned savanna grasses (striped pattern) produced by wind driving flames through limited grass fuels at such velocity as to limit lateral fire spread. Rupununi, Guyana (Photo by T. L. Hills).

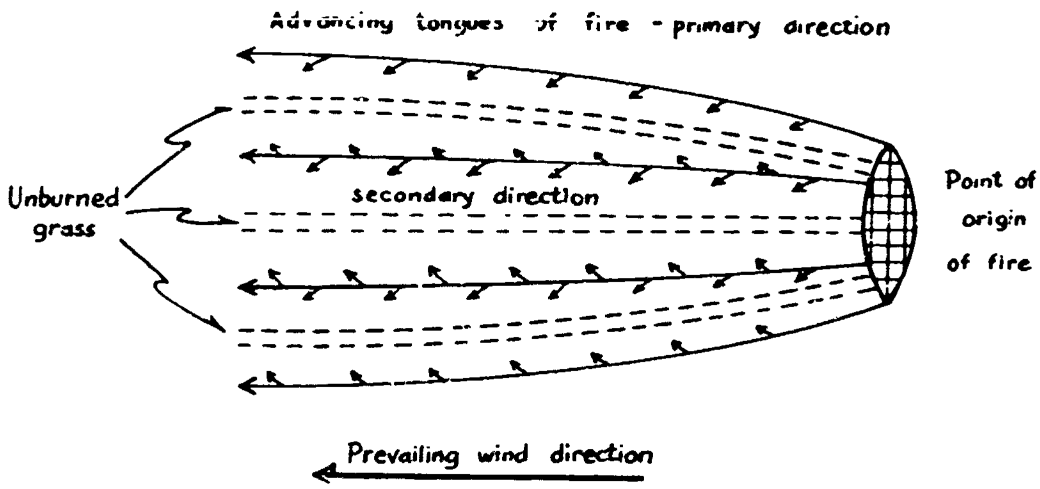
narrow bands of grass. This phenomenon is caused by the prevailing wind driving tongues of fire through a modest quantity of fuel at such a speed and constancy that little or no lateral burning occurs (PLATES 21 and 22). A diagrammatic outline of this process is shown in Fig. 15 (Waddell, 1963).

The occurrence of a striped pattern of burning is widespread. Numerous authors have noted similar patterns in the coastal savannas of Ghana, and in the parallelism of grass swards penetrating woodlands in Central and Southern Africa (Aubréville, 1947; Boughey, 1963; Phillips, 1964).

Often there is a relationship between the position of termite mounds and striped patterns. Thus the shrub savanna lying south of the tropical rainforest in Ghana is regularly and conspicuously patterned (Boughey, 1963). The stripes lie parallel to the prevailing winds, but unburnt portions coincide with the lee side of termite mounds, in which spear-sha ed patterns of unburnt grass may extend down wind distances of up to 100 to 200 m. (330 to 660 ft.) or more.

The e t of light winds and low fuel quantities can also be sig ant. Again in the Rupununi, a jeep track across a tered bush savanna dominated by Trachypogon plumosus a Curatella americana was a barrier to fire spread unde resumably light wind conditions. Fire propagated slowly from e grass ussock to another, halting at the jeep track (PLATE 18, p. 111).

The diurnal variation in winds, which tend to become light and variable at night, is significant to patterns of burning in open savannas. Boughey in a personal communication has witnessed grass fires all the way from the coastal savannas in the Ivory Coast, Nigeria and Ghana, through the various savanna types of the hinterland to the smaller but persistent fires in the short annual grasslands around Lake Chad. Flying over the area at night, he noted that fires



After Waddell, 1963

Fig. 15. Diagrammatic Representation of the Burning Process Resulting in a Striped Vegetation.

form fronts that were great arcs stretching for miles.

Finally, the pattern of burning in open grasslands on rolling terrain reflects the factor of terrain roughness. In the Rio Branco Savanna, the windward side and crests of the rolling uplands are burnt, but intervening lee hillsides and vales escaped fire. From the air, the pattern of burn is indicated by the darker tone of the landscape believe due to the reddish latosols becoming visible through the fire-thinned vegetative cover (PLATE 13, p. 101).

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Chapter IV

FIRE AND THE CULTURAL ENVIRONMENT

A. Introduction

The use of fire, together with the use of stone tools and the development of language, has probably been part of human culture since the time man first became distinguishable from other animals (Stewart, 1956). Definite archeological evidence exists that Peking man (Sinanthropus pekinensis) used fire in his caves. It is reasonable to suppose that primitive man very early discovered that fire was as capable of destroying vegetation as it was of cooking his meat. Yet it is likely that the earliest burning of vegetation by man was by accident rather than by design, as indicated by the widespread practices among primitive peoples of carrying fire with them in some slow-burning device, and of leaving campfires to smolder rather than extinguishing them.

Intentional burning is almost as ancient a practice as accidental burning. Fire clearance of forest, brush and grassland by present-day aboriginal peoples is a custom that has been carried on since prehistoric times. The comments of ancient writers, e.g., the Periplus of Hanno, the Carthaginian (circa 500 B.C.), lend support to this belief.

Intentional burning has been done for various purposes. Hunters use it to drive game, to clear bush so that game can be more easily seen, and to create an improved pasture to attract grazing animals. Gatherers use it to encourage the growth of desirable plants and to discourage the growth of others, and to smoke honey bees out of their nests. Farmers use it to clear and fertilize land for planting. Pastoral peoples use it to improve pasture for their flocks, to eliminate insects and snakes, and to discourage predators. The use of fire in war has been referred to as early as 477 B.C. by Herodotus. Pyromania and arson, whether chronic or occasional, are common among all peoples. The conclusion is inescapable that burning has been man's earliest, most important, and most widespread means of clearing vegetation, and that its significance as an ecological factor must not be overlooked.

Although the same reasons for burning exist today as in the past, swidden cultivation[1] and burning to improve tropical pastures are now the most important. In 1957, it was estimated that 36 million square kilometers (14 million square miles)--about 25% of the earth's land surface--was under swidden cultivation, inhabited by about 200 million people at an average density of 5.4 per square kilometer (14 per square mile) (F.A.O. in Watters, 1960). Thus it is apparent that fire and its relation to patterns of human culture are highly significant geographical factors.

A two-part analysis will be used in this chapter to throw light on the relationships between fire and the cultural environment. First, the characteristics of the cultural environment that are responsible for fires will be considered. Special attention will be paid to the technology of the use of fire. Second, regional differences in demographic characteristics that relate to fire will be explained. The numbers, densities, and distribution of fire-using people will be considered.

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[1]Swidden cultivation is the term commonly used by anthropologists to refer to the form of agriculture "characterized by a rotation of fields rather than of crops, by short periods of cropping (one to three years) alternating with long fallow periods (up to twenty years or more, but often as short as six to eight years), by clearing by means of slash and burn, and by use of the hoe or digging stick, the plough only rarely being employed" (Pelzer in Watters, 1960). Shifting cultivation, fire farming, slash and burn agriculture, bush fallowing and many local terms are also in use. Swidden refers to the agricultural clearing

The man-land ratios and the effects of increasing population density will be discussed. The social and economic factors that are conducive to the use of fire will be analyzed. Some cultural trends that affect the use of fire will be pointed out. Specific examples from the literature will be presented to illustrate the major concepts.

B. Cultural Characteristics Relating to Fire.

The intimate relationship that has developed between man and fire has brought about a variety of cultural characteristics connected with fire. They range from the worship of fire as a symbol of the divine by the Zoroastrians, to the controlled use of fire as a source of heat energy by modern man. Human societies have developed a great diversity of practices and tools to kindle, use, and control fire. In this section those that are relevant to the problem of man-made fires in the tropical forests and grasslands will be considered, under the categories of site selection, providing a supply of fuel, lighting the fire, fire control, fire legislation, and cyclical patterns of burning. Examples will be presented from the literature to illustrate these practices.

1. Selection of a Site for Burning

The first step in the burning cycle is the selection of a site. Hunters, swidden cultivators, herdsmen, foresters, forest gatherers, and honey collectors--each have different criteria to judge the suitability of a burning site. The religious or ritual aspect of site selection is often very important. Certain sites may be taboo, due to their use as cemeteries or their sacred character. The anthropological literature is rich in references to rituals that are used to propitiate the spirits. Pelzer (1945) mentions an example in southern Sulawesi, Indonesia, where the people send the village headman into the selected site to place betel leaves, lime, and a piece of areca nut under a tree, and to importune the spirits to show their approval by not scattering the offering. After three days he returns, and if the offering is scattered a new site is chosen and the process is repeated. If the betel leaves are undisturbed, the male villagers eat a meal on the site. Then the land is divided among them and the betel leaf augury is repeated on each plot. If the offering is scattered three times, the head man gives the villager a share of his own land to use. Huke (1954) describes the choice of sites by the Kachin farmer in Burma. A fire is built on the ground at the first site, and a piece of specially chosen bamboo is put in the flames. When the air inside expands it splits the bamboo into small splinters, which are then divined by a priest. An unfavorable augury makes it necessary to repeat the process until a site is found where a good crop can be predicted.

The qualities of the land also have meaning to the swidden cultivator. Often the criteria are the result of millennia of trial and error, and represent a workable adaptation to the variable qualities of the soil, topography, drainage, and microclimate. The Kachin farmer described by Huke selects slope with southern exposure, so that adequate sunlight will reach the land. The farmer then stamps his bare foot on the ground, seeking a firm, not spongy surface. The proper cover of canes and bamboos must be present, since they indicate rich soil. Finally the farmer tastes the soil. If it has an oily flavor, the farmer will ask the village priest to perform his divination. Among the Barama River Caribs of British Guiana (J. Gillin, 1936) the primary criterion is good drainage. Their fields are frequently referred to as cassava hills. Another criterion is the soil, which must be "white dirt", a very sandy loam.

Perhaps the most important and most widely used criteria for site selection are the ecological ones. De Schlippe (1956) in his analysis of the Zande tribe of central Africa, describes a complex set of criteria based on vegetation and site. The type of vegetation reflects the intrinsic fertility of the soil based on the following factors: climate; parent material; the soil forming process at work; the position of the site in the catenary succession from laterite crust to gently sloping red soils, steeply sloping yellow valley-side soils, and the clayey soils of the valley bottoms; the stage of regeneration of the abandoned field; and the effect of bush fires. The preferred site is on the gently sloping land, called pavuru-di, provided the vegetation is not a pyrophilous fire-resistant type that indicates frequent bush fires. Another favorite site is the mbudu-rago (soft place) or mbudu-sende (soft soil), a deep dark stoneless soil in well-drained depressions and on saddles. The stage of regeneration of the vegetation is indicated by the type of grass or shrub growing on the site. The Zande make use of their knowledge of the cycle of regeneration to plant the crop combinations that will have the best chance of succeeding.

Another important consideration is the spatial relationships of the swidden site. Baker (1965), in his study of the climatically transitional Walawe Ganga Basin of southern Ceylon, showed that the location of chena (swidden) sites is influenced by: proximity of paddy growing villages with tanks; proximity to roads, paths or tracks through the forests; and proximity to the heavily populated wet zone. For chenas used to grow illegal marijuana, isolation, rather than proximity, is the important criterion (See PLATE 23).

The criteria used by foresters for selecting a location for burning are different from those used by swidden cultivators. A. G. McArthur (1962) points out four main classes of site in Australian forests. They are: 1) areas where logging operations have been concluded, and it is desired to dispose of the tops and branches; 2) areas of catastrophe, such as blowdown or insect attack, and it is desired to reduce fuel accumulation; 3) areas where felled debris must be disposed of before exotic plantations can be established; and 4) most important, green timber areas where

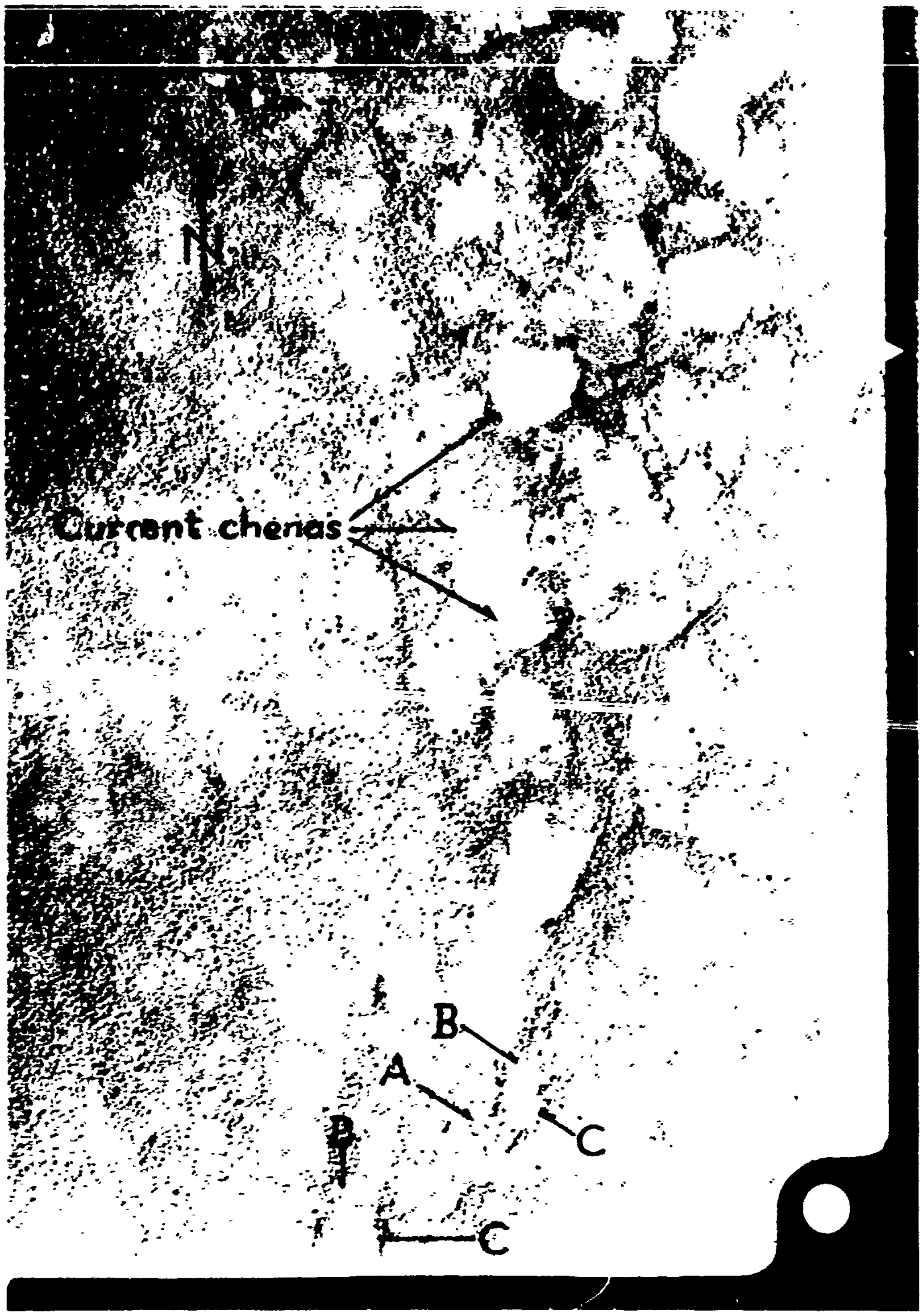


PLATE 23: Chenas (swiddens) in southern Ceylon, Lat. 6° 20'N., Long. 80° 57'E. Stage of regrowth shown by tone of photo. from light (currently in use) to dark. A-village; B-tank; C-paddy field. (Photo courtesy S. Baker).

fuel supply needs to be reduced (control burning). The ideal site is a "compartment" or group of compartments, or an area of 100-900 acres surrounded by a trafficable road or trail. The area should be sufficiently small so as to be completed in one operation.

Burning by pastoral peoples takes into consideration the variability of rainfall onset and the density of the animal population. C. M. Davis (1959) observed that stockmen in northern Australia burned late in the dry season in strips or patches, so that not all of the dry grass forage would be destroyed before the rains begin. They also sought to protect the cattle station by burning a fire break.

The native herders in Africa make regular use of fire to clear old dry grasses and encourage a flush of new shoots. At the same time they make it easier to protect the cattle from snakes, predators, and insects. A great variety of sites may be chosen. The prevailing practice of migratory Dodos herders in the Karamoja district of northeastern Uganda is to burn off the grasses in advance of their annual migration from the eastern to the western parts of the district. Peoples who do not migrate, such as the Acholi of northern Uganda, will burn off the upland grass in the dry season while their cattle graze in the grass swamps, where the grazing remains adequate during the dry season (Parsons 1960a, 1960b).

Burning sites may be as small as the fraction of a hectare used by a swidden cultivator or they may be very large, such as when they are used as a barrier against tsetse flies. Cockbill (1955) describes a strip of land 3.2 to 5.0 kilometers (2 to 3 miles) wide and 64 kilometers (40 miles) long in Southern Rhodesia on the border with Mozambique. This strip is cleared and burned. It acts as a barrier to certain tsetse species, thus permitting commercial cattle grazing in the southeastern part of the country. Elsewhere in Southern Rhodesia such a barrier is not effective against dominant tsetse species. Since wild game is often an important host for the trypanosome parasite, the grass is burned to make hunting of game easier.

The angle of slope of the land selected for burning will naturally vary according to the prevailing topographic conditions in an area. Level land is normally preferred by the swidden cultivator, but in the more densely populated parts of Southeast Asia, he has been forced into the hills by the wet rice cultivators. The "chimney effect" in which a fire burns fiercely and rapidly upslope, is used by the swidden cultivator. Oracion (1963) describes how the Bukidnons of Negros island in the Philippines light their fires at the bottom of a slope. Overholt (1963-64) observed a similar practice on Panay. Conklin (1957) in a study of the Hanunóo of Mindoro island, shows a photograph of a swidden plot on fire, where the line of flames is moving parallel to the angle of slope. This method combines the intense heat of the chimney effect with slower horizontal movement of the fire front. On the other hand, Ward (1960) describes a wet zone hill village on Vitilevu in the Fiji Islands, in which the top of a ridge is cleared, burned, and planted with taro and yaqona (Piper methysticum). As the taro is harvested, the garden is gradually extended down the slope.

The selection of a site for burning thus seems to be dependent on a variety of factors, and it is difficult to generalize about them. They include the magical qualities of the land; the traditional ecological judgement of the cultivator or herder; the use to which the land is to be put, whether for hunting, cultivation, forestry, or grazing; the seasonal pattern of rainfall; and the extent of regeneration of the vegetation cover from previous burns. In each area these and other factors make a unique combination.

2. Providing a Supply of Fuel

After selecting a site, the next stage in the burning sequence is the provision of a supply of dry fuel. A variety of factors influence the geographic distribution of techniques used to provide the fuel. Among the most important are climate, the type of vegetation, the purpose of burning, the amount of labor available, the tools, techniques and cultural practices of the people doing the burning.

The most important climatic factor is the length and severity of the dry season. If the dry season is well-defined and fairly severe, many forms of vegetation can be ignited easily without special preparation by man. If the dry season is short or non-existent, and the area is forested, it is necessary for man to cut or otherwise prepare the vegetation so that it may dry out for burning.

The purpose of burning, the cultural practices, tools and techniques, and the labor supply available are usually closely related to the nature of the cultural group occupying the land. Swidden farmers may clear the land communally or by individual families. The burning of grassland may be to prevent bush encroachment on lands pastured by commercial stockmen, or to secure a flush of new grass on lands pastured by migratory herders. The piling of felled vegetation may be to provide more fertilizing ash, or to foster a more intense fire when once ignited, or for both of these purposes.

The technique of clearing tropical forests has certain features in common wherever it is found. A division of labor between the sexes usually exists, in which the felling of large trees is the work of men, while small trees and brush are cut by the women. The individual family may clear its own plot, or the community may work in common. Huke (1954), describing a North Burma Kachin Village, says: "Every family clears its own plot of undergrowth, hanging vines, and small trees. This takes about a month of hard work by the entire family. The largest trees are felled by all of the village men working together, one day of community labor being devoted to each family's taungya [swidden]."

Primitive and advanced cultures both employ various devices to deal with large trees. For example, the Tobelorese people (Hueting, 1906) of Halmahera, Indonesia, and the plantation rubber workers of Malaya (Gawthorn, 1962) both employ a scaffold erected 4-6 meters high above the flaring buttresses of a large tree. This permits them to cut through it at a place of smaller diameter. Frequently nearby smaller trees are cut part way through, and the large tree takes them down when it falls. Trees too large to be felled may be killed by cutting a ring or girdle through the bark and cambium layer, or by building a fire around the base of the tree. When the tree dies, the leaves fall, permitting the sun to reach the soil below the branches. Generally the smaller trees and undergrowth are cleared first, so as to permit access to the large trees. White (1945), referring to clearing for plantations in the Ceylon Dry Zone, considers that this also helps to pack the jungle down and get a better burn.

The forest may or may not be cleared thoroughly. White (above) describes a method of reducing the cost of removing stumps by cutting the main lateral roots of very large trees a short distance from the base. At the same time the main stem is cut just enough to cause a slight bending over of the trunk. Then the whole tree will come down with much of the tap root. The remaining stumps are dug out by hand. Such thorough clearing is not usual among swidden cultivators. PLATES 24 and 25 illustrate an incompletely cleared swidden plot in British Guiana, where cassava roots are planted in the spaces between the partly burned logs.

There are other techniques of dealing with large trees that do not kill the tree. These are <u>pollarding</u>, or removing all the branches from the trunk; and trimming, or removing only the leafy branches of the trees. These practices permit rapid regrowth of the tree after the field is abandoned.

3. Lighting the Fire

Once a supply of dry fuel has been provided, the next step is to set it on fire. In most cases there is no problem in doing this. However, where the microclimate is humid and a long dry season does not exist, or where the

PLATE 24: A clearing in fairly mature second growth moist semideciduous forest near Aishalton, Rupununi District, Guyana, located on the savanna/forest boundary between the Rupununi R. and the Illiwa R. (Photo by T. L. Hills)

PLATE 25: Cassava roots (awaiting planting) leaning against charred logs near Aishalton, Guyana. Note density of unburned timber. Compare with "clean burn" in PLATE (Photo by T. L. Hills)

particular combination of fuels is intractable, or where specific limitations of area, shape, or quality of burn exist, it becomes necessary to take special measures.

The techniques used by the rubber planters of Malaya to set newly felled jungle on fire are illustrative of areas having a tropical rainforest vegetation with only a short, relatively dry season, and fuels that are difficult to set on fire. Gawthorn (1962) recommends that the burn should take place before the leaves drop from the felled trees, but not less than seven weeks after the last tree has been felled. The fire should be started about 11:30 A.M., after the dew has evaporated. A recommendation from another study of the same area is that firing is more likely to be successful after three days without rain and when there is light wind. Two methods of lighting are advocated. One is to light fires at frequent intervals around the perimeter of the clearing, and allow the fire to work inward. Another is to cut rough tracks through the felled jungle at intervals of five to ten chains (120 to 240 meters), and then send a gang of laborers through the clearing in line abreast formation, lighting fires as they proceed against the wind.

Sanderson, Menon, and Ganapathy (1962) point out how difficult it is to set fire to the Malayan forest, however, and they recommend the use of special combustible materials and time fuses, as shown in the following quotation.

> For various reasons there is never any certainty about the success of a burn. Often during a burn the laborers setting fire to the felled jungle are diverted, for one reason or another, from their normal courses through the area. The wind may change or there may be natural obstacles or the people to the left or right may have advanced too quickly. There is always some chance of individuals or groups of individuals being cut off and as a result patches of felled jungle are left unburned or only partially burned.

> Combustibles and Fire points.--Normally no action is taken to help felled jungle to burn. The fire-setters advance so quickly that they do not have time to insure that the ignited points continue to burn and spread. It would obviously be an advantage if, at various points throughout the felled area, combustibles could be laid down beforehand so as to make certain that a series of really large fires are started.
>
> Four main types of combustibles have been used: 1) pieces of old tyres; 2) scraps of foam rubber; 3) pieces of sacking soaked in damar oil [damar: a copallike resin chiefly from dipterocarpaceous trees of southern Asia, esp. Malaya and Sumatra, much used for making colorless varnish (Amer. Coll. Dict.)]; 4) sawdust and damar oil.
>
> Various types and combinations of fire points (preset combustibles) have been tried. A typical fire point now consists of the following: one piece of sacking soaked in damar oil, one or two pieces of foam rubber scrap, and one piece of old rubber tyre. Advantage is taken of a point where timber, both large and small, is denser than average. ... On the average, fire points are laid down at a density of thirty per acre.
>
> The [time] fuse consists of a Chinese joss stick half an inch in diameter mounted on a sliver of wood or bamboo which enables it to be stuck in the ground. The joss stick smoulders at the rate of approx. 10 inches per hour. At the bottom of the joss stick a jacket of five matches with heads upwards and all at the same level are secured to the joss stick by a 3 X 3 inch piece of sacking soaked in damar oil. The heads of the matches are just clear of the oil soaked sacking. ...With fuses, fire points are essential. All fire points ignite simultaneously, thus increasing the chances of a good burn. ... Burnings of 200-400 acres [81 to 162 hectares] are ideal (Sanderson, Menon, and Ganapathy, 1962, pp. 109-112).

A similar use of time fuses has been observed in Senegal, where rivalries between grazing and farming tribes, and between individual natives, have been the occasion for arson. A mixture of chopped straw, dry manure, and other vegetable matter is left smouldering, and after a time a fire begins and spreads.

A grid system of spot fires, one chain by one chain to ten chains by ten chains (24 X 24 meters to 240 X 240 meters) has been prescribed for control burning in Australian eucalypt forests by McArthur (1962). One objective of the system is to prevent the joining of spot fires. This reduces the possibility of damage to the trees resulting from excessively hot fires. Another technique is the use of a jeep-mounted flame thrower moving through trails cut through the forest.

The means employed by native peoples vary from place to place and from group to group. A torch of some kind is frequently used, as among the Hanunóo of Mindoro, who employ a torch of dried, cracked bamboo (Conklin, 1957). African hunters trail a lighted grass rope around the area selected for burning to flush out the game animals.

Accidental fires may be started in the steppes and savannas during the dry season by many different means. Honey gatherers' fires, travelers' fires, native cooking fires, muzzle loading muskets, housewives and children carrying live coals from one village to another--these and many other means can cause a conflagration.

4. Fire Control

In most parts of the tropical world, the subject of fire control is in the initial stages of planning and implementation. Policies and methods employed in controlling fire are usually adaptations of legislation and control practices successfully employed in middle latitudes. The increasing concern of governmental agencies, both local and national, reflects a greater awareness of the need to protect valuable forest and grassland resources. As commercial exploitation of these resources expands, there is little doubt that more stringent fire control legislation and enforcement will occur. The concern of many who have studied aspects of the tropical environment affected by fire is that adequate fire control may come too late to parts of the tropics, particularly Sub-Saharan Africa.

Methods of fire control include intensive fire lookout networks and modern fire suppression techniques and equipment, control burning to reduce fire hazard and fire severity by reducing the accumulation of fuels, and preparation of fire breaks. Control burning and use of fire breaks represent the most widely applied methods of fire control, regardless of the technological level of those using fire.

Although the technological level of native peoples is in most cases very low, they nevertheless have a variety of methods to control fires. Most of them are concerned with limiting fire spread and with reducing the effects of fire on vegetation to be spared. Among the pastoral Fulani of Ferlo in Senegal, a seasonal migration used to take place, wherein the tribe and its animals moved in the dry season to permanent sources of water. For a few members who stayed behind it was necessary to provide protection against uncontrolled brush fires. This was done by burning a radial-concentric firebreak 2 to 3 kilometers in radius (République du Sénégal, n.d.).

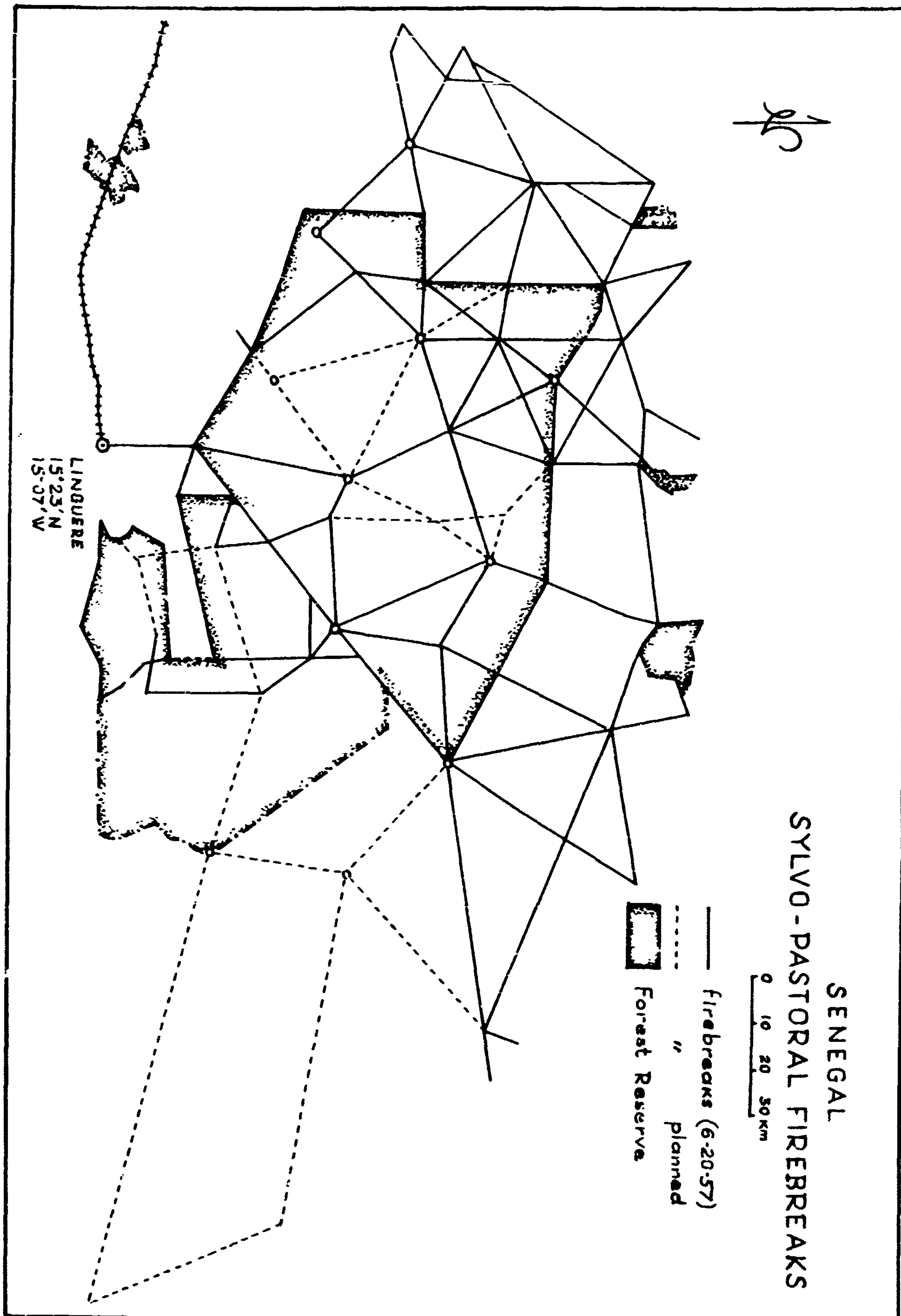
Among the Hanunóo Conklin observed similar protective fire paths, but in this case they were cleared by hand to limit the spread of fire when a swidden of felled trees and brush was burned. He also noted that the slashed vegetation was not allowed to cover places where root crops had been planted. These can survive the burn when protected by green banana sheaths. Neither was fuel piled around individually-owned trees that he calls "semi-domesticates." In northern Burma the Kachins rely on the perennially moist character of the forest to prevent the escape of fires (Huke, 1954). Allan (1916) describes how men, women and children armed themselves with leafy branches to beat out runaway fires in a <u>taungya</u> in bamboo land in Burma.

The "sylvo-pastoral" region of Senegal, is a good example of a tropical grass and wooded area subject to modern fire control methods. Located in the central and northwestern part of Senegal, the region covers about 40 per cent of its territory (Giffard, 1965). The region is partitioned by a network of firebreaks extending over 3,400 km. and having six to nine meters width (Map 2). The firebreaks also serve as routes of communication. The area is rainless during six months of the year. Deep wells (200-300 meters) have been constructed to provide water to herders and their animals during the winter. The network of firebreaks forms a series of triangles and polygons which enclose areas varying from 6 to 3,064 sq. km. In the classified sylvo-pastoral forest reserves, where the network is densest, the triangles vary from 48 to 450 sq km. The length of the firebreaks--completed and planned--ranges from 2 to 86 km. and averages 30 km.

It is questionable whether the firebreaks actually are able to prevent the spread of wild fire pushed by a strong wind through an area well supplied with fuel. It is not difficult for burning embers to be blown the 6 to 9 m. across them. Indeed, it has been estimated that under average conditions of fuel supply, air humidity, and wind force, there is a 50 per cent chance of a fire crossing a cleared strip 6.5 meters wide.

Perhaps the greatest value of the firebreaks is as routes making the region accessible to fire-fighting apparatus. From November to May every year operations are undertaken against fires. Use of modern equipment permits three procedures to be employed: 1, the direct projection of water into the flames by means of fire hoses; 2) the spraying of water from sprayers mounted on tractors; and 3) atomization and fogging with high pressure fog apparatus. The existence of deep wells makes it possible to refill water tanks conveniently.

A comprehensive study of the problem of veld fires in Southern Rhodesia, emphasizing the practical aspects, has been made and is a good example of fire control problems (Gammon, 1962). The sources of uncontrolled veld fires and suggested preventive measures, the establishment and construction of


SENEGAL
SYLVO-PASTORAL FIREBREAKS
0 10 20 30 km
firebreaks (6-20-57)
" planned
Forest Reserve
LINGUERE
15°23'N
15°07'W

Map 2

"fireguards" (firebreaks), the kinds and uses of fire fighting equipment, controlled burning, and fire control legislation are explained in detail and evaluated. Much of Gammon's article deals with the problem of fireguards, which are considered the most important means of defense against uncontrolled fires. It must be emphasized, however, that fireguards alone are inadequate protection. They serve as a base from which to actively fight a fire, and as a means of control in intentional burning.

Gammon emphasizes the need to take advantage of streams, roads, bare rock and other features in selecting sites for fireguards. Where there is a prevailing wind, it is desirable to align them in a direction slightly oblique to the wind, to reduce the chances of a fire striking the fireguard on a broad front In rolling country they should follow the ridges, and where there is both woodland and grassland, they should follow line of contact. The width of the fireguard should be from 10 m. either side of a common boundary, up to as much as 65 meters, depending on the severity of the conditions.

Fireguards vary in their sizes and type of construction. The simplest is a cleaned strip or "tracer", either plowed, disk harrowed, or hoed, until free of vegetation. A refinement of this is a cleared and rough-graded "fire track" along fence lines which also serves as a road. The most common form is the burnt fireguard, a strip burnt between two "safety strips" which may be plow furrows, watered strips, mown strips, or tracers. Where the fireguard is wide and the land is valuable, the fireguard becomes a "buffer strip" if it is used for non-combustible trees, shrubs, or crops. Finally there is the "boundary paddock", a long, narrow, fenced pasture bounding the property which is heavily stocked with cattle in the beginning of the dry season, so that the grass is eaten to the ground. In the Transvaal the European farmers allocate such strips as farm land to their laborers.

A variation of the boundary paddock is the practice of spraying a strip of grass along the edge of a field with a mixture of urea and molasses, which is attractive to the cattle, so that it is grazed to the ground. This saves the cost of building an additional fence.

The choice of fire fighting equipment in Southern Rhodesia is influenced by the availability of African labor. The use of native beaters is a very important aspect of early control. A five foot stick to which a flexible, flat, non-inflammable paddle is attached is recommended. Leather, tractor tubing, and fire hose are excellent. Mention is also made of spraying and fogging equipment, manual and powered by tractor power takeoffs.

Gammon's advice concerning fire fighting methods is concrete.

> In fighting a veld fire one must first decide whether to make a direct attack on it, wait for it to reach a fireguard, or backburn from a fireguard. In heavy grass with any wind it is virtually impossible to beat out a fire except at a fireguard. With little wind and a light grass cover... it may be worth making a direct attack on the fire, particularly if spray equipment can be used and if the fire still has a long way to go to reach the fireguard.... Veld fires generally take up a tongue-shape pattern, travelling in the direction of the wind, with a more or less gradual spread to either side of the line of travel. The basic principle in tackling any fire, therefore, should be to make flanking attacks from either side, driving it into an ever-narrowing wedge (Fig. 16).
>
> If one is sufficiently sure that the fire can be beaten out at the fireguard this can be done, but generally backburning is preferable. Backburning can be described as the deliberate firing of a strip of veld at a fireguard in such a way as to meet an oncoming fire. It has been said that the essential feature of back burning is to time the operation so that advantage can be taken of the updraught created by the main fire, so that the backburn fire is sucked back into the main fire which is thus burnt out. If, however, backburning has to be done along a wide front, which is usually the

> case, it will be dangerous to wait until the main fire is close enough for the effect of its updraught to be experienced. It is more advisable to start burning well in advance of the main fire. The back-burn fire will burn slowly upwind, till the main fire is fairly close, and then will be drawn rapidly back into it (Gammon, 1962, p. 186).

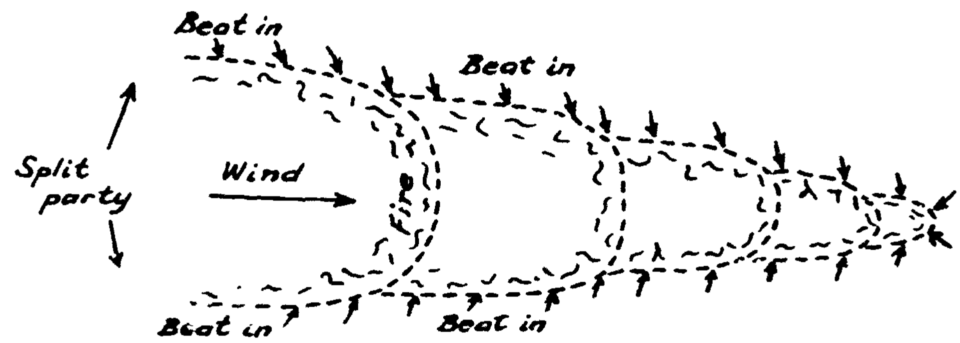


Fig. 16. Techniques Employed to Fight Grass Fires in the Absence of Modern Equipment, Southern Rhodesia.

After Gammon, 1962

Comprehensive legislation to regulate the setting and control of fires exists in Southern Rhodesia. The laws reflect the social and economic characteristics of the country. They take note of the need to burn for pasture improvement and for forest protection. They require notification of neighbors and the police before burning is begun. They require the cooperative efforts of all persons to prevent the spread of dangerous fires. They establish the right and responsibility of the individual to take action against fires deemed dangerous to life and property, and his authority to call upon others for assistance. They authorize the government to compel property owners to take protective measures, including fireguards thirty feet wide along common property boundaries.

Gammon's conclusions regarding veld fires in Southern Rhodesia are discouraging. He feels that the landowners have not been sufficiently convinced of the benefits of fireguards, that the legislation has not been adequately enforced, and that the estimated six million acres (2.4 million hectares) burned by uncontrolled veld fires in 1959 could have a seriously detrimental effect on the problem of preventing bush encroachment in veld management.

5. Cyclical Patterns of Burning

One characteristic of most intentional burning in tropical forests and grasslands is its cyclical nature. Non-cyclical or sporadic fires may be accidental or intentional, and they may cause considerable damage to life and property. However, they are not predictable, except in terms of probability. The cyclical patterns of burning, on the other hand, are part of some repetitive annual or longer-term cycle of activities. They are capable of being studied from the standpoint of their roles in man's economic life and their relation to the vegetation cover.

A distinction should be made between the annual cycle of burning and the perennial cycle of burning. The annual cycle refers to a pattern of activities, including burning, that is related to the seasons. The perennial cycle refers to a pattern in which a site is burned, and then a sequence of activities takes place leading to another burning of the same site after the passage of more than one year.

a. The annual cycle of burning.--This pattern of burning is typical of the swidden cultivators and tropical cattle-keeping peoples. In order to depict the complexity and variety of the practices followed by swidden cultivators, the studies of Miracle (1964) and Conklin (1957b) are discussed below.

The study of traditional agricultural methods in the Congo Basin by Miracle illustrates the annual or short-term cycles used by primitive African cultivators in tropical forest, woodland, and savanna environments. Miracle distinguishes six major types of land preparation, all using fire to help clear the vegetation or to reduce it to fertilizing ash. Compare the map depicting the location and distribution of these types with the map of tribal groups for essentially the same area in Central Africa (Maps 3 and 4). Note the diversity in time of burning due to cultural tradition. Compare these maps with Map 6 in Chapter V. (See Chapter V, page 186 for explanation of symbols.)

The most widespread system is type 1--cut, burn, and plant--in which the vegetation is felled near the end of the dry season, allowed to dry, and then burned just before the rains begin. There are ten subdivisions of this system, based on the amount of cutting and burning and the extent of cleaning and leveling operations. This system is found in forest, woodland, and savanna.

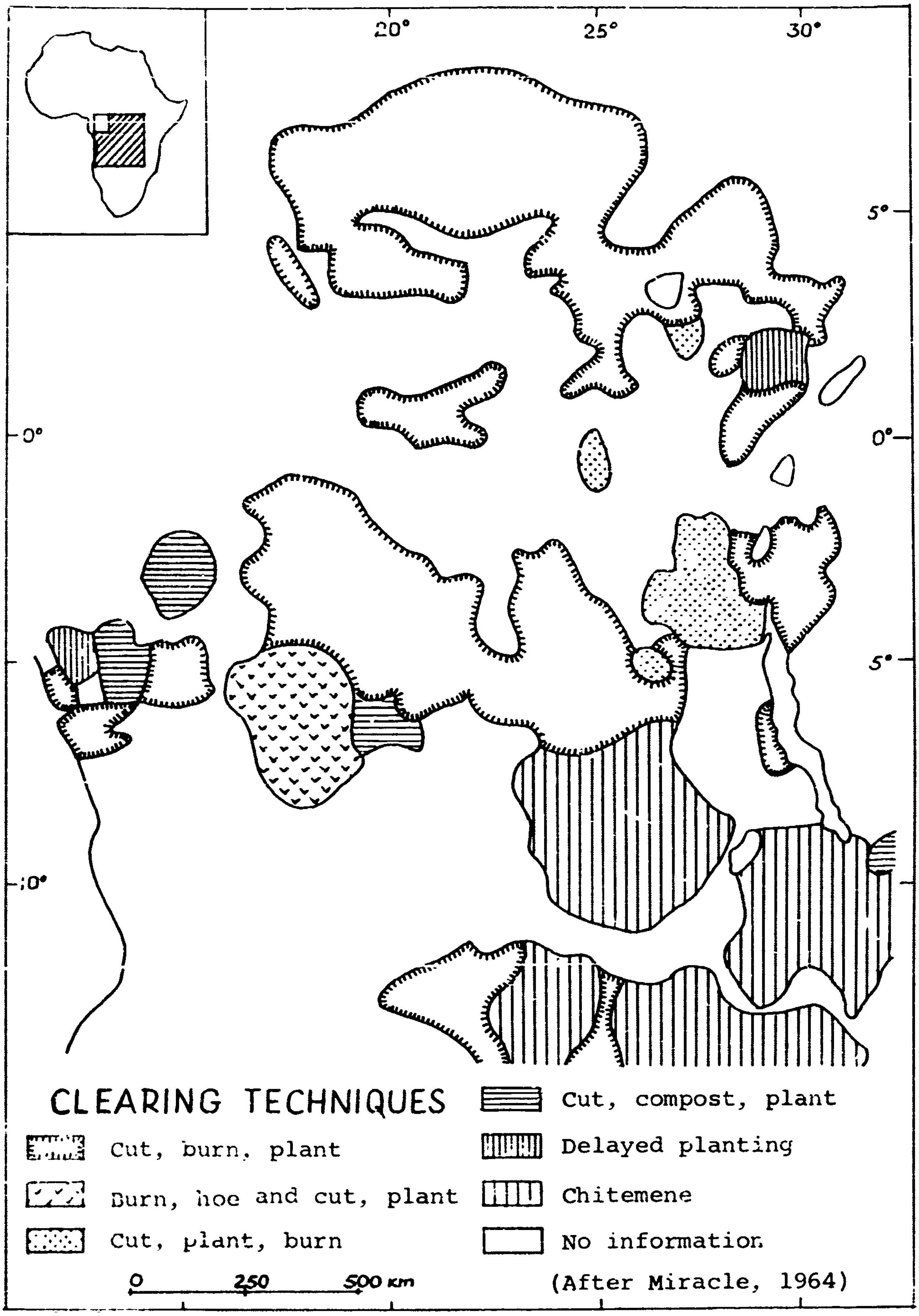
The type 2 system--burn, hoe and cut, plant--is found only in savanna areas. The savannas are burned in the dry season, and then the ashes and remaining refuse are hoed into large mounds about 35 cm. high.

The type 3 system--cut, plant, burn (forest)--is found in the tropical forest or "derived savanna." The burn takes place after banana, plantain, or manioc has been planted, but the crops are not damaged by the fire.

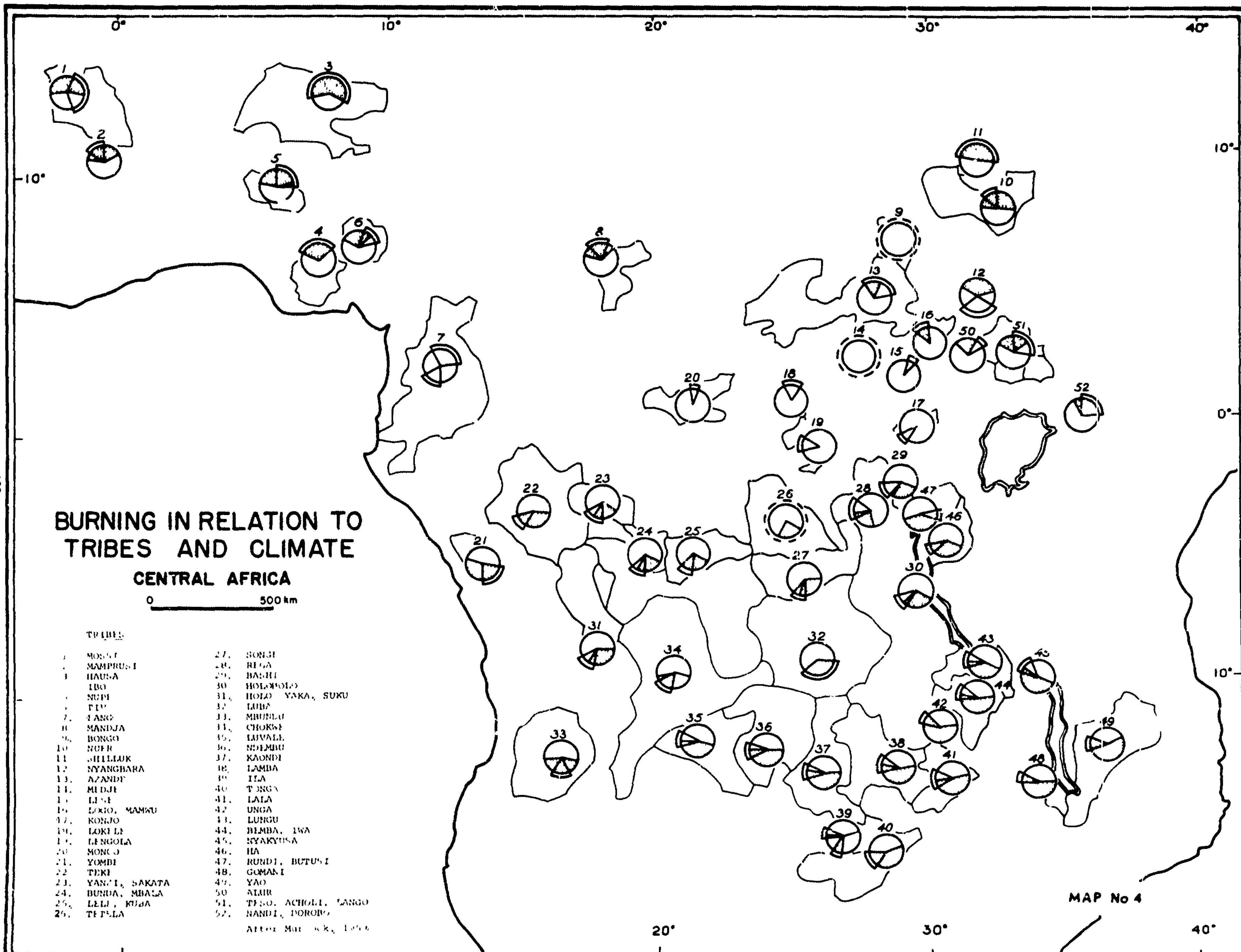
The type 4 system--cut, bury refuse in mounds, plant--is a system that involves a form of composting. On the Koukouya Plateau in Congo (Brazzaville) the Teke people cut and pile the grass, cover it with soil, and then ignite the mounds.

The type 5 system--cut, wait one season, plant (forest)--is a system found in the forest and park-like savanna near the mouth of the Congo River, and also in a similar area in the northeastern part of Congo Basin.

The type 6 system--cut, add extra wood, burn, plant, hoe--is a system commonly referred to as <u>chitamene</u>. Its main


20°
25°
30°
5°
0°
5°
10°
CLEARING TECHNIQUES
Cut, burn, plant
Burn, hoe and cut, plant
Cut, plant, burn
Cut, compost, plant
Delayed planting
Chitemene
No information
0
250
500 km
(After Miracle, 1964)

Map 3


BURNING IN RELATION TO TRIBES AND CLIMATE
CENTRAL AFRICA
0 500 km
TRIBES
1. MOSSI
2. MAMPRUSI
3. HAUSA
4. IBO
5. NUPI
6. TIV
7. FANG
8. MANDJA
9. BONGO
10. NUER
11. SHILLUK
12. NYANGBARA
13. AZANDE
14. MEDJE
15. LESE
16. LOGO, MAMWU
17. KONJO
18. LOKELE
19. LENGOLA
20. MONGO
21. YOMBI
22. TEKE
23. YANZI, SAKATA
24. BUNDA, MBALA
25. LELE, KUBA
26. TETELA
27. SONGE
28. REGA
29. BASHI
30. HOLOHOLO
31. HOLO YAKA, SUKU
32. LUBA
33. MBUNDU
34. CHOKWE
35. LUVALE
36. NDEMBU
37. KAONDI
38. LAMBA
39. ILA
40. TONGA
41. LALA
42. UNGA
43. LUNGU
44. BEMBA, IWA
45. NYAKYUSA
46. HA
47. RUNDI, BUTUSI
48. GOMANI
49. YAO
50. ALUR
51. TESO, ACHOLI, LANGO
52. NANDI, DOROBO
MAP No 4

feature is the cutting of vegetation from an area from five to twenty-times larger than the area to be planted. This technique provides a hotter fire and a greater amount of fertilizing ash. Among the other studies of peoples using <u>chitemene</u> are Richard's work on the Bemba of Zambia (1939) and Trapnell and Clothier's (1937) study of northwestern Zambia. The Bemba cut branches from an area up to six times as large as the area to be planted, pile the wood to a height of about 65 cm. in a large circle, and burn it after a period of drying. Other tribes, such as the Lala of Zambia, use several small circles, and cut vegetation from an area fourteen times larger than the planted area.

The annual cycle of burning is part of a complex sequence of inter-related agricultural operations, as revealed by the following list of stages in the Hanunóo agricultural cycle (adapted from Conklin, 1957b).

1.	<u>Garamasun</u>	Land selected as a site for clearing. Before planting the site is called <u>parayan</u>.
2.	<u>Gamasun</u>	A selected site in which the undergrowth has been slashed in preparation for the heavy work of felling the large trees.
3.	<u>Puklid</u>	The clearing after completion of felling.
4.	<u>Tutud</u>	The burned off clearing.
5.	<u>Tanman</u>	The planted clearing.
6.	<u>Dayamihan</u>	The clearing after rice has been harvested.
7.	<u>Lumun bag'uhan</u>	The almost completely harvested clearing in which pigs may be allowed to forage if there has been no supplementary planting.
8.	<u>Lumun da'an</u>	Trees and other long-persisting plants, such as bananas, are planted before the clearing is left for the long fallow (see below).
9.	<u>Ginaru'</u>	Low-growth fallow. During this and the fallowing period of fallow, the old clearing will continue to be visited for whatever produce it may yield, in the way of fruits, roots, etc.

10. <u>Talun</u> The clearing has largely been reclaimed by tree growth.

It is apparent that the first eight stages in the above cycle are parts of the annual cycle that the Hanunóo follow, clearing a new field each year for their rice planting. The last two stages are part of the perennial cycle, in which the forest regenerates itself. Thus the overlap between the annual and perennial cycles is evident.

The annual cycle of burning may also be seen in the practices of African and South American herders, who burn off the savannas each year in order to provide a flush of new growth for their livestock. This procedure has been noted in numerous publications, e.g., Tamayo (1962), Bates (1948), Aitken (1964). It is used by commercial livestock raisers as well as native subsistence grazers. Among the Swazi of Swaziland, for example, grazing is combined with agriculture. Part of the grazing land is burned every autumn, while the remainder is used for winter forage (Marwick, 1940). A high point in the annual grazing cycle of the Nyakyusa of Tanzania, is the burning of pasture during a brief dry period in October or November (Wilson, 1938)

Adoption of native methods of annual range burning by European commercial graziers, is mentioned by Stocker (n.d.) for northern Australia, and by Botha (1945a) for the eastern Transvaal. Interestingly, experimental evidence is accumulating that leads to the conclusion that burning cycles, including resting periods and controlled grazing, of several years duration are highly desirable, and are much less detrimental to quality and quantity of graze than annual burning (Scott, 1952).

There is another aspect to the annual cycle. This is the interconnection between the agricultural work associated with the clearing and cropping of the swidden site, and the other work that provides food or cash income between harvests. The agricultural year of the Semai Senoi aboriginals of Malaya reveals this interconnection (see Table 12).

TABLE 12

THE SEMAI SENOI AGRICULTURAL YEAR

Approximate Period	Agricultural Work	Other Work	Main Sources of Food	Subsidary Source of Food
i April - May	New ladang site selected and initial area--two to three acres--felled.	Some collection of jungle produce bamboos rotans and jungle gums.	Tapioca from last years ladang.	Purchased food from sale of jungle produce. Animals trapped and snared, fish, jungle roots.
ii May - June	Initial site burnt off and planted. (Usually maize, some tapioca and bananas). Felling of main ladang commenced.	Temporary shelters erected followed by new houses.	Do.	Do.
iii July-August	Main ladang burnt off and planted. General order: (i) Hill padi (ii) Tapioca (iii) Maize, keladi and sweet potatoes.	Fruit season. perah nut and Petai most important.	Do. plus jungle fruits.	Do. plus sale of jungle fruits particularly Petai and acorns.
iv. September-October	weeding	Repair of fish traps Fishing.	Do. plus first maize crop	End of Fruit season. Rather less collection of jungle produce.
v. November-December	Harvest of main padi crop.	Durian season	Padi	Do.
vi. January - March		Fishing and collection of jungle produce.	Padi and new tapioca, keladi, sweet potatoes, etc.	Sale of jungle produce.

(After Williams-Hunt, 1952)

Annual burning may also be done for other purposes than agriculture. In Laos it is a common practice to light fires during the passage of migratory birds in order to make them converge towards the nets (Turbang, 1961). Burning for hunting may have an annual cycle if it is associated with a regular period when other sources of food are unavailable, such as during growing seasons. In Brazil an annual religious festival, the Fiesta juanina (St. John's Day) in June is marked by the adoration of fire, and frequent fires break out (Gonzales Silva, 1957). Burning to clear snakes from rural paths will be more likely to take place during the seasons when travel is frequent, such as when the harvest is being brought to the towns for sale.

The time of annual burning varies widely in different areas of the world. The seasonal distribution of precipitation, the purpose for which burning is done, and the cultural patterns of the population are significant factors influencing the time of burning. Burning may occur as soon as the fuel has become sufficiently dry. The usual practice among farmers and herders is to burn as late in the dry season as possible, before the first rains of wet season. For Africa, South and Southeast Asia, and Latin America the dry season and burning period for numerous stations in various vegetation zones has been mapped (Maps 1 to 5).

In some areas a double minimum of rainfall makes it possible to burn twice a year, as shown for Ambam, Cameroon (Station No. 38), and as reported for Colombia (Suarez de Castro, 1953). Even brief periods of relatively less rainfall in areas of humid tropical forest may permit the burning of felled vegetation.

Among some forest cultivators, such as the Tim and Kamuk peoples of the northeastern mountains of Thailand, the initial burning is followed by later burnings to get rid of the remaining charred stumps and logs (Credner, 1935). A burned swidden plot in Guatemala illustrates a "good, clean" burn, in which the maximum ash has been produced and nearly all weeds have been killed (PLATE 26).

The practice of "early burning" (control burning) has been widely adopted by the forest departments of African countries. Burning early in the dry season is preferable to late burning because the flames are less intense and less destructive to the trees and seedlings, yet they reduce the accumulation of grass and undesirable brush from the forest land.

b. The perennial cycle of burning.--The annual cycle of burning described above is often a stage in a long term process by which the regeneration of the forest makes it possible for the swidden cultivator to return to a previously burned site after a period of years and repeat the annual cycle. This process is referred to here as the perennial cycle of burning. The term may also be useful to describe situations such as those in which control burning is used at intervals of greater than one year, as part of a program of forest or grassland management.

In Africa the use of fire by commercial cattle graziers has been recognized as a permitted, even desirable, practice to prevent bush encroachment on grasslands. "The intelligent and systematic use of fire in a properly designed system of veld management is the only means whereby the grazier can maintain the productivity of his grazing land" (West, 1958, p. 412). Whereas the forester prefers to burn early in the dry season to reduce the intensity of the flames and preserve the trees, the grazier requires a late burn so that the intense fire will do the greatest damage to the grass. A minimum interval of four years between burns and a rest period before and after burning are recommended by West (1958).

Pelzer (1945, p. 16) has succinctly described the perennial cycle of swidden cultivation in the tropical forest in the following terms:

PLATE 26: Burned second growth forest, eastern Guatemala, near Lake Izabal. A good clean burn, since nearly all weeds have been killed and maximum ash has been produced. (Photo by H. Popenoe).

> ... the shifting swidden cultivator does not use the same piece of land every year; instead, he kills or cuts down at regular intervals--every year, every other year, or every third year--the trees of a small forest patch. ...As forest land is generally free from weeds or grasses and the soil is usually rich in humus and well supplied with the ash of burned plant matter after clearing, it produces a very good, even excellent first harvest; the second harvest begins to show a decline in yield, and thereafter the returns diminish rapidly. ...for parts of the Lampoeng Districts ... a ladang (swidden) will produce from 15 to 25 quintals of rice in the first year and approximately 5 in the second year. Grasses and weeds invade the clearing. Rather than battle these, the peasant abandons his old ladang and cuts and burns a new patch of forest. The old plot reverts, under favorable conditions, to second-growth forest, ...and is not cleared again for a period, the length of which may vary from 8 to 15 years, or more.

There are several significant variables in the swidden cycle described above. One is the number of years the farmer can cultivate his patch, which depends on the inherent fertility of the soil, the type of crop, and his cultural tradition. If he can cultivate it for more than one year, his land requirements will be considerably less than if he must move every year. A particularly damaging form of swidden cultivation involving a long cycle has been termed the <u>exhaustion rays</u> by Turbang (1961) in his excellent survey of the Lower Mekong Basin. (<u>Ray</u> is the local term for swidden plot.) This system is characteristic of the Meo people of the hill and mountain country of southern China and northern Viet Nam, Laos, and Thailand. The <u>ray</u> is cultivated intensively for seven or eight years, and the result is a leached, eroded, and exhausted plot which even grass finds it difficult to colonize.

Another variable, whose importance cannot be understated, is the length of time that the plot will be allowed to remain in fallow before being cultivated again. After being abandoned, undesirable grasses and weeds appear in the swidden plot. With the passage of time the second-growth forest develops, consisting of light-loving trees and others that played a minor role in the original forest. Given the passage of decades, the original climax vegetation may reestablish itself, and the original soil fertility may be replenished. Unfortunately, it is most unusual for the fallow period to last for such a long time. Miracle (1964) records fallow periods in the Congo Basin ranging from one to twenty years. Credner (1935) reports periods as short as ten years. As a result of the pressure of population on the land, the shifting cultivator returns before the cycle has been completed. The productivity of the plot is now based on the degraded second-growth forest, and therefore is less than when first cleared.

All too often an abandoned swidden plot is burned before a second-growth forest can establish itself. The result is the development of the extensive open grasslands that are burned or catch fire annually, thus forestalling natural reforestation. The grasslands gradually expand at the expense of the forest by singeing the trees at the forest grassland border. These grasslands, called cogonales in the Philippines, alang-alang in Indonesia, and "derived savanna" by J. Phillips (1965), are now the dominant form of vegetation in many areas of the humid tropics, particularly where a dry season exists. It is apparent that the perennial burning cycle of swidden cultivation which involves a relatively lengthy period of forest or bush fallow, has within it a strong propensity to shorten the period and ultimately become an annual cycle when derived savanna has replaced the original or second-growth forests.

There is a variety of other perennial cycles in burning vegetation, some of which may be referred to briefly. One of these is the system wherein swidden cultivators, such as those in Indonesia, combine coffee or pepper cultivation with rice on their plots. The following table (after Pelzer, (1945) indicates how a two-year cycle of rice is combined with a five-year cycle of coffee.

TABLE 13

SCHEME OF OPERATION OF SWIDDEN CULTIVATORS RAISING COFFEE AS A CASH CROP IN SWIDDEN PLOTS, IN TERMS OF HARVESTS

YEAR	SWIDDEN PLOTS				
	First	Second	Third	Fourth	Fifth
1st	rice				
2nd	rice				
3rd	coffee	rice			
4th	coffee	rice			
5th	coffee	coffee	rice		
6th	coffee	coffee	rice		
7th	coffee	coffee	coffee	rice	
8th		coffee	coffee	rice	
9th		coffee	coffee	coffee	rice
10th			coffee	coffee	rice
11th			coffee	coffee	coffee
12th				coffee	coffee
13th				coffee	coffee
14th					coffee
15th					coffee

(After Pelzer, 1945)

James (1953) has described a cycle of land clearance and abandonment in the semi-deciduous forests of eastern Brazil. A large landowner, desiring to have his forested land cleared for pasture, contracts with a tenant to clear and burn an area of about four hectares. The tenant cultivates maize, rice, beans, and manioc for two or three years. Then he plants grass and moves to another plot. The landowner pastures his cattle for a few years, but gradually the grass is replaced by trees. Then the landowner moves his cattle to another pasture. By this process large areas of Brazil have been repeatedly cleared and abandoned.

c. Conclusions.--It is apparent that the levels of material technology range over a wide spectrum from the primitive to the ultra-modern. The levels of knowledge about how to use and control fire are equally disparate. Yet it is abundantly clear, from the great variety of practices that have been described in the literature, that fire and tropical agriculture are intimately related. Fire is an agricultural tool as important to the swidden cultivator as his digging stick, as important to the European farmer in Rhodesia as his tractor.

C. Man, Land and Fire.

In order to better understand the reasons why the practices discussed in the previous section are so widely used, we should examine the geography of cultural factors that are related to the use of fire. A variety of questions might be asked. How many people use fire, and where are they located? How much land is required to support people who rely on fire? How has population growth affected the man/land ratios among fire users? What social and economic characteristics favor the use of fire? What are the possible future cultural developments that might affect the use of fire?

1. Population

a. Population Numbers.--In many tropical areas the swidden cultivators are beyond the reach of the census taker. Therefore, it is very difficult to have more than a rough estimate of the number of people who use fire. The 1957 F.A.O. estimate of 200 million should be increased to about 240 million for 1966, based on an estimated world increase of 2 per cent per year. The rate of increase of swidden cultivators has probably been highest in Latin America, where the range of population increase varies from 1.5 per cent in Jamaica to 4.3 per cent in Costa Rica. Africa has had the lowest increases, ranging from 1.1 per cent in Chad to 3.3 per cent in Southern Rhodesia. The rates for South and Southeast Asia are intermediate, ranging from 2.1 per cent in Burma to 3.7 per cent in South Viet Nam (Population Reference Bureau, 1965).

b. Population Densities.--Considerable differences exist from place to place in the tropics in population numbers and densities. According to Gourou, in 1958 the wet tropics of Asia contained one quarter of mankind on 8 per cent of the earth's usable land at an overall density of about 55 per square kilometer. The remaining wet tropical regions contained 170 million people on 28 per cent of the usable area. Tropical Africa had an estimated 120 million people, with an average density of about 8 per square kilometer, while tropical Latin America had about 60 million, with an average density of about 4.5 per square kilometer.

A brief glance at a map of world population density will make it obvious that the above statistics oversimplify the situation. In the wet tropical regions of Asia more than one half of the area is very densely populated. In India and mainland Southeast Asia particularly the areas with 10 or fewer persons per square kilometer are discontinuous islands in a densely populated sea. The opposite is true of Africa and Latin America, where most of the land is sparsely populated. There are only a few spots of relatively dense population along the coasts, in the Central American mountains, in Nigeria, and around the East African lakes.

It has been established by numerous studies (Pelzer, 1945; Gourou, 1958; et al.) that swidden cultivation in wet tropical Asia is primarily found in the hilly or mountainous areas where the cultivation of irrigated rice has not penetrated. In the alluvial valleys, where the mass of the population lives, there is no room for the extensive land use that swidden cultivation involves. The contrast may be seen by comparing Cambodia, a country that consists mostly of lowlands, with Laos, a country that is mostly hilly and mountain land. In Cambodia less than 5 per cent of the population is supported by swidden cultivation, while in Laos the figure is about 40 per cent (Turbang, 1961).

The cultivation of irrigated rice is of minor importance in most parts of Africa and Latin America. The majority of the peasant population subsists on root crops, such as manioc, yams, taro, and potatoes: on unirrigated cereal crops, such as maize, sorghum, and millets; and on miscellaneous food crops such as bananas, peanuts, and beans. It is safe to say that while in tropical Asia swidden cul- - vation supports a minority of the agricultural population, in tropical Africa and Latin America swidden cultivators form the majority of the agricultural population.

c. Man-Land Ratios.--In the absence of detailed census statistics, it is difficult to state exactly the population densities that are found in the areas of swidden cultivation. However, several estimates have been made of the amount of land that is required to support a community on a permanent basis. In 1940 it was estimated by Van Beukering of the Department of Economic Affairs, Netherlands Indies, that swidden cultivation could permanently support up to fifty persons per square kilometer (Pelzer. 1945). Allowing five persons per family and a one-year cultivation with nine years of fallow, the average land requirement per year would be one hectare per family. Conklin (1957b) estimated the population capacity of the Hanunóo agricultural system at 48 per square kilometer. Watters (1960) has attacked the general applicability of these estimates, citing areas of infertile lard where, under the chitemene system, the durable carrying capacity is only 2.6 per square kilometer. The only certain statement possible is that swidden cultivation can persist on a stable basis only where the population density is low enough for the swidden plots to regain their fertility by a long fallow period. The length of the necessary fallow period will vary, depending on such factors as the climate, vegetation, soil parent material, and extent of damage by burning. Full recuperation after one crop may take from twelve years in Indonesia to thirty years in Southern Nigeria (Watters, 1960).

One of the most noteworthy characteristics of the agricultural population of tropical areas is their increase in recent years. Limitations on population growth, such as disease, wars, famines, and cultural restraints have gradually declined in their effectiveness. As population density has increased, the fallow period has been shortened, because less land is available for cropping and therefore a greater portion of land must be used more frequently. The tragic result of population increase often is the creation of large areas where soil is exhausted, land is severely eroded and forest vegetation has been permanently replaced by grasses and low shrubs (Turbang, 1961; Watters, 1965; Harroy, 1949; Bartlett, 1956).

2. Social and Economic Setting

Swidden cultivators and nomadic pastoralists have certain social and economic features in common. Conservatism, isolation, low level of cultural development, rudimentary land tenure relationships, and underemployment of labor are characteristic of most of these groups. Reluctance to change the patterns of living that have been developed over the centuries is not unusual among human societies. Many of their religious and social practices are intimately connected with the food-producing activities. This conservatism becomes a problem when the practices become detrimental to the survival of the group or of its neighbors, as the rise in population density and the reduction in the fallow period has proven. Perhaps basic to their conservatism and isolation are the low levels of literacy and cultural development that characterize most primitive fire users. Areas of dense population in South Asia and Southeast Asia are those where the cultures of the great river valley civilizations of India and China penetrated, bringing with them the irrigation techniques that enabled them to produce surpluses and develop a high level of culture. Except for the Mayan civilization, and perhaps those of Zimbabwe in Southern Rhodesia and Benin in Nigeria, no great civilization based on swidden farming has developed.

The technological level of swidden cultivators may be described as that of hoe culture in Africa and digging stick culture in Asia, Oceania, and Latin America. The use of the plow is unusual, and probably unsuited to the stump-filled forest clearings. Therefore, fire is the easiest and most efficient tool for the clearing of land. Through the centuries, swidden farmers and nomadic grazers have developed adaptations to environmental limitations that make possible a durable economy, so long as man/land ratios are low. The hoe and the digging stick disturb the soil very little. By mixed cropping and cropping in sequence, the soil is protected from sun and rain and the likelihood of total crop failure is lessened. Yet the low inherent productivity of the tropical soils makes it inevitable that crop yields decline. If enough land is available, however, the question as to which may be much more costly, to clear another swidden plot, or to use fertilizer to maintain existing plots, has yet to be answered.

The character of land tenure is intimately associated with fire and swidden farming and nomadism. Usually there is no attachment of an individual to a parcel of land. In Africa, numerous tribes have a variety of land rights that are largely communal in nature, and are still imperfectly understood (N.A.S.-N.R.C., 1961). The use of the land and the production from it are more important than its ownership as real property. The pastoral peoples have their own systems, which emphasize the right to graze their animals in certain places at certain seasons, and to use certain water holes and occupy certain camp sites. In Latin America much of the land has been occupied by squatters over the centuries in spontaneous settlement. In Latin America, there is a lack of clear titles and of clearly demarcated property boundaries. Since the farmer is planning to move in a few years, and since he has no property interest in the land, he has no inclination to improve it.

The use of fire by European controlled or influenced forestry services and commercial grazers is at a higher technological level than that by swidden cultivators and nomadic herders. Initially they attempted to prevent all fires by applying repressive measures copied from Europe. The results were unsatisfactory. Now it is recognized that it is necessary to develop suitable burning programs that are potentially capable of providing for durable watershed conservation, forest production, or high quality grazing (Guilloteau, 1957). The literature is replete with reports of experimentation on the time of burning, the immediate effects on the vegetation and soil, and the long term ecological results (Botha, 1945; Phillips, 1965; Rattray, 1964; et al.). The evidence shows the desirability that burning at this technological level continue, provided that adequate protection is provided to prevent escape of the fire.

What investment does the Latin American farmer make in the land? Watters (1965) has shown that the labor of the Venezuelan farmer and his family amounts to almost 90 per cent of his total investment, with tools and seed being the remainder. Yet only 26 to 32 per cent of the average available labor is actually utilized. The intimate interrelationship between the social and economic conditions and the persistent under-employment of labor is well expressed in the following statement:

> The failure of [swidden] cultivators to utilize labour more fully seems to be a consequence of the lack of capital which prevents [them] from planting semi-permanent or permanent crops, the high premium placed on leisure time, and above all the strength of traditional custom and unquestioning adherence to archaic

> methods which underlies the "culture of poverty". Increases in income rarely lead to increases in investment or labour input, but to increase leisure (Watters, 1965).

Although the statement refers to the Venezuelan swidden farmer, there is no question of its applicability to the rest of the tropical world.

3. Cultural Trends

An infinite number of variables, some known and many unknown, have contributed to the cultural mosaic of man's interaction with the diversity of tropical environments. What are the variables that contribute to perpetuating the use of fire? What are those already fostering cultural change, and hence change in the patterns of fire use?

Isolation, be it of swidden cultivators or nomadic pastoralists, promotes the persistence of cultural ways of life, inhibits contact with other cultural patterns, and promotes suspicion and resistance to change. Inasmuch as change would threaten not only economic conditions, but also deeply-ingrained cultural traditions, some of which may be most sacred, it is unlikely that the use of fire among peoples living in primitive isolation will change radically in the next half century.

Paradoxically, as contact between primitive cultures increases, there may be even greater use of fire and more damaging effects from such use. Numerous researchers have expressed deep concern over the effects of population increase, in both number and density, on the forest-fallow cycle of land use. A number of tropical countries are witnessing the expansion of swidden agriculture and the detrimental effects of fire to an even greater extent than in the past. Among such societies, where the rural population lives in a semi-feudal or tribal social and economic status, the impact of improved health and greater longevity--mixed blessings of modern technology--is either increased pressure on the land at the same low subsistence level, or migration from the countryside to the urban centers. In many areas, both phenomena are occurring.

The use of fire as a tool in forest and pasture management is increasing. It appears justified, since at the present time no alternative to fire exists, in terms of ease of use and cost. As commercial exploitation of these resources expands, also under pressure of increasing population, fire use is bound to expand. Fortunately, controlled burning and fire control go hand in hand. Thus devastation from accidental and uncontrolled fires may well decline.

A number of trends are observable in the tropical world that may alter the pattern of fire use. First, the number of dams and reservoirs is increasing. The need for watershed protection to reduce storm runoff, prevent excessive silting, and promote rainfall infiltration has been recognized. Second, need for timber from the tropical forests is increasing, both for domestic purposes and for export. Recognition by governments of the value of forest resources should facilitate the introduction of curbs on swidden cultivation, increase the use of control burning, and accelerate the planting of valuable species. Third, the rise of nationalism in the tropical world will lead to a greater consciousness of territorial integrity, the demarcation of boundaries and the extension of transportation routes to border areas. As a result the nomadic pastoralists and swidden cultivators who have been migrating across international boundaries without hindrance may be prevented from so doing. Fourth, the development of property rights in land, the expansion of cadastral mapping, and the granting of land titles will make it possible for small farmers to improve their land, and in so doing, develop changes in attitude. Fifth, improvements in transportation facilities will make it possible to introduce cash crops, commercial grazing and dairying to areas previously self-sufficient.

In all likelihood there will never be complete abolition of fire in the tropical world. Nevertheless, attempts have been made to transform the ways of life of the inhabitants so as to make burning less necessary. Planned settlement schemes, such as the <u>paysannats indigènes</u> in Congo (Léopoldville), the Native Land Husbandry Act settlements in Southern Rhodesia, and the activities of the Instituto Agrario Nacional in Venezuela introduce former swidden farmers to fertilizers and new techniques on permanently cultivated land. Various other measures have been suggested, such as non-inflammable forest belts between clearings, clearing on the contour, mixed farming (Pelzer, 1945), tree crops, dairying, commercial grazing (Watters, 1965), and irrigated rice cultivation (Gourou, 1958).

D. Conclusions

Man's activities have made a tremendous impact on the natural features of the tropical world. As a result of repeated burning, vast areas of tropical forest have been altered, an unknown portion permanently. Due to man's proclivity to select the savanna/forest boundary for his swidden cultivation, the forest has retreated, and many authorities question whether much of the humid broadleaf evergreen forest is not in fact mature second growth. Increase in runoff and soil erosion in many tropical areas has been documented in detail. Furthermore, river flows are known to have become much more fluctuating than in the past, particularly for parts of Africa and Asia.

The complexity of the problem is evident when it is realized that it is not possible to separate the cultural environment from the physical environment. Basic to the use of fire by swidden cultivators and pastoral peoples, for example, are the physical characteristics of the soil and vegetation. If tropical soils were of higher natural fertility, the necessity for the farmer to shift his swidden plot would not be present. The pastoralist burns pastures for many reasons, but they include recognition that he needs to remove old grasses prior to new growth, and that fire sustains grasses in areas that normally would support brush and woodland.

Yet these physical factors do not control man's use of the land. Equally important is the level of cultural development, in which the basic conservatism of man-land relationships all too often has retarded the acquisition of new technical skills and has magnified problems. Swidden cultivators and nomadic pastoralists long had developed a stable relationship with the land, dependent on low numbers of population per unit of land area. The impact of modern socio-economic values and technology upset the old balance between man and land. A major question, becoming increasingly more pressing, is what are the studies necessary to insure sound planning and stable future development at new economic levels of productivity between man and land, yet at the same time reduce the adverse effects of fire. More detailed understanding of the relation of cultural factors to the use of fire is needed. Selected examples of possible future studies that would contribute to the planning process are:

1) field studies in tropical regions to determine the spatial extent of burning and to gain more precise knowledge of changes that are taking place;
2) studies of the communication of information and the diffusion of change in preliterate societies, including the development of models;
3) studies of the psychopathology and sociology of pyromania and incendiarism;
4) studies on planning of fire reporting and fire control systems, with emphasis on the rational planning of facilities, personnel, methods, and objectives;
5) studies on the development and utilization of chemical and biological agents to fireproof susceptible areas, such as lands alongside roads, railroads, encampments, and settlements;

6) studies on the feasibility of remote sensing of potential combustibility by air and satellite-borne instruments;

7) studies to develop photo interpretation keys, automated photo interpretation, and computerized map compilation for tropical areas subject to burning.

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CHAPTER V

INCIDENCE AND DISTRIBUTION OF FIRE

A. Introduction

The range of occurrence and the extent of fire's effects on the physical and cultural environment have been examined in detail both from a topical viewpoint and for local areas. Equally as important are the range of occurrence, or incidence, of fire and its distribution througnout the tropical world. Certain limitations make them difficult to analyze, however. The incidence and distribution depend on a very large number of incompletely understood variables. Observations of burning vary according to date and place; therefore references to unpredictable natural or accidental fires are statistically of little value. Man-set fires, on the other hand, follow definite patterns adjusted to climatic seasons, combustibility of the environment, agricultural calendars, and religious beliefs and practices. Because references to cultural use of fire are numerous, and the climatic dry seasons and major vegetation formations are known, it is possible to present them cartographically. Consequently, in what is believed to be a first attempt, the relationships between burning, the climate, and the natural vegetation have been shown on maps of Africa, South America, Central America, South and Southeast Asia, and Southeast Asia and Northern Australia. Preceding the analyses of the maps is a discussion of the incidence and distribution of fires in terms of their cause, their frequency, and their relative significance.

B. Causes of Fire

1. Fires Due to Natural Causes

Over the centuries, man's use of fire has spread

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Controlled fires also may be set for control burning, that is, fire used as a tool to modify forest or range so as to enhance commercial exploitation. In the latter case measures employed in controlling the fire are advanced, often utilizing modern fire-fighting equipment.

The fires of swidden cultivators are in most cases controlled set fires. The area of felled forest to be used for a swidden site is usually surrounded by forest of low combustibility which acts as a green firebreak. Fires even those untended, dampen-down quickly at night in tropical rainy (Af) and monsoon (Am) climates. In dry forest formations, swidden plots frequently are aligned along the forest-savanna boundary. The grassland affords ease of movement, while forest soils are more fertile and easily cultivated. In such sites, and as population increases, the forest may become wooded savanna. The danger of fire escaping to the savannas becomes critical. Various other means of control by native peoples have been referred to in Chapter IV.

The humid tall forest environment and the forest-savanna mosaic are the most important places where swidden cultivation is found, although doubtless it is also practiced in the more wooded parts of the savanna environment (see Chapter III). It has been estimated that 36 million square kilometers are under swidden cultivation. Of these, perhaps 3 to 6 million are burned each year (see Chapter IV).

Burning with modern protective measures does not completely coincide areally with the use of control burning employed to prevent excessive accumulation of fuels. Gammon (1962) has referred to the burning of veld with inadequate precautions against the escape of fire, and to the neglect of precautionary measures such as fireguards. Nevertheless the use of controlled burning has become a common feature of pasture and forest management in Africa, India, Thailand, Burma, and Australia. The areal significance of modern controlled burning is greatest in Africa and Australia but it still is far less than swidden cultivation.

b. Uncontrolled Set Fires.--Uncontrolled set fires are the largest single group of causes of fires in the tropical forests and grasslands. Included as uncontrolled are fires accidentally out of control, fires set by aboriginals and left untended and fires set for the sheer pleasure of seeing flames sweep across the countryside. Additional causes of uncontrolled fires are hunters and honey gatherers, fires set by pastoral peoples to improve forage or to remove pests and predators, pyromania, and fires used to harass enemy peoples. It should be noted that numerous researchers believe that more recognition should be given to pyromania as a cause (Richards, 1964; Phillips, 1965; Boughey, 1963). Accidental fires, such as from steam locomotives, tractor exhausts, smoldering matches and cigarette ends, are widespread and their geographic distribution coincides with lines of communication, many of which are passable only during the dry season and therefore bear heavy traffic. The change in incidence of fire in remote area opened recently by a road has received comment by numerous authors.

The world-wide significance of uncontrolled set fires and accidental fires is difficult to assess. In the few places where adequate records are available, they refer primarily to forest reserves and plantations, rather than to wild lands or grasslands. It may be helpful to attempt a qualitative assessment of their importance on the basis of the literature. In terms of the area burned, pastoral activity is the leading cause, followed by hunting and gathering, and pest and disease control. These types of fires are found mostly among the pastoral peoples and swidden cultivators of the forest-savanna mosaic and savanna environments. Escape of fire from controlled burning is a frequent occurrence in areas where this technique is employed, such as in the pine, acacia, and eucalypt plantations of southern and eastern Africa and Australia. It is also common in swidden cultivation. Tribal warfare and pyromania may have a great impact locally, but they appear to be of less importance in terms of world distribution.

C. The Geographic Distribution of Burning

The areal distribution of burning is shown on the maps of Sub-Saharan Africa, Tropical Latin America, South and Southeast Asia, and Australia that accompany this chapter. The incidence of burning is related to major types of vegetation and the climatic dry season. The vegetation associations are based largely on physiognomy; they also take into account physiography, climate, and location. Circular symbols show the occurrence of a climatic dry season determined by the empirical method employed by Bagnouls and Gaussen (see Chapter III). A circular diagram divided into twelve parts represents the year. Analogous to the clock, each month represents one hour (Fig. 17). The dry season is shown as a stippled sector. The period of burning is shown by a wedge-shaped sector symbol, whose radius is slightly larger than the circle's. A dashed circle indicates that burning is not confined to one season, but takes place whenever a few days of dry weather permit. In all cases the presence of the burning symbol is based on specific references in the literature to the time of burning. For circles

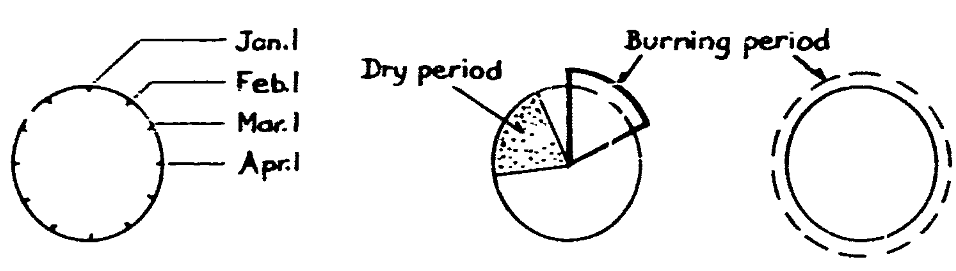


Fig. 17. Climatic and Burning Symbols used on Maps.

without the burning symbol burning may be possible and customary, but precise information was not found regarding its time of occurrence. Thus the various vegetative patterns and symbols presented on maps indicate the geographic distribution of burning, and permit comparisons to be made that are not otherwise possible.

The major contribution of the maps lies in their depiction of the interrelations of the vegetation, climatic dry season, and cultural habit of burning. But while the vegetation is shown by extensive areal patterns, the climatic dry season (an areal phenomenon) and burning season (a point phenomenon) are shown by point symbols. Undue emphasis should not be given to the vegetation patterns, since no such bias is intended. Obviously all three phenomena are highly important.

For the map of Africa, the classification and distribution of vegetation types is based on Aubréville, et al. (1958), with additional guidance from Phillips, (1965) and Rattray, (1960). The categories used on the other maps refer to climax vegetation in most cases. Since data comparable to that on Africa are not available, the vegetation categories were derived from the resources of the maps in Bartholomew's Advanced Atlas (1950), modified by information from maps and certain additional sources (Waibel, 1949; James, 1950; and the Map Division, Library of Congress).

The validity of the Bagnouls and Gaussen system has been evaluated (see Chapter III). Rainfall is subject to extreme variability from year to year in most areas, in date of seasonal onset, total amount, and date of termination. The burning symbol implies a cultural predilection for burning, not always with reference to the combustibility of the vegetation. Its accuracy depends on the reports of anthropologists, geographers, travelers, government officers, and others.

The reliability of the maps is contingent on the validity of sources. Every effort was made to assure that the utilization of the sources was accurate. However, it should be understood that the maps are "first approximations," whose chief contribution is to depict the overall pattern of burning. It is believed that they are a first attempt to combine on a single display the three factors that most influence the patterns of burning in the tropical world. Their value lies in the possibility that the patterns shown on them will stimulate further detailed research to describe and explain the distribution and changes in the use of fire.

1. Sub-Saharan Africa and Madagascar

The geographic distribution of burning in Africa and Madagascar is depicted on three map sheets (Maps 5, 6, and 7). Ten vegetation formations provide an indication of potential fuels, while the symbols indicate the correlation, if any, between climate and probable period of burning. The maps will be analyzed in terms of selected examples within broad groupings of natural vegetation and climate.

The maps indicate that burning is closely related to cultural traditions which are derived from centuries of interaction with the physical environment. The cultural factor is pronounced in those areas where the climate has no ecologically dry period (a month whose average precipitation is less than 25 mm.) and tall forest comprises the major vegetation association. Thus, in the Congo Basin, westward along the Gulf of Guinea, and eastward into East Africa, the burning symbols reveal a surprising diversity considering the overall uniformity of the environment. For example, at Lodja, Congo (Léopoldville) (Sta. 78), burning may occur at any time, while nearby it occurs in July and August at Port Francqui (Sta. 77), September and October at Kindu (Sta. 80), or December and January at Stanleyville (Sta. 75). In Cameroon burning takes place at Ambam (Sta. 38) in both the wet and dry seasons. In the highlands of

East Africa Usumbura, Burundi (Sta 84) and Bukavu (Sta. 81) across the border in Congo (Léopoldville) experience similar dry seasons, but burning takes place at opposite times of the year The explanation of these anomalies is that burning in the forested environment depends largely on human action in felling or killing the trees, rather than on the dry season. The cultural basis of this diversity is attested by Maps 3 and 4 (Chapter IV) which substantiates assertions of numerous writers that there is no significant climatic factor controlling time of burning in tropical rainy (Af) climatic areas supporting rainforest and humid montane forest.

Peripheral to the Congo Basin and the Guinea Coast, transition occurs in both climate and natural vegetation. Although no distinct dry season may occur, one to three months may be ecologically dry Shifting cultivation has degraded the tall, semideciduous forest so that forest and grass or brush covered abandoned clearings coexist as a mosaic. The period of burning in the forest-savanna mosaic reflects to a greater degree the influence of a drier season In this transitional zone south of the Congo Basin, burning takes place at the end of the dry season and possibly extending into the period of first rains. Topographic relief appears to exercise little direct influence, as indicated by Kabalo, Congo (Léopoldville) (Sta. 82) and Brazzaville, Congo (Brazzaville) (Sta. 95) In Nigeria, however, there are distinct differences in the periods of burning at Enugu (Sta 32) and Ibadan (Sta 31) Both stations are located in the forest savanna mosaic They have almost identical dry periods both as to time of occurrence and duration. A possible explanation is that adjacent grasslands are fired during the dry season whereas shifting cultivators clear and burn either in December and January, or in June or July Although specific references to burning could not be plotted for other stations in the West

African forest-savanna mosaic, it is known that burning early in the dry season is the official government forest policy.

Similarly, forest-savanna mosaic is found along the southeast coast of Africa and western coast of Madagascar. Indirect evidence suggests that the period of burning in these areas is during the last shower weather of onset of the dry period and extending well into the dry season. Because no specific references to the burning period were available, the sector symbol is not shown for stations in these areas.

Savannas of various types are very widespread in Africa, and therefore the symbols depict a number of variations of wet and dry tropical climate. At most stations, however, the dry season is well-defined, with ecologically dry months varying from more than three to more than six. The protracted period of desication is highly conducive to fire and it is so common that specific references to burning are surprisingly few. Generally, references to fire in the literature are so vague, that one may imagine that a whole area goes up in flames each year. Inspite of the widespread occurrence of fire, however, the period of burning at most stations for which information is available rarely coincides entirely with the dry period. It is for this reason, that generalized references suggesting fire during the entire season were not evaluated in the preparation of the maps.

There is little doubt that burning coincides with the dry season in a general way, but it also reflects both primitive cultural practices and the burning policies of technologically advanced people. For example, at Lomé, Togo (Sta. 25) and Tibati, Cameroon (Sta. 153) burning occurs early in the dry season, and may well reflect policies designed to use fire to reduce fuel accumulation in wooded savanna to promote regeneration of woodlands. Also, primitive cultivators frequently burn early preparatory to gathering and hunting expeditions in adjacent forests. Mid-dry season burning occurs at Bouca, Central African Republic, (Sta. 41) while at Wau, Sudan (Sta. 53) burning occurs in any season. Even though both stations experience a similar dry season, with a slightly longer period at Wau, the difference in burning may be related to pastoral activities at the latter station rather than significant changes in the vegetation and climate. In the eastern highlands of Africa, north and east of Lake Victoria, it is clear that burning occurs in relation to agricultural calendars of shifting and sedentary farmers rather than solely to climate, as evidenced by the periods shown at Juba, Sudan (Sta. 53), Kitgum, Uganda (Sta. 61) and Nakuru, Kenya (Sta. 65). Part of the reason for burning extending one or more months into what appears to be a rainy season is that there occurs a period of brief showers prior to onset of heavy rains.

In wooded savannas south of the Congo Basin the preferred burning period is at the end of the dry season or during first showers of the rainy season. Here too the period of burning reflects policies based on ecological studies of the effects of fires on grasslands and wooded areas. For a number of reasons, burning late in the dry season is both of frequent occurrence and the recommended practice (see stations 111, 113, 110, 107, 109 and 106).

As mentioned earlier, specific references to burning in the open grasslands both north and south of the equator are very few. Part of the reason is that rainfall variability is greater in the drier climates associated with the geographic distribution of these grasslands, than in the wooded savanna areas. Pastoral activities, both nomadic and commercial, occur as well as commercial irrigation and dry farm agriculture along with primitive cropping. Because of the diversity of land uses, it is probable that some burning is taking place within any area during most of the dry season. Examples would be burning of commercial cotton stubble following harvest, later burning of pasture grasses by nomadic herdsmen who will return to a new flush of grass after the first rains, burning late in the dry season by commercial graziers for the same reason, and clearing of wooded areas for swidden agriculture by primitive cultivators. To the uninitiated it may well seem that burning occurs everywhere during the dry season. In a sense this is true; however, it should be made clear that burning is not necessarily chaotic or random. One should also note that certain areas are sparsely populated, and hence burning is sporadic.

2. Latin America

The distribution of major types of vegetation and climate in Latin America is a complex pattern in which the factor of relief is very significant (Maps 7, 8 and 9). Major relief features, such as the Guiana and Brazilian Highlands, Andean Cordillera and the Central American mountains and Antillian Arch, all lie more or less transverse to prevailing seasonal winds. Consequently, orographic uplift and lee-slope rainshadow effects give rise to sharp differences in annual rainfall and seasonal distribution in a distance of a few kilometers in many areas. Vegetation types and their geographic distribution not only reflect differences in climate, but also are ecologically adjusted to new and old landscapes with young and senile soils. Centuries of burning, first by Amerinds, and later by European settlers, have completely altered the vegetation in many areas.

In Central America and the Islands burning, if and when it occurs, coincides with the drier or dry season occurring during the first months of the calendar year. Notable differences are evident for the stations shown, where the effects of topographic relief and orientation to prevailing winds are important factors. Although burning is widespread throughout Central America, it is practiced for a variety of reasons. Along the Pacific coast of the isthmian link between Mexico and South America, a pronounced dry season occurs; burning, particularly in pastoral areas, takes place at the end of the dry season. Although no specific data was available during the preparation of the map, it is known that shifting cultivators and sedentary farmers burn the subtropical montane forests. At San Andres Tuxtla, Mexico (Sta. 3) burning of the forest occurs at the end of a brief dry season extending from March to May. Merida, Mexico (Sta. 5) experiences a semi-arid climate, and the burning period is from March to May. At Belize, British Honduras (Sta. 9) burning takes place, largely by Maya Indians, as soon as the rains lessen, since the drier period is brief and frequently interspersed with showers. That burning occurs even in perhumid climates is evident in Puerto Cabezas (Sta. 12) and Bluefields (Sta. 13), Nicaragua, whose annual precipitation totals exceed 3,000 mm. and 4,000 mm. respectively. Although data is not available for many stations, burning in the central highlands of Central America and in remote parts of Hispaniola is widespread.

In South America, burning that is done by Amerinds is insignificant compared to the areas burned by the descendents of the European settlers. So ubiquitous is fire, that very few specific references describe in detail the times or purpose for burning. In many cases, references in which burning is mentioned are technical pamphlets or propaganda aimed at farmers. In either case, the audience of the author is presumed to be fully informed on local and regional agricultural practices in which fire is used. This is most unfortunate, because only 11 stations, located in diverse types of environment, could be plotted with a burning sector symbol. Conclusions concerning burning, therefore, must be drawn with care. At St. Ignatius (Sta. 39) and Tumeremo (Sta. 34), the period of burning refers to shifting cultivation by Caribs in the Rupununi district of Guyana. At San Fernando de Apure, Venezuela (Sta. 27) the reference is to the practices of the Yaruro Indians. Rather interesting is the fact that burning by the Indians, both in Venezuela and Guyana, coincides with the general practice of burning of the savannas at the end of the dry season throughout much of tropical South America. The uniformity and predictability of this practice is due mainly to the prevalence of extensive grazing and primitive shifting cultivation. Control burning in forests and advanced pasture management techniques, which might suggest the use of fire at other seasons, have made little headway.

3. South Asia, Southeast Asia, and Northern Australia

Nine major vegetation types are found on the maps of Asia and Northern Australia (Maps 10 and 11). Their geographical distribution is exceedingly complex, due to the influence of the monsoon circulation, the insular and peninsular shape of the land, the irregular topography, and the area's great latitudinal extent. It is important to bear in mind that, particularly in Southeast and South Asia, centuries of occupation under systems of intensive subsistence agriculture, swidden farming, plantation agriculture, and logging have largely transformed the original vegetation into agricultural land, second growth forest, and savanna. The climax vegetation persists only where the impress of man has been slight. Therefore caution should be used in assessing the interrelation of vegetation, climatic dry season, and burning. The cultural practices of the human society inhabiting an area may be to burn at certain seasons, but due to the fact that the forest has been degraded, and the abandoned clearings are overgrown with Imperata cylindrica, uncontrolled "accidental" fires can sweep through them practically anytime.

The pattern of burning in the forested environment, which includes the montane forest and grassland, the tropical rainforest, and the moist semideciduous forest, epitomizes the complexity resulting from varied physical conditions and diverse cultural practices. Numerous stations in the equatorial zone, extending from Colombo, Ceylon (Sta. 1) eastward to Madang, New Guinea (Sta. 65), have no climatic dry season, although brief periods of lower rainfall usually occur. The season of burning is extremely varied in this zone, however. Burning occurs all year in Madang, New Guinea and Buntok, Borneo, Indonesia (Sta. 40). Dual burning seasons are found in Jesselton, Sabah (Sta. 32) and in Kuala Pana, Malaya (Sta. 29). This indicates that advantage is taken of "breaks" in the rains that occur during the transitional period when the monsoon wind circulation is changing direction. Most of the remaining stations that have no dry season burn for two or three months during the period from May to October; e.g. the following locations in Indonesia: Manado (Sta. 44), Pontianak (Sta. 39), Lahat (Sta. 35), and Padang (Sta. 34). It should be borne in mind that orographic rainfall and rain shadows give rise to pronounced contrasts within the space of a few kilometers.

The islands of Java, Sulawesi, and Timor have dry seasons of up to seven months duration, although the vegetation remains forest. Burning occurs during the dry season, as in the Sulawesi locations of Kendari (Sta. 43) and Makassar (Sta. 42). In northern Australia the climatic dry seasons are considerably longer, yet tropical rainforest persists along the coast. The burning season is longer than the dry season at Crooktown (Sta. 61) and Darwin (Sta. 57). This indicates that burning before the last rains have ceased may be used to prevent accumulation of fuel in forests, while burning late in the dry season may be used as part of a program of pasture management.

The forested environment in the Philippines, mainland Southeast Asia, and South Asia has a climatic dry season that lasts up to eight months, and is associated with the "winter monsoon" period. For much of this area the use of fire is associated with swidden cultivation and occasional hunting and pyromania in the uplands and hills. Most of the level land and river valleys are in permanent paddy rice cultivation, where burning is rare, except for burning of rice stubble where it is not fed to animals. In India representative locations in the Central Indian Hills are at Bhopal (Sta. 8), Raipur (Sta. 9), Ranchi (Sta. 11), and near Calcutta (Sta. 12). Comilla, East Pakistan (Sta. 13), Toungoo, Burma (Sta. 16), and Luang Prabang, Laos (Sta. 21) ar similar. The burning takes place near the end of the d y season, after the forest has been felled and allowed to d A noteworthy exception is near Poona, India (Sta.7), w the characteristic early dry season burning pattern u for control burning in teak forests.

The forest-savanna mosaic includes the dry semi-de ous forest in North India and eastern Java, and the se rid woodland and thorn shrub in South India, the Dry Zon of Burma, and in Thailand and Indochina. These areas have long been under intensive cultivation. Little fuel is available to burn after the population has cut brush for firewood and the animals have grazed and browsed. Where burning does take place it is in the dry season, as shown by Bangalore, India (Sta. 5), Mandalay. Burma (Sta. 15), and Surin, Thailand (Sta. 19).

The savanna environment includes open wooded savanna in northern Australia and savanna grassland in northern Australia and New Guinea. The savanna grassland in New Guinea is believed to be due to wet soil conditions in the lowlands, and to swidden cultivation in the interior highlands. Burning has been mentioned in the literature for both locations. In northern Australia burning is used by cattle and sheep raisers in order to secure a flush of green grass. The symbols on the map show very lengthy burning seasons, lasting up to seven months, as in Broome, Australia (Sta. 56). The burning pattern of this area has been illustrated and discussed in Chapter III.

4. Oceania

The island chains of Melanesia, Polynesia, and Micronesia are, with the exception of New Guinea, too small to show vegetation at the map scale selected. Numerous references in the literature describe swidden cultivation and cattle grazing on the Pacific Islands. Many islands have turned from subsistence agriculture to commercial coconut and sugar production, but traditional forms of agriculture persist. Much of the original forest vegetation has been converted by annual burning to grass and bamboo, that regularly catches fire.

D. Distribution of Trends in Burning

The geographic patterns of burning in relation to climate and vegetation have been described and interpreted in this chapter. It must be remembered, however, that in addition to the limitations on the analysis that were referred to earlier, the maps are static. They cannot convey, except in a very limited way, the nature, direction and pace of the changes that are taking place in the incidence and distribution of fire.

What are the trends in the use of fire in the tropical world? What are the differences from place to place in these trends? A partial answer to the first question was presented in Chapter IV. On the basis of a literature survey, the answer to the second question can only be suggested. Field research is required to elicit more precise information.

Man's use of fire in the tropical world is no longer in the stage of "ecological climax", wherein a stable, harmonious relationship to the environment exists. The impact of the West has "set in train a process that has led to rapid changes in the environment, and destroyed the old balance between man and nature" (Watters, 1960, p. 95). Thus the specific conformation of the interrelations of man, land, and fire in any particular area can be seen as stages along a continuum of change. At one end are the areas just emerging from "ecological climax", with relatively little population increase, relatively long periods of forest fallow, and relatively little soil erosion and forest or pasture degradation. The highlands of New Guinea and the interior rainforests of the Amazon Basin are representative of this stage. Near the middle of the continuum are areas in "ecological disequilibrium", in which population growth, changes in value systems, soil erosion, and forest and pasture degradation have created a situation in which shortages of food in the rural areas have led to widespread undernourishment, accelerated deterioration of the land, and migration of rural people to cities in search of food and jobs. Many areas of tropical Africa and Latin America are representative of this stage. At the other end of the continuum, in the stage of "ecological rehabilitation". are areas in which the application of scientific knowledge and techniques has resulted in the use of fire as an instrument of forest and grassland management. Representative of this stage in the continuum are those areas in East Africa, South Africa and Australia where control burning is used, with adequate safeguards against escape of fire and a tested year-by-year plan of fire use.

With this concept of an ecological continuum in mind, it is possible, with the aid of detailed information gained from field work, to establish the position of any area in terms of the amount of progress it has made since "ecological climax". A degree of caution must be used, since a) there is spatial intermixture or interdigitation of areas of differing positions; b) individual areas will occupy either a broad or a narrow segment of the continuum, depending on the scale or level of generalization. It should also be noted that most areas of "ecological rehabilitation" are found where Europeans have settled lands that never passed through "ecological disequilibrium". Indeed, only one case is known where primitive use of fire has been partly modified by the introduction of modern technology. This is the "teak taungya" system first developed in Burma, and now used in India and elsewhere in Southeast Asia (Blanford 1925).

It is not possible to estimate the mean per cent of area burned annually with any reasonable accuracy. The areas that are subject to burning are not necessarily burned, since the cultural factors conducive to burning are so variable. Although these factors are discussed more fully in Chapter IV, it is appropriate to mention them once more.

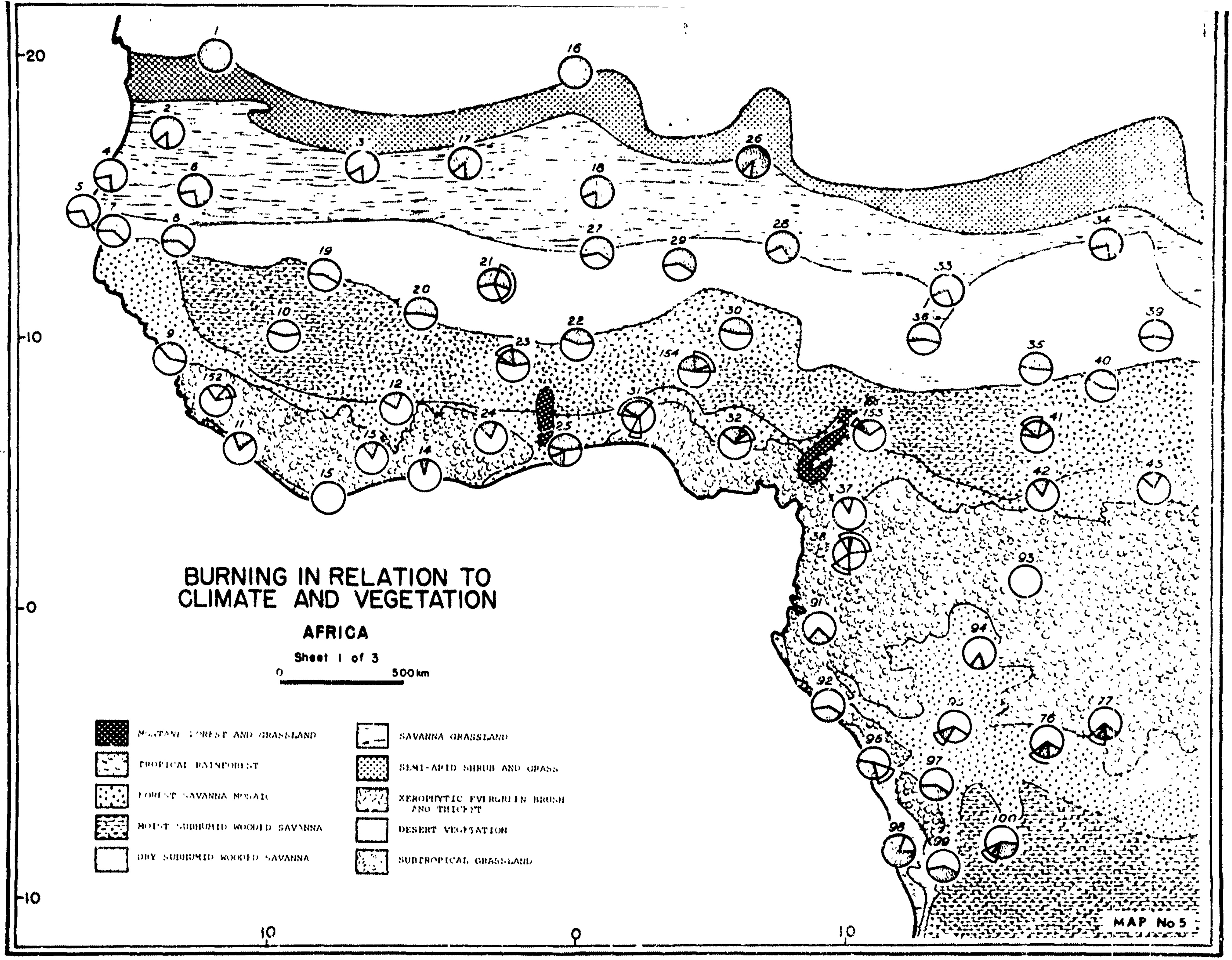
In areas of swidden cultivation the population density varies from 2 to 50 per square kilometer; the length of the forest fallow period may be as short as 5.5 years or as long as over 20 years; the swidden plot may be utilized from one to three years before abandonment; and the area felled may be many times larger than the area burned. In areas of the Forest-Savanna Mosaic the savanna areas are prone to annual burning, while the forest areas are used for swidden cultivation and are only partially cleared and burned. In areas where pastoral nomadism is practiced burning is more predictable than elsewhere, since there the vegetation is naturally combustible during the dry season, and the herders desire a flush of green grass for their cattle. The area burned may be as much as half of the total. In areas that are under advanced forest and pasture management practices using fire, a rotational system is normally used, in which blocks of forest or pasture are burned at suitable intervals of time.

For the foregoing reasons it is evident that an estimate of the percent of area burned would be mere conjecture. The actual per cent depends on the particular combination of physical and cultural circumstances in effect in a particular area at a particular time.

INDEX TO CLIMATIC STATIONS

Map of Africa, Sheet 1

Station Number	
1	Atar, Mauritania
2	Boutilimit, "
3	Nema, "
4	St. Louis, Senegal
5	Dakar, "
6	Matam, "
7	Kaolack, "
8	Tambakounda, "
9	Conakry, Guinea
10	Kankan, "
11	Monrovia, Liberia
12	Bouake, Ivory Coast
13	Gagnoa, "
14	Abidjan, "
15	Tabou, "
16	Tesalit, Mali
17	Tomboctou, Mali
18	Menaka, "
19	Bamako, "
20	Bobo Dioulasso, Upper Volta
21	Ougadougou, "
22	Natitingou, Dahomey
23	Tamale, Ghana
24	Kumasi, "
25	Lomé, Togo
26	Agades, Niger
27	Niamey, "
28	Zinder, "
29	Sokoto, Nigeria
30	Kaduna, "
31	Ibadan, "
32	Enugu, "
33	Fort Lamy, Chad
34	Abecher, "
35	Fort Archambault, Chad
36	Maroua, Cameroon
37	Yaonde, "
38	Ambam, "
39	Birao, Central Afr. Rep.
40	Ndele, "
41	Bouca, "
42	Bangui, "
43	Bangassou, "
76	Kikwit, Congo (Léo.)
77	Port Francqui, Congo (Léo.)
91	Lambarene, Gabon
92	Mayoumba, "
93	Impfondo, Congo (Brazz.)
94	Gambona, "
95	Brazzaville, "
96	Cabinda, Angola & Cabinda
97	Sao Salvador, "
98	Luanda, "
99	Casanha, "
100	Sunginge, "
152	Bo, Sierra Leone
153	Tibati, Cameroon
154	Bida, Nigeria



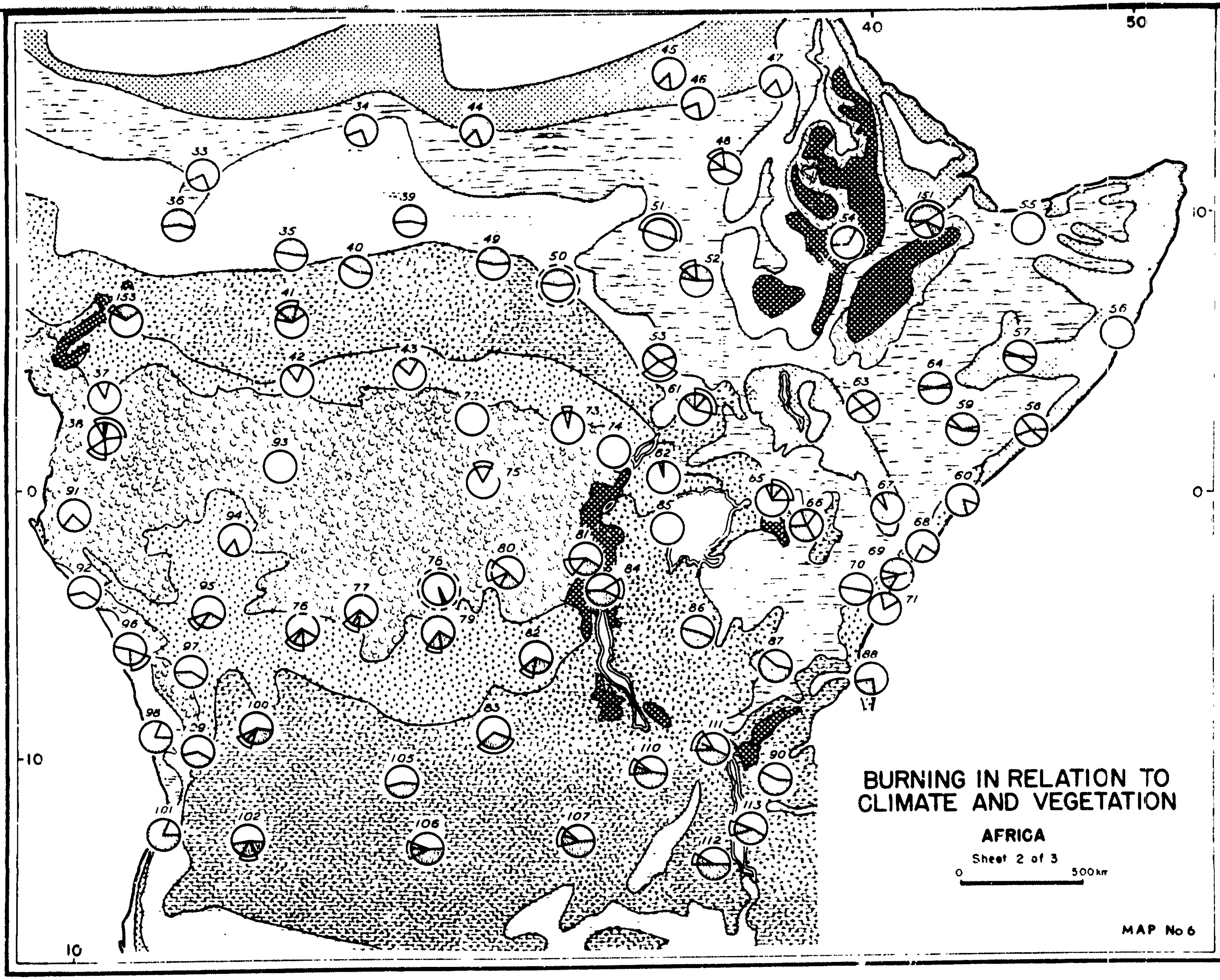
BURNING IN RELATION TO
CLIMATE AND VEGETATION
AFRICA
Sheet 1 of 3
0 500km
MONTANE FOREST AND GRASSLAND
TROPICAL RAINFOREST
FOREST SAVANNA MOSAIC
MOIST SUBHUMID WOODED SAVANNA
DRY SUBHUMID WOODED SAVANNA
SAVANNA GRASSLAND
SEMI-ARID SHRUB AND GRASS
XEROPHYTIC EVERGREEN BRUSH AND THICKET
DESERT VEGETATION
SUBTROPICAL GRASSLAND
MAP No 5

INDEX TO CLIMATIC STATIONS

Map of Africa, Sheet 2

Station Number	Name
33	Fort Lamy, Chad
34	Abecher, "
35	Ft. Archambault, Chad
36	Marua, Cameroon
37	Yaonde, "
38	Ambam
39	Birao, Cent. Afr. Rep.
40	Ndele, "
41	Bouca, "
42	Bangui, "
43	Bangassou, "
44	El Fasher, Sudan
45	Khartoum, "
46	Wad Medani, "
47	Kassala, "
48	Roseires, "
49	Raga, "
50	Wau, "
51	Malakal, "
52	Akobo, "
53	Juba, "
54	Addis Ababa, Ethiopia
55	Burao, Somalia
56	Obbia, "
57	Belet-Uen, Somalia
58	Afgoi, "
59	Bardera, "
60	Chisimaio, "
61	Kitgum, Uganda
62	Mubende, "
63	Moyale, Kenya
64	Mandera, "
65	Nakuru, "
66	Nairobi, "
67	Garissa, "
68	Lamu, "
69	Malindi, "
70	Voi, "
71	Mombasa, "

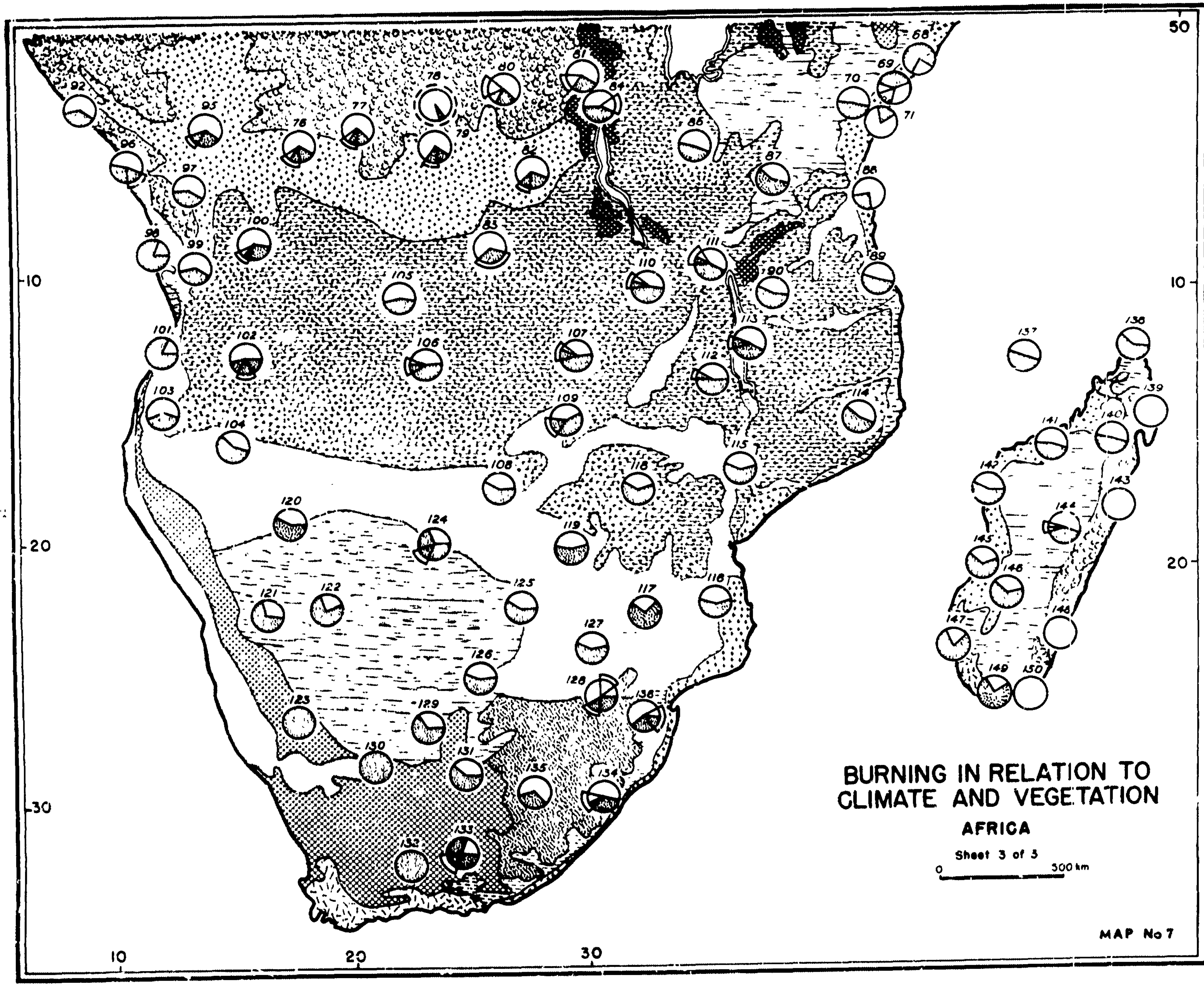
Station Number	Name
72	Buta, Congo (Léopoldville)
73	Paulis, "
74	Irumu "
75	Stanleyville, "
76	Kikwit, "
77	Port Francqui, "
78	Lodja, "
79	Lusambo, "
80	Kindu, "
81	Bukavu, "
83	Kamina, "
84	Usumbura, Burundi
85	Bukoba, Tanzania
86	Tabora, "
87	Dodoma, "
88	Dar es Salaam, Tanzania
90	Songea, "
91	Lambarene, Gabon
92	Mayoumba, "
93	Impfondo, Congo (Brazzaville)
94	Gambona, "
95	Brazzaville, "
96	Cabinda, Angola & Cabinda
97	Sao Salvador, "
98	Luanda, "
99	Casanha, "
100	Sunginge, "
101	Benguela, "
102	Chitembo, "
105	Villa Teixera, "
106	Balovale, Zambia
107	Ndola, "
110	Kasama, "
111	Karonga, Malawi
112	Lilongwe, "
113	Maniamba, Mozambique
151	Dire Dava, Ethiopia


BURNING IN RELATION TO
CLIMATE AND VEGETATION
AFRICA
Sheet 2 of 3
0
500km
MAP No 6

INDEX TO CLIMATIC STATIONS

Map of Africa, Sheet 3

Station Number			
68	Lamu, Kenya	114	Nampula, Mozambique
69	Malindi, Kenya	115	Chemba, "
70	Voi, "	116	Mabote, "
71	Mombasa, "	117	Pafuri, "
76	Kikwit, Congo (Léo.)	118	Salisbury, Rhodesia
77	Port Francqui, "	119	Bulawayo, "
78	Lodja, "	120	Tsumeb, Southwest Africa
79	Lusambo, "	121	Windhoek, "
80	Kindu, "	122	Gobabis, "
81	Bukavu, "	123	Keetsmanshoop, "
82	Kabalo, "	124	Maun, Bechuanaland
83	Kamina, "	125	Serowe, "
84	Usumbura, Burundi	126	Kanye, "
86	Tabora, Tanzania	127	Pietersburg, South Africa
87	Dodoma, "	128	Carolina, "
88	Dar es Dalaam, Tanzania	129	Kuruman, "
89	Lindi, "	130	Upington, "
90	Songea, "	131	Kimberley, "
92	Mayoumba, Gabon	132	Beaufort West, "
95	Brazzaville, Congo (Brazz.)	133	Graff Reinet, "
96	Cabinda, Angola & Cabinda	134	Pietermaritzburg, "
97	Sao Salvador, "	135	Masaru, Basutoland
98	Luanda, "	136	Stegi, Swaziland
99	Casanha, "	137	Dzaoudzi, Malagasy
100	Sunginge, "	138	Diego Suarez, Malagasy
101	Benguela, "	139	Antalaha, "
102	Chitembo, "	140	Mandritsara, "
103	Sa'da Bandeira, "	141	Marovoay, "
104	Mupa, "	142	Maintirano, "
105	Villa Teixera, "	143	Tamtave, "
106	Balovale, Zambia	144	Tananarive, "
107	Ndola, "	145	Morondava, "
108	Livingstone, Zambia	146	Beroroha, "
109	Lusaka, "	147	Tulear, "
110	Kasama, "	148	Farafagana, Malagasy
111	Karonga, Malawi	149	Tsihombe, "
112	Lilongwe, "	150	Fort Dauphin, "
113	Maniamba, Mozambique		



BURNING IN RELATION TO CLIMATE AND VEGETATION

AFRICA

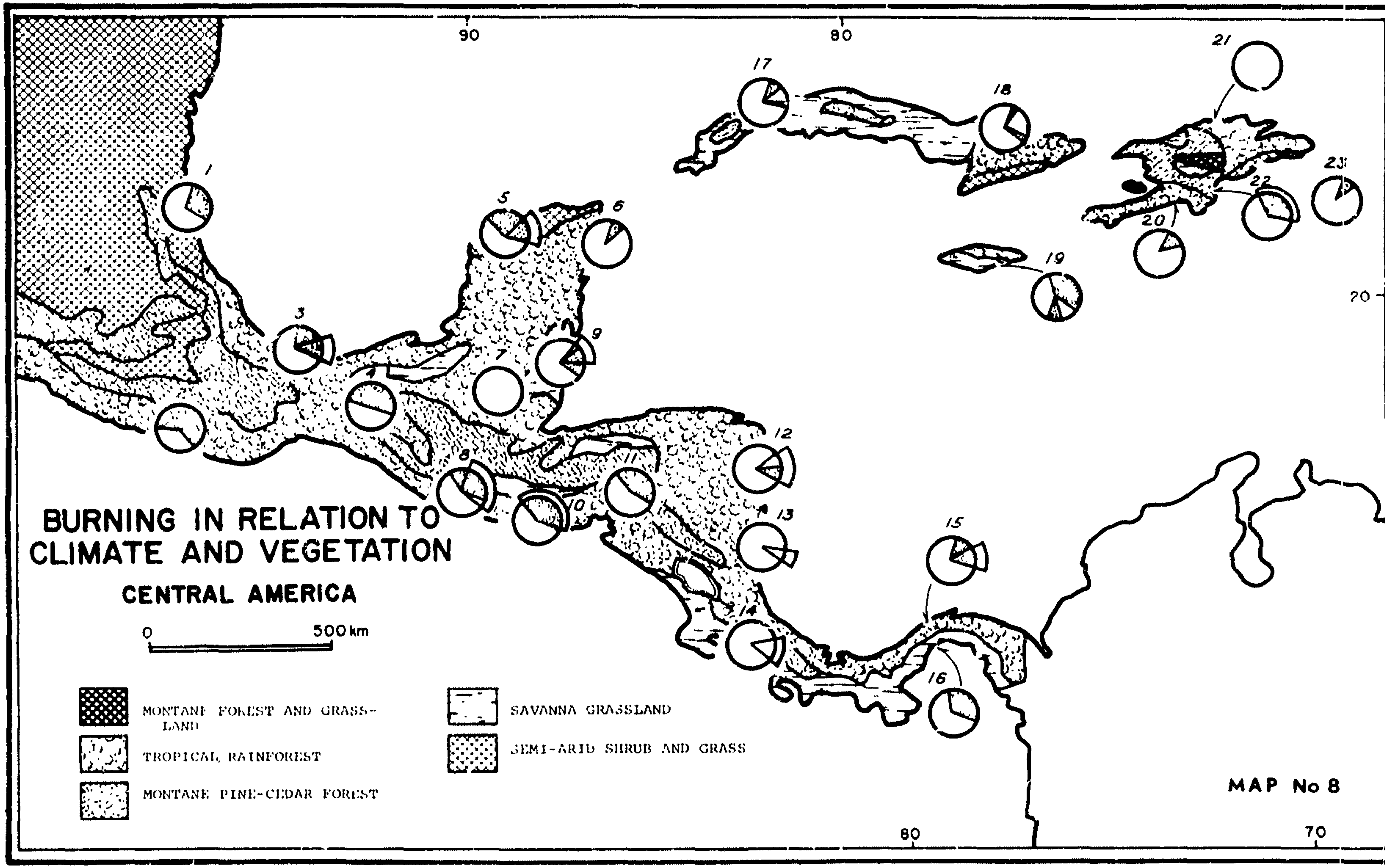
Sheet 3 of 3

0 500 km

INDEX TO CLIMATIC STATIONS

Map of Central America

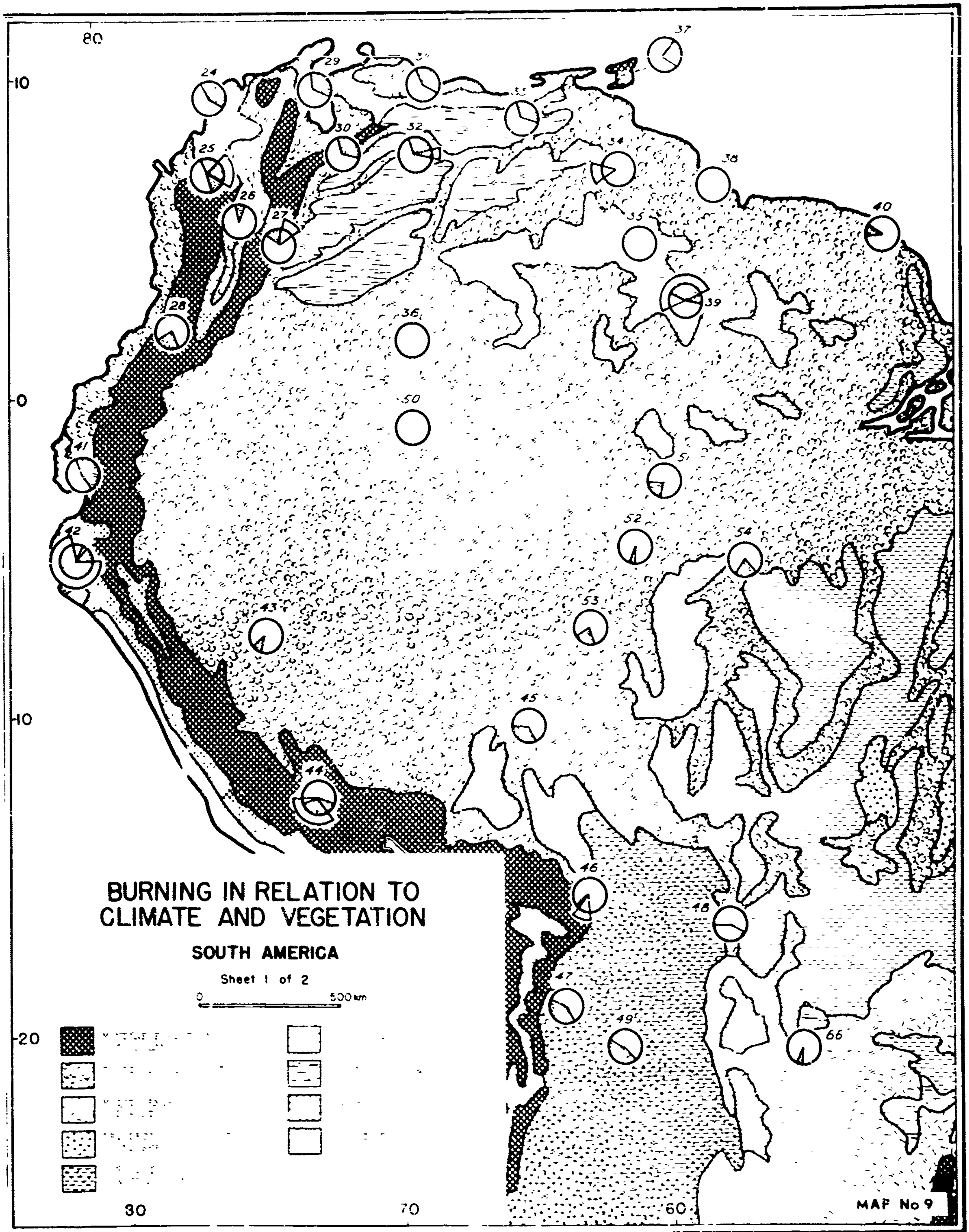
Station Number	Name of Station	Country
1	Tampico	Mexico
2	Ometepec	"
3	San Andres Tuxtla	"
4	Tuxtla Gutierrez	"
5	Merida	"
6	Cozumel	"
7	Flores	Guatemala
8	Amatitlán	"
9	Belize	British Honduras
10	San Salvador	El Salvador
11	Tegucigalpa	Honduras
12	Puerto Cabezas	Nicaragua
13	Bluefields	"
14	San José	Costa Rica
15	Cristobal	Panama
16	Balboa Heights C.Z.	"
17	Habana	Cuba
18	Gibara	"
19	Kingston	Jamaica
20	Port-au-Prince	Haiti
21	Puerto Plata	Dominican Republic
22	Barahona	"
23	Santo Domingo	"


BURNING IN RELATION TO CLIMATE AND VEGETATION
CENTRAL AMERICA
0
500 km
MONTANE FOREST AND GRASSLAND
TROPICAL RAINFOREST
MONTANE PINE-CEDAR FOREST
SAVANNA GRASSLAND
SEMI-ARID SHRUB AND GRASS
MAP No 8
90
80
70
20
1
3
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23

INDEX TO CLIMATIC STATIONS

Map of South America, Sheet 1

Station Number	Name of Station	Country
24	Cartagena	Colombia
25	Tolu	"
26	Barrancabermeja	"
27	Choconta	"
28	Popayan Florida	"
29	Maracaibo	Venezuela
30	Barinas	"
31	Puerto Cabello	"
32	San Fernando de Apure	"
33	Arajua de Barcelona	"
34	Tumeremo	"
35	Santa Elena	"
36	San Carlos de Rio Negro	"
37	Trinidad	Trinidad & Tobago
38	Georgetown	Guyana
39	St. Ignatius	"
40	Cayenne	French Guiana
41	Guayaquil	Ecuador
42	Piura	Peru
43	Agua Caliente	"
44	Cuzco	"
45	Riberalta	Bolivia
46	Santa Cruz	"
47	Villa Montes	"
48	Puerto Suarez	"
49	Mariscal Estigarribia	Paraguay
50	Sao Gabriel do Rio Negro	Brazil
51	Manaus	"
52	Manicore	"
53	Porto Velho	"
54	Alto Tapajoz	"
66	Bella Vista	"

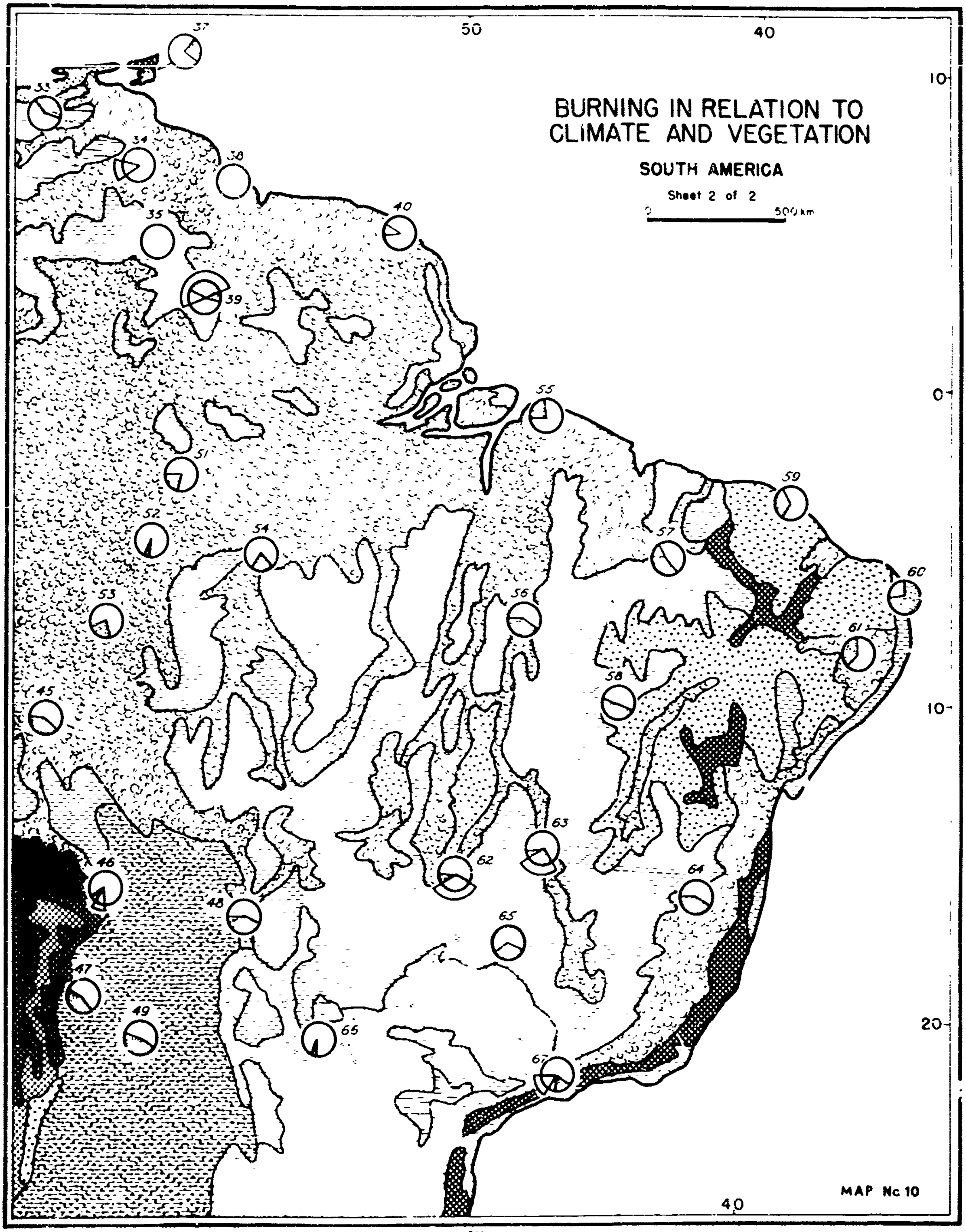


BURNING IN RELATION TO CLIMATE AND VEGETATION
SOUTH AMERICA
Sheet 1 of 2
0
500 km
MAP No 9

INDEX TO CLIMATIC STATIONS

Map of South America, Sheet 2

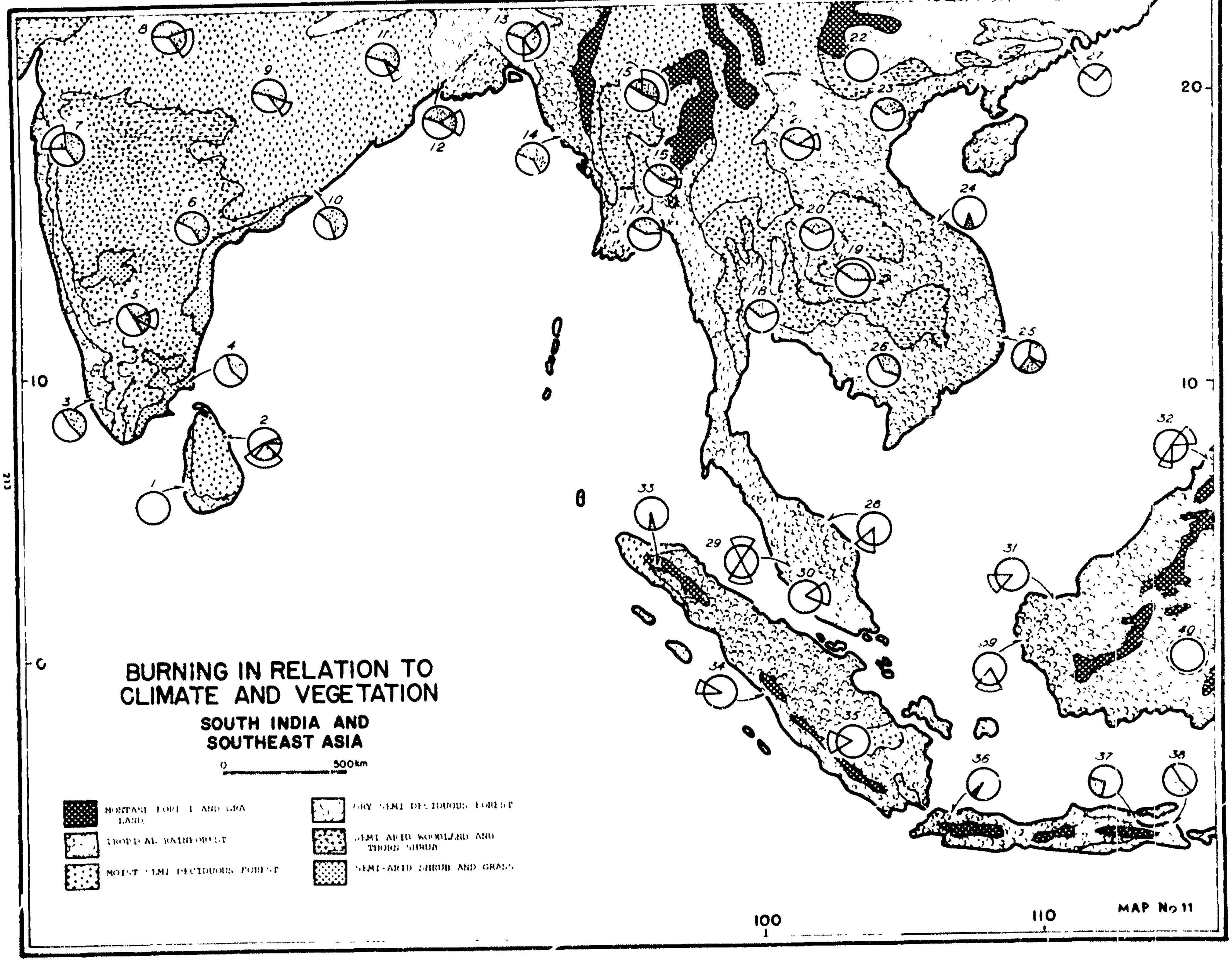
Station Number	Name of Station	Country
33	Aragua de Barcelona	Venezuela
34	Tumeremo	"
35	Santa Elena	"
37	Trinidad	Trinidad & Tobago
38	Georgetown	Guyana
39	St. Ignatius	"
40	Cayenne	French Guiana
45	Riberalta	Bolivia
46	Santa Cruz	"
47	Villa Montes	"
48	Puerto Suarez	"
49	Mariscal Estigarribia	Paraguay
51	Manaus	Brazil
52	Manicore	"
53	Porto Velho	"
54	Alto Tapajoz	"
55	Tracatena	"
56	Carolina	"
57	Terezina	"
58	Santa Rita do Rio Preto	"
59	Mondubim	"
60	Natal	"
61	Pesqueira	"
62	Goias	"
63	Formosa	"
64	Teofilo Otoni	"
65	Araguari	"
66	Bella Vista	"
67	Itajuba	"


BURNING IN RELATION TO CLIMATE AND VEGETATION
SOUTH AMERICA
Sheet 2 of 2
0
500 km
MAP No 10
50
40
10
0
10
20
40

INDEX TO CLIMATIC STATIONS

Map of South India and Southeast Asia

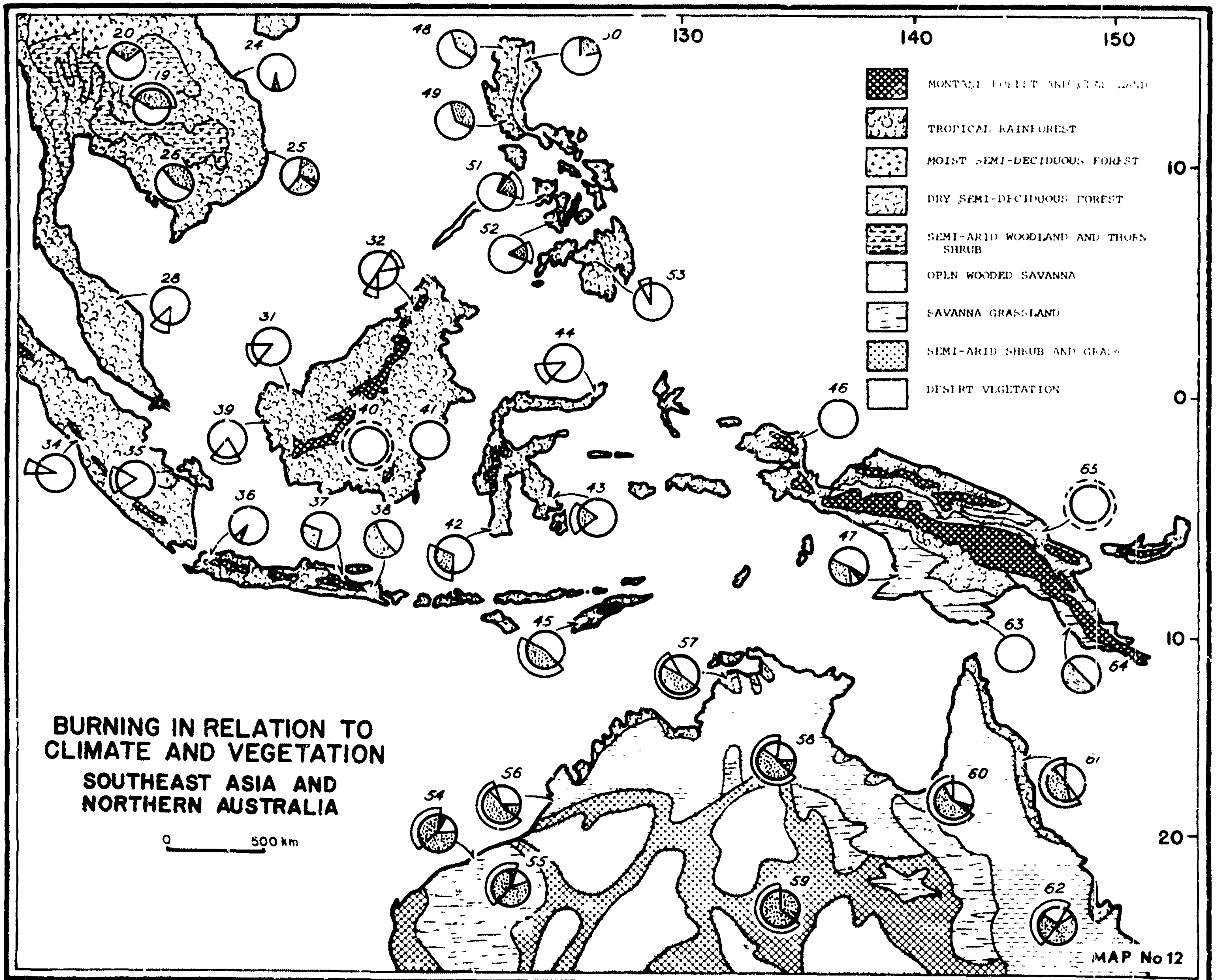
Station Number	Name of Station	Country
1	Colombo	Ceylon
2	Trincomalee	"
3	Cochin	India
4	Negapatam	"
5	Bangalore	"
6	Hyderabad	"
7	Poona	"
8	Bhopal	"
9	Raipur	"
10	Vizianagram	"
11	Ranchi	"
12	Calcutta	"
13	Comilla	Pakistan
14	Akyab	Burma
15	Mandalay	"
16	Toungoo	"
17	Rangoon	"
18	Bangkok	Thailand
19	Surin	"
20	Muang Khon Kaen	"
21	Luang Prabang	Laos
22	Chapa	North Vietnam
23	Hanoi	"
24	Hué	South Vietnam
25	Nhatrang	"
26	Phnom Penh	Cambodia
27	Macau	Macau (Port.)
28	Kota Bharu	Malaysia
29	Kuala Pana	"
30	Kuala Lumpur	"
31	Kuching	"
32	Jesselton	"
33	Takingeun	Indonesia
34	Padang	"
35	Lahat	"
36	Djakarta	"
37	Surabaja	"
38	Assembagus	"
39	Pontianak	"
40	Buntok	"


BURNING IN RELATION TO
CLIMATE AND VEGETATION
SOUTH INDIA AND
SOUTHEAST ASIA
0 500km
TROPICAL RAINFOREST
MOIST SEMI DECIDUOUS FOREST
DRY SEMI DECIDUOUS FOREST
SEMI ARID WOODLAND AND THORN SHRUB
SEMI-ARID SHRUB AND GRASS
MAP No 11

INDEX TO CLIMATIC STATIONS

Map of Southeast Asia and Northern Australia

Station Number	Name of Station	Country
19	Surin	Thailand
20	Muang Khon Kaen	"
24	Hué	South Vietnam
25	Nhatrang	"
26	Phnom Penh	Cambodia
28	Kota Bharu	Malaysia
31	Kuching	"
32	Jesselton	"
34	Padang	Indonesia
35	Lahat	"
36	Djakarta	"
37	Surabaja	"
38	Assembagus	"
39	Pontianak	"
40	Buntok	"
41	Balikpapan	"
42	Makassar	"
43	Kendari	"
44	Manado	"
45	Kupang	"
46	Manokwari	"
47	Mappi	"
48	Laoag	Philippines
49	Manila	"
50	Tuguegarao	"
51	Iloilo	"
52	Dumaguete	"
53	Davao	"
54	Port Hedland, W.A.	Australia
55	Nullagine, W.A.	"
56	Broome, W.A.	"
57	Darwin, N.T.	"
58	Daly Waters, N.T.	"
59	Alice Springs, N.T.	"
60	Croydon, Qld.	"
61	Crooktown, Qld.	"
62	Emerald, Qld.	"
63	Daru, Papua	"
64	Port Moresby, Papua	"
65	Madang, New Guinea	"


BURNING IN RELATION TO
CLIMATE AND VEGETATION
SOUTHEAST ASIA AND
NORTHERN AUSTRALIA
0 500 km
MAP No 12
TROPICAL RAINFOREST
MOIST SEMI-DECIDUOUS FOREST
DRY SEMI-DECIDUOUS FOREST
SEMI-ARID WOODLAND AND THORN SHRUB
OPEN WOODED SAVANNA
SAVANNA GRASSLAND
DESERT VEGETATION
130
150
10
0
10
20

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CHAPTER VI

MILITARY ASPECTS OF FIRE IN TROPICAL FORESTS AND GRASSLANDS

A. Introduction

Fires in tropical forests and grasslands are of potential military interest because of their ubiquity, their hazard to men, equipment and materiel, and their effects on the landscape. Therefore, the U. S. Army includes the factor of fire in its requirement for comprehensive and detailed knowledge of tropical physical and cultural environments. This chapter presents selected aspects of fire, derived from the literature survey, that are relevant to the conduct of military operations in tropical areas. Inasmuch as specific requirements can not be anticipated, the emphasis is upon the phenomena, be it the nature of fire itself or its effects upon a given aspect of the environment. The material contained in this chapter has been generated by the literature, and the organization of the material and conclusions derived have been extrapolated from the basic data.

B. Military Aspects of Fire as a Phenomenon

1. Tactical and Logistical Considerations

Certain aspects of fire in tropical forests and grasslands are presumed to be of tactical interest. These include: most prevalent type of fire, fire characteristics and behavior, smoke, and the ability of fire to hold or deny a given area for military purposes.

a. Type of Fire.--Surprisingly, the most prevalent type of fire in the tropics is one of rather low intensity, fed by fuels arranged relatively close to the ground. Regardless of the varying quantities of fuel potentially present in the major vegetation formations, environmental conditions tend to support only surface fires. Where fuel quantities per unit area are large, such as in tropical forests, the general climatic, microclimatic and biological environments are such as to render fuels essentially non-combustible. Conversely, in the dry margins of tropical wet-and-dry climatic areas, even though climate favors combustion at any time during the year, fuel quantities are low due to low annual rainfall. Conditions favorable to fire occur in areas experiencing a well-defined climatic dry season characterized by rapid desiccation of vegetation, yet receiving sufficient total precipitation to provide a relatively abundant vegetation cover. Some 17.4 million sq. km. (6.7 million sq. mi.) out of a total of 32.4 million sq. km. (12.5 million sq. mi.) of tropical forests and savannas possess conditions favorable to fire of tactical significance. Surface fires are also more significant than other types due to the prevalence of annual burning which reduces fuel accumulations in woodlands and grasslands.

Crown fires and fire whirlwinds, which occur in temperate forests, are rare in the tropics, having been reported only in parts of Australia. Generally, atmospheric conditions during the climatic dry season are not propitious for large scale convection. A tradewind temperature inversion, above which relatively dry air subsides, is present in much of the tropics, and in combination with anticyclonic atmospheric circulation it inhibits cloud development. Although fire-induced cumulonimbus clouds have been reported in Africa, for example, the fires were located in the tropical rainy (Af) and tropical wet-and-dry (Aw) climates of the Congo Basin and southern Sudan.

b. Characteristics of Surface Fires.-- Fire characteristics cannot be predicted accurately because of the number of variables involved. However, field experimentation has isolated the significant factors. They are the intensity of the fire, which is influenced by the fuel matrix and its spatial arrangement, and the rate of fire spread, which is influenced by local wind conditions, terrain roughness, and the length of time since the last rains.

Surface fires in savanna grasslands are fed by essentially fine-textured grass fuels, generally homogeneous in size, that form a matrix characterized by large surface exposure. Fuels quickly respond to spells of dry weather, so that burning is possible within a week following last rains. Fire moves rapidly through the fuel matrix. Temperatures rise above 850°C (1562°F) some two or three meters (6 - 10 feet) above the ground in the flame front. Generally, single fire fronts are typical of grass fires. Depending on the range of fuel sizes present, the width of the burning zone ranges upwards from as little as 3 meters (10 ft.). Passage of a fire is normally rapid, and reentry of personnel into the burned area can take place almost immediately.

Surface fires characterized by multiple fire fronts, and possibly by fire-brand fires spotted ahead of the general burning zone, are associated with natural vegetation possessing a wide range of fuel types and sizes arranged at various levels above the ground. Multiple-front fires are to be expected in wooded savannas and dry deciduous forest, where there is a diversity of fuels in the vegetation complex. The resulting fires are intense ones in which flame temperatures may exceed 1200°C (2,192°F). Since rates of burning depend in part on fuel sizes, the flame front proceeds through the vegetation irregularly, leaving behind burning areas, smoldering logs and hot embers. Consequently, the width of the burning zone is much greater than in grassland fires. Spotting by fire brands ahead of the general flame front depends on the character of fuels, convection within the burning zone, and prevailing winds. Among the highly inflammable eucalyptus fuels of Australia, spotting 10 km.

(6 miles) ahead of the fire has been observed. Elsewhere in the tropics, spotting is mentioned, but it rarely ignites vegetation more than 2 - 5 km (1 - 3 miles) ahead of the main burning zone.

Fire behavior in wooded savanna and dry forest areas is such that entry into a burned area following fire passage may be delayed for a period of time inimical to military operations. On the other hand, unfriendly forces are also denied entry into such an area.

c. Effect of Fire Passage on Buried Material.--The downward penetration of heat into the soil accompanying fire passage is of both operational and logistical significance. Regardless of the type of fire, a significant increase in soil temperature (greater than 2°C) during a fire has never been recorded deeper than 80 cm. (31.5 in.). Furthermore, the change in temperature is for a limited time, from 2 to 30 minutes. In grassland fires the depth of penetration of heat rarely exceeds 10 cm. (4 in.). Consequently, the impact of fire passage on buried weapons or stored materiel is limited. Of much greater significance than fire to burial of equipment would be the change in soil-water relationships accompanying the wet and dry climatic seasons

d. Smoke and Visibility.--Smoke is significant in the tropics because widespread burning at the end of the dry season and the low mean altitude of the trade wind temperature inversion favor the concentration of smoke in the lower layers of the atmosphere. Poor visibility due to haze and smoke, both from the air and on the ground, has been referred to frequently in the literature. Bare ground exposed by burning also contributes dust and ash particles whipped into the air by winds. Certain combustion products are highly hygroscopic, and possibly are a significant source of nuclei for the definite increase in atmospheric haze that accompanies smokiness. Poor visibility conditions can persist for weeks. Numerous reports of pilots flying in parts of South America, Africa and Southeast Asia suggest that visibility often is reduced to less than 5 km. (3 mi.).

The color of smoke is indicative of the type and intensity of the fire. Fires fed by natural vegetation tend to have smoke with visual properties ranging from dense, opaque white to dark tones in which the opacity depends on the size of the fire. Intense fires characterized by high flame temperatures have dark smoke due to the range of fuels being consumed, and a marked increase in carbonized fragments borne aloft.

e. Causes of Unpredicted Fires.--Unpredicted fires in tropical forests and grasslands can be expected to occur; their probability depends on environmental conditions. In savanna areas, fire is possible if a week or two of dry weather occurs regardless of the climatic season. In humid forested environments, fires do not constitute a significant hazard, except where grasslands abut forests. In this case, fire may penetrate a few meters into the forest edge.

Unpredicted fires due to natural causes are relatively insignificant compared to fires set by local inhabitants. Natural causes of fires are limited largely to lightning. However, in the tropics, lightning fires are surprisingly few in number, in spite of the high frequency of thunderstorms. The combination of dry fuels and thunderstorm activity, propitious to lightning fires, is limited largely to the few weeks of shower activity that precede the onset of heavy rains. Fuels are dry enough at this time to sustain fire spread. On the other hand, widespread burning for cultural reasons by this time has usually resulted in removal of readily available fuels, principally grasses, so that the probability of fire is lower than would otherwise be expected.

Man-set fires probably account for more than 97 per cent of all forest and grassland fires in the tropics. These include fires set under measures of precaution and control as a practical tool in commercial forest and range management. More widespread and frequent are fires set by indigenous peoples engaged in primitive agriculture and grazing. Although fires are not randomly set, control of fires in grasslands is minimal. Accidental fires, due to escape of fire from an area, are common. Pyromania is a significant factor, because the use of fire in many tropical areas is so widespread that no cultural inhibitions exist

Consequently, all semi-permanent and permanent military installations in tropical areas should consider precautionary measures to ensure safety from unpredicted and accidental vegetation fires.

C. Military Aspects of Fire-Altered Vegetation

Centuries of fire use have transformed large portions of forested tropical areas. experiencing relatively humid climates, into grass and open forest environments. It is here that relatively large quantities of fuel occur in combination with a fairly well defined dry period to produce potentially severe fire. Fires in this type of environment could become sufficiently intense to deter movement of ground personnel and light equipment. Tactical operations dependent on concealment and surprise could be influenced by destruction of the vegetation cover by fire An approximation of potential fire hazard in relation to climate and natural vegetation can be gleaned by inspection of the various maps found in Chapter V. For example, the area indicated as "derived savanna" on the map of Africa, represents the alteration of an originally continuous cover of tall forest to one characterized by frequent forest relics, open brush and grass areas (see PLATE 6. p. 88. and PLATE 23, p. 140).

1 Recognition Factors

a. Forested Environments.--Certain characteristics of tropical forested environments reveal that fire and clearing have altered the floristic and physiognomic composition of the communities. For example, the absence of large trees is indicative that clearing has occurred and that the trees present represent an evenly aged stand of successional growth. A dense tangled undergrowth, including large, woody climbers, is characteristic of early stages of regeneration following clearing, fire cultivation, and abandonment of swidden plots in the forest. An altered forest community is indicated by the presence of a large number of species characterized by large broad leaves. The hardness and weight of wood (significant in terms of potential construction materials) depends on clearing and fire. Trees recently reclaiming land tend to be soft and light, whereas old aged trees have hard and heavy wood.

b. Wooded Savanna Environments.--Regardless of how tropical savannas came into being, at the present time most of them are subject to annual fires. Where patches of dense forest appear, they are isolated relics reduced by fire and ax. Within the grassland areas, brush and tree species may have a gnarled, twisted appearance suggestive of vegetation commonly associated with semiarid and arid climates. The physiognomic appearance of these woody plants is due to singeing of branches and coppicing by fires that sweep the area. Incongruous combinations of plant forms, such as tall, large trees with a grass understory also indicate fire, with the trees being the relics of a once extensive forest.

c. Open Grasslands --It is safe to assume that open grasslands are maintained by frequent fire. In most parts of the tropics the natural plant succession is from grassland to various associations of dry and subhumid deciduous forest. Open savannas, recently burned, will exhibit a new flush of ground and shrub cover even though rains may not have occurred. Regeneration occurs due to the ability of plants to draw upon food reserves stored in deep extensive root systems and rhizomes.

2. Concealment and Camouflage

a. Concealment.--Concealment is possible in nearly all types of tropical environment, depending on configuration of terrain and size of operating force. Concealment in forested environments not only depends on the overall physiognomic characteristics of the major types of vegetation but on their areal spacing as well. Furthermore, the nature of the regenerating vegetation following fire, is important. In highly humid forests associated with the tropical rainy climate regeneration of burned areas is so rapid that dense brush may exceed 5 meters (15 ft.) in height in one year, thereby limiting horizontal visibility to a few meters (see PLATE 5, p. 88). Penetration into regenerating areas is extremely difficult due to the density of the rank growth. Passage through a mature forest, however, is not difficult. Under the leaf canopy of the rainforest the undergrowth is sparse, and horizontal visibility may extend from 18 to 35 meters (60 to 110 ft.) It is clear that ease of movement of personnel in forested environments depends on the areal distribution and frequency of regenerating clearings and their stage of development.

The overall character of a forest area that has been subjected to clearing and fire depends also on the cultural practices employed by indigenous peoples. Of importance here is that the average size of clearings may be modest, but depending on the man-land ratio extensive areas of once forested land may be in various cycles of regenerative growth. Such areas should be identified and marked as areas difficult for movement of personnel and equipment (see section F (1) below).

In semideciduous tropical forests where the climate is characterized by a well developed dry season, as for example in the monsoon climate, plant succession on abandoned plots is slower than in rainforest and passes through a greater number of stages For much of tropical Asia bamboo thickets and/or tall, coarse grasses reclaim abandoned land. Both successional stages are highly inflammable during the dry season, and severely limit horizontal visibility of ground personnel. Grasses may reach heights in excess of 3 meters (10 ft.), and certain species (Imperata spp.) will burn fiercely even when green. Horizontal visibility in such areas may be limited to less than 1 meter (3 ft.). While movement through grass and bamboo is exceedingly difficult for ground personnel, the value of such areas for concealment should not be overlooked.

Concealment and ease of movement are inversely related in open grassland environments. The diversity in the proportion of low trees and bush to grass in the various types of savanna is such as to make generalizations misleading.

b. Camouflage.--Detailed studies have been carried out with respect to the need and types of camouflage used in the tropics and subtropics. The techniques and requirements of camouflage are not examined here, but certain factors of the environment are noted. The transformation of the natural environment at the onset of the dry season proceeds at varied rates depending not only on the amount of rain that fell in the preceding season, but also upon bioclimatic characteristics of the dominant vegetation, soil-water relationships and availability of ground water. Numerous researchers consider that savannas are edaphic in origin. The combination of heavy impermeable soils and widely fluctuating rainfall seasonally produces severe flooding, followed by rapid water loss largely through evapotranspiration. In some instances sedge lands have been fired, thereby indicating their ability to sustain combustion, even while the surface soil is wet. Consequently, in these areas, where natural vegetation is composed of sedges and low herbaceous forms, one would expect transformation of color to begin early after the onset of the dry season. The succession of changing color from green to tan would be first the wet sedge lands, second, the various types of grass cover, and finally, the shedding of leaves in savanna bush islands and neighboring forest.

Another important consideration is the lapse of time between fire and the flush of new growth occurring in response to light rains. Savannas are fired near the end of the dry season, largely for cultural reasons. Surprisingly small amounts of rain initiate vegetation response, quickly transforming the blackened land surface to light green. It has been noted in many parts of the tropics that light "dry season" rainfall is sufficient to transform the landscape in a matter of days.

3. Barriers to Fire Spread

The role which various aspects of the physical environment play to prohibit fire spread must be examined within the context of a specific area in which operations are contemplated. A generalized list of types of barriers to fire, such as cliff faces, surface streams, and so forth, has little tactical value in itself. Instead, certain barriers are suggested below, whose tactical importance may not have been given full consideration, but which should be evaluated in the appraisal of the tropical environment. They are: 1) the forest/savanna boundaries, 2) the presence and relative significance of savanna bush islands, 3) the possible significance of relatively narrow bands of pyrophilous vegetation acting as a barrier, and 4) the effects of fauna upon patterns of vegetation, considered in relation to the ability of an area to support fire.

a. Vegetation Barriers.--Vegetation barriers are considered from a different viewpoint than the potential combustibility of a given vegetation environment. In the latter case, for example, tropical rainforest environments are essentially non-combustible. The viewpoint expressed here is the ability of vegetation to halt or damp the fire spread from a fire already in progress.

Much has been written on the sharpness of the forest savanna boundary in many parts of the tropical world. Contrary to what might be expected, the grassland area changes to forest within a distance of a few meters rather than passing through a transitional zone in which the grasses gradually give way to forest (see PLATES 9 and 10, p. 93, and PLATE 21, p 126). The reasons for the sharpness of the savanna/forest boundaries are not fully understood, but important factors include the fact that grassland fires are low intensity surface fires. The abrupt change in microclimate and vegetative environment between the forest and the open savanna restricts penentration of any one fire to a matter of a few meters. Where the forest/savanna boundary is sharp, there frequently exists an abrupt change in topography, soils, and edaphic conditions, as well as the ability of the vegetation to carry fire. There is little doubt that the sharpness of the boundary is fire-maintained. Hence, the forest bordering savanna assumes a tactical significance due simply to the abruptness of contrasts across the two environments.

There are many types and subtypes of tropical savanna, whatever may be their origin. Isolated areas of forest surrounded by relatively open grassland have been termed bush or wooded islands. These islands, depending on environmental conditions, vary from areas of low thorn bush and other woody growths not more than 3 to 10 meters (10 to 30 ft.) in height, to relics of a former more extensive humid semi-deciduous forest with trees 30 meters (100 ft.) tall or more. Numerous studies have shown that the various species near the center of large bush islands are not particularly fire-tolerant. These in turn, are encircled by highly tolerant species. The conclusion appears to be valid that fire is unable to sweep to the center of such islands despite the frequency of burning of the grasslands. The military significance of such wooded areas rests not only upon their value as places of concealment, but also on the fact that bush islands of moderate size are havens from fires sweeping the surrounding grasslands.

The sweep of fire in open grassland savannas is not unlimited. but is contained within the general limits of galeria, palm, and swamp forest communities that occupy perennially wet sites, areas experiencing high water table, or land adjacent to the courses of streams. The spatial distribution of these wooded and forested areas depends on surface and subsurface hydrography. Either the forest communities occupy sites too wet to sustain fire, or the vegetation is fire-resistant. Operational and logistical planning therefore, should consider the tendency of such forests to intercept fires.

b. Bare Ground Acting as a Barrier.--The persistence of bush islands in annually-burned open grassland savannas has been attributed to the trampling of the ground around the trees by domestic livestock and wild game seeking shade during midday. The obliteration of vegetation around water holes by livestock and wild game has also been described as extensive. The trampling effect may establish a fire free area 3 km. in radius, as has been noted in parts of Africa during periods of severe drought. Game trails and preferred paths of movement of animals in open grasslands also produce trails crisscrossing open areas which may act as fire breaks in areas where fuels are sparse.

D. Military Aspects of Fire and Surface Conditions

There would appear to be relatively little direct effect of fire upon the soil trafficability of an area in the tropical forest and grassland environments. Studies of the impact of fire upon the physical characteristics of soils indicate that surprisingly little change occurs in the bulk density and soil structure after a fire. Furthermore. frequent and repeated burning may affect soil characteristics that are important to agricultural productivity but would be of no significance in terms of those criteria significant in determining trafficability (see Chapter III). Of much greater importance would be that of clearing and fire in a forested environment in removing the vegetation cover with resultant increase in runoff, erosion and landslides. The permanent disruption of trails or roads by fire seems less likely except where wooden bridges occur.

E. Military Aspects of Burning Patterns

Two aspects of the patterns of burning need to be examined for their potential military interest: 1) the patterns associated with swidden agriculture in the forested environment; and 2) the patterns of burning and forms of clearing of land in the various savanna environments. PLATE 23, p. 140 and PLATE 24, p. 145 clearly indicate that the amount of area subjected to fire in any one swidden season is very small. Consequently, resulting fires are limited to cleared areas, and their contribution of smoke and other factors significant to military operations resides not so much in what takes place in any one season but what happens to the environment over a period of years. For various reasons, swidden agriculturists may concentrate at forest/savanna boundaries or follow lines of easier ingress into the fore', both of which have tactical significance.

Patterns of burning in woodland savanna, particularly bush islands, are easily identified from aerial photography (see PLATE 21, p. 126). It is also clear that the extent to which uncontrolled fire may cover an area is limited even on relatively level terrain (see PLATE 20, Point A, p. 123). The influence of termitaria on the pattern of burning in wooded savanna has been described in Chapter III. Termite mounds are of two kinds: those that are inhabited and bare of vegetation, and the abandoned ones on which a patch of forest has become established. Both kinds may serve as havens of refuge in fire, either on the mound or in the spear-shaped fire-free area on its lee side.

Burning patterns on savanna grasslands are controlled primarily by the state of the fuel, wind velocity and direction, and topography. In areas of undulating to hilly terrain the pattern of burns tends to occur on downwind slopes and crests of elevated landforms, while intervening vales and hollows escape fire (see PLATE 7, p. 89). In level topography discontinuous and striped patterns can be expected when accumulated fuels are low and wind velocity high. Depending on the driving force of the wind, linear patterns with subsidiary finger-like appendages can be expected (see PLATE 20, p. 123, and PLATES 21 and 22, p. 126). Instructions to ground personnel should include training in recognition of factors affecting patterns of burning and in precautionary techniques to be used in case of fire in various types of environments.

F. Military Aspects of Cultural Use of Fire

The ubiquitous use of fire by the peoples in the tropical world has implications of which military personnel need to be aware in planning tactical operations and logistical support. The purpose of this section is to bring together the cultural variables in the use of fire and to suggest their military significance.

1. <u>Site Selection</u>

The kinds of sites selected by swidden cultivators, nomads, and technologically advanced fire users differ considerably. Swidden cultivators select small patches located with respect to roads, villages, the forest/savanna boundary, soil types, or ecological criteria, such as the type and size of regenerated vegetation, and so forth. The result is that in areas of swidden cultivation the landscape is subdivided into small, irregular patches of open fields, regenerating vegetation, grass, or forest (see PLATE 23, p. 140). Nomadic herders and hunters commonly burn much larger areas than do swidden cultivators. The differences in gross spatial burning pattern have significance in predicting the nature of the landscape that might be an area of military operations.

2. <u>Providing a Supply of Fuel</u>

The presence of a long and severe dry season often makes special measures to provide a supply of fuel unnecessary, since dry savanna grass and brush will burn easily if ignited. Where a humid forest exists, or the dry season is less severe, it is necessary to kill or fell the vegetation so that it may dry out before burning. Thus the cultural practices used in providing a supply of fuel are indicative of the potential combustibility of the vegetation, and can be used as a guide to the expected fire hazard. Felled forest is visible on air photographs. During the forest felling period the area slashed and cut is normally the area that will be burned. However, where the <u>chitemene</u> system is used the area felled is many times larger than the area burned. Thus the extent of cutting is not indicative of the area that later will be burned

3. <u>Lighting the Fire</u>

The difficulties involved in lighting a fire in humid forest, and some of the techniques used to overcome them, are discussed in Chapter IV. It has been observed that even flame throwers are of little value in igniting uncut moist Malayan forest. However, the change in forest microclimate that results when the trees are lopped or felled vastly increases the potential combustibility, and hence the fire hazard, even of tropical rainforest. Thus the contrast between felled and undisturbed forest has significance from the standpoint of havens of refuge, storage of vehicles and equipment, and troop bivouac. A similar contrast in combustibility exists in areas of the forest/savanna mosaic between the savanna grasses and the patches of relict or galeria forest scattered within it.

4. <u>Fire Control</u>

Many authors have noted that measures to prevent fires, confine their spread, or reduce their severity exist even among the most primitive users of fire. Swidden cultivators often leave a green fire break of forest around their villages and swidden plots. Nomadic pastoralists as well as technologically advanced peoples burn fireguards to reduce the danger of fire spread. The adoption of such indigenous fire control techniques by United States personnel offers a useful and low cost means of temporary reduction of fire hazard. The use of more sophisticated fire fighting and fire control equipment and methods, such as those described in Chapter IV, may be justified by the size of operation contemplated.

5. Cyclical Patterns of Burning.--Except for the areas of tropical rainforest where it may occur at practically any time, burning in the tropics occurs regularly according to an annual cycle. Various burning periods have been discussed in Chapters IV and V and illustrated on maps. The military significance of cyclical burning lies in its predictability in time, if not in place. In areas where swidden cultivation or nomadic grazing is the way of life, the people will burn when the annual burning period arrives, since it is an inherent part of their economy and cultural tradition. Therefore, the seasonal increases in fire hazard, smoke, haze, reduced ground visibility, and other hazards referred to above may be planned for in advance.

6. Population Distribution.--The military significance of population characteristics is primarily in their relationship to the geographic location and incidence of fire. For example, in South Asia and Southeast Asia the river valleys and coastal plains are settled by dense populations cultivating paddy rice, and are rarely burned Nomadic pastoral activities are rare. The area under swidden cultivation is primarily confined to the uplands and hills, where the population density is comparatively sparse. In Latin America and Africa on the other hand, where intensive agriculture is unusual, and extensive pastoralism and swidden cultivation are widespread, fire may be expected to occur much more widely, even in areas settled by people of European descent.

Another element is the migratory nature of swidden agriculture. The cycle of migration varies in length, but the maximum time that one forest patch is cultivated is usually three years. Therefore, older maps and aerial photographs may be of questionable reliability in terms of their depiction of land use and vegetation cover.

7. Fire and Aerial Photography.--Aerial photography is of great potential value, from both the tactical and logistical standpoints, in evaluating the characteristics of tropical areas subject to burning. Soil and vegetation associations can be identified on the photographs after sampling studies have been carried out on the ground. If information about the time of burning, the quantity and type of fuel present, and recent meteorological information are brought to bear on an area, an up-to-date assessment of fire danger, expected fire intensity, recommended fire control measures, and location of havens and barriers to fire spread could be provided to field commanders.

Cultural features related to fire may also be located on aerial photographs. By pointing out sacred groves, fetish trees, wooded burial places, swidden plots in various stages of regrowth (see PLATE 23, p. 140), paths and tracks leading to swiddens, ponds, streams, and villages, needless damage to the feelings of the indigenous population may be avoided.

The quality of aerial photography may be affected by smoke and haze during the fire season. Loss of definition, changes in tone and blurring of shadows may occur. Consequently, problems of establishment of photo identification keys, target identification, and evaluation of trafficability may develop. Infra-red photography may be of value in identifying recently burned areas and creeping subsurface fires in forested areas. Further research is needed to develop more fully the capabilities of aerial photography and remote sensing techniques in relation to fire in the tropical forests and grasslands.

APPENDIX I

SEARCH FOR A REALISTIC MODEL OF FIRE-FRONT PROPAGATION[1]

The search for knowledge about fire is complicated by the fact that the number of combinations of physical circumstances producing an accidental fire is almost infinite. Chemical kinetics, fluid mechanics, heat and mass transfer enter and interact in such varied ways as to make difficult any meaningful generalized statement about their relative significance.

Transport Phenomena and Propagation Principles

All fires involve transport of energy, mass, momentum. To indicate the nature of these transport processes as they apply particularly to fires, and the way such processes interact, the problem of how a fire moves through a forest is chosen. This serves both to illustrate the approach to quantitative treatment of steady fire-front propagation and to illustrate some of the other factors relating to fire problems.

Consider fire moving through a forest, forming a fire front of great length; let the problem be to formulate a mechanism of spread which is near enough to reality to predict reasonably good answers to such questions as how fast the flame front is moving, how much a change in wind velocity or air humidity would affect the speed, how wide a firebreak or how much water application is required to stop it. The problem is so complex as to seem beyond analysis at first, but certain assumptions can be made which although over-

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1. Adapted from National Academy of Sciences, N.R.C., A study of fire problems, Washington, D. C., 1961, 176 pp.

simplify the nature of the problem do permit an approach toward solution.

Consider fire spread in the forest litter. Flame is creeping forward in response to several mechanisms. The fire front is the burning zone, extending from the locus of ignition to the depth where combustion intensity is too weak to affect the leading edge. The burning embers are warming the adjacent unignited elements by radiative transport which may be treated as normal to the ignition surface in the litter, if the reach of this radiation is small relative to the depth of the litter. Assume that the complex of flame and burning embers behind the ignition surface radiates like a black body at an assigned flame temperature T_F, the radiative flux to any element dx, a distance x ahead of the ignition surface can be readily calculated if an adequate quantitative description of the litter is available (see Fig. 1). For later reference let this energy rate per unit of ground area be designated $q_1(x)$.

Added to the horizontal radiative transport is a convective energy transport, consequent on the fact that twigs and needles find themselves in the path of gaseous combustion products rising or being blown sideways from burning elements. The reach of this mechanism in litter is also small, and could become negligible in response to the action of inflowing air preventing any unignited elements from lying in the path of the combustion products. Still a third mechanism, of unknown importance, is the explosive ejection of gas jets, associated with rupture of a wall entrapping evolved gas. The mathematical expressions of these mechanisms

[1]Any quantitative consideration of fire propagation must be preceeded by a quantitative description of the fuel complex. The total fuel mass per acre, its total surface area, the distribution of mass and surface with height (to account for multistoried egetation) and distribution function representing the randomness of placement of fuel at various levels, are all of prime importance.

are represented by functions (1) and (2) which are taken up later.

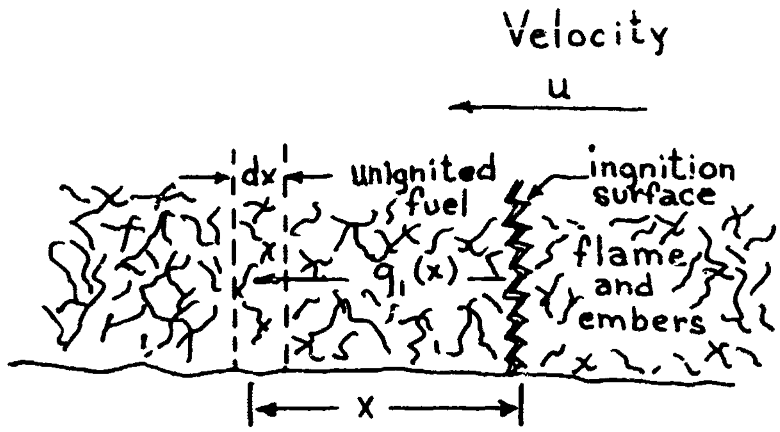

Figure 1. Structure of fire propagation in forest litter.

The problem now arises of coupling heat transfer into the unburned fuel with the ignition process, which is itself intimately related to the chemistry of wood pyrolysis and the chemical kinetics of combustion. For the present purpose the chemical details can be isolated for separate treatment by postulating that ignition occurs when the fuel reaches a certain surface temperature T_i or has absorbed energy of a certain magnitude Q_i, sometimes referred to as the critical ignition impulse, where T_i and Q_i are treated as properties of the fuel under consideration. This is certainly not true; T_i or Q_i depends on the wood thickness and on the heating schedule. Consequently it is necessary to estimate the value of Q_i, use it in calculating the propagation and, if necessary, to iterate. One thus achieves an important simplification of the fire-spread problem by separating it from the ignition problem, which can more effectively be studied by itself in the laboratory.[1]

[1] This decoupling of two problems at a point where their interaction is weak is an important and very necessary trick in achieving any answer to so complex a problem as fire spread. Nowhere is there a suggestion that the element decoupled lacks importance to the ultimate objective.

With the flame front defined as a locus of build-up of the thermal impulse into the litter to the lue Q_i, it is possible to formulate the first statement about the fire front. With the x-coordinate representing distance from the fire line and negative values of x located in the unignited fuel,

$$Q_i = \int q\,dt = \frac{1}{u}\int_{-\infty}^{0} q\,dx, \qquad (1)$$

where u is the velocity of the flame front and q is the total heat-transfer rate to fuel by all mechanisms, per unit of ground area (unit length along the fire line is the basis of calculation). u here has been assumed constant for simplicity; in fact, during fire build-up or firebreak jumping, u will not be constant and must be left inside the integral. Further progress must await discussion of the factors contributing to q. Although there may not be enough flame above the litter to make flame radiation downwards and towards unignited fuel important, there is significant irradiation of the litter by other flames from the burning brush. Within this brush there is forward movement of heat from the flame by a process of convective action-at-a-distance. The fine structure of the wind is such that an eddy of flame or of partially ignited gas mixture may be moved forward a distance x, where it bathes a twig or branch and transfers heat to it in proportion to the difference between flame temperature T_F and local twig temperature T; and the chance that this will happen is a sensitive function of wind structure (spectrum of turbulence), mean wind velocity V_w and, particularly, the distance from the flame front. The chance, of course, goes down rapidly with increasing x. This transport term, energy flux per unit ground area, then takes the form

$$q_2 = \left[f_2(x,\ \text{flame height},\ V_w,\ \text{wind structure}) \right] (T_F - T) \quad (2)$$

where the function f_2 depends on fuel type.

A transport mechanism varying greatly in importance in different fire types is that of ignition by firebrands ahead of the continuous burning zone. There are many small islands of flame far ahead of the main front, irregular, large islands near it, and peninsulas formed by recent merging of islands with the continuous ignition line. It has been suggested that the mathematics of epidemic propagation is applicable, with its analogues to the varying potential of firebrands to serve as igniters, the varying sensitivity of the forest areas to respond; but with an added factor of sensitivity increasing with the preheat caused by the approaching fire.

The need for adding the radiative transfer from brush flames to the other mechanisms which operate to bring the litter to its ignition point produces realization of an important feature of fire spread, the interaction of fire in different levels. There is one problem of evaluating fire spread in the litter, with a term included which represents interaction between litter and brush. There is another problem of evaluating fire spread in the brush, with a term representing inter-action between brush and litter and another between brush and tree crowns, since the crowns will send up high flames, the radiation from which is a major contributor to spread. There thus emerges a picture not of a single front moving forward but of two or perhaps three, of markedly different structure, each propagating forward as a result of the combustion of fuel in its own level of the forest and of the transfer into it of heat from other levels. From a mathematical point of view, the propagation of this compound fire front can be described by three systems of equations which are coupled by terms representing the exchange of heat between the layers. In principle such a set of equations can be solved together. In some situations there will not be a sufficient supply of heat to one or other level of the fire, and combustion will stop altogether in this level although it may continue in the remaining level or levels. Thus in a forest with a clear floor level and with dry foliage, a fire may crown and race ahead without damaging the lower levels at all. In the evening, as the humidity increases and temperatures fall, the fire may drop out of the crowns because it no longer generates sufficient heat, and it burns quietly in the lower levels with only occasional crowning and damage of the foliage of larger trees. Recognition of coupled levels of flame propagation is of great importance in the design of model experiments.

With the major mechanisms of energy transport identified, there remains for consideration the source of that energy, the burning process. Consider a brush fire, with the fuel packing sufficiently dense to suggest that much of the process of completion of combustion occurs in the flames above the brush. Take the local burning rate, or fuel weight loss per unit ground area lying behind the ignition line, to be directly proportional to the local rate of heat absorption by the fuel on unit ground area. As the char thickens on the larger fuels the accumulating thermal resistance will cause reduction in the gas-evolution rate of a level incapable of flame support. For simplicity the gradual loss of proportionality assumed above will be replaced by a sudden cutoff; and combustion, at least insofar as it affects flame spread, will be assumed to cease when a definite fraction α of the initially available fuel has been consumed. This is the locus of the back of the burning zone.

The gas evolved by the mechanism just described burns in a buoyant flame, and the progress of combustion, the shape, the temperature, and the concentration pattern in the flame, are determined by the dynamics of the gas flow. The irradiation pattern on the fuel can now be calculated or estimated, provided that sufficient information is available on the pattern and strength of the external wind, and its effect on the flame shape.

The coupling is now complete, i.e., all the elements of a chain of interactions have been described, and a quantitative formulation of them will permit a solution of the propagation problem, including the velocity.

Now that certain statements have been made concerning fire propagation in the forest litter, it becomes possible to formulate a fire model in a semi-quantitative way.

Consider the steady advance of a long straight flame front at speed u through the brush, and take a coordinate system with the origin at the locus of ignition of the fuel and the x-axis in the direction opposite to that of propagation. The front speed u, the flame height H, and the depth of burning zone W are at present unknown. (Fig. 2).[1]

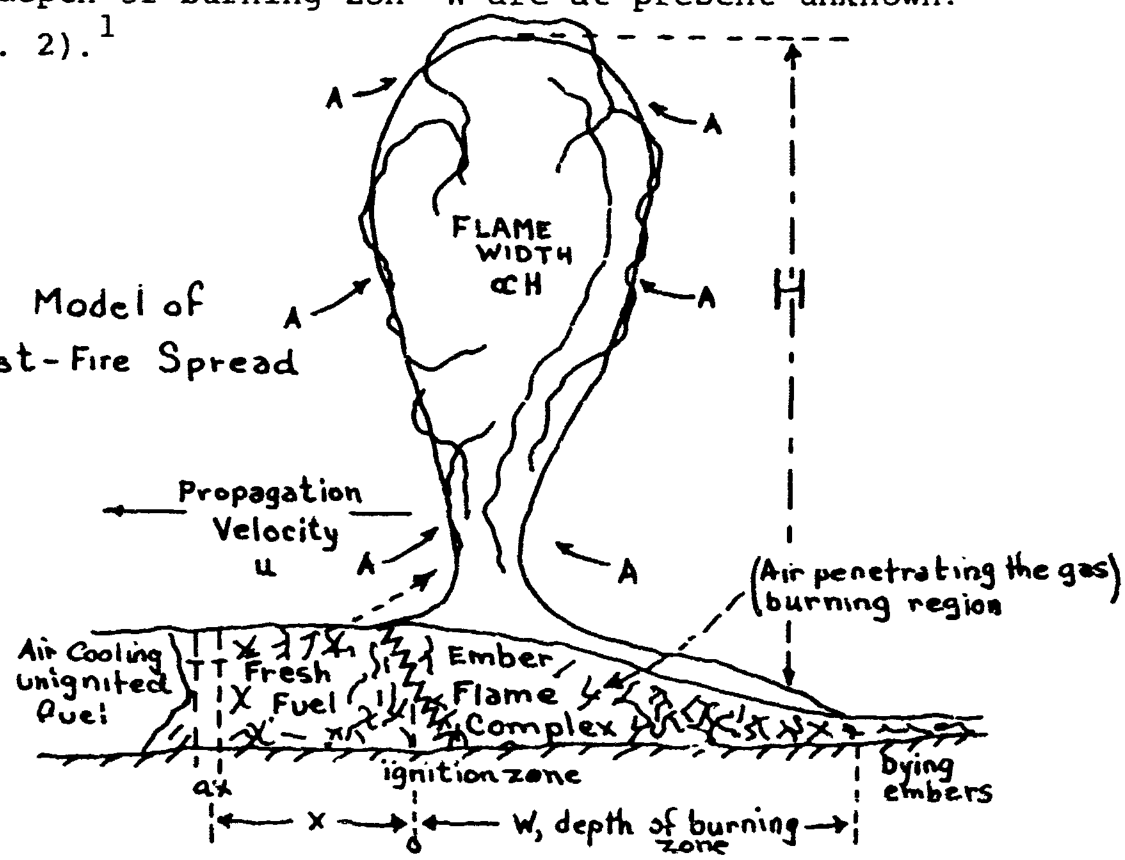

Fig. 2 Model of Forest-Fire Spread

[1] The fuel used in the model is visualized as dense brush representing a relatively homogeneous fuel complex of limited depth.

Focus attention first on the unburned fuel ahead of the ignition zone, and accept the assumption previously discussed that ignition occurs when the cumulative flux into the fuel associated with unit ground area reaches Q_i, the critical ignition impulse. The accumulation of energy in the fresh fuel is assumed to be due to the following terms, all in units of energy-reception rate by the fuel on unit ground area:

q_1 (x) is the more or less horizontal flux from the ember-flame matrix behind the ignition zone through the distance x to the fuel. The radiating matrix is taken as a black radiator at flame temperature T_F, assumed known. The absorption by the fuel in width dx is then

$$q_1 = B \sigma T_F{}^4 e^{-ax} a \, dx \tag{3}$$

where B is the height of the ember-flame matrix, assumed to be brush height; a is the reciprocal mean free path or projected area per unit volume of intervening brush; σ is the Stefan-Boltzmann constant. To justify treating the source as black, the burning zone w must be thick compared to the mean free path 1/a; and to justify ignoring losses up through the top of the brush, the brush height B must also be large relative to 1/a.

$$q2 = \left[f2(x, H, Vw, \text{ wind structure}) \right] (T_F - T) \tag{4}$$

is function (2) previously described, and represents convection due to flame transport. V_w is the wind velocity and experimentation is needed to establish a suitable form of this function.

$q_3(x, H, V_w)$ is the downwardly directed radiative flux from the over-head flame, dependent on the composition of the gaseous products of pyrolysis feeding the flame and on the distribution, in space, of temperature and radiator composition. There is evidence that, for a fixed gaseous fuel type and in the absence of wind disturbances, radiation from the flame plume is uniquely determined by H.

$$q_4 = \left[f_4(V_w, H) \right] (T_a - T) \tag{5}$$

is the convective cooling of the heated but not yet ignited fuel by air flowing through it.

The accumulation of energy to produce ignition may be formulated

$$Q_i = \int_{-\infty}^{0} q(x,\ H,\ V_w,\ T)\ .\ \frac{dx}{u} \tag{6}$$

where $$q = q_1 + q_2 + q_3 + q_4$$

Consider now the burning zone where the pyrolysis which feeds the overhead flame is occurring, and which is assumed to proceed at a rate proportional to the local input of energy. This input is provided by the overhead flame radiation q_3 and by local burning of some of the embers where fresh air reaches into the zone. Call the latter input $q_5(V_w,\ H)$, indicating its dependence on the external wind and on the induced wind that is related to H.

The heat of combustion q_G of the gas evolved, or loss of chemical enthalpy of the fuel, is assumed to be proportional to the input energy flux $q_3 + q_5$. Thus

$$q_G = \beta\ (q_3 + q_5) \tag{7}$$

Furthermore, this energy evolution in gaseous from from the fuel is assumed to continue until the fraction α of the total heat of combustion Q_c of fresh fuel has been evolved. At this stage active burning ceases. This gives

$$\int_{0}^{W} q_G\ \frac{dx}{u} = \alpha\, Q_c \tag{8}$$

Combining these relations gives

$$\int^{W} \left[q_3(x, H, V_w) + q_5(H, V_w) \right] dx = \frac{\alpha}{\beta} u Q_c \qquad (9)$$

where the fire velocity u has been assumed constant.

There remains the problem of relating H with the other variables. Theory, supported by experiments, show that the height of a flame is proportional to the two-thirds power of the gaseous fuel feed rate, provided negligible momentum is brought in by the gas. Applying this to the present situation gives

$$\int_0^{W} q_G \, dx = H^{3/2} \qquad (10)$$

where γ is a proportionality constant and hence

$$\int^{W} (q_3 + q_5) dx = \frac{\gamma}{\beta} H^{3/2} \qquad (11)$$

Equations (6), (9), and (11), together with knowledge of the forms of the five q-functions, would constitute the complete set in the variables u, H, and W if the local temperature T of fuel ahead of the fire were not involved in the integrand of equation (6) . A reasonable approximation could be obtained by using some estimated functional form for T(x) running from T_a to T_{ig}. Rigorous treatment would involve a study of unsteady heat flow in the fuel, leading to a family of curves relating fuel surface temperature to heat impulse Q for different values of heat input rate. It would then be possible, using stepwise integration from far ahead of the flame to the ignition locus--all based on an assumed flame height and heating schedule of the wood--to evaluate the integral in equation (6), combine it with (9) and (11) and obtain a solution. The process would require iteration, and is to be avoided by replacement by some such approximation as that suggested.

Clearly this is a tentative model requiring further development and calling for supporting experiments.

APPENDIX II

PROBLEMS IN THE CLASSIFICATION OF TROPICAL FORESTS AND SAVANNAS

Generally, three main criteria are evident in the various classifications of tropical vegetation and in the descriptive names employed to designate certain vegetation types. In addition to location, there is habitat or environment, physiognomy and floristics. Unfortunately, knowledge of tropical vegetation does not permit a classification based on the relationships between vegetation and its habitat. The principal reasons are that the technical problems of description (physiognomy) and identification (floristics) are so great, that little progress has been made toward relating these characteristics to effects of climate, soil and other living organisms on the vegetation.

Some of the problems involved in classifying tropical forests are:

1) determination of representative area;

2) criteria necessary for correct choice of stand because of the great richness of the tropical tree flora.

   Wyatt-Smith, according to Poore (1963), has recorded in the Malaya mixed Dipterocarp forest (rainforest) 2,366 individuals belonging to 444 species in 11 acres of forest belonging to two types. This is an average of only 5.3 individuals to each species. Poore continues by doubting the "homogenuity" of the enumerated sites.

3) meaningful description of an area in which there are no dominants;

4) subdividing tropical formations into units that are smaller and more precise than the

generally agreed upon larger units determined by gross climatic or edaphic differences.

A most important question, as yet unanswered is to what extent is tropical forest a climax formation. Many investigators believe that most humid tropical forest, appearing undisturbed, is actually mature second growth.

Hills (1965) in reviewing major research problems associated with tropical savannas includes a most useful listing of descriptive terms for vegetation types classified or mapped as "savannas", drawn from investigation of the literature. The list is reproduced below.

ENGLISH

semi-deciduous tropical forest
caatinga xerophilous forest
cerrados subtropical forest
savanna woodland
low tree savanna
ceradão
low-layered forest
high grass/low tree savanna
orchard savanna
savanna parkland
tropical deciduous xerophytic woodland
campo cerrado
caatinga
dry mixed forest
bushveld
subtropical bush
open grass woodland

semi-deciduous woodland
tall mesophytic grassland
open savanna
palm savanna
pine savanna
shrub/grass savanna
savanna grassland
campo limpo
tall grass savanna
bunch-grass savanna
steppe
steppe grassland
low grass savannas
tussock grassland
open seasonal grassland
desert grass savanna
high-grass savanna
sedge savanna
Acacia desert-grass savanna

FRENCH

savane forestière
savane boisée
savane arborée
savane arbustive
savane arbustive riche
savane arbustive pauvre
savane hallier

savane garrigue
savane herbeuse
savane macrécageuse
savane inondable
savane steppique
savane pseudosteppe

Numerous classifications of savanna vegetation have appeared in the literature. A table comparing selected classifications of savanna vegetation appears below and is also drawn from Hills (1965).

TABLE I

Selected Classifications of Savanna Vegetation[1]

Author	Woodland and/or forest type	Parkland type	Grassland type	Shrub type
Beard[2]		tall bunch-grass savanna: open savanna orchard savanna palm savanna pine savanna	short bunch-grass savanna sedge savanna	
Brazilian[3]	cerradão campo cerrado	campo cerrado	campo limpo	campo sujo
Williams[4]	woodland: low-layered forest low-layered woodland	tree savanna low tree savanna	tussock grassland	savane herbeuse
Aubréville[5]	savane boisée	savane arborée	savane herbeuse	savane arbustive
Trochain[6]	savane forestière	savane arborée savane verger savane palmeraie savane bambousaie	savane: savane steppique savane marécaguese savane inondable	savane arbustive
Shantz[7]	high grass/ low tree savanna	Acacia tall-grass savanna	Acacia desert-grass savanna	
Cole[8]	savanna woodland	savanna parkland	savanna grassland	low tree and shrub savanna
McGill University Savanna Research Project	savanna woodland	open savanna woodland	herbaceous savanna: grass dominant sedge dominant	shrub savanna

[1] Several authors, e.g. Cole, include in their classification 'Thicket and scrub'. This category has value for vegetation associations found within or adjacent to savanna regions that are best categorized in this way.

[2] Beard, J. S., "The Savanna Vegetation of Northern Tropical America," Ecol. Mon., XXIII (1953), 213.

[3] This is a widely used and acknowledged classification that is frequently used in English language texts.

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APPENDIX III

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The bibliography contains references largely more recent than 1920, and relating directly to the interaction of fire and the environment. To facilitate its use, the bibliographic references have been grouped into broad geographic areas and listed alphabetically. They are further identified as to location by country included within the broader geographic area.

There are two sections to the bibliography. The location and content of each reference in Section I is indicated by a series of Arabic numerals, Roman numerals, and letters set off from the end of the reference by parentheses. References in Section II are identified by their geographic location only.

The classification system used is presented before the main body of the bibliography. The following examples illustrate and explain the arrangement of the classification numbers and letters:

A. Sample reference Section I - fully classified.

Budowski, Gerardo (1951) Los Incendios Forestales en Venezuela, Agr. Venezol. 16, No. 155:24-28. (255: I 2: III C 0: III D 0: III E 0,1: III G 0,1).

255	refers to the geographic location, in this case Venezuela.
I 2	refers to the appraisal of the reference.
III C 0	refers to the effects of fire on rates of runoff.
III D 0	refers to the effects of fire on productive response of soils.
III G 0,1	refers to fire-induced changes in the physiognomic and ecological character of the natural vegetation

B. Sample reference Section II - identified as to location only.

Ferguson, H. (1944) Deterioration of soils and vegetation in Equatoria Province with special reference to grass fires, in: <u>Sudan Govt. Soil Conservation Committee's Report</u>. 138-142. (166)

166 refers to Sudan (formerly Anglo-Egyptian Sudan).

GEOGRAPHICAL CLASSIFICATION

<u>Tropical World General</u>

000 Tropical World General

<u>Africa South of the Sahara General</u>

100 Africa South of the Sahara General

<u>Western Africa</u>

120 West Africa General
121 Liberia
123 Spanish possessions
130 Afrique Occidentale Française
131 Mauritania
132 Senegal
133 Guinea
134 Ivory Coast
135 Mali (French Sudan)
136 Upper Volta
137 Niger
138 Dahomey
139 Togo
150 British West Africa
151 Gambia
152 Sierra Leone
153 Ghana (Gold Coast)
154 Nigeria

<u>Central Africa</u>

122 Portuguese possessions: Angola, Guinea, Rio Muni, Cabinda & Islands
124 Belgian possessions
125 Congo (Leopoldville)
126 Rwanda
127 Burundi
140 Afrique Equatoriale Française
141 Gabon
142 Chad
143 Central African Republic (Ubangi-Shari)
144 Cameroon
145 Congo (Brazzaville)

<u>Eastern Africa</u>

160 Northeast Africa General
161 Somali Republic (Somalia)
162 Somali Republic (British Somaliland
163 French Somaliland
164 Ethiopia
165 Eritrea
166 Sudan (Anglo-Egyptian Sudan)
170 East Africa General
171 British East Africa possessions
172 Kenya
173 Tanzania (Tanganyika)
174 Uganda
175 Tanzania (Zanzibar & Pemba)
176 Zambia (Northern Rhodesia)
177 Rhodesia (Southern Rhodesia)
178 Malawi (Nyasaland)
179 Mozambique (Port. East Africa)

Southern Africa

180 Malagasy Republic & Comoro Islands
181 Other Western Indian Ocean Islands
190 Southern Africa General
191 Republic of South Africa
192 South West Africa
193 Bechuanaland
194 Basutoland
195 Swaziland

Latin America

200 Latin America General

Middle America

220 Middle America General
221 Mexico
222 Guatemala
223 El Salvador
224 Honduras
225 Nicaragua
226 Costa Rica
227 Panama and Canal Zone
228 British Honduras

Insular Caribbean and Bahamas

229 West Indies General
230 Cuba
231 Haiti
232 Dominican Republic
233 Jamaica
234 Puerto Rico & U. S. Virgin Islands
235 Trinidad & Tobago
236 Lesser Antilles
237 British Caribbean possessions
238 French and Dutch Caribbean Possessions
239 Bahama Islands

South America

240 South America General
241 Brazil
250 Colombia
251 British Guiana (Guayana)
252 Surinam (Dutch Guiana)
253 French Guiana
255 Venezuela
260 Ecuador
261 Peru
262 Bolivia
263 Paraguay

Asia

300 Asia General
320 Southwest Asia General
330 South Asia General
331 West Pakistan
332 Kashmir
333 Nepal
334 Sikkim
335 Bhutan
336 Ceylon
337 Maldive Islands
338 Andaman & Nicobar Islands
339 East Pakistan
340 India

Southeast Asia

350 Mainland Southeast Asia
351 Burma
352 Thailand (Siam)
353 French Indo-China
354 Laos
355 North Viet-Nam
356 South Viet-Nam
357 Cambodia
358 Malaya
359 Singapore
360 Island Southeast Asia
361 British Borneo
362 Sarawak
363 Brunei

Southeast Asia (continued)

364 Sabah (North Borneo)
365 Malaysia
366 Philippines

Indonesia

370 Dutch East Indies
371 Indonesia
372 Sumatra
373 Java & Madura
374 Bali & Lesser Sunda Islands, Indonesian Timor
375 Kalimantan (Borneo)
376 Sulawesi (Celebes and other Islands)
377 Portuguese Timor
378 New Guinea (West Irian, Australian New Guinea & Papua)

Australia & Oceania

400 Australia & Oceania General
420 Melanesia
430 Micronesia
440 Polynesia
450 Australia

North America

500 North America

Non-Regional

600 Non-Regional

TOPICAL CLASSIFICATION

0. Reference Identification

    A. Form number of extracted material

    B. Geographic location indicated by content of reference

I. Appraisal of Reference by its Content

    0. A general account - reference incidental, mentioned in passing
    1. A narrative account - reference part of general, broad discussion
    2. A detailed narrative account - reference includes specifics as part of a qualitative analysis
    3. Analytical account - reference includes systematically organized qualitative information derived in part from field observation
    4. Analytical account - reference includes quantitative data and observations derived from field observation and experimentation

II. <u>Occurrence and Nature of Fire</u>

A. Incidence and Frequency of Occurrence
   0. Year - Date
   1. Month - by calendar month or months
   2. Season - as indicated by precipitation regime, or vegetative period, or "fire season"

B. Nature of Fire
   0. Cause - natural or cultural
   1. Site location
   2. Type and speed of movement of fire front; characteristics of flame
   3. Characteristics of smoke, e.g., height, density, color, drift
   4. Direction and areal pattern of burning
   5. Duration and cause of cessation of burning

III. <u>Effects of Fire on the Environment</u>

A. Topoclimatology
   0. Precipitation and humidity regimes (seasonal, diurnal, other)
   1. Temperature regimes (seasonal, diurnal, lapse rates, height of inversion)
   2. Wind, e.g., local surface winds
   3. Visibility (surface, and from the air)
   4. Local storms, also fire induced weather

B. Topography
   0. Alteration of rates of erosion
   1. Alteration of rates of deposition
   2. Distinctive landforms

C. Hydrography
   0. Rates of runoff
   1. Surface water flow
   2. Flood hazard
   3. Pollution

D. Soils
   0. Productive response, e.g., fertility, organic matter, structure, aeration
   1. Chemical characteristics, e.g., nutrients, exchange capacities
   2. Physical characteristics, e.g., texture, erodability, bulk density
   3. Microbiology of solum

E. Natural Vegetation
   0. Physiognomic change due to fire
   1. Ecological change
   2. Vegetative indicators, e.g., pyrophiles, others
   3. Combustibility regions

F. Cultural Landscape
   0. Land uses, e.g., forestry, agriculture, grazing
   1. Structures, e.g., buildings, lines of communication, others
   2. Settlement patterns, e.g., sedentary, nomadic

G. Long Term Effects
   0. Long term effects on the physical landscape
   1. Long term effects on the cultural landscape

IV. <u>Physical Environmental Influences on the Incidence and Occurrence of Fire</u>

A. Regional Climatology
   0. Precipitation and humidity, e.g., precipitation regimes, orographic effects, effective precipitation, mist, fog, drought
   1. Temperature, e.g., annual and diurnal march, range, variability, lapse rates, inversions
   2. Weather, e.g., prevailing winds, fronts, storms
   3. Air masses, e.g., frequency of occurrence, duration and characteristics
   4. Seasons, e.g., criteria, indices, and formulae used to define seasons

B. Topoclimatology
   0. Local winds, e.g., land and sea breezes, upslope and katabatic winds, shelter belt effects
   1. Local storms
   2. Other local climatic phenomena

C. Surface Configuration
   0. Relief features, local relief
   1. Surface materials, e.g., rock outcrops, sterile surface materials, laterite layers, others
   2. Hydrographic and hydrologic factors, e.g., surface drainage as barriers, flood hazard, runoff, characteristics of ground water table
   3. Edaphic factors, e.g., soil types and characteristics, soil-water relationships

D. Natural Vegetation
   0. General physiognomic character noting a few dominant species
   1. Broad classification of vegetation with geographic distribution
   2. Vegetation types, including site location, dominant and subdominant species
   3. Seasonal change in vegetation affecting combustibility
      a) climatic factors, e.g., moisture regimes
      b) vegetative factors, e.g., pyrophiles
      c) cultural factors, e.g., lack of fuel to sustain fire due to man's activity

V. Cultural Environmental Influences on Incidence and Occurrence of Fire

A. Peoples and Population
   0. Numbers, density, man-land ratios
   1. Ethnic and racial factors, e.g., cultural history and economic history
   2. Religious and political factors, e.g., tribal taboos and religious practices associated with fire, tribal organization
   3. Settlement pattern and ways of life, e.g., nomadic, sedentary, shifting cultivation

B. Technology of Use of Fire
   0. Preparation for burning, e.g., site location, supply of fuels, fire control
   1. Techniques of firing
   2. Seasonal or cyclical patterns of economic use of fire, e.g., land clearing, grassland management, forestry
   3. Seasonal or cyclical patterns of biotic use of fire, e.g., gathering, hunting
   4. Repeated patterns of fire use, e.g., disease or insect control, warfare or raiding, pyromania

C. Distribution of Cultural Practices of Fire Use
   0. Seasonal, monthly, or planting and harvesting patterns
   1. Types and kinds of burning regions identified by cultural criteria

SECTION I

Tropical World General

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DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author)

Department of Geography
Boston University

2a REPORT SECURITY CLASSIFICATION

Unclassified

2b GROUP

3 REPORT TITLE

FIRE IN TROPICAL FORESTS AND GRASSLANDS

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

5 AUTHOR(S) (Last name, first name, initial)

Batchelder, Robert B. and Hirt, Howard F.

6 REPORT DATE

June, 1966

7a TOTAL NO OF PAGES

380

7b NO OF REFS

166

8a CONTRACT OR GRANT NO

DA19-129-AMC-229(N)

b PROJECT NO

1V025001A129

c

d

9a ORIGINATOR'S REPORT NUMBER(S)

ES-23

9b OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

67-4-ES

10 AVAILABILITY/LIMITATION NOTICES

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11 SUPPLEMENTARY NOTES

12 SPONSORING MILITARY ACTIVITY

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13 ABSTRACT Fire in the tropics has a long history in which frequent wide-spread burning has profoundly altered physical and cultural environments A vast and diverse literature pertaining to fire and its effects in tropical forests and grasslands has been evaluated, classified and presented in a selected bibliography. Emphasis is on the relation of fire to climate, natural vegetation, soils, cultural origins, technological level and way of life and other significant factors of the total environment. The incidence and frequency of occurrence of fire are examined in terms of the geographic distribution of passive and active environmental characteristics. The relationship of burning to climate and natural vegetation is shown on maps which represent a first attempt to depict the geographic distribution of fire in the tropics. Potential combustibility and the implications of fire to military operations are discussed.

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Fire						
Tropical Environments						
Applied Climatology						
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