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Fire spread in lodgepole pine stands

Bruce Duncan Lawson
The University of Montana

FIRE SPREAD IN LODGEPOLE PINE STANDS

By

Bruce D. Lawson

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CHAPTER I

INTRODUCTION

Prediction of forest fire behavior has occupied the efforts of fire researchers since the pioneering days of fire science of the 1930's. Many of the basic physical laws governing how fire behaves have been described over the past four decades with the aid of laboratory and field modeling techniques. The problem remains, however, of how best to incorporate physical laws into predictive tools which are usable in the field for decision making by forest land managers. They deal with fire not in an environmentally controlled laboratory, but in a highly variable and complex natural system where the individual effects of each variable cannot be quantified or isolated. It is understandable that most fire management people feel they require guidelines which come from the "real world", rather than from laboratory modeling procedures alone, since the latter may provide useful information to the researcher but may lack generality.

The Forest Fire Behavior System of the Canadian Forestry Service (Can. For. Serv. 1970b) is a current approach being developed to provide guidelines of fire behavior to various levels of fire management personnel. The first phase of this system has been adopted by Canadian fire control agencies, and consists of a fire danger rating scale called the Fire Weather Index (Can. For. Serv. 1970a).

The purpose of the present study is to provide information on important fire behavior characteristics for the initiating phase of forest fires in lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engel.) stands. It is the intention of the study to test whether empirical quantification of fire behavior in forest stands on small research plots is a usable approach to providing basic data for development of the predictive guides envisioned for the Canadian Forest Fire Behavior System. The field test fires were conducted during three fire seasons in the Prince George Forest District of central British Columbia.

Objectives

The first objective is to develop a field technique to quantify fire behavior parameters in standing timber from time of ignition to time of steady state behavior in surface fuels. Head fire spread rate, flame length and depth, and fuel consumption will be measured. It is intended that the study also provide information on fire crowning potential by documenting threshold conditions for vertical fire growth.

Such a test fire technique will be employed over a range of fire environments in lodgepole pine stands. Observed fire behavior parameters will be related to descriptors of the fuel complex, to weather parameters, and to indices of the Canadian Forest Fire Behavior System. Guides for fire management in this fuel type relating to expected fire behavior at various levels of Fire Weather Index will be prepared.

Observed spread rates and the measured fuel and weather elements of the fire environment will be used as input into the U.S. Forest Service fire spread model to determine the relationship of model predictions to fire spread observed in a specific natural environment.

CHAPTER II

REVIEW OF LITERATURE AND CURRENT RESEARCH

Development of Fire Danger Rating

Most past and present fire behavior and fire modeling studies have been oriented towards directly or indirectly improving fire danger rating systems. This study has a similar goal and hence a mention of danger rating principles is in order. The U.S. Forest Service (1956) defined fire danger as the "resultant of both constant and variable fire danger factors which affect the inception, spread, and difficulty of control of fires and the damage they cause." Fire danger rating was defined as "a fire control management system that integrates the effects of selected fire danger factors into one or more qualitative or numerical indices of current protection needs."

This concept of fire danger rating has not drastically changed since the need for objective estimates of fire control requirements was first recognized early in this century. What has changed fire danger thinking is the recognition that a single comprehensive system is now required for efficient administration. Such a system must be applicable to any geographic region by being designed to account for all significant climatic differences and resultant fuel complex differences. It is the tremendous geographic variability in fuels and hence in fire behavior that led to a great many regional danger rating systems being developed in Canada and in the United States. However, for danger rating to be used most effectively for fire control resource allocation, all agencies and all parts of the country should be able to communicate and make decisions in terms of a single system. National systems of danger rating are current goals of U.S. and Canadian fire research organizations.

Empirical Fire Behavior Studies

Empirical studies of fire behavior in a natural environment began some fifty years ago (Show 1919) and were continued by Curry and Fons (1938, 1940). Some of the first fires in artificially constructed fuel beds under a controlled environment to determine the physical laws governing fire spread were reported by Fons (1946). His spread model defined the relationships of spread rate to such fundamental measurable variables as wind speed, moisture content, time, and slope. Fons also considered the importance of fuel bed compactness, fuel particle size and density, and fuel temperature. He was probably the first to suggest the concept of equilibrium or steady state fire behavior in terms of a constant fire environment producing a constant spread rate.

In Canada, early fire research studies were conducted by Wright (1932) and Beall (1947) primarily to produce fire danger rating systems with regional application. Paul (1969) and Russell and Pech (1968) described the standardized methodology used for several decades of Canadian fire danger rating, which included correlation of incipient test fire behavior with weather and fuel moisture conditions. Spread rate, flame size, and smoulder characteristics were some of the fire behavior properties evaluated. Behavior of these very small, point-source, two minute duration test fires in natural surface fuels under timber stands was studied not for developing scaling laws of fire behavior but for correlating incipient fire behavior with indexes of fuel moisture content.

Canadian studies of steady state fire spread in timber stands on instrumented plots and on a scale such that all fire environment factors could be evaluated were limited to those of Van Wagner (1964, 1965, 1968a) until the present national fire behavior rating development program was undertaken in 1968. The two-minute duration incipient test fire technique of predicting fire behavior has been abandoned in favor of techniques which will provide fire behavior information for the period of growth up to steady-state spread in the surface fuel complex.

Countryman (1964) described the problems of extrapolating from small laboratory or field test fires to large fires, noting that a different set of controls of fire behavior may take over after a fire reaches a certain size or intensity. He suggested that for very small fires, burning characteristics of individual fuel particles and their arrangement and continuity are of paramount importance to growth and spread. As a fire grows horizontally and vertically, behavior is controlled by the more gross elements of the fuel bed. For instance, in the initial growth stage, burning rate of each pine needle in the surface litter and distance to the next unburned needle will control spread, but at the crowning stage it is the burning characteristics of individual trees and spacing of trees which determines whether crowning can be sustained and what intensity and spread rate will be exhibited.

Buck (1971) described stages in fire growth. First is a period of initial heat buildup which persists from ignition until a sufficient rate of heat output is achieved so that the fire can react with forces causing spread. The burning area from point ignition becomes doughnut shaped as the central portion burns out in the absence of wind or slope (Curry and Fons 1938). As flame angle becomes vertical with continued fire growth, rather than angled away from the unburned fuel as occurs initially, more effective heat transfer in the horizontal direction is possible (Buck 1971). Presence of slope or wind reduces the establishment period required before fire environment interactions can occur. Buck suggested 10 to 30 B.t.u./min. as the minimum rate of heat output from an established fire to make it susceptible to spread forces.

The next stage of fire growth is described as the acceleration period, the duration of which depends on a number of complex interactions between fuels, wind, and slope. Buck lists several fuel factors determining acceleration of spread and intensity, including kinds, sizes, distributions, moisture contents and moisture gradients, loading, and burnout time. A fire may stabilize in rate of spread and heat output or may enter what Buck terms the transition stage, which begins when heat output rate is sufficient for convective activity to begin to offset near-ground forces which normally regulate surface fire behavior. Three criteria given by Buck as requirements for the transition growth stage are large depth of flaming front in relation to frontal length, large enough flaming area to be considered an area heat source rather than a line or point source, and total heat output rate sufficient to significantly disturb the surface wind field around the fire. Buck therefore rules out the probability of fires in forest litter entering the transition stage, principally because of low available fuel loadings and short fuel burnout times. The results of the present study would support this reasoning.

Thomas (1967, 1971) suggested a spread theory and presented data which allows two possible stable spread rates through forest fuel complexes, dependent on the dominating heat transfer mechanism, fuel bed depth, and bulk density. In a "fast" but stable spreading fire, flames are thick, with flame fronts at least 30 feet deep, and radiation from the overhead flame controls spread. The other type of equilibrium spread is the "slow" spread rate accompanied by thin flames of low emissivity. Such behavior is typical of fires in forest litter. Spread rate of fires in these shallow fuel beds may be controlled by overhead flame radiation at lower wind speeds than for deep fuel beds. In shallow fuels, the small thin flames are subject to deflection by very light winds, whereas thick flames in deep fuel beds resist deflection by wind. The low emissivity flame fronts observed in the present study were subject to drastic deflections by winds as light as 3 mph in the forest stand.

Besides the early work of Curry and Fons, which involved small scale point ignited surface fires in California ponderosa pine (_Pinus ponderosa_ Laws.) stands, some important fire behavior work in timber stands has been conducted by Russian researchers. Amosov (1964) conducted surface fires using point ignition in lichen-moss fuel types in Siberian jack pine (*Pinus banksiana* Lamb.) stands. Plots ranged up to one tenth acre and frontal spread rates were measured as they varied with wind, fuel moisture and fuel type. He concluded that after an initial period of acceleration, spread rate reached an equilibrium, generally after 18 to 24 feet of frontal spread. Curry and Fons (1938) suggested for the more flammable ponderosa type that 30 to 45 minutes are probably required for stable spread rates to be achieved and perhaps longer for stand wind speeds above 5 mph. Similar growth periods were observed in the present study.

Another Soviet, Vonskii (1957), quantitatively defined surface fire intensities which could be expected in three different surface fuel complexes under jack pine stands in the Soviet Union. He defined intensity as the quantity of heat released per unit time per unit length of fire front, similar to Byram's (1959) definition. He described fire intensity in terms of rate of spread, flame height, depth of flame front, and fuel consumption. In Vonskii's view, the principal controllers of intensity are fuel type, moisture content, wind, and topography, with wind being most important. Vonskii suggested that only low to medium intensities will be observed in lichen-moss surface fuels and these intensities will not generally produce crowning of pine stands. These intensities include rates of spread below 15 fpm, flame heights below 6 feet and frontal flame depths less than 9 feet. The present study corroborates Vonskii's results.

Relevant studies of fire behavior on a small scale in a laboratory-controlled environment have been conducted in many fuels ranging from the vertical twigs of Fons (1946), to the U.S. Forest Service Project Fire

Model studies in wood stick cribs (Byram et al. 1966), to the pine needle test fires of Rothermel and Anderson (1966), and the powdered artificial fuels of Murphy et al. (1966). The conclusions of this host of studies could be summarized as follows: Rate of spread varies directly with wind velocity, fuel loading, fuel temperature, and fuel bed porosity. Rate of spread varies inversely with fuel moisture content, fuel particle size and bulk density of the fuel bed (Fons 1946; Anderson 1964; Anderson and Rothermel 1965; Beaufait 1965; Rothermel and Anderson 1966; Anderson et al. 1966).

Stocks and Walker (1968) concluded from laboratory studies that the presence of green vegetation has little effect on rate of spread in no-wind fires and backing fires, due to heat transfer being primarily through the fuel bed. They suggested that herbaceous material may retard the spread of head fires due to suppression of flame size, as the overhead flames are the major heat transfer mechanism in headfires in shallow fuel beds. The present study would suggest that herbaceous material increases spread rate of head fires, as long as there is sufficient dead fuel dry enough to supply the large heat of preignition of the moist, green vegetation.

Murphy et al. (1966) documented the phenomenon of decreasing head fire rate of spread as wind increases from zero to 2 mph, followed by increasing spread rates at higher winds. Such a tendency was observed on the point-ignited fires in the present study. They attributed this feature to the formation of a vertical convection column at zero wind which permits entrainment of air at the fuel surface on both sides of the front. A light wind of 1 to 2 mph, however, bends the smoke column over the heading front, preventing entrainment of fresh air from the burned side and causing dilution of the available oxygen with combustion-inhibiting products.

Fire Behavior Modeling

The most significant early attempt at mathematically representing fire spread in forest fuels was the model of Fons (1946) who described flame propagation through a fuel bed as a series of successive ignitions. The rate of spread was considered to be controlled by the ignition time of the fuel particles and the distance between them. No significant variables of the fire environment have been found since Fons' pioneering work, with the exception of some fuel chemistry factors now known to be important in determining combustion rate (Philpot 1970).

Project Fire Model, reported by Fons et al. (1960, 1962) and Byram et al. (1964, 1966), used laboratory fires in stick cribs to define functional relationships between many fire behavior characteristics and fire environment variables. These studies determined that for wind-driven fires, the contribution of flame radiation to the ignition of new fuel is small compared to that of flame envelopment and flame contact. The effect of flame radiation was suggested to increase with increasing fire intensity, however.

Emmons (1963, 1965) presented a theory of energy transfer which encompassed all methods of energy transfer from a fire to unburned fuels, including turbulent eddies and fire brands. Emmons (1965) noted in these discussions that:

> There is little hope and little incentive to try to understand the rate of fire spread along a particular branch of a tree. Rather it appears more profitable to try to find a statistical method of defining the fuel distribution and then to find the fire-front propagation rate as a statistical average.

Similarly, Thomas (1971) suggested with respect to wildland fire behavior modeling that:

> ...the problems raised by the convection in high winds, the inhomogeneities of natural fuels, the non-uniform distribution of moisture in depth in duff and litter, make it difficult to present a useful physical theory for natural fuels without a considerable element of empiricism. Statistical models are perhaps more appropriate for systems subject to so much variation, but some physical interpretation is clearly a useful ingredient.

Fang (1969) used mathematical modeling to correlate observed wind-driven spread rates in fine fuels with energy transfer mechanisms, including both overhead flame radiation and convection. Experimentally he found convective heat fluxes to be significantly greater than burning zone radiation under wind conditions. In fact when allowing for both flame radiation and radiation through the fuel bed, heat transfer to unburned fuel was 1.5 times as great for hot gas convection as it was for total radiation.

Other fire spread models of varying degrees of generality include the following:

Albini (1967) presented a graphical model of fire spread through a brush fuel with spread rate, flame length and flame depth as functions of fuel bed parameters and wind.

Steward (1971) described a spread model based on heat transfer to and from the unburned fuel considering radiation through the fuel bed, convective transfer to fuel ahead, and convective loss from fuel ahead by air drawn through the fuel bed into the burning zone. This model ignores overhead flame radiation as being insignificant in still air fires. Acceptable spread correlations were obtained with experimental fires in wood excelsior.

Berlad (1970) presented a theoretical model of quasi-steady fire spread through solid fuel arrays, including a detailed analysis of fire spotting processes.

Kourtz and O'Regan (1971) modeled surface spreading fire through varying fuel types. They used a probabilistic approach to spatial fuel distribution, making this model different from most preceding ones which made no attempt to account for nonhomogeneous fuels. Spread rate and flame persistence is predicted for a number of fuel types and fuel moisture contents, although wind and slope are not accounted for.

Van Wagner (1969) described a simple geometric model for large fire growth over time, specifically for fire control planning. Perimeter and area are predicted from spread rate and time from ignition, assuming that fire growth produces an elliptical fire shape.

Recent work by several U.S. Forest Service fire researchers has resulted in a model of fire spread through continuous surface fuel arrays. Anderson (1969) experimentally tested a mathematical model adapted from earlier work of Fons (1946) and Thomas and Sims (1963). He found reasonably accurate predictions of spread rate in porous fuels were possible by making assumptions about horizontal convective heat transfer. Total radiant heat transfer could not account alone for more than 40% of the total heat flux required to maintain fire spread. Frandsen (1971) corroborated the earlier work of Thomas and Sims (1963) and Anderson (1969) by applying the conservation of energy to a unit volume of the fuel bed ahead of an advancing flame front, i.e. during the preignition phase. Rothermel (1972) has experimentally tested and quantified a number of parameters suggested by the model theory as being significant in accounting for spread rates in wildland fuels.

Rothermel (1972) has adapted this fire spread model such that it is applicable to heterogeneous fuel arrays and such that input variables of fuels, fuel beds, and the fire environment are measurable in the field. The model is applicable to initiating fires which have reached steady state combustion, and excludes spread by fire brands. This spread model is integrated into the U.S. National Fire Danger Rating System by way of a series of fuel models (Deeming et al. 1972). Fuel complexes have been defined in terms of loading, depth, and particle size for both dead and living fuels. Rates of spread and energy release for the various fuel complexes are presented as component indices of a universally applicable Danger Rating System (Deeming et al. 1972). The spread model is described in Appendix II.

Measurement of Forest Fuel Complex

Fire researchers are in general agreement on the most significant characteristics of a fuel complex which affect fire behavior. Quantity, arrangement, and size distribution of fuel components are the basic fuel factors governing ignition, spread, and intensity of fire (Fons 1946; Fahnestock 1960). Fuel particle geometry, including size, shape, and density can account for differences in ignition time and burning rate (Fons 1946). An accepted measure of fuel particle size is surface-area-to-volume ratio, or σ (Curry and Fons 1938). Fuel bed arrangement can be described in terms of porosity, or void volume to total fuel bed volume ratio of the fuel complex, expressed by the symbol ϕ . Rothermel and Anderson (1966) accounted for fire spread in needle beds with the combined fuel variable $\sigma\lambda$, where λ is the hydraulic radius of the fuel bed, defined as the ratio of void volume to surface area. Bulk density (weight per unit volume) is another measure of fuel bed porosity, having an advantage over ϕ and λ of easy measurement (Brown 1970). Compactness of a fuel bed can be quantified by the packing ratio, β , which is the ratio of fuel array bulk density to fuel particle density (Rothermel 1972). Loading (weight per unit area) is important as a measure of potential fuel energy or fire intensity (Brown 1970).

The total fuel complex, including both ground and aerial fuels, must be accounted for when fire behavior in forest stands is of interest. The ability of fire to become established in tree crowns depends on transport vertically via some type of ladder fuel and a suitable degree of horizontal continuity of the tree crowns to permit continuous spread (Molchanov 1957; Muraro 1965). Distribution of aerial fuels, including distance from the ground fuels and continuity of aerial fuels, is the key to being able to predict whether a given flame length and fire intensity in the ground fuels can move into the aerial fuels (Muraro 1971). Quantification of aerial fuel distribution is difficult, although Muraro (1971) presented a number of measured distributions for various lodgepole pine stands. A subjective system of rating the crowning potential of various fuel distributions was suggested by Fahnestock (1970).

Some of the important fuel complex parameters present few measurement difficulties in heterogeneous forest stands. Simple methods of measuring volumes and surface areas of discrete particle-type fuels lying on or near the ground surface have been developed. Examples are the line and planar intersect methods of Van Wagner (1968) and Brown (1971). Also weights of crown fuel components can be satisfactorily predicted from such measurements as tree diameter, height, stand density, and site quality (Brown 1965; Kiil 1967, 1968; Johnstone 1970; Muraro 1971; Smith 1970a and b).

Indirect estimation of litter and duff surface fuel loadings from easily measured stand parameters has not been generally successful, however. Muraro (1971) and others suggest that current stand measurements do not reflect the past fire history of the stand sufficiently to allow prediction of surface fuel quantities. Direct measurement of duff and litter depths and weights are still required.

A number of other studies have been reported which can eliminate some fire-related fuel measurement problems. Muraro (1964) described surface-area-to-weight relationships for branch litter under lodgepole pine stands. Brown (1970a and b) and Countryman and Philpot (1970) measured fuel bed porosities and such fuel particle characteristics as surface-area-to-volume ratio and particle density for a number of fuels. Some fuel chemistry studies have provided a data source for such important fuel characteristics as caloric value (Bliss 1962; Mutch 1964; Hough 1969).

Kilzer and Broido (1965) and Shafizadeh (1968) described some effects of fuel chemical composition on flammability. Philpot (1968, 1970) measured ash contents for a number of fuels, noting that small differences in silica-free ash content of fuels can greatly affect flammability. Philpot and Mutch (1971) suggested that although conifer foliage moisture content tends to rise through the fire season, the highly flammable foliar extractives increase to their maximums through the fire season and could affect crown fire potential.

Summary

The preceding literature review is not complete but represents the highlights of the reviewed works which helped define the scope and methodology of the study and helped to explain some of the observed results. It was possible to bridge the gap between methodology suited to the laboratory and what is possible to quantify in the field only through such an extensive review of the related work of others.

CHAPTER III

FIELD PROCEDURE

Introduction

It had been planned to conduct a test fire program on two physically different lodgepole pine sites and measure fire behavior over a range of stand, surface fuel, and weather conditions. The stand conditions selected were representative of a dry pine site and a fresh or moist pine site in the Montane Transition or M.4 forest classification type (Rowe 1959). However the moisture regime and fuel arrangement on the fresh site permitted conducting of only two fires on this site, so the test fire program was confined mainly to the dry pine type.

The Study Area

A study area was selected in the north-central interior plateau of British Columbia, in the Prince George Forest District. This area is rolling upland interspersed with broad valleys. Topography is gentle and elevations vary from 1500 to 2500 feet in the valleys and from 3000 to 4000 feet along the ridges. Glaciation has left glacial till and glacio-lacustrine deposits and drumlins over much of the area. Precipitation occurs throughout the year, with summer and fall months receiving the heaviest amounts, and annual precipitation ranges from about 20 to 36 inches. Soils vary from excessively drained sands and sandy loams on the drumlins to poorly drained organic bogs and mucks in depressions.

Forests in the Montane Transition (M.4) and in the Subalpine (SA.2) sections (Rowe 1959) are spruce (Picea engelmannii Parry and P. glauca (Moen.) Voss) and Alpine fir (Abies lasiocarpa (Hook.) Nutt.) climax with extensive pioneer lodgepole pine stands established as a result of fire history. Pure pine stands normally develop on dry to fresh sites while mixed pine-spruce stands often occupy moist sites (Armit 1966). Douglas fir (Pseudotsuga menziesii (Mirb.) Franco), birch (Betula papyrifera Marsh var. subcordata (Rydb.) Sarg.), and aspen (Populus tremuloides Michx.) are often present in minor amounts in the M.4 transition zone (Rowe 1959).

Description of Study Sites

The main weather station and fresh pine site were 36 miles north of Prince George, B.C. adjacent to Highway 97, at an elevation of 2350 feet (lat. N. 54° 22', long. W. 122° 38'). The dry pine sites were four miles further north, one-half mile east of Highway 97. (Fig. 1). These locations are in the B.C. Forest Service Summit Lake Ranger District.

Forests in this area are transitional in nature between montane types to the south and subalpine types to the north and are difficult to classify. The dry pine sites closely resemble the Arctostaphylos-Lichen (AL) site type described by Illingworth and Arlidge (1960), which is an abundant, poor site quality lodgepole pine stand type characteristic of

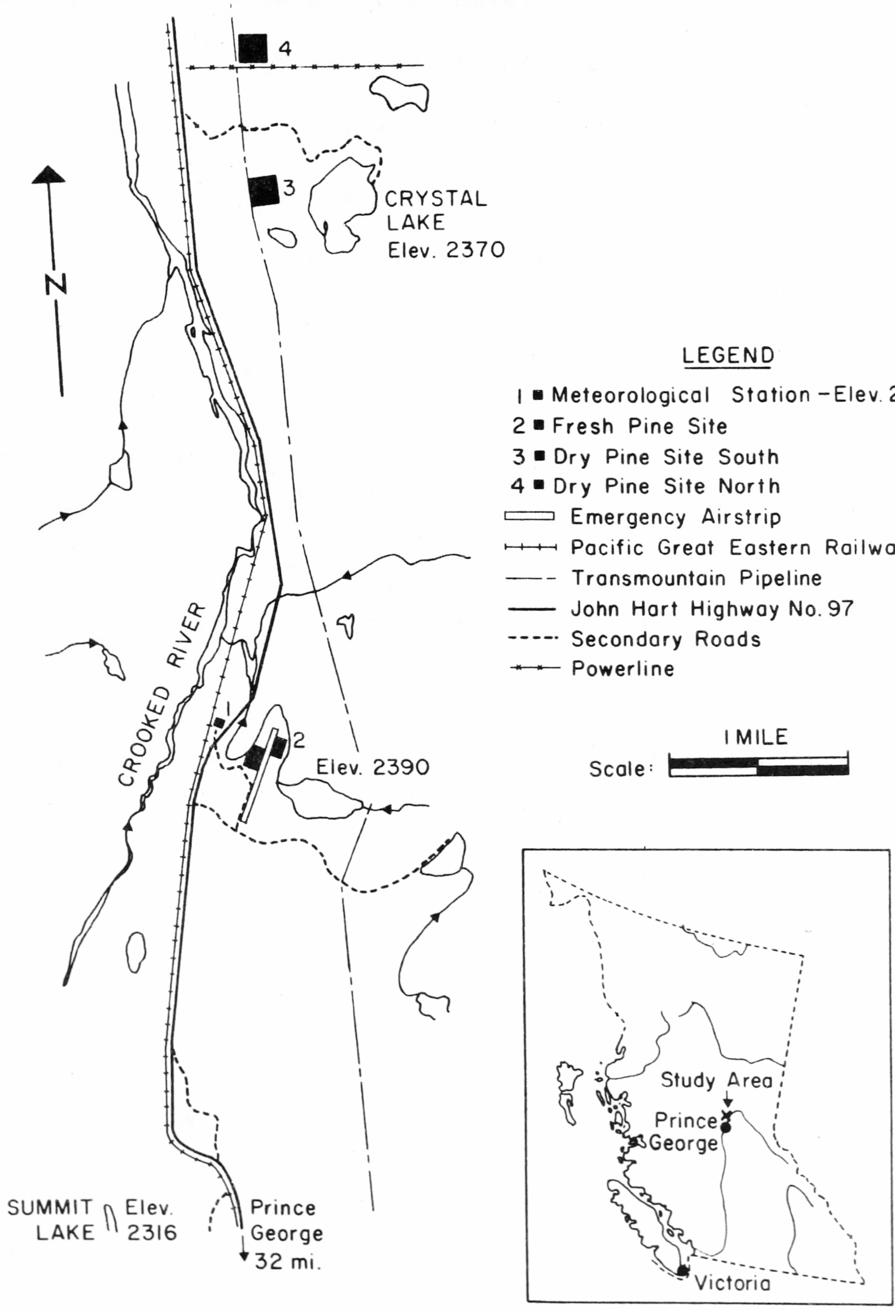

Fig. 1.--Study area location

drier parts of the Cariboo and Chilcotin regions. However, precipitation in the study region is not limiting, although the sandy soils are excessively drained. As a result, mosses form the principal continuous ground vegetation, with moderate cover of Cladonia spp. (reindeer lichen), while Arctostaphylos (bearberry) is of less importance than on a true AL site. The fresh pine site most closely resembles Illingworth and Arlidge's (1960) Cornus-Moss (C-M) site type, which is second lowest of the five spruce-alpine fir site types of this region, in terms of productivity.

Dry lodgepole pine sites

The two dry pine sites are basically pure lodgepole with a scattered low understory of lodgepole pine, spruce, alpine fir, and Douglas fir. Stand characteristics are presented in Table 4. Both dry pine sites have rather open, parklike stands, with the north site stand being denser and shorter than on the south site. The principal stand difference between the sites from a potential fire behavior viewpoint is that the north site has smaller trees with lower green crowns. Both sites are on well drained deep sandy soils.

Differences in organic layer composition are quite pronounced between the two sites. The south site has a well-developed continuous moss layer, mainly Pleurozium schreberi. Reindeer lichen, which includes several species of Cladonia, is fairly abundant, but patchy. Several species of Vaccinium form an almost continuous light herbaceous cover six to eight inches high. Other species forming a minor part of the herb layer include Cornus canadensis, Arctostaphylos uva-ursi, and Chimaphila umbellata. The north site, however, has Cladonia as its best developed, almost continuous ground fuel component, with moss being scattered and patchy. Vaccinium is present but forms a lighter cover. Arctostaphylos forms a fairly complete low cover with the reindeer lichen. No other herbaceous or low shrub species play an important role on the north site. There is no tall shrub layer on either site but a fairly heavy pine advance regeneration layer of 2300 stems per acre averaging 3.5 feet high covers both sites. A light pine needle litter layer lies on and intermixed with the moss and Cladonia layers of both sites.

Fresh lodgepole pine site

This site supports what would appear to be a seral stage of a developing spruce-alpine fir climax. Presently 80% of the stand basal area is lodgepole pine with 20% accounted for by Douglas fir, spruce, alpine fir and scattered birch and aspen. This may be termed a "fresh" pine site (Armit 1966) since the soil is not as excessively drained as on the dry sites, allowing the sub-climax and climax tree species to develop more rapidly and also allowing the continuous lush moss layer to flourish. The soil here is a stoney loamy sand. The moss layer is thicker than on the dry sites, principally Pleurozium and Calliergonella. Vaccinium spp. form a complete, though not a dense cover, about one foot high. Other components of the herbaceous layer include Cornus canadensis, Clintonia uniflora, and Chimaphila umbellata. Cladonia spp. are present, but in small scattered patches, except for stand openings where they dominate the ground layer along with several species of foliose-type lichens, mainly *Peltigera* spp. A shrub layer is generally absent, with the exception of scattered low *Sorbus sitchensis*, *Amelanchier alnifolia*, and *Salix* spp. The herbaceous layer also contains *Lycopodium annotinum*, *Pyrola* spp., *Arctostaphylos uva-ursi*, and *Gaultheria humifusa*. Advance regeneration is moderate, about 1500 stems per acre and five feet in height, composed 50% of alpine fir, 25% Douglas fir, and the remainder spruce and pine.

The site is of higher productivity than the dry sites, with the fresh site having produced approximately the same basal area and cubic volume in 75 years that has been produced on the dry sites in 100 years. Higher productivity is due to this fresh site being less excessively drained, but this factor also accounted for the heavier cover of mosses and herbaceous growth and reduced cover of *Cladonia* which precluded obtaining extensive fire behavior data on this site.

Test Fire Experimental Design

Plot description

Fire spread was evaluated with two plot designs. A circular, centrally-ignited plot and a square, edged-ignited plot were used. Plots were located subjectively on the study areas rather than randomly, so that stand openings and small topographic features could be avoided. It was felt that neither a random selection nor a mechanical grid would offer any advantage over a strictly subjective plot selection.

The circular plots had a 50 foot diameter and an area of .045 acre. Design of the plot is shown in Fig. 2. Twelve radii were staked at 30 degree intervals about the plot centre. Aluminum stakes were used to mark reference points at 5-foot intervals along each radius. Other instrumentation on plots is discussed in the fuel inventory and fire behavior sections.

The square plots were 50 feet on a side or .057 acre. A 10 foot by 10 foot stake grid for reference points was established as shown in Fig. 3.

Fuel inventory

Amounts of fuel in several strata from mineral soil to live crown were measured for each site as follows:

The organic layer was stratified into upper and lower horizons and sampled for density and loading. The moss-*Cladonia* composition of the duff layer did not lend itself to characterization into standard L, F, and H[1] (litter, fermentation, humus) horizons with distinctly different physical characteristics. The low density upper horizon, consisting of needle litter and growing vegetative parts of the moss and *Cladonia* plants, was easily and consistently distinguishable from the lower, densely matted fermentation layers. No humus layer could be distinguished.

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[1] forest floor layers as defined in Glossary of Soil Science Terms, Soil Sc. Soc. Amer. Proc. 29(3): 330-351, 1965.

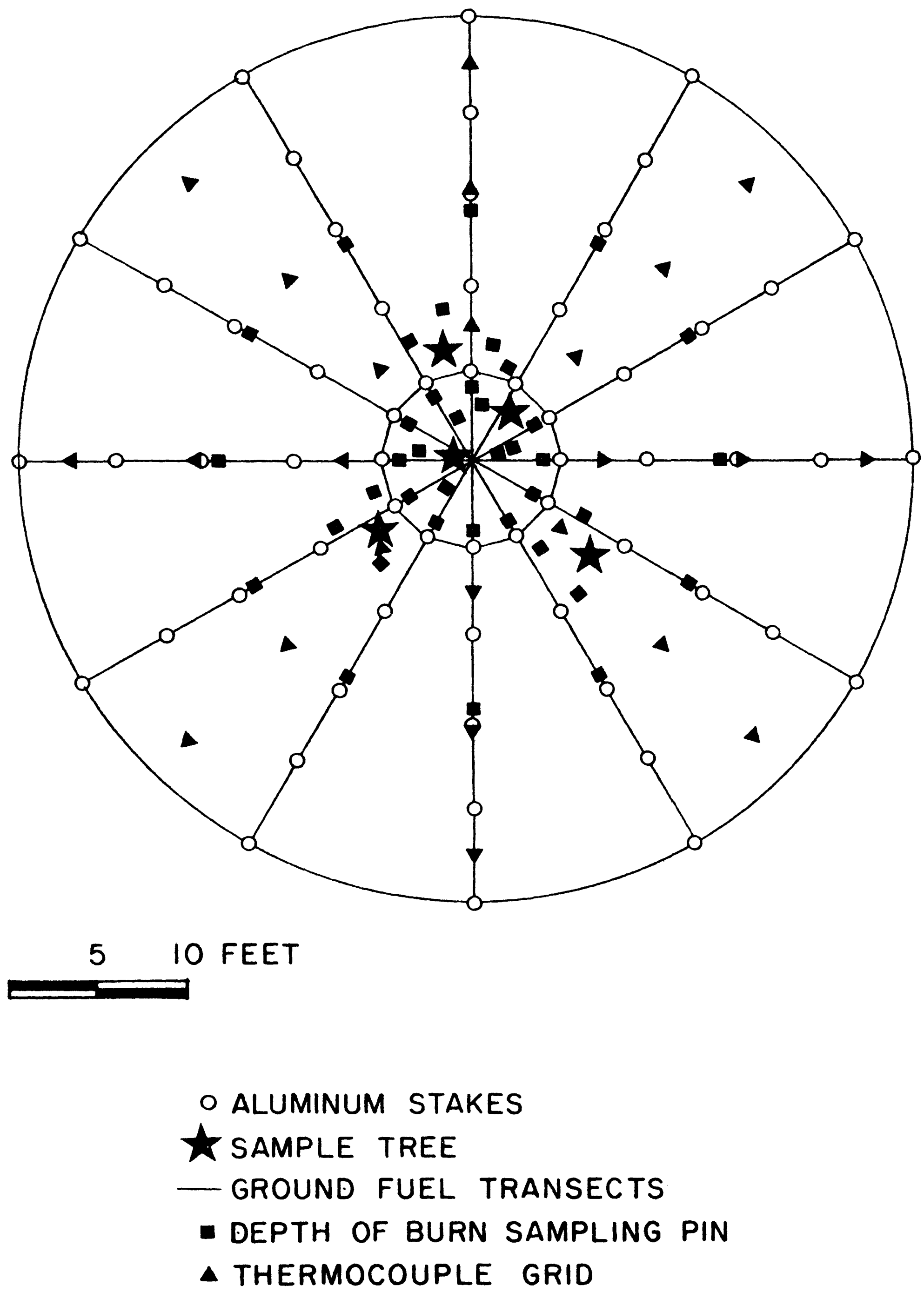

Fig. 2.--Circular test fire plot design

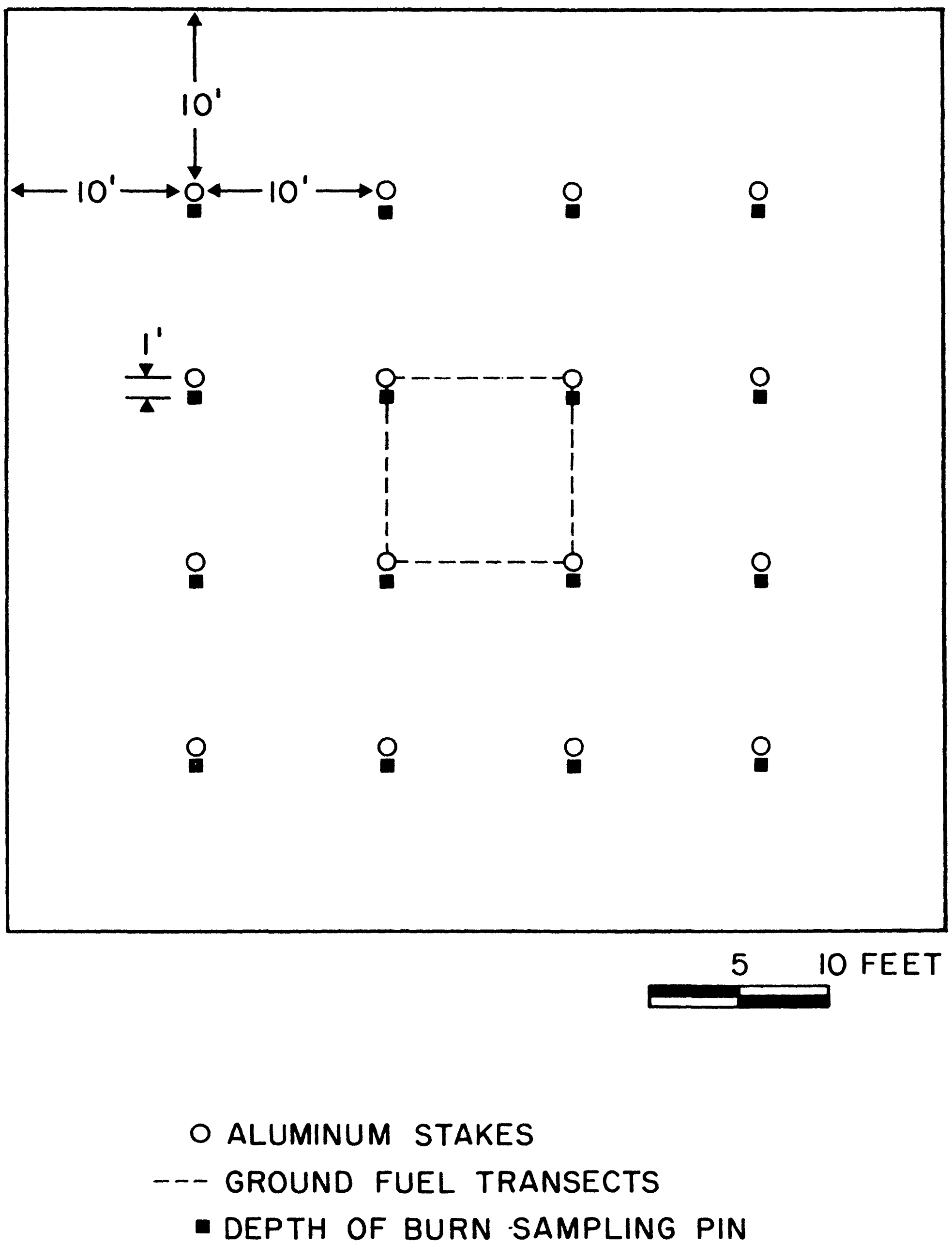

Fig. 3.—Square test fire plot design

Organic layer sampling was based on randomly located one-foot-square plots. Depths of the upper horizon and total depth of the organic layer from the top of the litter layer to mineral soil, but excluding herbaceous material, were an average of four measurements for each sample. The herbaceous and dwarf shrub layer was separated from the remainder of the organic layer, and its contribution to fuel loading determined. Similarly, fine surface litter, including needles and small twigs up to 1/4 inch were sampled separately.

All fuel loading determinations were on an oven-dry weight basis, the samples being dried for 48 hours in a forced circulation oven at 105°C.

Twig, branch, and down-log fuel loading was evaluated on each test fire plot using a line intersect sampling method as described by Van Wagner (1968) and Brown (1971). This method involves tallying only the number of intersections of fuel pieces, by diameter class, over a known length of sample line. The following formulae were used to derive volume, weight and surface area of the cylindrical fuels on each plot:

$$V = L\left(\sum_{i=1}^{k} \frac{\pi^2 N_i d_i^2}{8}\right)$$

where: V = fuel volume per unit area (ft^3/ft^2)

L = unit length perpendicular to sampling line (=1ft)

N_i = number of fuel particle intersections for i^{th} diameter class

d_i = diameter of i^{th} size class (ft.)

k = number of size classes used.

$$S = L\left(\sum_{i=1}^{k} \frac{8.238\ N_i\ d_i}{2}\right)$$

where: S = fuel surface area (ft^2) per unit area.

$$W = V\rho$$

where: W = oven dry weight of fuel per unit area (g)

V = volume of fuel (cm^3)

ρ = density (g/cm^3)

The following diameter classes and modal diameters (d_i) for each class were used in the fuel inventory determination:

diam. class (in.)	modal diam. (in.)
< 0.1	0.08
0.1 to 0.5	0.15
0.51 to 1.0	0.55
1.1 to 2.0	1.50
2.1 to 3.0	2.50
3.1 to 4.0	3.50
> 4.0	5.00

Lengths of sample line tallied were 31.2 feet on each circular plot and 40 feet on each square plot. Fuel loading was based on a specific gravity for lodgepole pine of 0.41 (Kennedy 1965). The modal diameters were used rather than arithmetic mean or class mid-point diameters because of the skewness of the population distributions, particularly in the small diameter range. The data collected by Muraro (1964) was used to determine modal diameters of the three smallest classes.

Shrubs and advance regeneration were mapped and tallied by species and height for each plot. With the exception of *Vaccinium* spp., shrubs were an insignificant component of the fuel complex on all three sites, but advance regeneration did contribute to the total available fuel, principally as a vertical flame-carrying medium, and warranted consideration in the fuel inventory.

Low dead branches on tree boles were considered to add to vertical fuel continuity and were therefore tallied by diameter class and length on each tree, to a height of ten feet. Three diameter classes and three length classes with the following class limits were used:

diam. class (in.)	length class (ft)
$< 1/4$	< 1
1/4 to 1/2	1 to 2
$> 1/2$	> 2

All trees were inventoried as to diameter at breast height (dbh), total height, and height to live crown.

Crowning potential of individual trees was subjectively estimated by examining vertical fuel continuity and type of fuel at the tree base and up the bole. Five trees on each plot were designated on a scale of 1 to 5 as being the most likely to transport a surface fire into the aerial fuels. Factors given weight in this subjective crowning potential determination included accumulation of fine fuel material such as needles and twigs around the tree base, presence of dry "deer moss" and dead branches on the lower bole, and a low green crown.

Fuel moisture content

Destructive samples from several fuel strata were taken on a daily basis, with the exception of days with measurable rain, in order to determine moisture content trends and to permit correlation of fire behavior with moisture content of important fuel components. On days that test fires were conducted, moisture samples were taken on the plot to be burned, immediately prior to ignition. On other days, samples were taken from a designated area adjacent to the test fire plots.

The organic layer was divided into the same strata for moisture content determination as for loading samples. Herbaceous material, including the low shrub layer of *Vaccinium* spp., was the first stratum removed. Fine surface material, which included needles, twigs less than 1/4" diameter, and the ventilated tips of *Cladonia* spp. and moss was considered as the stratum most influential on fire rate of spread, from a moisture content viewpoint. Next, the upper horizon or low density portion of the organic layer was removed down to the compact F - horizon. Finally, the lower F - horizon was removed as a stratum down nearly to mineral soil. Care was taken when sampling organic material next to mineral soil not to attempt to remove all the F - layer, since inclusion of even small amounts of mineral soil in the sample renders it useless as a moisture content indicator. Organic layer sampling was on a square-foot basis, and two samples were taken on each test fire plot prior to burning.

Cylindrical ground fuels were sampled in three diameter classes, as random composite samples taken from the test fire plot on burning days and from the designated sampling area on non-burning days. Twig, branch, and downlog fuels were sampled from the following diameter classes:

1/4" to 1/2"
1/2" to 1 1/2"
1 1/2" to 3"

Samples of regeneration and tree needle moisture content were taken on burning days from randomly selected trees.

Oven drying of samples for 48 hours at 105^{o}C was the standard for determining oven dry weights for moisture content calculation.

Weather measurements and Forest Fire Behavior System indices

Significant fire weather variables were measured on continuous-recording instruments at a weather station adjacent to the fresh pine experimental site in a large, fully exposed opening. Measurements included temperature and relative humidity, recorded by means of a hair hygrothermograph, daily rainfall, using a siphon-type recording gauge, continuous wind speed and direction at a height of 33 feet, using an analog recorder for speed and eight-point event recorder for direction. These are the variables required for calculation of the Canadian Forestry Service Fire Weather Index (Can. For. Serv. 1970a), which was one basis of accounting for test fire behavior. Additional background meteorological data were collected, including daily duration and intensity of solar radiation, relative amounts of dew and maximum and minimum temperature.

An auxiliary weather station was operated adjacent to the dry pine sites to account for local precipitation differences, because of large areal variability of summer rainfall in this region. Only temperature, relative humidity and rainfall were monitored at this station, along with B.C. Hazard Stick moisture.

Components of the Canadian Forest Fire Weather Index were calculated for each weather station, with main weather station wind data being applied to the auxiliary station readings of temperature, relative humidity and rainfall.

Temperature, relative humidity and B.C. Hazard Stick moisture were measured in the timber stands on both fresh pine and dry pine test fire sites, using a hygrothermograph exposed in a shelter at 4 feet.

Weather measurements taken during test fires are discussed in the next section.

Fire behavior and impact measurements

Ignition of the point-source fires was accomplished by assembling a cubic foot pile of dry twig and branch material at the plot centre and lighting it with matches. Because this heat source influenced the initial fire behavior, observed spread rates for the first six minutes were eliminated from analysis.

The strip plots were ignited by drip torch using a single line of gasoline-diesel fuel as the initial energy source. Because of the rapid burnout time of this fuel, only the first minute of fire spread after ignition was affected by the added fuel.

Rate of spread was measured by plotting the fire front position at three-minute intervals for circular plots and at minute-intervals for strip plots. Mean and maximum heading flame lengths and fire front depths to the nearest half foot were also estimated at these intervals. A grid of 24 thermocouples provided auxiliary spread and residence time data on some tests. Time-lapse 35 mm photographic records were also made of some of the test fires. Tape recorded notation and spot photographic records were made of changes in fire behavior such as sudden accelerations of spread or movement into tree crowns.

Wind speed over the time interval used to measure spread rate was measured in the stand adjacent to the test fire at a height of 3.5 feet with a sensitive cup anemometer. Wet- and dry-bulb temperatures were recorded prior to ignition at the ignition point, 4 inches above the duff surface.

Fire impact was determined by measuring fuel quantities removed and by observing mortality of advance regeneration one month and again one year following the fire. Organic layer fuel depletion was indirectly measured by multiplying the measured length of exposure of depth-of-burn pins by site mean fuel loadings per inch of depth, as determined in the pre-fire fuel inventory. Cylindrical-type fuels were retallied after the burns on the same intersect lines as the pre-burn inventories, and depletions calculated.

Fire control precautions

Test fire plots were individually protected by 18 inch wide, hand-dug fire lines. Hand tools for a crew of four were provided, including hand-tank pumps, shovels and pulaskis. A fire pump and hose line supplied water to each test plot. Complete mop up of all hot spots followed each test fire, but this task was minimal because of the small quantities of fuels having long burnout times. No control difficulties were experienced, although numerous spot fires resulted outside the plot areas from firebrands falling from individually crowning trees.

CHAPTER IV

RESULTS

Fuel Distribution

Surface fuels

Loadings, depths and bulk densities of the surface fuels on each test fire site are presented in Table 1. The sampling unit was one square foot and the reported values are means of 43, 24, and 20 randomly located samples for the Dry Pine South, Dry Pine North, and Fresh Pine Sites, respectively.

Loadings by diameter class and site are given in Table 1 for branch and log fuels lying on the ground. These are the means of the line intersect samples for the 25 Dry Pine South plots, 8 Dry Pine North plots, and 11 Fresh Pine plots.

It is apparent from these data that the surface fuel characteristics of loading and bulk density were similar on all three sites. There was significantly more branch and log fuel of sizes greater than one inch on the Dry Pine South site than on the other sites, but most of this fuel was not a significant contribution to fire front propagation, due to its long burnout time.

In order to more completely describe the surface fuel complex, individual fuel particle measurements were made on the three dominant

TABLE 1.--Surface fuel loadings and bulk densities by site

	Dry Pine South	Dry Pine North	Fresh Pine
Loading of herbs and low shrubs (lb/ft^2)	.008	.010	.006
Depth of herbs and low shrubs (in.)	6	6	12
Loading of fine surface litter (lb/ft^2)	.011	.007	.009
Loading of upper organic layer (lb/ft^2)	.139	.128	.128
Depth of upper organic layer (in.)	.77	.85	.86
Bulk density of upper organic layer (g/cm^3)	.035	.029	.029
Loading of total organic layer (lb/ft^2)	.333	.229	.386
Depth of total organic layer (in.)	1.2	1.2	1.4
Bulk density of total organic layer (g/cm^3)	.053	.037	.053
Loading of surface branch fuel 0-1/2 in. (lb/ft^2)	.008	.005	.007
" " " " " 1/2-1 in.	.003	.002	.002
" " " " " 1-2 in.	.013	.005	.003
" " branch and log fuel 2-3 in.	.016	0	.008
" " log fuel greater than 3 in.	.087	.052	.016
Total surface fuel loading (lb/ft^2)	.468	.303	.428

particles and the results are listed in Table 2. Sampling was limited because the microscopic measurements required to determine particle density and surface-area-to-volume ratio (σ) are tedious. The results show the moss particles to be almost as dense as the needles, whereas Cladonia particles are extremely low in mass. The low density and hollow stems of Cladonia are the reason for its very rapid response to climatic change and, when coupled with its fineness as indicated by the high surface-area-to-volume ratio, it is apparent why this fuel is a rapid fire carrier. The moss showed a very high surface-area-to-volume ratio primarily because of the large contribution of its numerous very thin "leaves" to surface area. These leaves make a very small contribution to the available energy of the fuel, however, so that the high σ is not indicative of its fire potential.

Standard bomb calorimetry tests were run on the fuel particles to determine low heats of combustion and ash contents (Table 2). The results showed significant differences between the three particles with Cladonia having the lowest heat yield and pine needles the highest. The reported values are the means of three test runs.

Because there were obvious surface fuel differences between organic layers containing Cladonia as opposed to those without Cladonia, a separate sampling experiment was run to determine quantitatively what these differences were. Twelve 15 cm.-square samples of the upper organic layer were randomly selected, seven from areas with Cladonia and five without. All three test fire sites were included in the sampling. These samples were dissected in the laboratory to determine proportions of moss, needles and Cladonia by weight and by volume and to determine fuel descriptors for the fuel complex as a whole. The results shown in Table 3 indicate no difference in loading between areas containing Cladonia and those without, but the bulk density for Cladonia types is somewhat higher. Surface-area-to-volume ratio for Cladonia complexes is slightly lower, porosity of the fuel bed somewhat lower and the dimensionless variable $\sigma\lambda$ is lower than for fuel samples with no Cladonia. Also the packing ratio (β) of bulk density to particle density was considerably higher on the Cladonia samples.

These results would suggest the non-Cladonia fuel complexes to be better fire carriers than Cladonia types. This was found experimentally not to be the case and the reasons are due to factors not accounted for by the basic fuel descriptors. Fuel descriptors describe surface area of the fuel particles but not necessarily the relative importance of the arrangement of that surface area. For instance moss had a high σ, but 87% of the surface area was in minute microscopically thin leaves with a low volume and negligible energy contribution. Cladonia, on the other hand, has a lower σ but its surface area is advantageously distributed from the point of view of carrying fire from particle to particle.

Figures 4 to 7 show the gross and detailed surface fuel complexes of both Cladonia and moss types.

TABLE 2.--Fuel particle descriptors

	Mean	Range	n
Cladonia particle density ρ_p(g/cm^3)	.15	.14-.19	4
Moss particle density	.54	.48-.62	4
Pine needle particle density	.59	.56-.72	6
Cladonia surface area:volume ratio σ(cm^{-1})	170	165-175	7
Moss surface area:volume ratio	318	250-367	11
Pine needle surface area:volume ratio	83	74-84	12

	Heat content[1] (Btu/lb)	Ash fraction (%)
Cladonia	7425	2.0
Moss	8141	2.6
Pine needle	8925	1.5

[1] heat contents are "low" heats of combustion, ash free weight basis, means of three sample runs.

TABLE 3.--Upper organic layer fuel bed descriptors

	Cladonia Present			Cladonia Absent		
	Mean	Range	n	Mean	Range	n
Loading (lb/ft^2)	.136	.093-.167	7	.136	.108-.166	5
Depth (in.)	1.0	0.6- 1.2	7	1.3	1.0- 1.6	5
Bulk density ρ_b (g/cm^3)	.027	.017-.039	7	.021	.018-.027	5
Surface:volume ratio σ(cm^{-1})	141	128- 165	7	154	105- 186	5
Fuel bed porosity λ(void vol./surface area) (cm)	.152	.119-.206	7	.212	.150-.280	5
$\sigma\lambda$ (dimensionless)	21.6	16.1-34.0	7	31.3	27.9-35.7	5
Packing ratio β ($\rho b/\rho p$) (dimensionless)	.075	.039-.126	7	.037	.032-.047	5

Fig. 4.--Total fuel complex, Dry Pine South site

Fig. 5.--Surface fuels, Dry Pine sites

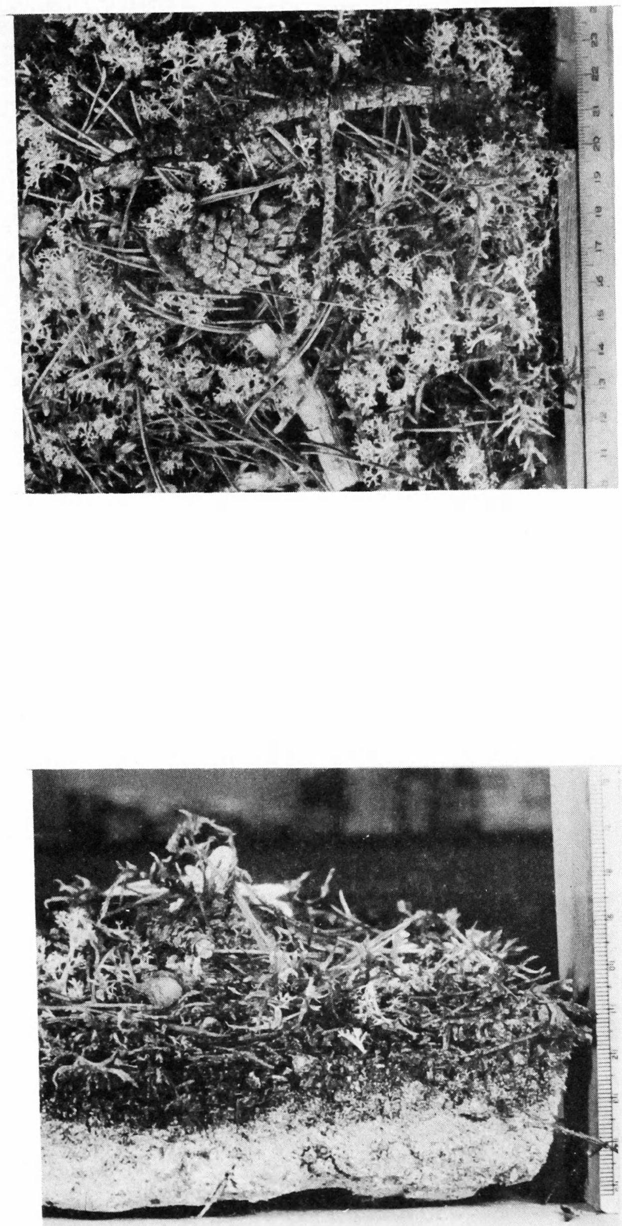

Fig. 6.--Plan and side views of *Cladonia*-type surface fuel complex

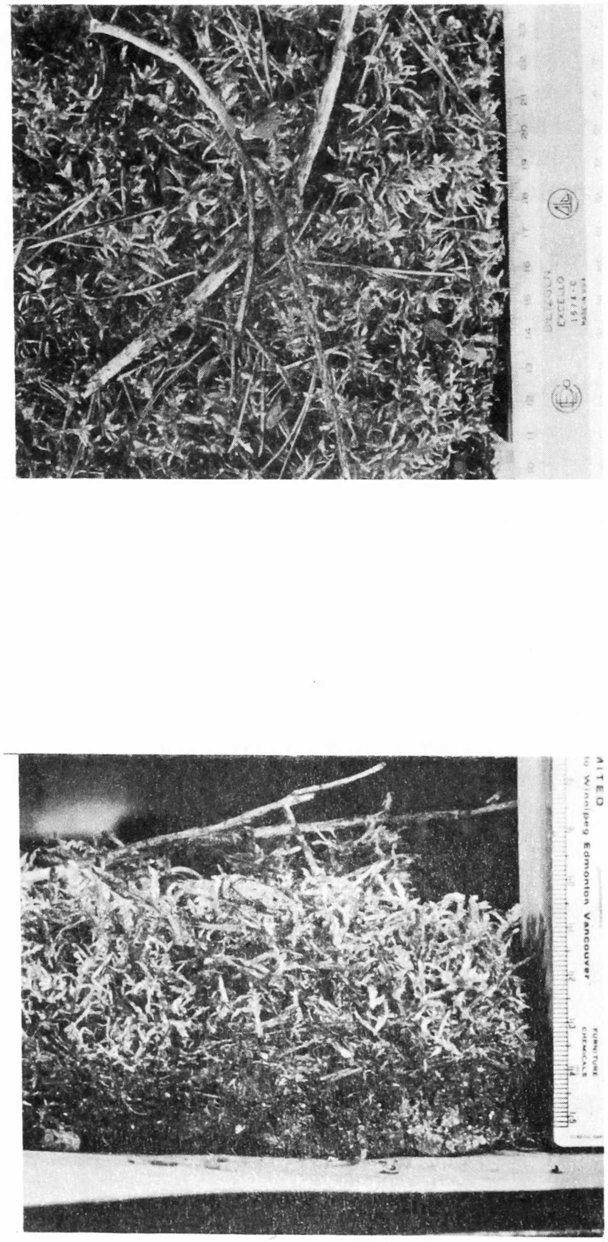

Fig. 7.--Plan and side views of Moss-type surface fuel complex

Aerial fuels

There were major differences between test sites in some of the characteristics of the standing fuel complex, which includes standing trees and advance regeneration. While it was recognized that the surface fuel complexes would likely be limiting to extensive vertical fire growth in these stands, a range of aerial fuel conditions was desirable. Figure 4 shows the standing fuel complex of the Dry Pine South site.

As Table 4 shows, the Dry Pine North site had more live trees per acre and the height to the live crown base was considerably shorter than for the Dry Pine South site. Also more bridge fuels capable of carrying fire up the tree boles were present on the North site and slightly more and taller advance regeneration on the average. With respect to regeneration, however, it was found that a few tall regeneration trees were more important than many shorter ones. In this respect, the South site had more significant fire carriers, represented by the taller D ouglas fir and spruce regeneration (Table 4).

The Fresh Pine site had denser stocking than the other sites, but crown heights were too great to permit significant vertical fire transfer from the generally mossy surface fuels. The limited vertical fire mobility which was observed on this site was due mainly to the presence of short understory Douglas fir and spruce trees reaching to the main canopy.

TABLE 4.--Standing fuel characteristics

	Dry Pine South	Dry Pine North	Fresh Pine
Number of live trees per acre	322	374	454
Number of standing snags per acre	101	71	44
Basal area per acre (ft^2)	102	80	102
Total gross vol. per acre (ft^3)	3400	2160	3300
Mean lodgepole dbh (in.)	7.5	5.9	7.4
Mean lodgepole age (yrs)	100	77	74
Percent of basal area in lodgepole	97.5	99	82
Percent of basal area in Douglas fir	0.4	0	9
Percent of basal area in spruce	2.0	1	5
Percent of basal area in alpine fir	0.1	0	4
Mean height of lodgepole (ft)	67	48	63
Mean height to base of green crown (ft)	32	22	37
Mean crown length (ft)	34	26	24
Mean No. branches/tree<1/4" on boles to ht of 10ft	4.1	6.9	8.4
Mean tot. No. branches/tree on boles to ht of 10ft	15.2	18.0	22.3
Pine regeneration No. per acre	2000	2300	130
Pine regeneration mean height (ft)	3	3.5	6
Douglas fir regeneration No. per acre	4	0	400
Douglas fir regeneration mean height (ft)	8	0	4
Spruce regeneration No. per acre	90	20	250
Spruce regeneration mean height (ft)	5	3	5
Alpine fir regeneration No. per acre	140	0	725
Alpine fir regeneration mean height (ft)	3	0	4
Total regeneration per acre	2234	2320	1505
Mean regeneration ht (ft)	3	3.5	4

Fire Behavior

General

A total of 28 test fires were conducted over the range of burning conditions encountered in three fire seasons. Eighteen of the tests were undertaken on the Dry Pine South site, eight on the Dry Pine North site and two on the Fresh Pine site. Twenty of the tests were circular plots which permitted the observation of fire growth from a single small firebrand ignited at the plot centre. Eight tests were strip-head fire ignited along one edge of the square plots. Basic fire behavior and fire environment data is presented in Tables 6 and 7, Appendix I. A summary of the range of burning conditions follows.

Heading Rate of Spread (fpm)	Stand Wind Speed (mph)	Fuel Moisture Content (%)	Initial Spread Index	Fire Weather Index
0.4 to 6.5	0.8 to 3.3	7 to 28	5 to 14	14 to 35

With the two test fire procedures utilized, it was not possible to achieve a threshold of fire behavior above which sustained crown spread appeared feasible on any of the three sites. The two chief factors accounting for this low probability of crowning were the limited maximum rate of energy release from the surface fuels and lack of sufficient continuity of the aerial fuels. Single trees and groups of several trees "candled" on all three sites, but the energy flux from the ground was not sufficient to sustain fire movement through the rather open canopies.

A wide range of burning conditions was tested, with moisture content varying from the upper limit of marginally sustained combustion (or dead fuel moisture of extinction) of approximately 30% to fuel moisture of less than 10%. Wind speeds varied from about 1 mph to 4 mph measured at flame height in the stand and this range represents velocities up to about 12 mph measured in the open at 10 m. It is reasonable to conclude that over this range of conditions, pine stands of the type tested do not present a serious threat of sustained crowning. Limited excursions into the aerial fuels will occur and cause spotting ahead of the surface fire front.

Differences between ignition patterns

Rates of spread reported in Table 6 were calculated as means over discrete time intervals rather than as total distance divided by total time. In this way, effects of wind shifts which temporarily cause a heading front to back or flank could be separated out of the data. Also the winds were measured over one and three minute time intervals to more accurately represent the velocity affecting spread rate at any given time than is possible with a mean wind over an extended time period.

It is readily apparent that the mean spread rates for strip-ignited plots are generally higher than for central point-ignited plots. This is due to the extended period of initial establishment and growth of the point fires during which time the spread rate is slow regardless of wind or fuel moisture. This growth period is bypassed by the strip ignition technique, due to the creation of a single-strip fire-front intentionally oriented to the maximum advantage of the prevailing wind direction. The spread rate exhibited by the strip head fire as soon as the influence of the diesel-gasoline fuel mix used to ignite it is gone (approximately one minute) is effectively the steady state fire behavior condition for the fuel complex. The point-ignited plots, however, do not begin to exhibit steady state spread until such time as a front has elongated sufficiently to overcome the effects of inward convection from the rest of the fire. Only in their latter stages could the point-source fires tested here be considered to approach steady state spread rate because of the small plot sizes. Up to 48 minutes were required before steady state spread was achieved on point fires.

Figure 8 illustrates the typical behavior of a point fire under very low wind conditions. The mean wind on this plot was 0.8 mph and a dominant linear-spreading front is slow in developing. After 10 min. the fire is still spreading uniformly around the entire perimeter with the small flames leaning away from the unburned fuel because of convection in towards the burned out plot centre. Under these conditions radiation is the only significant heat transfer mechanism propagating this fire. A period of growth or acceleration in spread rate continues as a front finally gains dominance and the effects of inward convection are overcome. Figure 9 is an example of a point fire with a fully developed linear heading front 32 min. after ignition, with convective heat transfer ahead contributing significantly to spread. Figure 10 shows a strip fire immediately after ignition with convection transferring energy ahead to the unburned fuels. No growth period exists with

Fig. 8.--Initiating behavior of point-source fire subject to inward convection

Fig. 9.--(left) Fully developed front in late stages of point-source fire with convective heat transfer ahead

Fig. 10.--(right) Ignition of strip head fire

this ignition pattern. The fire behaves in equilibrium with its environment as soon as the effect of the ignition fuel is overcome.

Because equilibrium behavior could be observed over a longer time on the strip plots, this ignition pattern was more favorable to the study of vertical growth patterns than the point source fires which continued to accelerate their spread rate through most of their duration. Figures 11 to 13 show a sequence of transient vertical development of a rapid spreading front on a strip plot. Figure 11 shows the leading edge of the fire front moving easily through bridge fuels on the tree bole, but Figure 12 shows that only 1.5 min. later the front has passed the tree base and strong convection is transferring most of the energy forward rather than upward so that the tree crown did not become involved. Figure 13 shows after another 0.5 min. that with the heat source below now removed, even the bridge fuels on the tree bole can sustain only weak flaming. The spread rate on this plot averaged 6.5 fpm. Under somewhat slower spread rates, a greater proportion of energy can be transferred upward over a longer time interval, and crown fuels may become involved in combustion as shown in Figure 14. The crown fuels typically consumed are the older, drier needles and fine twigs towards the centre of the crown. Figure 15 shows a spot fire ignited ahead of the main front on a strip fire caused by a fire brand falling from a "candling" tree crown.

Fig. 11.--Transitory vertical growth of fast spreading strip heading front

Fig. 12.--Rapid spread and forward convection halts vertical growth after 1.5 minutes

Fig. 13.--Vertical bridge fuels sustain only limited flames 2 minutes after frontal passage has removed heat source from below

Fig. 14.—Typical crown fuel involvement showing consumption of mainly fine fuels near centre of crown

Fig. 15.--Spot fire ignited by firebrand falling from candling tree contributes to frontal spread

Fig. 16.—High surface wind velocity reduces flame angle and deepens frontal flame zone depth

An example of steady state behavior being achieved on a point-source fire is shown by Fig. 16. The fire is spreading at 3.0 fpm here under a 2.4 mph wind but it has taken 30 min. from ignition to produce this essentially straight line front. The wind velocity was sufficient to reduce the flame angle between the advancing front and the unburned fuel so that flame radiation and convection were both significant heat sources for preheating the fuels. This figure shows the importance of the living green fuel component, mainly *Vaccinium*, as an energy source. As long as the other surface fuels can produce sufficient heat to overcome the preheating requirements of the very moist *Vaccinium*, the green fuel will contribute to fire spread. *Vaccinium* moisture content ranged between 100 and 130%. Figure 16 shows that only small diameter branch and log fuels less than 0.5 in. contribute significant energy to the moving front whereas the green *Vaccinium* is completely consumed in this particular fire environment.

Fire growth from point ignition

In order to determine what the growth period is for point ignited fires, the rates of spread by time interval were analyzed for all fires. There was no significant relation of spread rate to time from ignition for strip fires but there was a definite growth curve for dependency of spread rate on time from ignition for point fires. Determination of the spread rate growth curve allowed the mean rates of spread for point-source plots to be re-calculated by adjusting each time interval's observed spread rate up to the rate which would be expected at equilibrium. After these "adjusted" spread rates for point fires had been calculated, all fires from both ignition patterns could be pooled for the determination of spread relationships to fire danger indices.

The growth curves for point fires were determined using the multiple curvilinear regression by successive approximation technique described by Ezekiel (1930). This involved computing linear partial regressions for the dependent variable (rate of spread) on the most significant independent variables (time from ignition, wind, and moisture content). The dependent was then adjusted for the deviations from the means of all independents except one, and a correlation graph was then plotted for the adjusted values of the dependent against that independent. From this plot, a first approximation curve for the net regression of the dependent on that particular independent was drawn. The dependent was then corrected for all but the next independent, corrected Y's plotted against those X's, and a first approximation curve plotted with respect to that variable. The procedure was repeated for the third independent so that three first approximation curves to the net regressions were obtained. Then these first approximation curves were used as bases for correcting the dependent for the approximate curvilinear effects of all independents but one, omitting each in turn, and then determining second approximation curves by plotting the new corrected Y's against each X in turn. New corrections were made in these curves until no significant improvement in the net curvilinear regression could be obtained.

Logarithmic transformations were used on the dependent, rate of spread, and on the independent, time from ignition. The other independents, wind measured at flame height and organic layer moisture content, were not transformed.

Figures 19 to 21 in Appendix I show the curves derived for the effects of time, wind, and moisture content on spread rate for the point fires.

Table 8 in Appendix I lists the values from these curves which provide a means of obtaining expected rates of spread for point-source fires for any time interval up to 48 minutes after ignition. For times greater than 48 minutes, spread rate is assumed to be the value predicted for 48 minutes, corrected only for wind and moisture content.

Table 9 in Appendix I lists the corrections for time from ignition which were added to the observed spread rate to derive the adjusted spread rate for each three minute time interval. Plot mean adjusted spread rates for the point fires were calculated as the means of each time interval's observed spread rate after its adjustment for time from ignition.

Figure 22 in Appendix I shows the relation of calculated spread rate based on the curvilinear functions of Figures 19, 20 and 21 to observed time interval spread rates for point fires. Although the curved functions decreased the standard error of the estimate of spread rate somewhat over that obtained using a multiple linear regression of spread rate on time and wind, low spread rates are overestimated and high spread rates are underestimated. The highly significant (.01 level) multiple linear regression of spread rate on time and wind was as follows:

$$\log (R \text{ (fpm)} + 1) = .0534 + .1846 (\log \text{Time (min)} + 1) + .0508 \text{ (Wind)}$$

R squared = .293 ; SE_E = .098

The curvilinear functions presented in Table 8 yielded the following equation of calculated spread rate in terms of actual spread rate:

$$\log (R + 1) \text{ calculated} = .2722 + .3493 (\log R + 1) \text{ observed}$$

R squared = .299 ; SE_E = .062

While the overall improvement in time interval spread rate prediction by use of curvilinear relationships and introduction of moisture content as an independent is small, the use of this time function in adjusting the observed interval spread rates on the point fires was felt to be justified in view of the data distribution. The mean adjusted spread rates for point ignited fires are listed in Table 10 in Appendix I.

Intensities calculated after Byram (1959) are listed in Table 10 in Appendix I. The concept he advanced for frontal intensity utilized the expression

$$I = hwr$$

where I is energy output of the fire, in terms of Btu per sec. per lineal foot of fire front, h is heat yield of the fuel consumed, w is the loading in terms of lb/ft^2 of fuel consumed, and r is rate of spread (fps). Table 10 includes heat yield used for each plot, since this is a variable dependent on moisture content as well as fuel type. The only corrections made to the heats of combustion of the fuel components were for energy losses due to vaporization of moisture contained by the fuel. No energy losses due to incomplete combustion of fuel or to radiation were considered to apply to these highly efficient small fires in timber stands. Emitted smoke was very light colored, indicating relatively complete combustion of the fuel, and all radiated heat had some element of the fuel complex to absorb and utilize it for effective preheating. Convection on these low intensity fires was not sufficiently strong to produce a unified smoke column above the tree crowns and smoke dispersal was rapid even with very light winds.

The loading of consumed fuel is a figure based on the depth of organic layer removed, bulk density of the organic layer, and loading of branch litter and down log fuel consumed as measured on each plot by line intersect sampling. Apportioning of the energy released from branch and log fuels as to the fraction of fuel consumption assumed to contribute to frontal propagation was done as follows: 100% of the fuel depletion from sizes up to 0.5 inches diameter was considered to be released to the fire front, 80% of the depletion of fuel from 0.51 to 1.0 inches, 50% of the fuel from 1.1 to 2.0 inches and 30% of the fuel from larger size classes was considered as a frontal energy source. These percentages can be considered only as subjective estimates since no reference data could be found and direct measurements could not be made. Long burnout times of the larger fuels effectively excluded them from contributing to the heading front on these fires, whose frontal residence times ranged from only one to two minutes.

The adjusted spread rates for point fires were used to calculate the Byram intensities reported in Table 10.

Relationships of fire behavior to weather variables and Fire Behavior System indices

The fire behavior aspects considered to be most important from an initial attack view point of fire growth in these stands were rate of spread, size of fire front, i.e., flame zone length and frontal depth, and probability of vertical growth into aerial fuels.

Adjusted spread rates of point source fires were pooled with spread rates from strip ignited fires and a multiple regression analysis run to determine relations of spread rate to Indices of the Canadian Forest Fire Behavior System and to selected weather variables. Fire Weather Index alone accounted for as much of the variation in spread rate as was possible, because the addition of the next most significant variable caused an increase in standard error of estimate, even though R-squared increased by including additional variables.

Table 11 in Appendix I summarizes the most significant simple linear regressions which could be obtained for spread rate, flame length and flame depth on weather and danger index variables.

Figures 23 to 33 in Appendix I illustrate these regressions graphically, with the addition of supplementary data points from other sources in some cases.

For instance Figure 23 shows the regression of rate of spread on Fire Weather Index, which is the principal administrative danger index of the Forest Fire Behavior System. Five jack pine fires from a study of Van Wagner's[1] in eastern Canada were included in this figure, though they were excluded from the regression analysis. These data were collected on .1 acre strip-ignited plots in jack pine stands with similar fuel arrangement and type, although heavier loading, particularly of needle litter, than existed in the present study. None of these five fires crowned, although a sixth fire under much higher wind conditions than were monitored on the present study (6.8 mph) and on a larger plot (2 ac.) was reported by Van Wagner to have partially crowned. The greater available fuel loadings (up to .5 lb/ft^2) on these fires appears to account for their considerably higher spread rates at high danger indices than those observed on the present study.

Figures 24 to 26 also show that generally there is a reasonable correlation of Van Wagner's observations of spread rate at the low end of the fire danger scales, but that as the fire environment worsens, much greater spread rates are reached in the heavier fuel loadings under his jack pine stands.

Also included in Figure 26 are four data points from Vonskii (1957) representing observed spread rates for initiating fires in Soviet jack pine stands where the fuels were reported as moss-type and *Cladonia*-moss type. The Russian data was not included in the regressions but there appears to be reasonable correlation with observations from the present study. This is true for spread rate and wind (Fig. 26) as well as for the other variables. Flame length vs. spread rate

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[1]C.E. Van Wagner. Unpublished data supplied April, 1970.

(Fig. 30), flame length vs. frontal depth (Fig. 31), flame length vs. intensity (Fig. 32), and flame depth vs. rate of spread (Fig. 33) all show reasonable correlation with the Russian data.

Interestingly, Amosov (1964), who observed similar point source fires in soviet pine stands did not obtain significantly higher correlations of spread rate to wind, moisture content, humidity, "aridity index", and cloud cover than were obtained with similar variables in this study.

Implications of fire behavior results for fire management

Fire behavior results are summarized in Table 5 in terms of the most significant variables which would affect initial attack decisions for fires occurring in these timber stands. Initiating fire behavior, in terms of rate of spread, flame length and frontal flame depth are predicted primarily in terms of Fire Weather Index, with secondary limits of Fine Fuel Moisture Code and Initial Spread Index.

A growth period of approximately 48 minutes can be expected before a fire in these stands which was ignited by a standard firebrand such as matches or a camp fire would be spreading at the steady state spread rates given in the table.

Empirically, the probability of new ignitions caused by firebrands thrown ahead of the fire front was 1.0 when Fine Fuel Moisture Code exceeded 90.

A probability of at least limited movement of surface fire into tree crowns can be suggested as equalling 1.0 when Fire Weather Index exceeds 20, providing accessible bridge fuels exist. However, no threshold conditions for crown fire spread can be suggested for these stands from the present study. The author has observed crown fire behavior on wildfires in similar stands, but ambient winds were considerably higher than those monitored in the present study, as was the case on the experimental crown fire cited by Van Wagner.

As noted in Table 5, Fire Weather Index (FWI) is the principal index of the Canadian Forest Fire Behavior System used for administrative actions. FWI can be used alone to determine fire behavior predictions from Table 5, but the other two component indices, the Fine Fuel Moisture Code (FFMC) and the Initial Spread Index (ISI) should be considered in conjunction with FWI. This is due to the fact that FWI is a composite index, derived from fine fuel moisture input, wind input, and heavy fuel moisture input. An FWI value within the limits of Table 5 values could exist with greatly different combinations of FFMC and ISI than were monitored in this study. This situation may or may not affect the accuracy of predicted fire behavior from FWI, but the greatest confidence would be expected when at least two of the component Danger Indices in Table 11 fall in the same class. Initial Spread Index is itself a composite of fine fuel moisture and wind and was almost as significant a predictor of spread rate as FWI (Table 11, Appendix I) so ISI should be considered as the most important of the two secondary indices to match with the FWI for the purpose of using Table 5. For example if the FWI is 30, ISI should be between 9.1 and 11 for using the predicted spread rate of 3.2 fpm with confidence.

TABLE 5.--Expected fire behavior in lodgepole pine stands with *Cladonia*-moss surface fuels as dependent on Canadian Forest Fire Behavior System Indices

Fire Weather Index[1] (FWI)	Initial Spread Index (ISI)	Fine Fuel Moisture Code (FFMC)	Heading Rate of Spread (fpm)	Heading Flame Length (ft)	Heading Flame Depth (ft)
8-12	≤4	≤88	1.1	0.7	0.3
13-17	5-6	89-90	1.5	1.2	0.9
18-22	6.1-7	90-91	2.0	1.8	1.5
23-27	7.1-9	91-92	2.5	2.2	2.0
28-32	9.1-11	93-94	3.2	2.8	2.7
33-37	12-14	95-96	3.9	3.3	3.3
38-42	15-16	96+	4.8	3.8	3.8

Probability of firebrands causing new ignitions ahead of main fire front is 1.0 when Fine Fuel Moisture Code exceeds 90.

Probability of transitory vertical development of fire into standing fuels is 1.0 when Fire Weather Index exceeds 20, providing bridge fuels capable of carrying fire to tree crowns exist on the site. Such fuels include dead branches on tree boles, suppressed understory conifers and standing snags. No potential for sustained crown fire spread can be given.

Spread rates are assumed to be in equilibrium. Expect fires originating from point ignition sources to require up to 48 minutes to achieve these spread rates.

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[1] Fire Weather Index (FWI) is the principal administrative index of the Canadian Forest Fire Behavior System. Limits are suggested for two other component indices (Fine Fuel Moisture Code and Initial Spread Index) only as additional refinements to check on the applicability of a given FWI value to a particular fire environment as determined by fuel moisture and wind. Maximum confidence of predicted fire behavior requires at least two of the three indices to fall in the same class.

No further extrapolation beyond the data limits was felt to be justified nor was a finer breakdown of index classes or fire behavior predictions. Fire management agencies can only be expected to utilize rather broad classes of interpretive fire behavior guides at this time. The rather low statistical predictability of the dependent variables here does not warrant the suggestion that more should be read into the data than actually exists.

Fuel Moisture Content Relationships to Danger Indices

It was hoped that fuel moisture content of the duff layer and of various sizes of branch and log fuels on the ground would be predictable within operationally useful limits of accuracy from the various fuel moisture codes making up the Fire Weather Index. Multiple linear regressions were calculated for fuel component moisture contents on weather parameters and fuel moisture codes of the Fire Weather Index. Generally the fuel moisture contents were most significantly correlated to a particular moisture code, but even the best combinations of up to four moisture code and weather parameters could not account for more than 60% of the variation in fuel moisture content as measured by R-squared, the coefficient of determination.

The fuel moisture content data are rather high in sampling error, mainly because of the lack of sufficient replication of measurements in such a highly variable medium as the fuels under a forest stand. The sampled fuel moisture contents were means of two individual samples of each kind of fuel taken from two areas on the test site about two hundred yards apart. Ideally up to ten samples of each fuel component should have been taken daily from widely separated areas throughout the test site, but this sampling intensity was not possible on this study. Presumably the moisture codes of the Fire Weather Index can account for area averages of fuel moisture better than would be indicated by the correlations of limited point samples of fuel moisture. It is the average fuel moisture condition which controls gross fire behavior once the initial fire establishment phase has been achieved, rather than the square-foot-to-square-foot variability of moisture content, so the Moisture Codes should be expected to be better integrators of the average moisture condition of the fuels than spot destructive samples would be.

The moisture content variables which were tested for their predictability by Danger Indices are listed and described in Table 12 in Appendix I.

Coefficients of determination for the single or multiple regressions and the significance of each variable's contribution to total variation in the dependent (as determined by F-test of variance ratio) are given in Table 13 in Appendix I.

It is easily seen that, although most fuel moisture variables are significantly related to one of the Forest Fire Behavior System Indices, the accuracy of prediction is rather low.

The most usable relationships are presented in Table 14 in Appendix I, with the equations given here having R-squared of at least .45. For example, the prediction of moisture content for the upper organic horizon of the <u>Cladonia</u> fuel type on the Fresh Pine site (Y10) takes the following form:

$$\log_{10}(Y10) = 2.800 - .0173(FFMC) - .0042(DMC) + .0125(R.H.)$$

If FFMC = 90, DMC = 60, R.H. = 30

Then Y10 = 23%

This equation accounted for 50.6% of the observed variation in fuel moisture content (as determined by coefficient of determination). This level of predictability could be considered usable as a rough field guide to moisture content for this specific fuel.

Prediction of Spread Rate by U.S.F.S. Spread Model

W.H. Frandsen of the Northern Forest Fire Laboratory, Missoula, Montana, tested the adjusted spread rates and fire environment data reported in this study as to their relation to spread as predicted by the U.S.F.S. spread model described in Appendix II.

Frandsen's analysis separated the surface fuel complex into two strata. The first stratum consisted of ground fuels in a one-inch-deep fuel bed on the surface. These fuels included needle litter, *Cladonia* lichen, living *Pleurozium* moss, and dead branch debris on the ground, less than one half inch in diameter. The second stratum consisted of the low herbs and shrubs in a six-inch-deep fuel layer lying immediately above the ground fuels. This fuel stratum was principally *Vaccinium* (low blueberry).

Frandsen assumed that the lower stratum of ground fuels was the heat source supplying energy to make the high-moisture-containing *Vaccinium* layer available as the principal fire carrying fuel. Fig. 16

shows the important role in carrying the fire front which the Vaccinium plays under a high energy output situation. Fig. 8 on the other hand shows that in the initiating low energy phase of the fire, or under high moisture content and/or low winds, the Vaccinium serves as a heat sink and retards fire spread.

In order to allow for the contribution to fire spread of live Vaccinium with moisture contents exceeding 100%, the 30% moisture of extinction for dead fuels suggested by Anderson (1969) could not be accepted. Frandsen used a computational method suggested by Fosberg and Schroeder (1971) to derive the availability of Vaccinium for combustion in this model test. Basically this approach says that the availability of green herbaceous fuels for active combustion depends on the moisture content of the dead fine fuels and the ratio of live-to-total fuel loading.

Fosberg and Schroeder's approach to fire propagation in these fuels was that the ground litter fuels supply heat in excess of that required for fire propagation through those fuels alone. The excess heat supplies the heat of preignition required by the green, high moisture Vaccinium layer to change that fuel from an effective heat sink to a heat source for further fire propagation. Frandsen assumed the two fuel strata to be separate entities, the upper Vaccinium stratum accepting heat from the lower ground litter stratum. This mechanism permitted the raising of the moisture content at which fire spread extinction takes place in the Vaccinium layer. Rate of spread was calculated for the herbaceous stratum separately, but the derived moisture content of extinction was calculated from loading and moisture content data from both strata.

Rates of spread were calculated for the test fires using the preceding interpretation for spread model input parameters. Results as compared to observed spread rates are shown in Fig. 34 and in Table 15, both in Appendix I. The model predictions were generally lower than the time-adjusted observed spread rates, with three exceptions, and the generally higher spread rates observed on the strip ignited plots were the most under-predicted. However, the model over-predicted unadjusted point fire spread rates with almost the same frequency as under-predictions (10 over-predicted and 9 under-predicted). Deviations of model predicted values from observed spread rates (calculated as predicted value minus observed value divided by observed value) ranged from -76 to +65%.

A regression of calculated spread rate on actual spread rate produced a coefficient of determination of only 16% and was not significant using F-test at .05 level. The slope on this regression line was significantly different from 1.0, or the 45^{o} line of perfect correlation.

It should be noted that the model is highly sensitive to some of the fuel descriptors which are very difficult to measure, such as surface-area-to-volume ratio and porosity. The estimates of these descriptors, which came from a limited macroscopic and microscopic study of the fuel beds and fuel particles, can be considered only first approximations of the true values. The heterogeneity and the non-geometric shape of the predominant fuel particles in this fuel type and indeed in most wildland fuels is a severe limitation to application of physical fire spread models.

These problems of fuel description were compounded by such features of the fuel complex as irregular distributions of log and branch fuels on the ground. No attempt was made to account for the distribution of these fuels in applying the model. The loading of the significant portions of these fuels was merely added to the loading of other surface fuels as if all fuels were uniformly distributed over the site. Such is not the case in nature and this is a hindrance in applying a spread model realistically. Such fuels, in fact, have a different effect on spread, depending on combustion rate. For instance, spread was observed to be retarded by logs and branch fuels under low wind, high moisture and early in the fire growth period on point fires. Under higher combustion rates, however, when wind and moisture content were more favorable to rapid energy release, rate of spread was greatly increased by the contribution of such fuels. This was observed on Plot No. 119 which had the highest observed spread rate of 6.5 fpm although the predicted rate from the model was only 1.6 fpm. On this plot, the fire encountered a dramatically increased loading of available branch fuel which superseded the effects of all other variables, a situation which cannot easily be accounted for with the model.

A non-conceptual but equally important factor in limiting the validity of the model test on this study data was the difficulty in obtaining moisture contents of acceptable accuracy with the limited sampling possible. Fire behavior correlations with danger indices are better than with the actual moisture contents of the fuels largely because of the sampling errors in determining the fuel moistures. A calculated index based on weather observations smoothes out sampling error, but the errors in measurement of fuel moisture are not smoothed in any way when the data goes into the model.

The test of the spread model reported here can be considered only as a preliminary one due to the low confidence which can be placed in many of the measured fuel descriptors and fire environment variables. Such difficulties are to be expected when dealing with natural variation in a heterogeneous environment. They make definitive scaling tests of relationships found in laboratory tests to full scale fire behavior relationships very difficult, however.

While the spread model could not predict observed spread rates with statistical accuracy or precision, a conceptual contribution in terms of better understanding the effects of living herbaceous fuels on fire propagation was achieved. Without treating the fuel bed as two separate strata, Frandsen could not predict spread rates higher than 0.4 fpm. This value corresponds to the mean spread rate observed on point source fires for the first six minutes following ignition before a linear heading front developed. At this stage of fire growth, *Vaccinium* and other herbaceous fuels were observed to be a heat sink with much of the heat output of the fire being utilized to remove moisture from the living fuel. Allowing the *Vaccinium* stratum to contribute its loading to frontal propagation in the model resulted in spread rate predictions up to six times the values predicted for ground surface fuels alone. Because of the relative crudeness of the input data, favorable shifts of these orders of magnitude in predicted values were felt to be significant gains in understanding the fire spread mechanisms, even though statistically the predicted and observed spread rates could not be satisfactorily rationalized.

Fire Impact on the Site

The short term effects of these low intensity, essentially two dimensional surface fires on the site were minimal. Energy release was sufficiently low that mineral soil was exposed only rarely, where a concentration of heavy branch and down log fuels continued to burn after the passage of the fire front.

Standing trees were scorched to a height of several feet in some cases (Fig. 17) and the advance regeneration was nearly all killed with the exception of taller, larger diameter trees on the lower intensity fires (Table 10 in Appendix I). Standing trees which candled were not killed within a year even if they lost up to 80% of their foliage.

A comparison of Figs. 17 and 18 shows the rapid accretion of a new surface fuel complex soon after the fires. Fig. 17 shows the rapid accumulation of dead pine needles after only six weeks, and after one year (Fig. 18) the *Vaccinium* and *Cladonia* lichen had begun to revegetate the site.

Fig. 17.—Fire impact after six weeks showing scorched tree boles, heavy dead needle fall and killed advance regeneration

Fig. 18.—One year following burn showing rapid re-establishment of surface fuel complex

CHAPTER V

DISCUSSION AND CONCLUSIONS

This study has pointed out the difficulties of predicting fire behavior in naturally occurring complexes of wildland fuels, even when a specific attempt was made to select a relatively homogeneous fuel type.

The results of the study should be valuable in establishing initial attack priorities for lodgepole pine stands by fire management decision makers. These managers are now using the Canadian Forest Fire Behavior System which can be calibrated in terms of expected fire behavior at various index levels. Ideally, the fire manager should have a number of field tested "Burning Indices" which would predict the relative difficulties of fire control for any fire environment in the major high fire risk and high hazard fuel complexes.

It is clear that such a system of predictive tools cannot be developed solely by laboratory scale modeling of fire behavior through homogeneous fuel beds. Neither can a complete system of Burning Indices be developed in a reasonable time solely through empirical field observation of incipient point fires, initiating fires on small plots such as those used in this study, or probably any other scale of experimental field test fire. A combination of the best features of both modes of experimentation will likely achieve the most usable results.

As this study and other cited examples have shown, field observations of fire behavior cannot be expected to produce much more than rather crude correlations of data with danger indices, which themselves are models of a fire environment. Still this is a useful approach in putting realistic limits on just how much can be inferred from danger indices for making rate of spread-based fire management decisions. Danger rating systems should be used as guides to fire management rather than as inflexible rules.

The objectives of the study were partially met in that initiating fire behavior was measured in lodgepole pine stands and found to be predictable in terms of Danger Indices currently in use. The range of fuels and scale of test fire were insufficient to completely meet the study objectives of developing and testing a field method of determining crowning thresholds of the fire environment in these stands, however.

Such a determination is still felt to be a need before a Burning Index for lodgepole pine stands can be developed which will satisfy the expected range of needs of improved fire suppression decision making.

Conclusions

The following conclusions were reached from this study:

1. Initiating fire spread and the related characteristics of flame length and frontal depth are predictable in lodgepole pine stands from indices of the Canadian Forest Fire

Behavior System. Accuracy and precision of prediction is sufficient that initial attack priorities and manpower requirements could be selected on the basis of these guides for similar fuel types.

2. Mature lodgepole pine stands with moss and Cladonia lichen surface fuels do not present a threat of crown fire spread at low wind velocities (under 4 mph measured in the stand). Transitory vertical excursions of the surface fire into aerial fuels will occur if some form of bridge fuels such as suppressed trees, advance regeneration or dry moss and dead branches on tree boles exist on the site. These "candling" or flaring trees produce numerous fire brands which can be thrown ahead of the fire front several hundred feet and cause new ignitions if fuels are receptive. Surface fuels will produce fire fronts of sufficient dimensions for limited vertical growth when Fire Weather Index exceeds 20. Surface fuels are susceptible to ignition from small firebrands when Fine Fuel Moisture Code exceeds 90.

3. Initiating fire spread in timber stands can be studied on plots as small as 1/20 acre, but larger plots are desirable if the transitional period of fire growth from a two dimensional field into a three dimensional field is to be studied. A plot size sufficient to allow the fire to overcome near-ground forces and edge effects is necessary if crowning mechanisms are to be studied.

4. Spread rate from a single firebrand ignition source increases with time up to approximately 48 minutes before spread rate stabilizes and responds in equilibrium to near-surface changes in fire environment. This growth period may not be valid for high wind velocities (greater than 4 mph in the stand) because an essentially linear fire front would be expected to be produced sooner under high wind conditions.
5. A strip ignited fire along one edge of a rectangular plot as small as 1/20 acre will produce equilibrium surface fire spread for a reasonable period of time for documentation. Such a plot size even with strip ignition would not appear large enough for adequate study of crowning mechanisms.
6. The two so-called "Dry Pine" sites which had predominantly pine needle, Cladonia (reindeer) lichen and moss surface fuels, but differed in standing fuel distribution, did not produce significantly different fire behavior. Lower live crowns on the "North" site did not produce significantly more aerial fuel combustion than on the "South" site. The south site compensated for higher tree crown bases by having more bridge fuels in the form of tall advance regeneration and suppressed understory trees reaching into the crown zone. Flammability of the "Fresh" pine site was significantly lower than the dry sites, due both to less severe fire climate (higher fuel moisture contents) and less flam-

mable surface fuel characteristics (predominantly green Pleurozium moss rather than the highly flammable Cladonia lichen of the drier sites). While it was not possible to conduct test fires on this "Fresh" site under equivalently high fire danger conditions as on the "Dry" sites, spread rates should be expected to remain lower on sites where Cladonia lichen is absent and moss predominates. An additional factor in reducing spread rate as a site shows evidence of being subject to a more moist environment is a greater component of low herbaceous species which require a large proportion of the heat generated to remove their moisture.

7. Moisture content of certain fuel components of lodgepole pine stands can be predicted by indices of the Canadian Forest Fire Behavior System, although sampling intensities utilized on this study were in some cases too low to be considered true means of the actual moisture contents existing on the site. Because of the difficulties in representatively sampling the highly variable natural fuel moisture, the predictive equations for moisture content presented in this study cannot be considered as more than first approximation calibrations of the Danger Indices.

8. A test of the U.S. Forest Service fire spread model could not produce spread rates which correlated statistically with observed spread rates. This was due in part to the

relatively crude levels of measurement of many of the input fuel and fire environment variables from the field and the sensitivity of the model to small changes in some of these variables. W.H. Frandsen used the study results to derive a two-stratum theory of how fire propages through these fuel complexes which have a low density layer of green herbaceous or low shrub-type vegetation overlying a rather high density surface litter layer. Allowing for the contribution of green vegetation to fire propagation rate considerably improved the spread rates predicted by the model.

9. The impact of low intensity surface fires in mature lodgepole pine stands is minimal in terms of tree mortality. Total surface fuel reduction seldom exceeds 50% of initial loading. Mineral soil is exposed in only minor amounts, and surface fuels consumed by the fire are rapidly replaced. Advance regeneration is almost completely killed because of thin bark near the root collar and low crowns in or near the flame zone.

Recommendations

Recommendations for future research resulting from this study are:

1. In order to complete the data input necessary for a lodgepole pine stand "Burning Index", a series of large scale test fires should be conducted. High hazard immature stands

should be selected and plots should be large enough that full crown fire behavior can be observed. Plot sizes of .5 to 1 acre would probably be required and rectangular plots with strip head fire ignition should be used. A burning index for standing timber types should provide the fire manager with rate of spread and probabilities of crown fire spread so that suppression decisions can be planned accordingly.

2. An attempt should be made to monitor fire behavior over as wide a range of weather and fuel conditions as possible in lodgepole pine stands. Higher wind velocities than those obtained in this study are desirable. Because a normal study could be expected to intensively sample only a limited range of fuel conditions, crude data such as could be obtained from wildfires should be utilized to supplement intensive research data.

3. Because of the sensitivity of fire spread to fuel bed parameters which are difficult to measure in the field, particularly in heterogeneous fuels, new methods of quantifying fuel particle and fuel bed descriptors must be found if the gains from fire spread modeling are to be taken from the laboratory to the field.

4. More intensive sampling of fuel loading and moisture content than was undertaken on this study is desirable, particularly from the point of view of utilizing or constructing models

which depend on accurate fuel input data. The duff layer should be sampled for loading, bulk density, and moisture content in small depth increments throughout the available fuel zone, because the spread-controlling variables change rapidly with depth. A large number of samples is necessary to obtain representative values of fuel variables even in an apparently homogeneous complex such as a pine stand. Living herbaceous and low shrub fuels should be intensively sampled with an appropriately sized plot to suit the distribution pattern of this important fuel component. Adequate description of aerial fuels for prediction of crowning would appear to require the measurement of loading and bulk density over small vertical height increments, perhaps as small as five feet.

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APPENDIX I

Tabular and Graphical Results of Analyses

Heading R.O.S. (fpm)	Heading flame length (ft)	Heading flame depth (ft)	Stand wind (mph)	Open wind (mph)	Air temp at 4 ft (°F)	R.H. at 4 ft (%)	Surface litter M.C. (%)	Organic layer M.C. (%)	Fine Fuel Code	Duff Moisture Code	Initial Spread Index	Fire Weather Index
0.9	1.4	1.5	0.8	2	78	29	9.8	17.4	90	37	5	14
0.4	0.3	0.2	2.2	4	65	52	17.4	28.4	90	44	6	17
1.9	1.6	2.1	2.1	4	78	32	9.6	18.1	90	43	6	17
1.4	1.3	1.6	2.3	4	75	30	13.5	12.8	90	47	6	19
1.5	2.7	1.6	1.5	3	80	17	14.7	13.4	92	38	7	19
1.7	2.8	2.6	2.7	5	71	45	14.3	18.4	90	50	6	19
1.9	1.6	1.6	1.9	4	74	25	10.8	6.9	90	45	6	19
0.8	1.1	0.9	1.9	4	81	25	8.8	19.1	91	47	7	20
1.3	1.3	1.2	2.5	5	76	23	10.8	6.9	91	45	7	21
1.5	2.2	1.4	2.9	6	80	19	14.7	16.0	91	40	8	21
1.5	1.8	1.8	2.3	4	78	22	14.0	11.6	91	65	7	23
2.0	2.0	1.1	2.3	4	83	22	11.7	11.7	96	34	13	23
1.6	2.1	1.9	2.4	4	72	18	11.0	17.6	91	92	7	24
2.8	1.4	1.4	2.6	5	82	14	10.9	10.9	93	68	9	24
1.5	1.5	1.2	2.8	6	72	22	17.6	14.0	92	70	9	25
3.0	1.6	1.5	2.4	4	72	22	6.6	12.3	93	70	9	25
3.6	3.2	2.8	2.4	4	76	26	15.6	11.9	91	99	7	25
3.6	3.4	3.4	2.2	4	72	16	9.3	7.9	92	92	8	26
1.4	1.5	1.2	2.1	4	78	26	14.3	10.2	92	99	8	27
1.4	2.1	1.7	2.0	4	78	21	14.0	11.6	93	65	9	27
2.1	2.1	2.2	2.2	4	78	22	9.2	10.4	94	76	10	28
1.8	2.1	1.8	2.4	4	81	16	12.7	11.0	94	82	10	29
1.4	1.6	1.1	2.5	5	74	16	9.1	9.9	93	96	9	30
3.8	2.6	1.9	2.7	6	74	18	9.1	16.8	92	96	9	30
3.2	2.4	2.5	2.3	4	82	15	10.3	9.8	95	82	12	33
1.9	2.2	2.1	3.2	6	74	14	7.1	8.5	95	72	14	34
3.9	2.6	2.6	3.3	8	73	14	7.1	8.5	94	72	14	34
6.5	6.0	6.2	2.8	6	79	21	8.8	13.5	95	76	14	35

s numbered in 100's are Dry Pine South, in 200's are Fresh Pine, and in 400's are Dry Pine North.
risks indicate strip head fire ignition.
winds were derived from stand winds for danger index calculation from relationships in Cooper (1965).

.E 7.--Consumption of branch and log fuels on ground

0-.09"		0.10-0.50"		.51-1.00"		1.01-2.00"		2.01-3.00"		3.01-4.00"		4" +		Tot. consump. and % of tot. fuel consumed	
lb/ft^2	%	lb/ft^2	%	lb/ft^2	%	lb/ft^2	%	lb/ft^2	%	lb/ft^2	%	lb/ft^2	%	lb/ft^2	%
.004	95	.003	91	0		0		0		0		0		.007	30
.001	50	.001	25	0		0		0		0		0		.002	2.2
.003	100	.004	88	0		0		.044	50	0		0		.051	19
.002	100	.002	65	.006	100	0		0		.086	33	0		.096	36
.003	94	.002	81	.017	100	0		0		0		0		.022	96
.002	100	.008	92	.002	25	.016	33	0		0		0		.028	42
.003	100	.006	98	0		0		0		0		0		.009	98
.002	86	.010	94	.006	100	0		0		.086	100	0		.104	99
.004	98	.005	97	.002	100	0		0		0		0		.011	97
.003	100	.004	99	0		0		0		0		0		.007	100
.002	95	.004	97	0		0		0		0		0		.006	96
.004	97	.003	96	0		0		0		0		0		.007	18
.001	92	.002	78	0		0		0		0		0		.003	82
.002	95	.002	87	0		.016	50	.044	100	0		0		.064	39
.002	100	.003	82	.008	67	.016	100	0		0		0		.029	85
.002	98	.002	94	0		0		0		0		0		.004	96
.003	100	.004	100	0		.025	100	0		0		.141	34	.173	39
.002	100	.002	79	0		0		0		0		0		.004	65
.002	94	.003	90	0		0		0		0		0		.004	63
.003	95	.003	100	.004	100	0		0		0		.180	51	.190	53
.002	100	.001	74	.002	50	0		0		0		0		.005	68
.002	95	.005	89	.006	75	0		0		0		0		.013	82
.001	75	.002	85	0		0		0		0		0		.003	82
.002	92	.004	93	0		0		0		0		0		.006	93
.003	100	.005	100	0		0		0		0		0		.008	4.9
.004	100	.007	98	.002	100	.016	33	0		.086	25	0		.115	29
.002	100	.003	96	.004	100	0		0		0		0		.009	98
.005	100	.007	100	.006	100	0		0		0		.176	50	.194	52

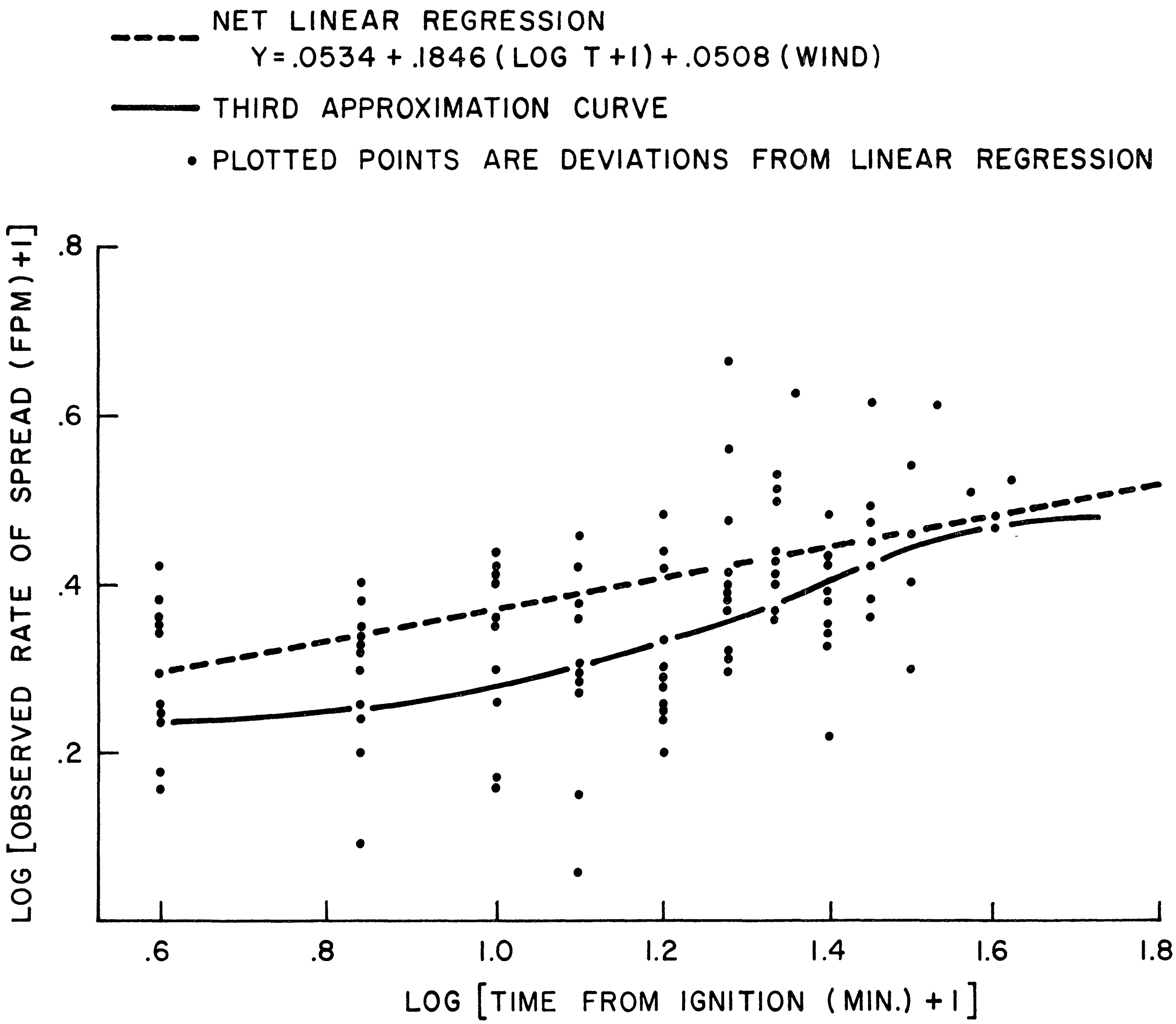

Fig. 19.--Relation of spread rate to time from ignition for point source fires

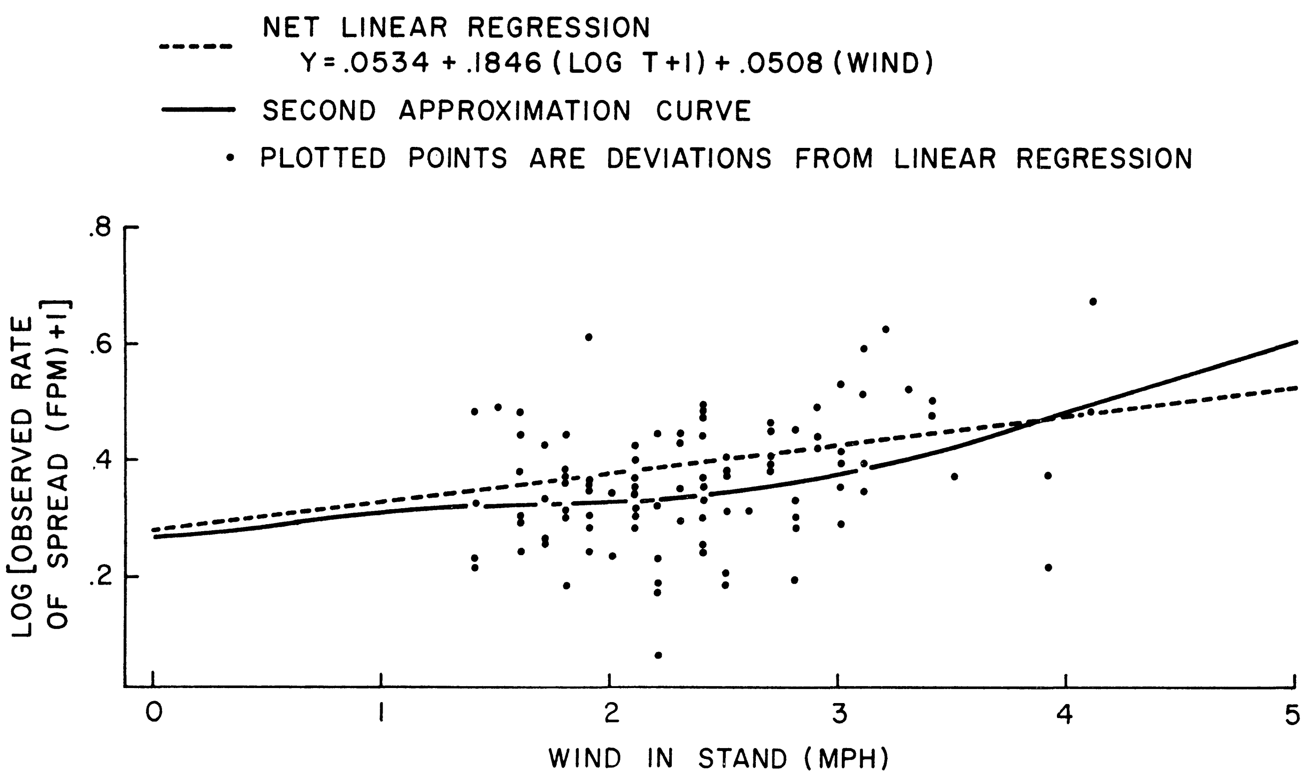

Fig. 20.--Relation of spread rate to wind for point source fires

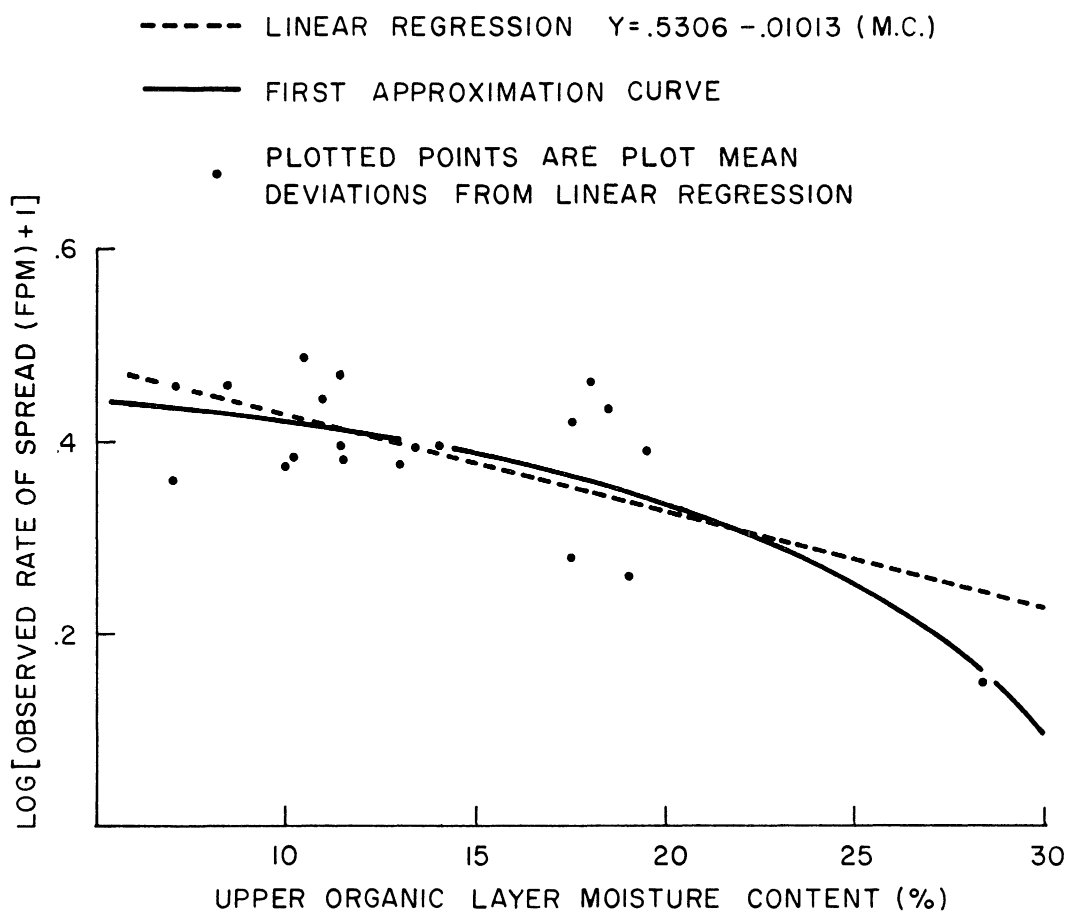

Fig. 21.--Relation of spread rate to upper organic layer moisture content for point source fires

TABLE 8.--Prediction of rate of spread for point source fires dependent on time from ignition, wind and upper organic layer moisture content

Time from ignition (min.)	Predicted log (ROS+1) Y	Correction to Y for stand wind		Correction to Y for moisture cont.	
		Wind (mph)	Correc. to Y	M.C. (%)	Correc. to Y
				limit of data	
3	.245	0.6	-.049	7	+.049
6	.258	0.8	-.041	9	+.037
9	.280	1.0	-.035	11	+.023
12	.306	1.2	-.030	13	+.006
15	.328	1.4	-.029	14	0
18	.356	1.6	-.027	15	-.008
21	.380	1.8	-.024	17	-.026
24	.404	2.0	-.021	19	-.045
27	.420	2.2	-.015	21	-.069
30	.440	2.4	-.008	23	-.097
33	.450	2.6	+.001	25	-.133
36	.458	2.8	+.015	27	-.182
39	.467	3.0	+.027	28	-.214
42	.472	3.2	+.045	limit of data	
45	.475	3.4	+.063	30	-.294
48	.478	3.6	+.082		
48+	.478	3.8	+.105		
		4.0	+.130		
		4.1	+.145		
		limit of data			
		4.5	+.193		
		5.0	+.253		

Y (Predicted log (ROS (fpm) +1) = Y + Wind correc. + Moisture correc.

A valid predicted spread rate for any time period greater than 3 min. requires a positive value of Y for 3 min. If this requirement is not met, the fire environment will not sustain a spreading fire, and predictions made for later times since ignition could not be valid.

Sample calculation of predicted spread rate Y:

Assume time from ignition of 30 min., stand wind speed of 3.0 mph, and fuel moisture of 15%.

Y = .440 + .027 - .008
Y = .459

Taking the antilog of .459 and subtracting 1.0 gives a predicted spread rate for these conditions of 1.9 fpm.

TABLE 9.--Correction factors added to observed rate of spready for point source fires for any time interval since ignition to remove effect of fire growth with time

Time from ignition (min.)	Factor added to Observed (log ROS+1) to correct ROS to 48 min.
3	.233
6	.220
9	.198
12	.172
15	.150
18	.122
21	.098
24	.074
27	.058
30	.038
33	.028
36	.020
39	.011
42	.066
45	.003
48	0

Sample calculation of an adjusted observed spread rate:

Plot number 109, observed log (ROS (fpm) + 1) for 3 min. following ignition was .114 (corresponding to 0.3 fpm). This value was adjusted upwards by adding .233 to give an adjusted log (ROS + 1) of .347, corresponding to 1.2 fpm. This adjustment has the effect of correcting the slow spread rate which follows ignition up to the spread rate which would be expected when the fire has reached the steady state.

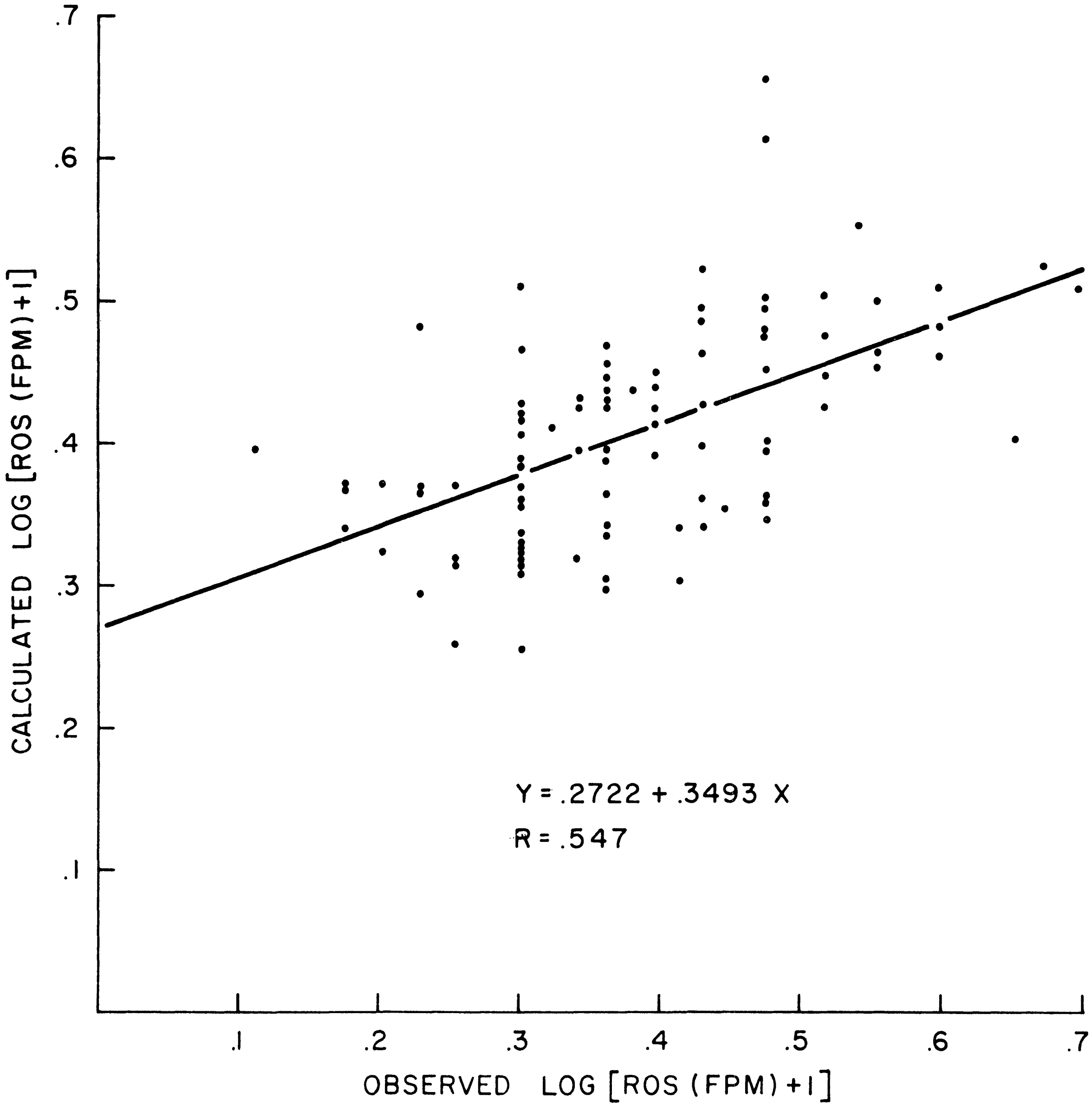

Fig. 22.--Relation of calculated spread rate based on time, wind, and moisture content to observed spread rates for point source fires

TABLE 10.—Adjusted spread rates, fuel consumption and fire intensities

Plot No.	Adjusted Heading R.O.S. (fpm)	Backing R.O.S. (fpm)	Depth Organic Depletion (in)	Fuel Consumed By Heading Front (lb/ft^2)	Heat Yield (Btu/lb)	Heading Intensity (Btu/sec/ft)	Mean Scorch Height (ft)	No. of Candling Trees	Surviving Regeneration %	Surviving Regeneration Ht(ft)
109	1.3	0.5	.55	.066	8476	12	.8	0	6	9
205	0.9	N.A.	.30	.050	8464	6	0	0	100	5
108	2.4	0.5	.46	.091	8476	31	.6	1	0	0
110	1.8	0.5	.57	.130	8470	32	1.7	0	0	0
111	2.2	0.5	.46	.093	8470	29	2.4	4	3	9
107	2.6	0.4	.51	.121	8464	44	1.3	1	3	7
112	2.4	0.7	.53	.102	8476	35	2.7	3	8	7
106	1.1	0.4	.39	.098	8476	14	1.2	1	3	8
118	1.8	N.A.	.47	.078	8476	20	6.3	10	0	0
211	2.2	0.7	.41	.095	8464	30	3.1	4	3	10
114	2.1	0.7	.58	.116	8470	35	6.9	6	0	0
103	2.9	0.5	.32	.057	8476	23	1.5	1	N.A.	N.A.
429	2.1	0.5	.42	.089	8476	26	1.6	2	"	"
124*	2.8	N.A.	.27	.070	8476	27	2.6	1	"	"
426	2.2	0.5	.27	.055	8464	17	1.4	0	"	"
430*	3.0	N.A.	.27	.038	8476	15	4.5	2	"	"
432*	3.6	N.A.	.39	.124	8470	63	5.2	1	"	"
433*	3.6	N.A.	.47	.083	8476	42	4.8	5	"	"
428	2.1	0.5	.62	.088	8470	26	1.4	1	"	"
113	1.9	0.6	.69	.154	8470	42	5.3	7	1	4
105	2.9	0.5	.33	.055	8476	23	1.3	3	N.A.	N.A.
121	2.5	0.6	.21	.047	8470	17	2.5	4	"	"
427	2.0	0.6	.50	.073	8476	20	1.9	2	"	"
431*	3.8	N.A.	.67	.115	8464	61	2.7	2	"	"
120*	3.2	N.A.	.22	.038	8476	17	3.3	4	"	"
122	2.5	0.6	.28	.087	8476	31	1.8	1	"	"
123*	3.9	N.A.	.30	.058	8476	32	2.9	1	"	"
119*	6.5	N.A.	.41	.129	8476	118	5.9	2	"	"

Plots numbered in 100's are Dry Pine South, in 200's are Fresh Pine and in 400's are Dry Pine North.
Asterisks indicate strip head fire ignition (R.O.S. not adjusted).
N.A. - data not available.

TABLE 11.--Regression equations for fire behavior parameters as predicted by fire environment variables and Canadian Forest Fire Behavior System Indices

Y Dependent	X Independent	Inter-cept	Regr. Coef.	SEE	R^2	Mean Y	Mean X
$\log_{10}$(ROS+1)	Fire Weather Index	.1766	.0146	.094	.446	.534	24.6
"	Initial Spread Index	.2785	.0296	.100	.396	.534	8.6
"	Fine Fuel Moist. Code	-3.015	.0385	.104	.317	.534	92.2
"	Wind in stand	.2523	.1202	.110	.230	.534	2.35
"	Relative Humidity	.6765	-.0662*	.113	.198	.534	22.9
"	Org. Layer M.C.	.6857	-.0116*	.113	.190	.534	13.0
"	Fine Fuel Moist. Cont.	.7141	-.0156*	.116	.149	.534	11.5
Flame Length	$\log_{10}$(ROS+1)	-1.550	6.820	.338	.684	2.1	.534
"	Front Flame Depth	.392	.8949	.349	.886	2.1	1.9
"	$\log_{10}$(Intensity (Hwr))	-2.494	3.206	.633	.626	2.1	1.43
Front Flame Depth	$\log_{10}$(ROS+1)	-1.802	6.922	.655	.639	1.9	.534

Note: All regressions significant at .01 level by F-test except those noted * which are significant at .05 level.

Regressions include all 28 test fires (strip and point ignition) with point source fire ROS adjusted for growth with time.

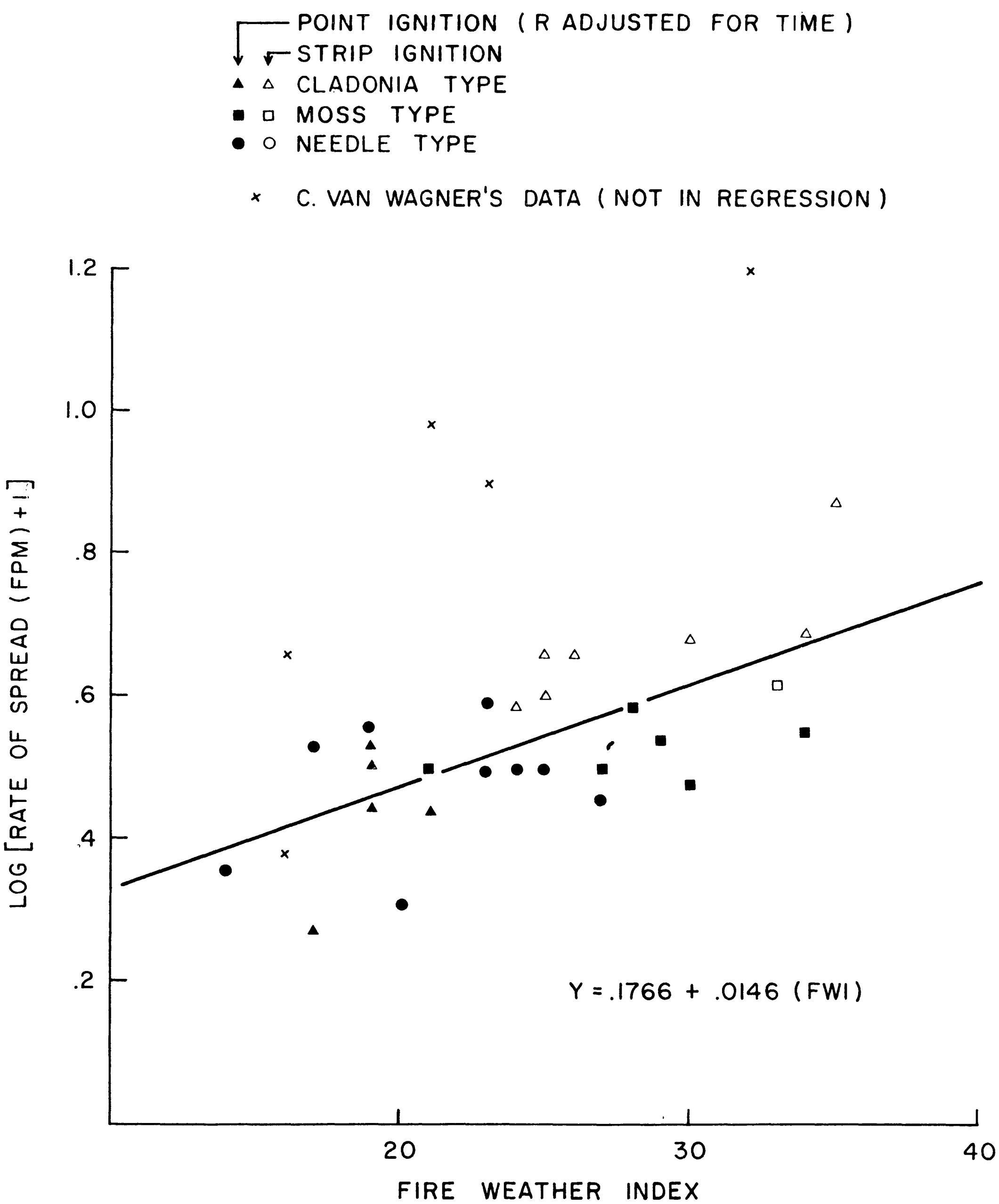

Fig. 23.--Relation of spread rate to Fire Weather Index

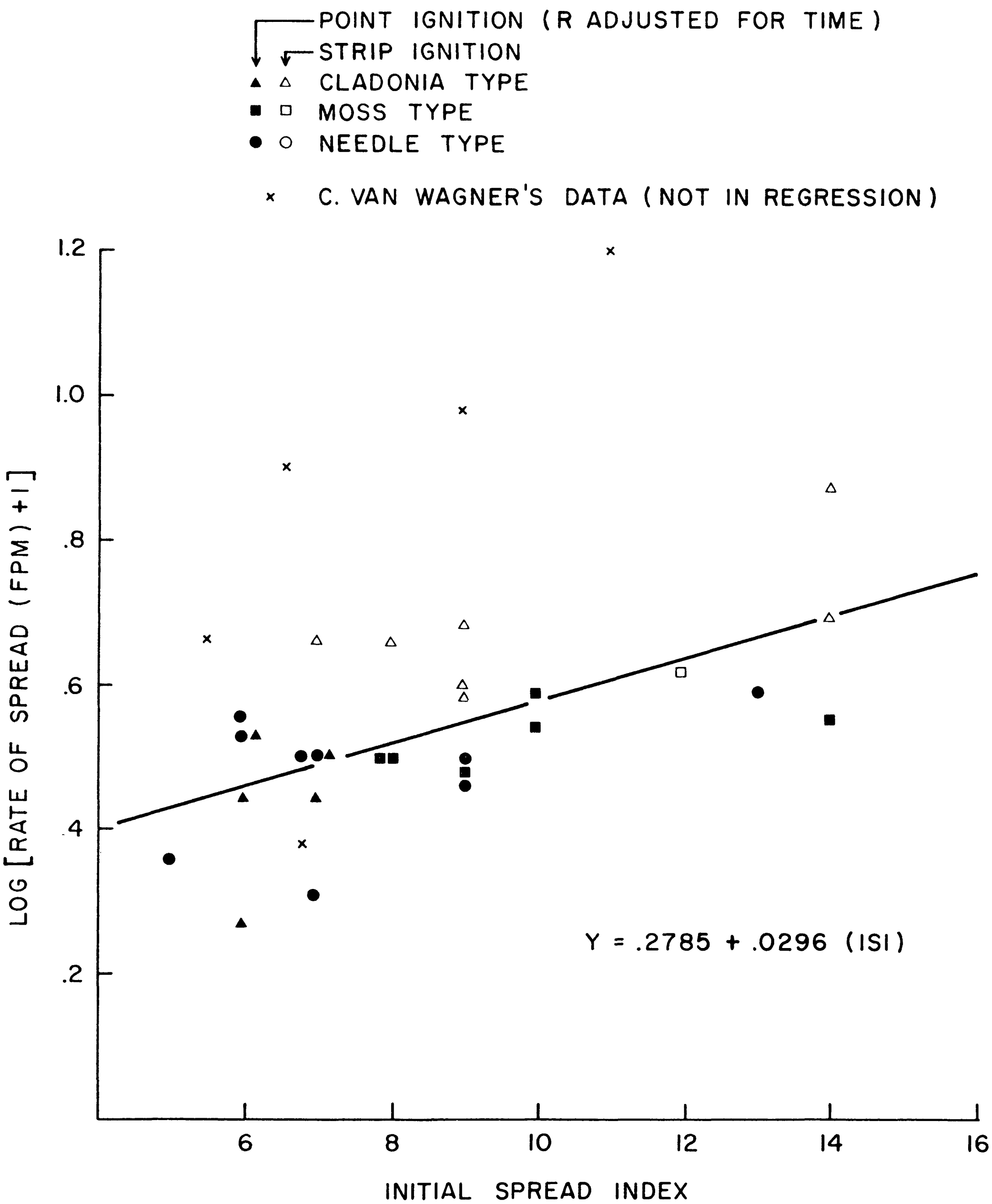

Fig. 24.--Relation of spread rate to Initial Spread Index

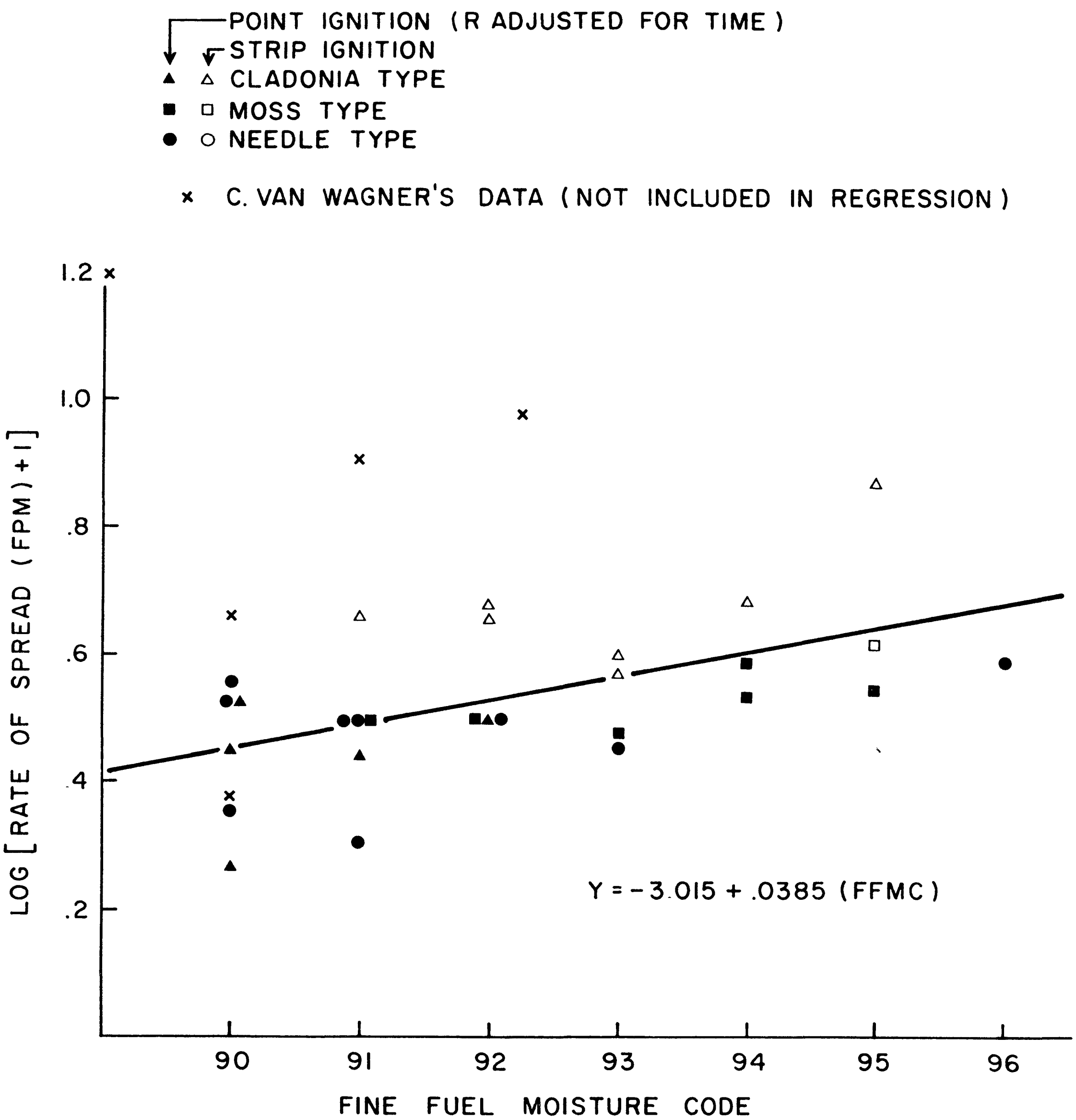

Fig. 25.—Relation of spread rate to Fine Fuel Moisture Code

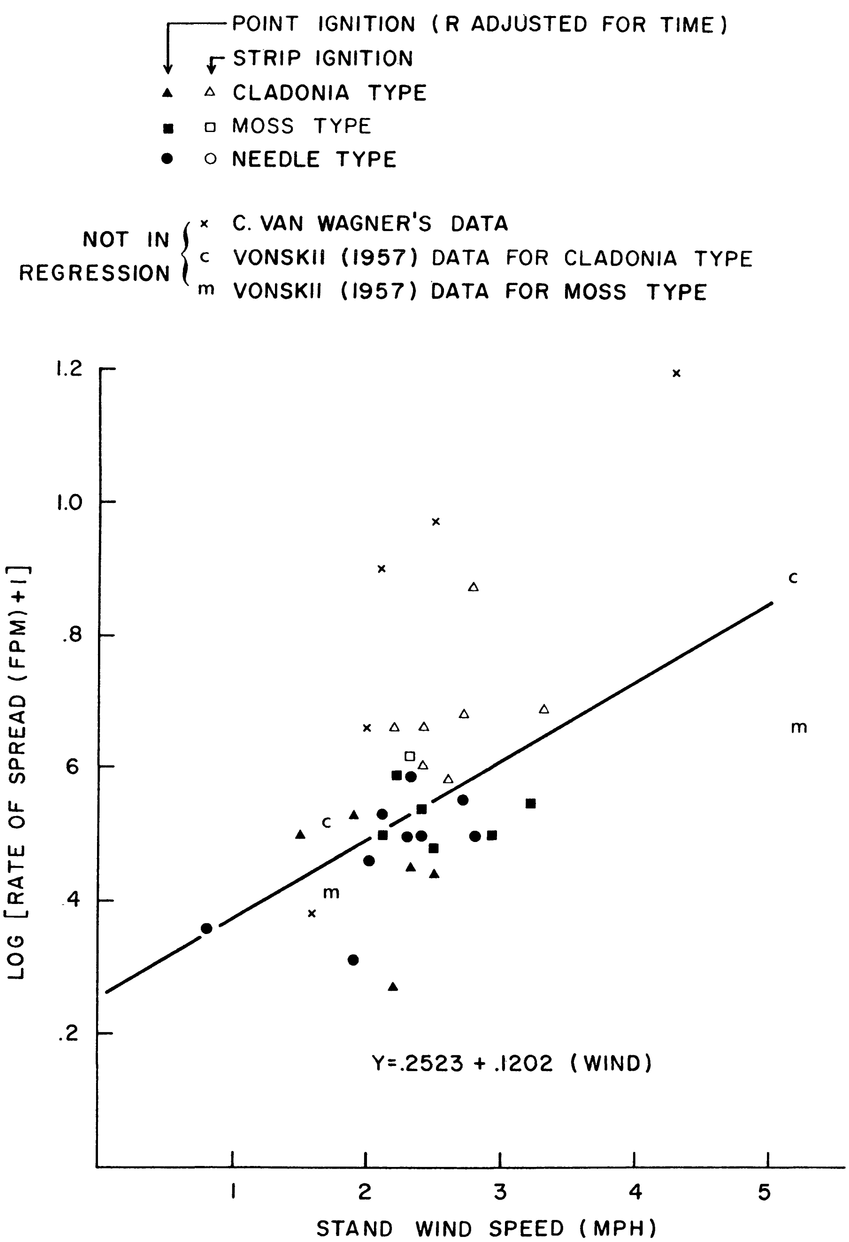

Fig. 26.—Relation of spread rate to stand wind speed

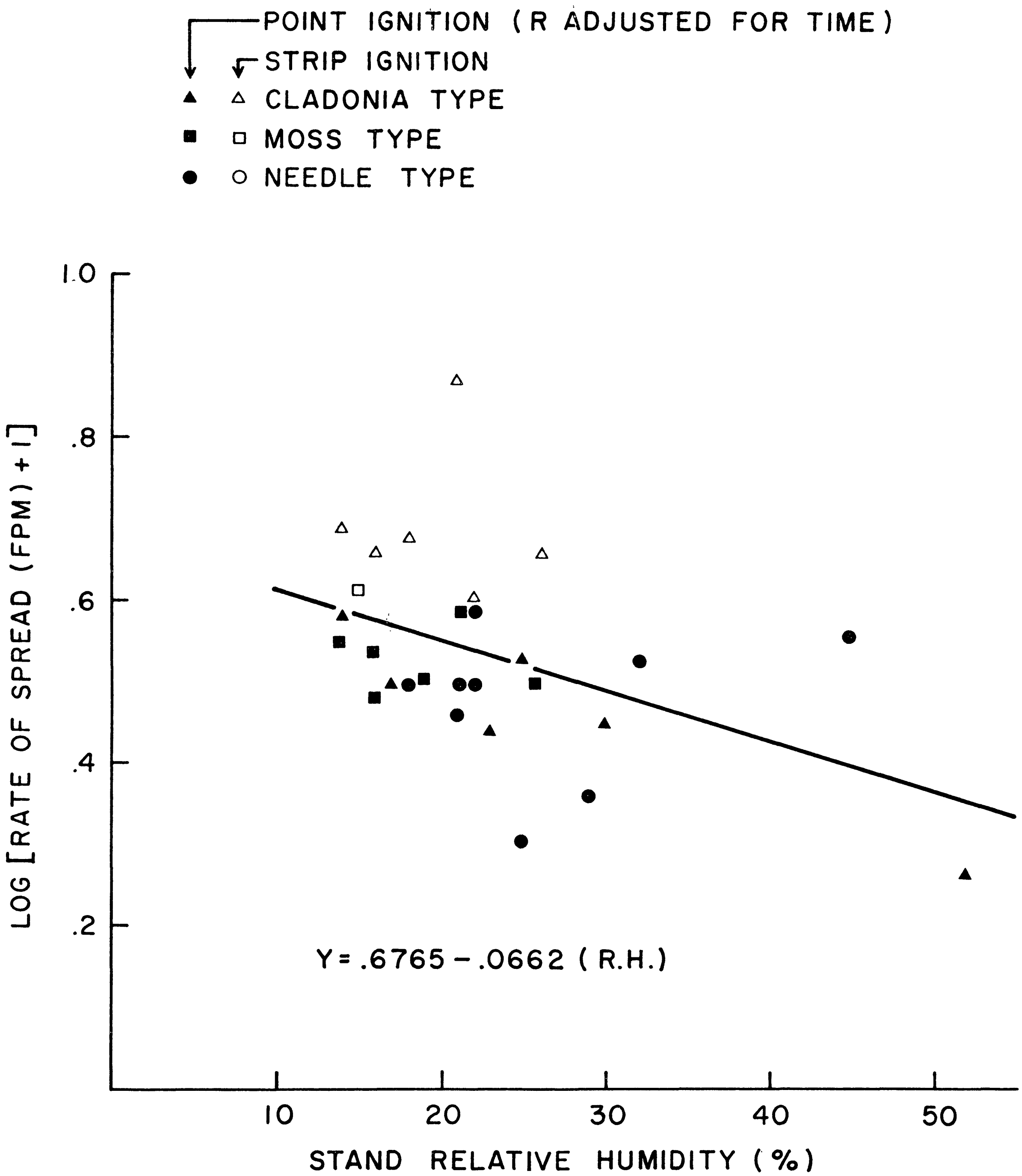

Fig. 27.—Relation of spread rate to stand relative humidity

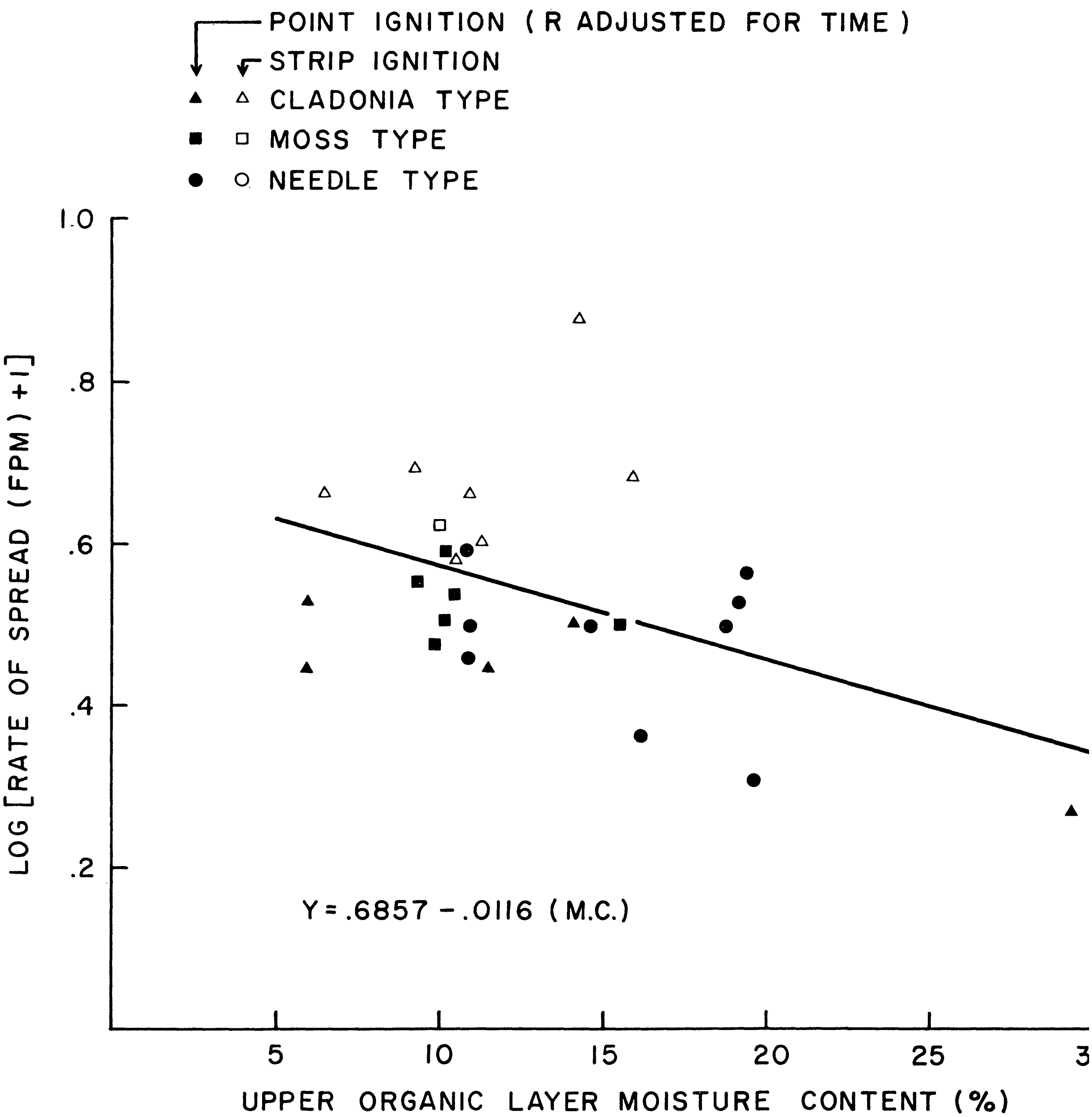

Fig. 28.--Relation of spread rate to upper organic layer moisture content

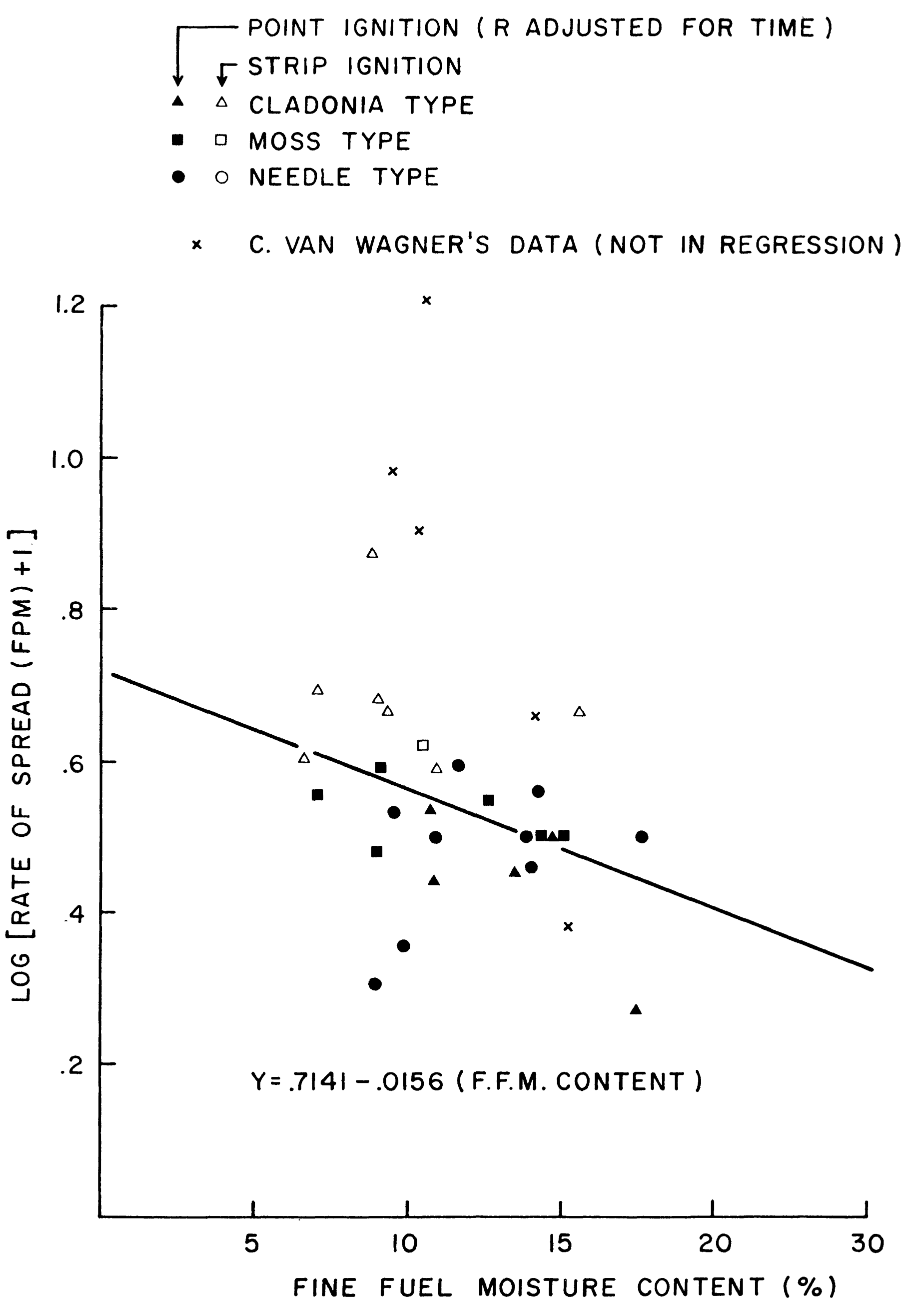

Fig. 29.--Relation of spread rate to fine fuel moisture content

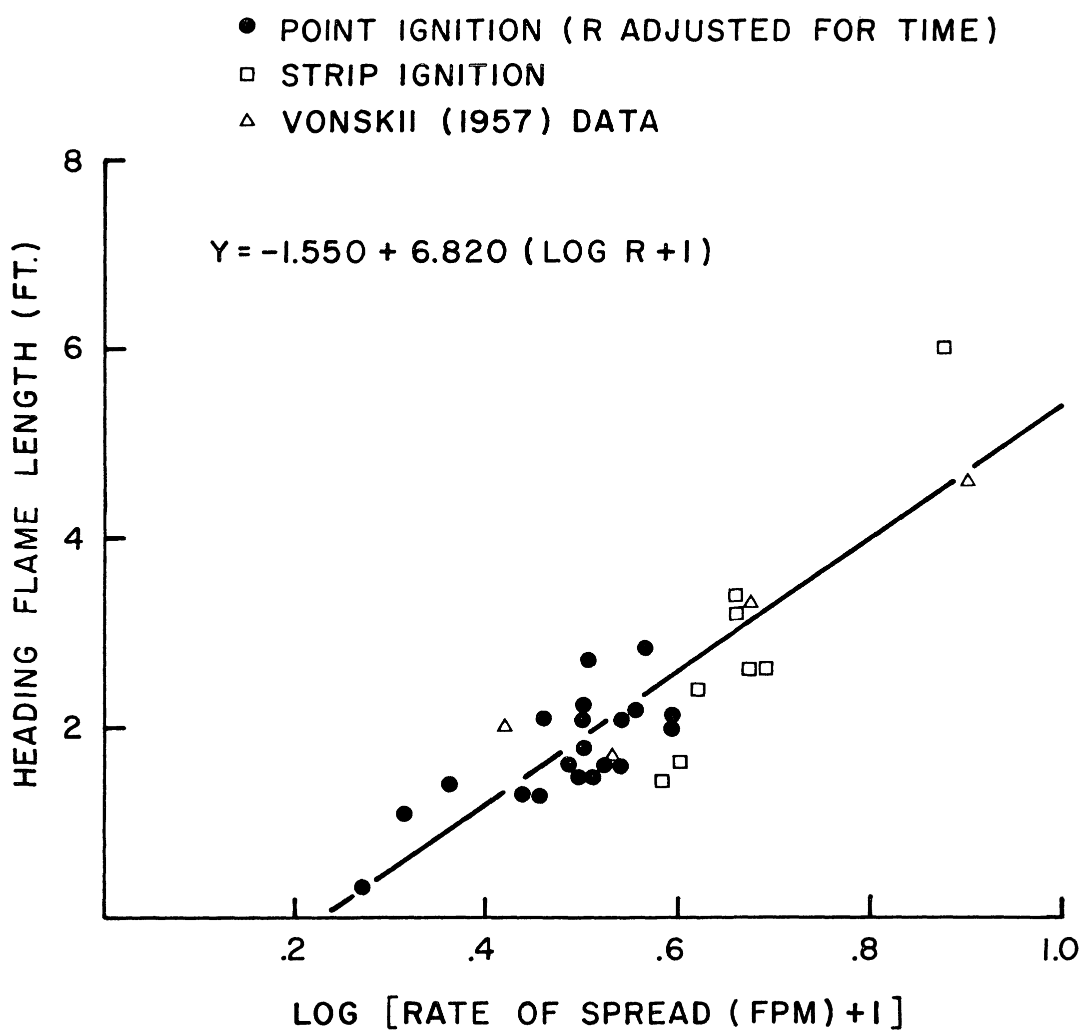

Fig. 30.—Relation of heading flame length to rate of spread

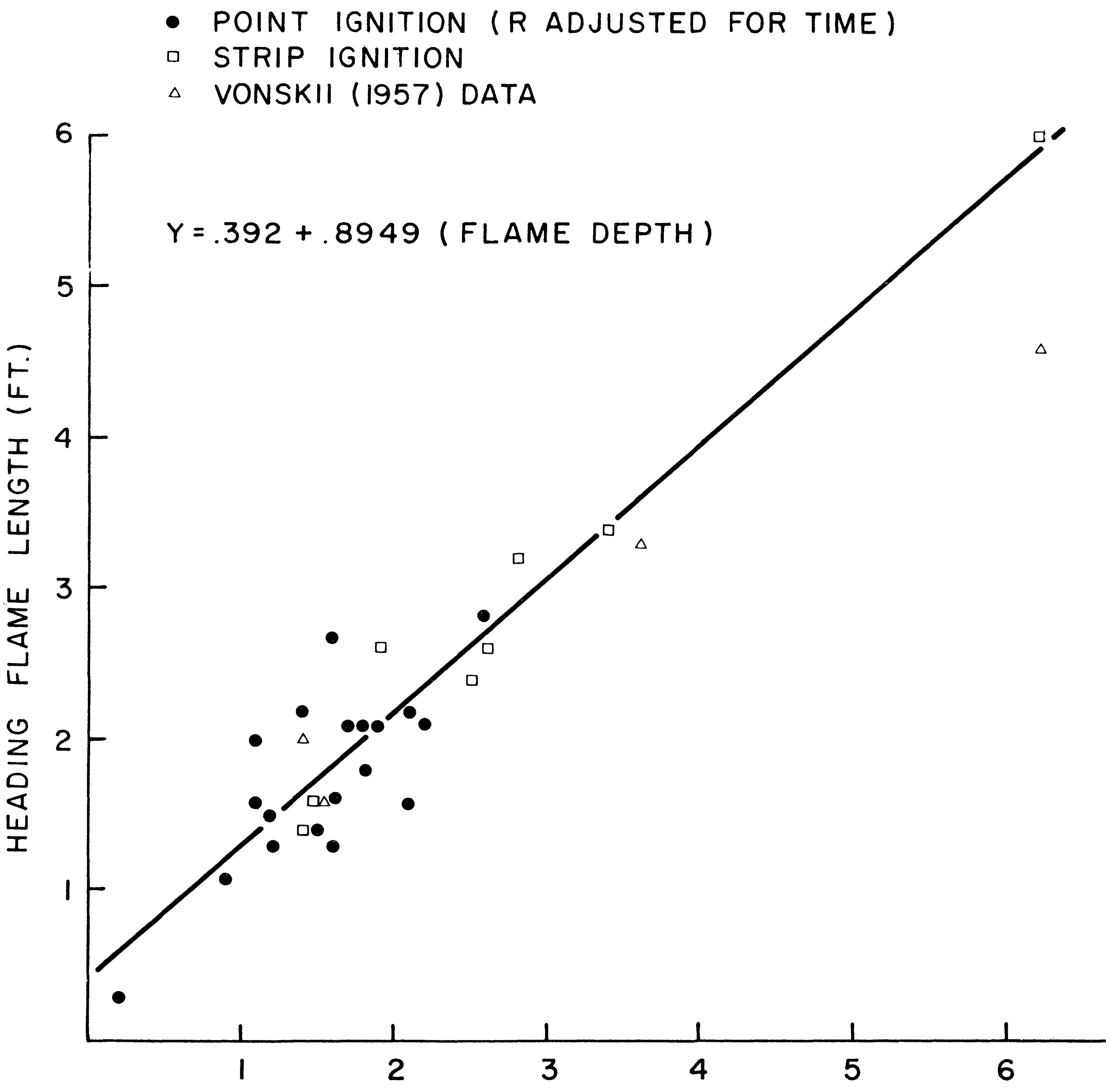

Fig. 31.--Relation of heading flame length to head fire frontal depth

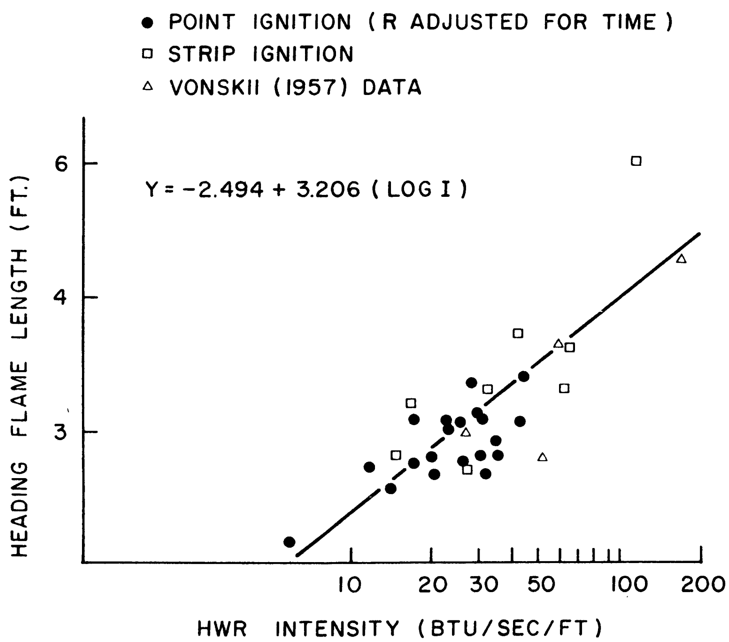

Fig. 32.--Relation of heading flame length to intensity

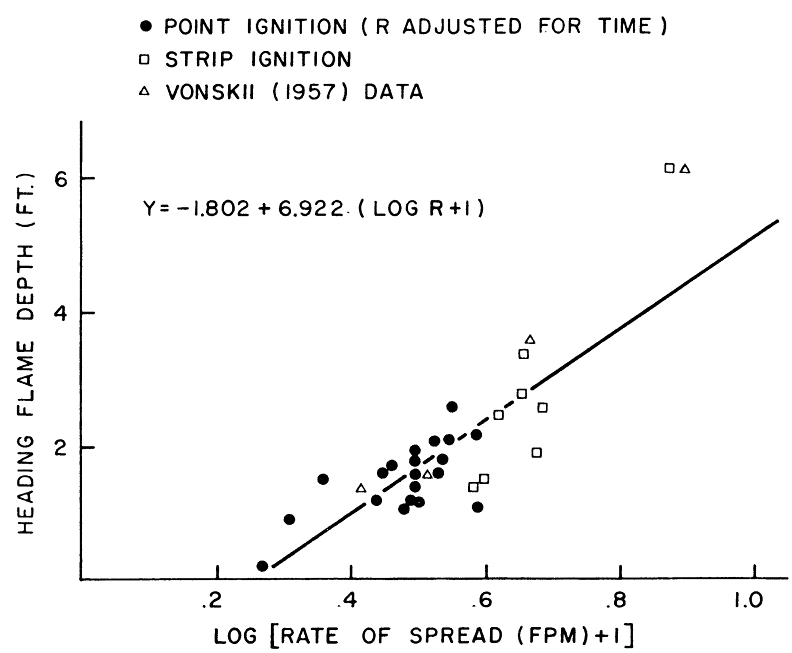

Fig. 33.--Relation of frontal depth to spread rate

TABLE 12.—Description of variables in fuel moisture-danger index regression analysis

Dependent *		Description
Moisture content % ovendry weight of:		
Fine Surface Litter	Y1, Y2	Dead pine needles and twigs less than 3/16 in. from top surface of duff layer.
Twigs $\frac{1}{4}$-$\frac{1}{2}$ in.	Y3, Y4	Dead twigs and branches from ground surface.
Branch $\frac{1}{2}$-$1\frac{1}{2}$ in.	Y5, Y6	Dead branches from ground surface.
Logs $1\frac{1}{2}$-3 in.	Y7, Y8	Dead down logs or branches from ground surface.
Upper Org.-*Cladonia*	Y9, Y10	Upper approx. one inch of predominantly *Cladonia* duff.
Entire Org.-*Cladonia*	Y11, Y12	Full organic layer in which *Cladonia* predominates.
Upper Org.-Moss	Y13, Y14	Upper approx. one inch of duff in which moss predominates.
Entire Org.-Moss	Y15, Y16	Full organic layer in which moss predominates.
Hazard Stick-Open	Y17, Y18	B.C. hazard stick composed of $\frac{1}{2}$ in. dowelling exposed in full clearing at height of 10 in.
Hazard Stick-Stand	Y19, Y20	B.C. hazard stick exposed in pine stand at height of 10 in.

* Note: Y9 to Y16 analyzed as $\log_{10}$ (Moisture content %)

Independent		Description
FFMC	X1	Fine Fuel Moisture Code - index of moisture content of cured fine fuels in forest stand.
DMC	X2	Duff Moisture Code - index of moisture content of 2-4 in. deep, loosely compacted duff.
ADMC	X3	Adjusted Duff Moisture Code - slower responding index of duff moisture content than DMC.
Temp.	X4	Air temperature at 4 ft. in. screen in full opening at time of sampling.
R.H.	X5	Relative humidity at 4 ft. in. screen in full opening at time of sampling.

TABLE 13.--Coefficients of determination (R-squared) for fuel moisture content related to danger indices and weather parameters in multiple linear regression

Site		Dependent Variable	Independent 1.			Independent 2.			Independent 3.			Independent 4.			n.
Dry Pine	Y1	Fine Surface Litter	Temp.	**	.300	FFMC	N.S.	.300	RH	**	.447		**		73
Fresh Pine	Y2	Fine Surface Litter	DMC	**	.202	FFMC	**	.368							40
Dry Pine	Y3	Twigs $\frac{1}{4}$-$\frac{1}{2}$ in.	DMC	**	.280	Temp.	**	.352	RH	N.S.	.360	FFMC	**	.536	71
Fresh Pine	Y4	Twigs $\frac{1}{4}$-$\frac{1}{2}$ in.	FFMC	**	.410	DMC	N.S.	.451							50
Dry Pine	Y5	Branch $\frac{1}{2}$-1$\frac{1}{2}$ in.	DMC	**	.176										70
Fresh Pine	Y6	Branch $\frac{1}{2}$-1$\frac{1}{2}$ in.	DMC	**	.447	Temp.	*	.495							49
Dry Pine	Y7	Logs 1$\frac{1}{2}$-3 in.	ADMC	**	.479	RH	*	.561							33
Fresh Pine	Y8	Logs 1$\frac{1}{2}$-3 in.	ADMC	N.S.	.110										35
Dry Pine	Y9	Upper Org.-Cladonia	DMC	**	.269										71
Fresh Pine	Y10	Upper Org.-Cladonia	FFMC	**	.347	RH	*	.429	DMC	*	.506				41
Dry Pine	Y11	Entire Org.-Cladonia	DMC	**	.286										72
Fresh Pine	Y12	Entire Org.-Cladonia	ADMC	**	.583										41
Dry Pine	Y13	Upper Org.-Moss	DMC	**	.263	Temp.	*	.335							52
Fresh Pine	Y14	Upper Org.-Moss	FFMC	**	.413	ADMC	**	.502							45
Dry Pine	Y15	Entire Org.-Moss	DMC	**	.462	FFMC	**	.546							52
Fresh Pine	Y16	Entire Org.-Moss	ADMC	**	.532										45
Dry Pine	Y17	Hazard Stick-Open	Temp.	**	.344	DMC	N.S.	.370	FFMC	N.S.	.380	RH	**	.449	58
Fresh Pine	Y18	Hazard Stick-Open	DMC	**	.174	RH	**	.533	FFMC	**	.576	Temp.	*	.601	52
Dry Pine	Y19	Hazard Stick-Stand	DMC	**	.454	Temp.	**	.540	RH	N.S.	.543	FFMC	**	.578	60
Fresh Pine	Y20	Hazard Stick-Stand	FFMC	**	.957	DMC	**	.967							52

* indicates significant contribution of variable to total variation explained by F-test at .05 level of significance.
** " " " " " " " " .01 " "
N.S. " not significant contribution of variable to total explained variation at .05 level.

Note: logarithmic transformation was made on Y9 to Y16 prior to analysis.

TABLE 14.—Regression equations for selected fuel moisture content variables on danger indices and weather parameters

Dependent	Independents	Intercept	Regression Coefficients b_1	b_2	b_3	b_4	Std. Error of Est.	R^2 *	Mean Y
Y1	X1, X4, X5	61.39	-.5056	-.0183	-.2114		5.17	.447	14.2
Y3	X1, X2, X4, X5	81.28	-.7540	-.0231	.0016	-.0320	2.18	.536	10.6
Y4	X1, X2	105.03	-.9742	-.0724			5.17	.451	14.4
Y6	X2, X4	66.77	-.3081	-.4092			8.34	.495	21.7
Y7	X3, X5	21.96	-.1139	.0036			3.04	.561	13.6
Y10	X1, X2, X5	2.800	-.0173	-.0042	.0125		.225	.506	1.409
Y12	X3	2.349	-.0110				.182	.582	1.671
Y14	X1, X3	6.644	-.0520	-.0069			.278	.501	1.564
Y15	X1, X2	2.626	-.0057	-.0067			.214	.547	1.691
Y16	X3	2.531	-.0119				.219	.531	1.801
Y17	X1, X2, X4, X5	40.80	-.2734	-.0032	-.0933	-.0108	1.41	.449	9.04
Y18	X1, X2, X4, X5	19.20	-.0537	-.0450	-.0596	.0357	1.23	.601	8.90
Y19	X1, X2, X4, X5	12.60	-.0478	-.0316	-.0766	.0022	.29	.578	9.26
Y20	X1, X2	98.20	-1.010	.0501			2.52	.967	12.16

* All equations significant by F-test of variance ratio at .01 level.

Note: Y7, Y10, Y12, Y14, Y15, Y16 are $\log_{10}$ (Moisture content %).

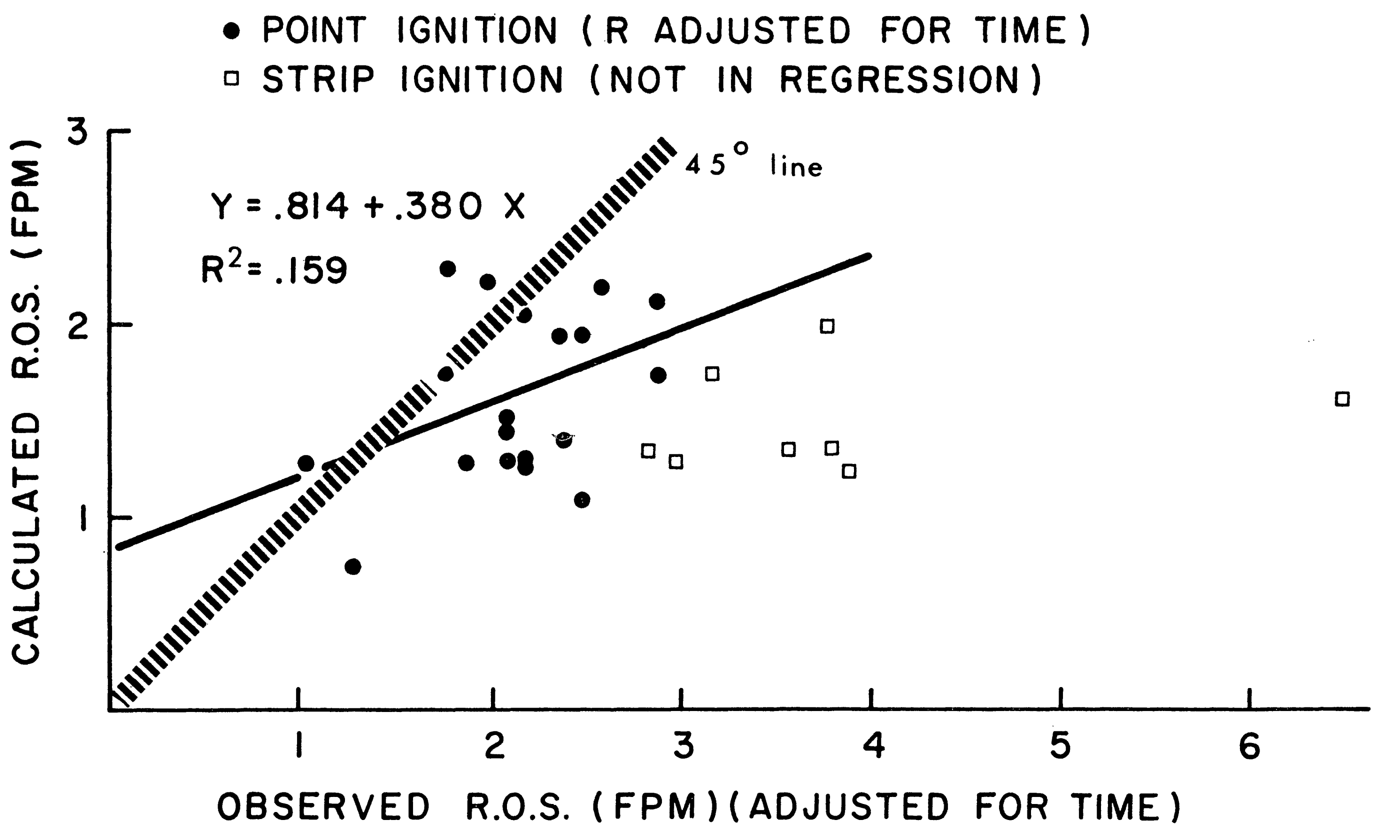

Fig. 34.--Relation of U.S.F.S. spread model predicted rate of spread to observed spread rates

TABLE 15.--U.S.F.S. spread model-predicted rates of spread with observed spread rates with percentage deviations

Plot No.	Rate of Spread: Predicted (fpm)	Rate of Spread: Observed Adjusted for time from ignition (fpm)	Rate of Spread: Observed Unadjusted (fpm)	Deviation: From adjusted R.O.S. $\left(\frac{P-0}{0}\right)$ (%)	Deviation: Unadjusted $\left(\frac{P-0}{0}\right)$ (%)
109	0.75	1.3	0.9	- 42	- 17
205	..[1]	0.9	0.4	..	..
108	1.96	2.4	1.9	- 18	+ 3
110	2.31	1.8	1.4	+ 28	+ 65
111	1.26	2.2	1.5	- 43	- 16
107	2.22	2.6	1.7	- 15	+ 31
112	1.42	2.4	1.9	- 41	- 25
106	1.32	1.05	0.8	+ 26	+ 65
118	1.73	1.8	1.3	- 4	+ 33
211	2.07	2.2	1.5	- 6	+ 38
114	1.29	2.1	1.5	- 39	- 14
103	2.12	2.9	2.0	- 27	+ 6
429	1.45	2.1	1.6	- 31	- 9
426	1.28	2.2	1.5	- 42	- 15
428	1.52	2.1	1.4	- 28	+ 9
113	1.28	1.9	1.4	- 33	- 9
105	1.75	2.9	2.1	- 40	- 17
121	1.96	2.5	1.8	- 22	+ 9
427	2.24	2.0	1.4	+ 12	+ 60
122	1.09	2.5	1.9	- 56	- 43
124*	1.34	..	2.8	..	- 52
430*	1.29	..	3.0	..	- 57
432*	1.98	..	3.6	..	- 45
433*	1.36	..	3.6	..	- 62
431*	1.35	..	3.8	..	- 64
120*	1.76	..	3.2	..	- 45
123*	1.22	..	3.9	..	- 69
119*	1.59	..	6.5	..	- 76

[1] Not calculated because of high moisture content.

Note: asterisks indicate strip head fire ignition, with spread rates unadjusted for time growth.

APPENDIX II

U. S. Forest Service Fire Spread Model

APPENDIX II

U. S. FOREST SERVICE FIRE SPREAD MODEL

A mathematical model of fire spread in wildland fuels has been developed for the U.S. National Fire Danger Rating System at the Northern Forest Fire Laboratory, Missoula, Montana (Rothermel, 1972). The model integrates the effects of wind and slope, together with fuel bed and fuel particle properties to compute the fire spread rate. The basic structure and input parameters required to utilize the model are given below.

Model

Rate of Spread: $R = I_o\ (1 + \phi_w + \phi_s)\ /\varepsilon\rho_b Qig$

where: R is rate of spread;

$I_o(1 + \phi_w + \phi_s)$ is the propagating intensity (Ip); and

$\varepsilon\rho_b Qig$ is the volumetric heat of preignition.

To expand on these expressions, the propagating intensity (Ip), or fraction of the total reaction intensity effective in advancing the fire, is a function of I_o, the no wind propagating flux, and the wind and slope effects, as contained in the expressions ϕ_w and ϕ_s respectively. The fraction of the fire intensity which serves in frontal propagation varies directly with the fuel packing ratio (β) and the surface : volume ratio (σ).

The numerator of the spread equation can be presented as

$I_R \xi (1 + \phi_w + \phi_s)$ where I_R is the reaction intensity and ξ is the propagating flux ratio. This expression permits the illustration of how the fuel bed and fuel particle parameters are employed in the model, without fully deriving the model expressions.

$$I_R = \Gamma' W_o \, h \, \eta_M \, \eta_s$$

where Γ' is reaction velocity, η_M is the fuel moisture damping coefficient, η_s is the mineral damping coefficient, and other terms are described in the list of input parameters in the following section. I_R is derived from the mass loss rate of the fuel and its heat content.

The express for wind effect, ϕ_w, takes the following form:

$$\phi_w = CU^B \, (\beta/\beta \text{ op})^{-E}$$

where C, B and E are all expressions varying directly with surface: volume ratio, U is the wind velocity and β op is the optimum fuel packing ratio, which is related to a specific value of σ.

The slope correction, ϕ_s, varies directly with the tangent of the slope angle and inversely with the packing ratio.

The denominator of the spread equation is the product of ε, an effective heating number, ρ_b, the bulk density of the fuel array, and Qig, the heat per unit mass of dry fuel required for ignition. The fractional amount of fuel involved in the ignition process, ε, depends on surface-area-to-volume ratio. Heat of preignition, Qig, depends on moisture content.

Heterogeneous mixtures of wildland fuels are accounted for in the model by weighting each particle's contribution according to its exposed surface area. Fine fuels with large σ contribute most to fire spread rate.

<u>Fuel and fire environment input parameters</u>:

Wo = initial oven dry fuel loading, lb/ft^2

h = low heat content of fuel, oven dry, Btu/lb.

ρ_b = fuel bed bulk density, fuel mass per unit volume of fuel bed, lb/ft^3

ρ_p = fuel particle density, lb/ft^3

β = packing ratio, ρ_b/ρ_p or total fuel volume/total fuel bed volume

δ = depth of fuel bed, ft

M_f = moisture content, fraction of dry wt.

Se = silica - free ash content, fraction of dry wt.

σ = fuel surface-area-to-volume ratio, ft^{-1}

U = mean wind velocity at flame ht., ft/min.

$\tan \phi$ = slope, vertical rise / horizontal distance

M_x = moisture content of extinction, fraction of dry wt.

APPENDIX III

Scientific and Common Names of Species on Study Area

APPENDIX III

Scientific and Common Names of Species on Study Area

Trees

Scientific Name	Common Name
Abies lasiocarpa (Hook.) Nutt.	Alpine fir
Betula papyrifera Marsh var. *subcordata* (Rydb.) Sarg.	White birch
Picea engelmannii Parry	Engelmann spruce
Picea glauca (Moen.) Voss	White spruce
Picea mariana (Mill.) B.S.P.	Black spruce
Pinus contorta Dougl.var. *latifolia* Engel.	Lodgepole pine
Populus tremuloides Michx.	Aspen
Pseudotsuga menziesii (Mirb.) Franco	Douglas fir

Tall Shrubs

Amelanchier alnifolia (Nutt.) Nutt.	Saskatoon or Service berry
Juniperus communis L.	Juniper
Rosa spp.	Rose
Salix spp.	Willow
Sorbus sitchensis Roem	Mountain ash

Low Shrubs

Vaccinium spp.	Blueberry, Huckleberry
Arctostaphylos uva-ursi (L.) Spreng.	Bearberry, Kinnikinnick
Chimaphila umbellata (L.) Nutt	Prince's Pine, wintergreen

Herbs

Clintonia uniflora (Schultz) Kunth.	Queen's cup
Cornus canadensis L.	Bunch berry
Galium boreale L.	Northern bedstraw
Pyrola secunda L.	One-sided wintergreen

Fern Allies

Lycopodium annotinum L.	Stiff clubmoss

Mosses

Pleurozium schreberi (Brid.) Mitt.

Calliergonella schreberi (Bry. Eur.) Grout

Lichens

Peltigera spp.	
Cladonia spp.	Reindeer lichen, Reindeer moss