P. J. ROUSSOPOULOS

PH. D.

This is to certify that the

thesis entitled

AN APPRAISAL OF UPLAND FOREST FUELS AND
POTENTIAL FIRE BEHAVIOR FOR A PORTION
OF THE BOUNDARY WATERS CANOE AREA

presented by

Peter Jon Roussopoulos

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Forestry

Victor J. Rudolph
Major professor

Date October 5, 1978

O-7639

AN APPRAISAL OF UPLAND FOREST FUELS AND POTENTIAL FIRE BEHAVIOR FOR A PORTION OF THE BOUNDARY WATERS CANOE AREA

By

Peter Jon Roussopoulos

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Forestry

1978

ABSTRACT

AN APPRAISAL OF UPLAND FOREST FUELS
AND POTENTIAL FIRE BEHAVIOR FOR A
PORTION OF THE BOUNDARY WATERS CANOE AREA

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Forest flammability conditions were quantitatively appraised within a 40,000 hectare portion of the Boundary Waters Canoe Area (BWCA), where a pilot study has been proposed to determine the feasibility of using naturally occurring wildfire to restore and maintain pristine wilderness environments.

A broad-scale inventory of upland forest fuels was conducted within the study area during the summer of 1976. An assortment of vegetation and detritus sampling techniques was used to quantify the living and dead fuel components at each inventory site. Amounts of both surface and aerial fuel components were recorded by species, size class, condition, and height above the ground in increments of 30.5 cm.

Total fuel loading ranged from 3.8 to 17.2 kg/m^2, with most of the variation attributable to humus and large diameter downed deadwood. Eighty percent of the inventory samples were within aspen-birch communities. Repeated burning in the late 19th century is thought to be responsible for the abnormally high representation of aspen-birch types within the study area. The remaining 20% of the samples fell within a variety of conifer and mixed deciduous-conifer community types.

Little of the dispersion in fuel loading estimates could be attributed to differences among forest community types. Variation was greater within these types than it was among them.

For each inventory sample, potential fire behavior was predicted under standard weather conditions using available fire behavior models. A cluster analysis, performed on transformations of the fire behavior predictions, identified four major groups of samples on the basis of fuel flammability. The largest cluster contained 81% of the inventory samples, reflecting the apparent homogeneity of upland stands in the study area. Unfortunately, there was no clear relationship between the fuel type classification and recognized vegetation types, while a multiple discriminant analysis required 42 descriptor variables to correctly classify 91% of the inventory samples on the basis of observed stand and site characteristics alone. Results suggest that a single fuel model should be used to represent the entire study area.

Nomographs were constructed for the two most representative sample clusters to display predicted surface fire intensities and spread rates, as well as threshold conditions for vertical fire development into tree crowns. Predicted occurrence of long-distance spotting, using one nomograph, compared favorably with actual conditions on three project fires in or near the study area, suggesting that the nomographs may be operationally useful for assessing the threat of fires escaping the study area. Further analysis is recommended before extending these results to the entire BWCA.

ACKNOWLEDGMENTS

I am deeply indebted to the many individuals whose effort and cooperation have made this study possible. First, I would like to acknowledge the U. S. Forest Service for providing the opportunity and resources for this research. In particular, I am grateful to Project Leaders Von J. Johnson and Stanley N. Hirsch for their administrative support and personal encouragement throughout the study.

To my colleagues at the North Central Forest Experiment Station I offer thanks for their interest, cooperation, and expert counsel. Special thanks go to Robert M. Loomis, Richard W. Blank, and William A. Main. Their technical contributions and assistance proved invaluable in all phases of the study. I also would like to thank the many field and laboratory assistants whose long hours and diligent effort provided the database for this analysis.

Appreciation is also extended to the Superior National Forest for the cooperative work environment it provided. Fire Management Officer Clifford E. Crosby, Jr. and District Rangers Ray C. Chase, A. Earl Niewald, and Wayne A. Smetanka deserve a personal thanks for logistic support in the field and constructive criticism of study results.

I am especially grateful to Dr. Gary Schneider for his guidance, encouragement, and patience throughout my academic program, and also to Dr. Victor J. Rudolph, who accepted me as his own upon Dr. Schneider's departure. May I also offer thanks to Dr. Erik D. Goodman, Dr. James B.

Hart, Jr., and Dr. Peter G. Murphy for their friendship and assistance, and for serving on my graduate committee.

Finally, and most importantly, I wish to thank my wife Cori, son Andrew, and daughter Nicole for their patient understanding and encouragement despite the many family plans and opportunities foregone.

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INTRODUCTION

The extent to which unplanned forest fires should be used as a tool to manage wilderness vegetation has recently become an important and controversial issue among conservationists, ecologists, land managers, and forest product manufacturers. All have identified a need for better understanding of fire's role in establishing and maintaining natural ecosystems. Accordingly, a vast body of literature, including several symposia and at least one full book (Kozlowski and Ahlgren 1974), has been devoted to this topic. One common thread woven through much of this literature is the recognition that fire has been an important ecological factor for as long as terrestrial plant communities have existed. Over fifty years of aggressive fire suppression, however, have minimized its influence, often facilitating gradual fuel accumulations and notable successional changes over relatively broad areas.

Because wilderness managers are charged with preserving or maintaining a "natural landscape," one in which man is only a temporary occasional visitor (Heinselman 1965), they have become concerned over observed changes brought about by their own management activities. Many have advocated that fire be allowed to play a more natural role in wilderness environments. Although the realization that fire is needed to maintain certain ecosystems is not new (Soper 1919, Maissurow 1935), two simultaneous developments can be given much of the credit for its recent revival. First, mounting evidence of fire's historical role in North American forests, and of adverse or potentially adverse ecological responses to past fire suppression activities has provided motivation for public and professional concern. Second, the advent of quantitative models for predicting fire behavior (Rothermel 1972, Albini 1976) and improved methods for inventorying forest fuels (Van Wagner 1968, Brown 1971, Brown and Roussopoulos 1974, Sando and Wick 1972) has helped make the restoration of fire to wilderness a realizable objective. Potential answers to some of the "Hows?" as well as the "Whys?" of fire management are now beginning to appear.

Though certainly not without controversy, the net result has been a marked liberalization of fire suppression policies among public land management agencies. Several attempts to reintroduce fire to natural ecosystems have recently been evidenced in the literature (Agee 1974, Aldrich and Mutch 1972, Butts 1976, Daniels 1974, Devet 1976, Gunzel 1974, Kilgore and Briggs 1972, Kilgore 1975, Loope and Wood 1976, Sellers and Despain 1976). At present, at least 20 land units within national parks, monuments, or national forest wilderness areas totalling roughly two million hectares are being managed with provisions for "supervised" wildfire activity under prescribed conditions.[1/] Furthermore, a 1978 revision to the USDA Forest Service Fire Management Policy (FSM 5100-5130) promises to extend and tailor similar programs to a great variety of additional wildlands throughout the United States.

1/ Personal communication, November 7, 1977. Richard J. Barney, Intermountain Forest and Range Experiment Station, USDA Forest Service, Missoula, Montana.

The BWCA Fire Management Proposal

A plan[1/] is now being considered to restore fire, on a pilot basis, to a portion of the Boundary Waters Canoe Area (BWCA), a lakeland wilderness occupying more than 400,000 hectares in northeastern Minnesota (Figure 1). The historical role of fire as an environmental factor in the BWCA has been well documented by several investigators (Heinselman 1969, 1970, 1973; Swain 1973; Wright 1969, 1974), while evidence of successional change in absence of disturbance has been discussed by Ohmann and Ream (1971b), Grigal and Ohmann (1975), and Ahlgren (1974, 1976).

The proposed fire management pilot study is intended to determine the feasibility of using natural fire ignitions in the BWCA to restore and maintain a pristine wilderness condition.

To initially reduce the complexity of the program and ease the transition from the BWCA's traditional fire exclusion policy, a contiguous 40,000 hectare pilot study area--completely bounded by established canoe routes--was selected (Figure 1). Inside this area, the plan will allow fire, within given prescription guidelines, to resume a more natural ecological role.

Criteria for a candidate "prescribed natural fire" include:

1. The fire must be lightning-caused.
2. It must be within the pilot study area.

1/ Crosby, Clifford E. 1978. BWCA Pilot Study on Prescribed Natural Fire. Unpublished draft plan on file at the Superior National Forest Supervisor's Office, Duluth, Minnesota.

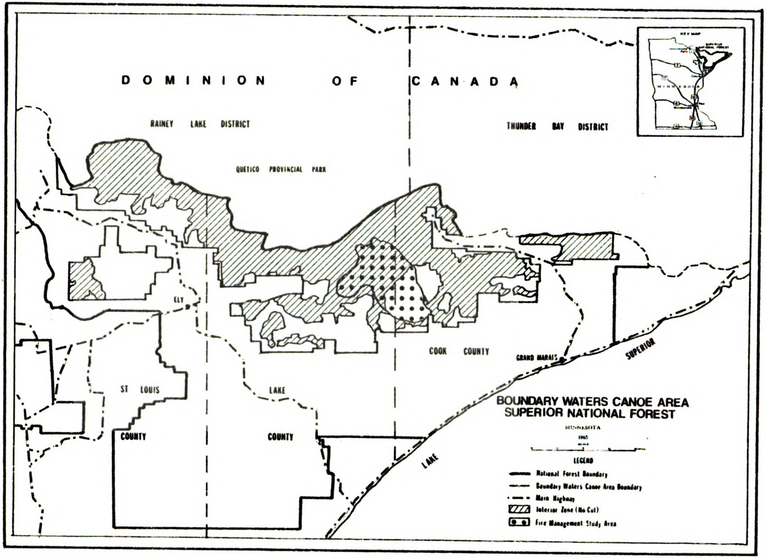

Figure 1. Geographic location of the BWCA and fire management pilot study area.

3. It must be in an area with an established preattack plan.[1/]

4. It must be within the established weather prescription for the fuel type in which it is burning.

5. There must be no threat of unacceptable adverse inpacts.

Unacceptable adverse impacts, according to the plan, are:

1. Personal injury or loss of life.

2. Damage to cabins or other structural improvements.

3. Damage to private property not covered by prior agreement.

4. Disturbance of eagle/osprey nests during the nesting season.

As indicated above, weather prescriptions, established from local fuel and weather data, will be required prior to implementation of the plan. If all prescription requirements are met, along with the other conditions for prescribed natural fire, delayed initial attack on the fire will be allowed. If any one condition is not met, a wildfire will be declared, preattack plans will be activated, and overhead personnel and suppression crews will be mobilized as needed to effect control.

Problem Formulation

Problems involved in restoring natural fire to wildland ecosystems are relatively new to land managers in North America. Few universal

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1/ An operational plan showing potential locations of fire lines, pump positions, etc., should a wildfire ever occur in the subject area.

guidelines have been established regarding the setting of criteria for fire suppression action so that natural fire regimes are simulated as closely as practicable without jeopardizing public safety or compromising off-site management objectives. Although these problems have been addressed in several western parks and wilderness areas, the solutions may not be directly applicable to midwestern conditions. Relatively flat landscapes and large continuous blocks of uniform vegetative cover create a high level of uncertainty concerning the potential outcome of a fire, a level that is uncommon in the broken terrain and discontinuous vegetation characteristic of the mountainous west.

The recent 32,000 hectare Walsh Ditch fire in northern Michigan offers one scenario of what can happen in the Lake States when fire management objectives and decision criteria are not formally established (Miller 1978). Clearly, specific prescriptions are needed for deferring fire control action in such an uncertain environment, and the task of defining these prescriptions merits objective and preferably quantitative thought.

Since wilderness is the principal resource under management in the BWCA, and since a broad range of fire sizes and intensities has historically contributed to the development of that resource (Heinselman 1973), fire managers can base their decisions primarily on the likelihood of the unacceptable adverse impacts listed previously and the chance that a prescription fire will escape the study area. Furthermore, the remote location of the area chosen for the pilot study, its relatively light visitor traffic, its dearth of structural developments, and its small proportion of non-federal land allow decision-makers to focus mainly on the latter of these concerns.

The potential for a fire to escape the study area is dependent on several factors--the location of the fire, its size, growth rate, direction of spread, the effectiveness of control efforts once initiated, and future changes in fuel, weather, and topographic conditions that may influence these factors. Some insight into the problem can be gained by examining historical fire activity in the BWCA. Due to the characteristically broken landscape of this region, the primary mechanism for large fire development is long distance spotting--the aerial transport of glowing sparks or embers beyond the zone of direct ignition by the main fire. Large fires normally "hop" from high ground to high ground, sometimes coalescing in the low areas, but often leaving the interjacent lowlands entirely unburned. Lakes are often insufficient barriers to fires of this nature. Spotting across water bodies more than a kilometer in width, though infrequent, has been observed. Furthermore, the abundance of forested islands on many lakes offers a pathway for consecutive spotting across yet larger waterways.

Although modern suppression methods and the availability of water in the BWCA allow rapid containment and control of most surface fires, serious control problems are encountered whenever crowning and/or spotting occurs. Since the study area is bounded by canoe routes, spotting seems the most likely means by which prescription fires could escape its boundaries. The ability to anticipate fire behavior, especially the likelihood of spotting conditions, would therefore be useful in deciding whether or not suppression action should be taken on any given fire.

Three conditions appear necessary and sufficient for fire spread by spotting in the BWCA.[1/] First, surface fuels must be dry enough to ignite on contact with glowing firebrands. A 10-hour timelag fuel moisture content (Deeming et al., 1972) at or below 7 or 8 percent indicates satisfaction of this requirement.[2/] Second, a wind speed of 4.5 m/sec. or more above the canopy is required to transport firebrands sufficiently ahead of the contiguous fire front. Following periods of prolonged drought, however, strong plume development may slightly reduce this threshold value. Finally, in closed forest stands, flaming combustion within the canopy space (i.e. torching or crowning) is required to loft potential firebrands into the super-canopy flow field.

The first two criteria are relatively straight-forward and measured daily at all fire danger rating weather stations. The third, however, poses a more vexing problem of fire behavior prediction. This document describes efforts to inventory, classify, and rate upland forest communities of the pilot study area in terms of their combustion properties. It provides a means for assessing the potential for torching or crowning

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1/ Personal observation as fire behavior consultant on the Prayer and Magnetic Fires (1974) and the Roy Lake, Rice Lake, and Fraser Fires (1976), all within 25 kilometers of the pilot study area.

2/ Also confirmed by observations of local fire management personnel, (Crosby, Clifford. Personal correspondence dated December 1977).

and ultimately spotting fire behavior that may be useful in establishing decision criteria for alternative fire management actions in the BWCA.

OBJECTIVES

The operational objectives of this study are to:

1. Discriminate, on the basis of fire behavior potential, a finite number of mutually exclusive and exhaustive "forest fuel types" occurring on upland sites within the study area. Attention was limited to upland sites because it is primarily these areas that become involved in spotting fire behavior.
2. Relate these fuel types to readily observable stand and site characteristics or familiar forest classification systems to facilitate field application of results.
3. Delineate current boundaries of these fuel types within the study area.
4. Develop numerical models of the fuel types to allow quantitative prediction of fire behavior, particularly spotting potential, under known or anticipated weather regimes.

On the subject of fuel typing, E. L. Demmon wrote the following:[1/]

> Regardless of the basis of classification, the system will fail to be accepted and used if the fuel types are not quickly and easily recognized on the ground or from maps. As a result, it is a requirement that if a fuel type as classified is not clear cut for recognition, it must be related to some other feature that is readily recognized. We believe that an association with cover type may be the logical solution if due allowance is made for slash areas, blowdowns, old burns, and so forth.

The fuel classification sought in this study is one that is operationally manageable, able to discriminate meaningful differences in

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1/ Demmon, E. L. 1949. Unpublished memo to the Chief, USDA Forest Service, dated October 18, 1949.

forest flammability, and easily related to readily observable site characteristics.

In pursuit of the above objectives, an assessment of forest flammability was conducted within the pilot study area. This effort proceeded in six project-phases:

1. On-the-ground vegetation and fuel inventory at randomly located sample points. This phase provided basic biomass data on the amount and character of organic materials potentially available for combustion.
2. Characterization of chemical and physical fuel particle inputs required by available fire behavior models.
3. Appraisal of the potential flammability of inventoried forest communities using these models.
4. Classification and aggregation of inventoried forest communities with similar burning characteristics to form a manageable number of distinct "fuel types" that may be identified on-the-ground or from remote sensing imagery.
5. Discriminant analysis of identified fuel types on the basis of readily measured stand and site characteristics and comparison of the classification scheme with an existing forest type classification.
6. Integration of local climatic data with fuel inventory data gathered in phase 1 to ascertain the range of forest flammability conditions likely to be experienced. Also, means for predicting fire behavior given specific weather conditions were developed during this phase.

Subsequent sections deal with the details of each phase.

THE BWCA

AND PILOT STUDY AREA

The BWCA is centered at about 48° N latitude, 91° W longitude, and stretches for almost 170 kilometers along the U.S.-Canadian border, immediately to the south of Ontario's Quetico Provincial Park (Figure 1). Collectively, these areas offer about 4 million hectares of lakeland wilderness. On both sides of the border the land is managed primarily for its recreational values.

The BWCA itself is over 400,000 hectares in size, comprising about a third of the Superior National Forest. It is the only large federal wilderness in the northeastern United States; the largest east of the Rocky Mountains. Receiving over a million visitor days per year, it sustains more recreational use than any other unit of the National Wilderness Preservation System. Its popularity is due both to its location and its uniqueness. Interlaced throughout this area is a distinctive labyrinth of waterways; in all, roughly 2,000 kilometers of canoe routes that constitute its most unique resource. The Canoe Area includes over 1,000 lakes at least 4 hectares in size, totalling more than 70,000 hectares - 18 percent of its gross area. It is the only lakeland wilderness in the National Wilderness Preservation System. Understandably, over 70% of the BWCA's use is by paddle canoe.

Besides its water resource, the BWCA is unique with regard to the plant and animal communities it supports. Within this area are some of the largest blocks of virgin northern conifer forest remaining in the northeastern United States (Heinselman 1970). It is estimated that 40% of the BWCA is occupied by virgin vegetation (Ohmann and Ream 1971b).

These areas are remnants of the natural ecosystems of Minnesota's Laurential Shield country, untouched by axe or plow. Both flora and fauna are nearly intact (Heinselman 1973). On the balance of the landscape, logging activities, either in the "Great Timbering Era" of the early 1900's or more recently in regulated harvests, have produced second growth stands on cut-over land.

Though the Canoe Area is managed primarily for its wilderness values, there remain some limited (and much contested) provisions for timber harvest and motorized travel within its boundaries. Two management "zones" have been delineated. In the "Interior Zone", 250,000 hectares in size, the law prohibits timber harvesting, while in the remaining "Portal Zone" logging is permitted with certain restrictions, subject to the Shipstead-Newton-Nolan Act of 1930. Motorized travel is permitted along certain routes in the Portal Zone. The Interior Zone is denoted by cross-hatching in Figure 1.

The selection of a contiguous 40,000 hectare study unit completely within the Interior Zone turned out to be a physical impossibility due to constraints on land use and ownership patterns, as well as the need for a buffer zone adjacent to lands under other jurisdiction. As a compromise, the selected area is split roughly equally between the Portal and Interior Zones. It is situated about eight kilometers south of the Canadian Border and 13 kilometers southwest of the Gunflint Trail (Figure 1). Administrative responsibility is divided among three ranger districts of the Superior National Forest. Ninety-five percent is accounted for by the Kawishiwi and Tofte Districts, while the Gunflint District manages the remainder. The area is entirely bounded by established canoe routes, with numerous irregularly shaped lakes scattered throughout (Figure 2). Prominent boundary lakes include Alice, Thomas, Fraser, Kekekabic, Ogishkemuncie, Gabimichigami, Little Saginaga, Mesaba, Sawbill, Alton, Phoebe, and Malberg.

Of the 40,000 hectares within the selected area, 1,600 are in state or county ownership. The remainder are federally owned. Structural developments are few; a personal cabin land use reservation on Fraser Lake, a Forest Service administrative cabin on Kekekabic Lake, and a state cabin on Little Saganaga.

One of the strongest attributes of the area contributing to its selection is its relatively light visitor traffic. Though it makes up 10% of the BWCA's gross area, it supports only 4% of the total recreational use. This amounts to about 1,450 visitor groups each year--confined primarily to the waterways, portages, and overland trails. Within the study area are 175 kilometers of canoe routes--mostly around the exterior--11 kilometers of hiking trails, and 160 campgrounds or campsites. Recreational access is regulated by a permit system.

Physiography and Soils

The entire Boundary Waters Canoe Area is part of the Laurentian Upland Physiographic Province (Fenneman 1938), and is quite complex from a geological standpoint. Precambrian bedrock, primarily granites, greenstones, and slates, underlies Pleistocene glacial drift over most of the area (Leverett and Sardeson 1932).

Topography may be characterized as gently rolling to moderately rugged, depending to a large extent on bedrock configuration. Long, narrow, steep ridges predominate over slates, while on granites, low,

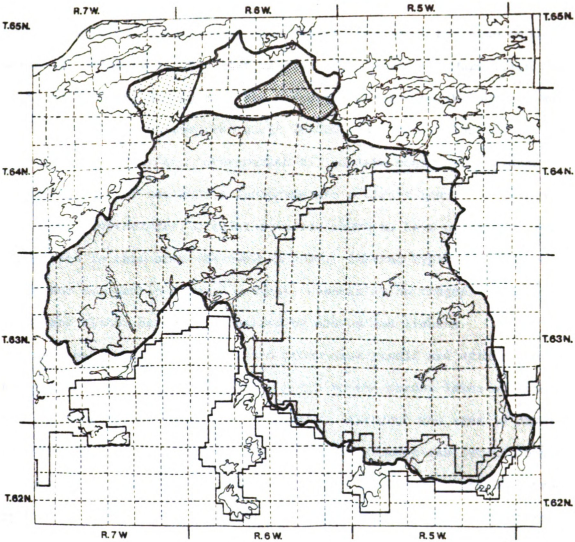
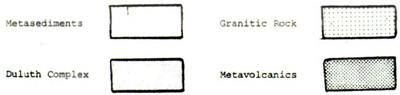


Figure 2. Bedrock geology of the fire management pilot study area.



irregular, round-topped hills are common (Ohmann and Ream 1971b). Terrain elevation ranges from 340 to 680 meters with generally slight relief. Local elevation differences rarely exceed 50 meters.

Repeated glaciation during the Pleistocene epoch has also been strongly influential. The last glacial advance was the Vermillion phase of the Rainy Lobe during the late Wisconsin glaciation (Wright and Watts 1969). Deglaciation occurred about 16,000 years ago (Wright 1971). The many lakes, cliffs, and interspersed filled-lake bogs and peatlands characteristic of the BWCA's landscape are a direct result of glacial activity. Furthermore, glacial scouring seems to have prevailed over deposition in this area (Heinselman 1973), leaving typically shallow soils and frequently exposed bedrock, especially on ridges. Rock outcrops are either bare, or colonized by mosses and lichens.

All but 1,600 hectares of the study area itself are within the Rainy River Watershed, which flows north to the border lakes of Canada. The remainder flows toward Lake Superior. Although the area is underlain by four separate bedrock complexes, the homogeneous Duluth Complex is by far the most prominent (Figure 2).[1/] This area is characterized by broad, gently sloping topographic features, while the more heterogeneous areas in the north have noticeably steeper slopes, higher hills, and deeper lakes.

A great diversity of soil parent material exists within the BWCA, including glacial till, outwash, and lacustrine sediments (Arneman 1963).

1/ Memorandum dated 30 December 1975 from Stuart Behling, Forest Geologist, to Clifford Crosby, Fire Management Officer, Superior National Forest.

Soils are coarse to fine textured, depending on parent materials. Coarse-textured heterogeneous soils on glacial depositions of gravels, sands, or boulder till are common. Although sandy and gravelly loams seem to predominate, lacustrine clays also occur (Heinselman 1973, Grigal and Arneman 1970). Glacial boulders are numerous, as typical of till soils.

Soils of the study area are for the most part typical of the BWCA in general. Thin glacial deposits of sandy boulder till and bedrock rubble cover most of the area. Thicker local deposits of stratified drift are less prominant. Within the study area, soils have been inventoried and classified by Prettyman.[1/] Main differences in these soils include: 1) depth to bedrock, 2) drainage, 3) organic material, and 4) presence of a restrictive layer within the rooting zone.

Climate and Weather

Northern Minnesota has a generally homogeneous macroclimate (Baker and Strub 1965, Baker *et al.*, 1967). It is characterized as "cool temperate" (Hovde 1941) and is markedly midcontinental, with long, cold winters and warm, moist summers (Ahlgren 1969). The most important climatic factor is the regular succession of barometric "highs" and "lows" that continually sweep over Minnesota from west to east, resulting in alternating periods of heat and cold, wet and dry. For Minnesota as a whole, this succession of pressure systems results in a sunshine average of 2,604 hours per year, 57% of that possible for the latitude (Hovde 1941).

1/ Prettyman, Donald. Personal communication dated 13 December 1976.

Lake Superior undoubtedly affects portions of northeastern Minnesota (Grigal and Arneman 1970), but its influence in the BWCA is minimized by prevailing westerly winds and protective uplands bordering the lake (Baker and Strub 1965).

The mean annual temperature at Ely, Minnesota is 4°C, with reported extremes of -41° and 40°C for the 30 year period preceeding 1960. High and low mean monthly temperatures are -14° and 19°C for January and July respectively (Baker and Strub 1965). Temperatures between 26° and 32°C in the summer and below -30° in the winter are ordinary, reflecting a marked seasonality typical of continental climates.

Average annual precipitation is 698, 752, and 677 milimeters at Gunflint Lake, Isabella, and Winton Powerplant respectively (U.S. Department of Commerce 1956-1975). The divisional mean annual precipitation for northeastern Minnesota is 715 mm., with 53% falling between June 1 and September 30. Thunderstorms are the main source of summer precipitation (Hovde 1941). Winter snowfall is moderately heavy, about 1500 mm. per year. By late November, snow cover is generally persistent, lasting about 140 days, and 50 percent of the ground is normally bare by mid-April (Peek et al., 1976).

The first frost occurs about September 20 and the last about May 30; the normal growing season lasting roughly 118 days (Peek el al., 1976).

From a fire management perspective, though, climatic anomalies are often more noteworthy than statistical norms. Deviations from these norms are substantial. Precipitation deficits large enough to significantly influence forest fire activity occur every few years, while prolonged droughts, with precipitation reduced by 40 to 50 percent of the normal for a year or more have been recorded several times in the last century (Heinselman 1973). Under these conditions, summer thunderstorms provide a significant ignition source for forest fires.

Severe weather phenomena such as tornadoes and ice storms that can create hazardous fuel situations are relatively infrequent, but do occur.

Vegetation

The BWCA is within the Quetico section of the Great Lakes - St. Lawrence Forest Region (Rowe 1959). The recent history of vegetation in this area has been studied by Heinselman (1969), while studies of its Pleistocene flora have been conducted by Wright (1969) and Swain (1973). Contemporary plant communities in or near the BWCA have been described by Buehl and Niering (1957), Butters and Abbe (1953), Flaccus and Ohmann (1964), LaRoi (1967), Maycock and Curtis (1960), Ohmann and Ream (1971a,b), Ohmann et al. (1973), and Grigal and Ohmann (1975). According to Peek et al. (1976), the work of Cooper (1913) on Isle Royale Forest succession is also applicable to parts of the BWCA.

A great variety of dominant tree species exist within the BWCA. Several species characteristic of the boreal forest region, on which the BWCA borders, are abundant. These include jack pine (*Pinus banksiana* Lamb.), balsam fir (*Abies balsamea* (L) Mill.), black and white spruce (*Picea mariana* (Mill.) B.S.P. and *P. glauca* (Moench) Voss.), tamarack (*Larix laricina* (DuRoi) K. Koch), northern white cedar (*Thuja occidentalis* L.), quaking aspen (*Populus tremuloides* Michx.), and paper birch (*Betula papyrifera* Marsh.). More characteristic representatives of the Great Lakes Region are red pine (*Pinus resinosa* Ait.) and eastern white pine (*P. strobus* L.), also in abundance. Other species frequently encountered are red maple (*Acer rubrum* L.), balsam poplar (*Populus* *balsamifera* L.), bigtooth aspen (*P. grandidentata* Michx.), black ash (*Fraxinus nigra* Marsh.), mountain-ash (*Sorbus americana* Marsh.), and northern red oak (*Quercus rubra* L.) (Heinselman 1973, Ohmann and Ream 1971b).

These species grow together in a variety of mixtures at various locations in the BWCA. Although spatial variation in community composition seems to have little to do with differences in most environmental parameters (Ohmann and Ream 1971b, Ohmann et al. 1973), a fairly strong relationship exists between dominant vegetation and topographic class (Nordin and Grigal 1976). Topographic depressions generally support lowland shrub, black spruce and non-productive swamp vegetation, while upland sites, defined as areas where surface water never accumulates, support quaking aspen, paper birch, jack pine, balsam fir, and red or white pine.

Upland Plant Communities

The natural vegetation of upland BWCA sites is a mosaic-like mixture of hardwood and conifer forest types constituting roughly 81% of the remaining virgin landscape (Heinselman 1973). These sites are generally only marginally productive, due to thin soils and bedrock outcrops (Grigal and McColl 1975).

The upland mixed deciduous-conifer forest communities of the BWCA have been quantitatively described and classified by Ohmann and Ream (1971a, b), Ohmann et al. (1973), and Grigal and Ohmann (1975). Ohmann and Ream (1971b) present basic ecological information for upland natural plant communities. They collected data on nearly 200 species of trees, shrubs, herbs, mosses, and ferns from 106 virgin stands. Using numerical techniques (Orloci 1967), they classified their sample stands, on the basis of species occurrence, into 12 plant communities.

Grigal and Ohmann (1975) performed a secondary analysis on the 106 stands of Ohmann and Ream (1971b), along with 68 additional BWCA stands that had been disturbed by logging, usually followed by slash fires, during the period 1890 to 1930. The resulting classification included 13 community types that were roughly equivalent to those from the earlier study. Table 1 (after Heinselman 1973) shows the representation of these community types for virgin upland areas of the BWCA. The jack pine community types appear to be the most abundant in virgin areas, with the hardwood types running a close second. White and red pine communities comprised only 10% of the sample, while the maple-oak type occurred only in logged areas. For the 68 logged stands the community type composition was: 10% jack pine types, 1% red pine, 20% black spruce-feather moss, 58% broadleaf types, 4% fir-birch, and 7% white cedar. No lichen communities were sampled in the logged areas.

For the study area itself, a first glance impression is that conifer types are much less abundant than indicated in Table 1 for virgin areas within the BWCA as a whole. The type distribution for the logged stands seems more representative. This may be due in part to the area's logging history. Much of the south half of the study area has been harvested since 1940, while portions of the Interior Zone were logged earlier (Figure 3). One timber sale remains open in the Portal Zone, although it is currently inactive due to a lawsuit against the government. Another explanation involves the area's fire history. Most of the study area burned in 1863-64 and again in 1875 (Heinselman 1973). Because most conifer species first bear cones at 20 to 50 years of age (10 to 15

Table 1.[1] Area of Virgin Landscape[2] by Plant Communities in the Boundary Waters Canoe Area, Minnesota, January 1973.

Plant Community	Hectares	Percent
Upland types[3]		
Lichen outcrop	8,460	4.7
Jack pine-oak	8,460	4.7
Red pine	7,000	3.9
Jack pine-black spruce	20,190	11.2
Jack pine-fir	11,330	6.3
Black spruce-feather moss	11,330	6.3
Maple-oak	0	0
Aspen-birch	11,330	6.3
Aspen-birch-white pine	8,460	4.7
Maple-aspen-birch	12,700	7.1
Maple-aspen-birch-fir	11,330	6.3
Fir-birch	28,850	16.0
White-cedar	7,000	3.9
Total upland types	146,440	81.4
Lowland types[4]		
Mixed conifer swamp	890	0.5
Black spruce bog forest	12,990	7.3
Tamarack bog forest	160	0.1
Sphagnum-black spruce bog	3,760	2.1
Ash-elm swamp	160	0.1
Shrub carr	4,490	2.5
Marsh and open muskeg	7,890	4.4
Open water communities	2,870	1.6
Total lowland types	33,210	18.6
Total all communities		100.0
Lakes and streams	35,610	-
Total virgin areas	179,650	-

[1]After Heinselman (1973).

[2]Only solid contiguous tracts within generally uncut regions are included.

[3]From Grigal and Ohmann (1975).

[4]Adapted from Superior National Forest Timber Management Plan, July 1, 1964 - July 1, 1974 for Extensive Zone BWCA.

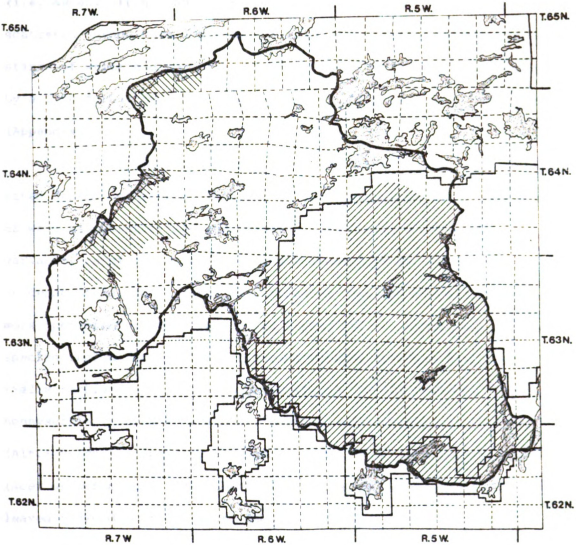


Figure 3. Logging history of the fire management pilot study area.

years for jack pine and black spruce), the two fires effectively eliminated this forest component. Consequently, it is primarily the sprouters (i.e. aspen, birch, and red maple) along with a few jack pine and scattered spruce that dominate the study area today. A few isolated stands of white and red pine are still found in the north, as indicated by a 1976 forest type map prepared specifically for the pilot study area (Appendix).

The distribution and abundance of shrubs and herbs on upland forest sites depend on several factors, including topographic slope and aspect as well as overstory age and density. Understory cover is highly variable, ranging from a few moss and lichen species on rock outcrops and in dense stands to a virtually continuous cover of shrubs and herbs in more open stands with deeper soils (Swain 1973). Common tall shrub species include beaked hazel (*Corylus cornuta* Marsh.), Bebb willow (*Salix bebbiana* Sarg.), bush honeysuckle (*Diervilla lonicera* Mill.), fly honeysuckle (*Lonicera canadensis* Marsh.), green alder (*Alnus crispa* (Ait.) Pursh.), juneberry (*Amelanchier* spp. Medic.), mountain maple (*Acer spicatum* Lam.), pin cherry (*Prunus pensylvanica* L.F.), and round-leaved dogwood (*Cornus rugosa* Lam.). Important low shrubs include creeping snowberry (*Gaultheria hispidula* (L.) Muhl.), dewberry (*Rubus pubescens* Raf.), late sweet blueberry (*Vaccinium angustifolium* Ait.), pipsissewa (*Chimaphila umbellata* (L.) Bart), prickly rose (*Rosa acicularis* Lindl.), red raspberry (*Rubus strigosus* Michx.), velvet-leaf blueberry (*Vaccinium myrtilloides* Michx.), and wintergreen (*Gaultheria procumbens* L.).

Herbaceous species worthy of mention are bishop's cap (*Mitella nuda* L.), bunchberry (*Cornus canadensis* L.), Clinton's lily (*Clintonia* *borealis* (Ait.) Raf.), common twisted-stalk (*Streptopus roseus* Michx.), false lily-of-the-valley (*Maianthemum canadense* Desf.), goldthread (*Coptis groenlandica* (Oeder) Fern.), large-leaf northern aster (*Aster macrophyllus* L.), one-sided pyrola (*Pyrola secunda* L.), star-flower (*Trientalis borealis* Raf.), sweet bedstraw (*Galium triflorum* Michx.), twin-flower (*Linnaea borealis* L.), violet (*Viola* spp.L.), wild sarsaparilla (*Aralia nudicaulis* L.), and a variety of sedges (family *Cyperaceae*) and grasses (family *Gramineae*). A more complete listing of common BWCA species including ferns and fern allies, mosses, and lichens along with presence values has been compiled by Ohmann and Ream (1971b).

Lowland Plant Communities

Vegetation of lowland sites in the BWCA has not been extensively studied. Some lowland spruce-fir communities have been described by Buehl and Niering (1957) and Maycock and Curtis (1960), while Dean (1971) suggests that the BWCA's lowland communities are close allies to those of the Lake Agassiz region described by Heinselman (1963). Table 1 shows the distribution of lowland types in virgin areas as adapted by Heinselman (1973) from the Superior National Forest Timber Management Plan, July 1, 1964 - July 1, 1974 for Extensive Zone BWCA.

Fire Activity and Fire Management

Until the recent U.S. Forest Service fire policy revision, fires in national forest wilderness were to be controlled, unless otherwise approved by the Chief for individual wilderness units, according to the "10 a.m. policy." That is, fire managers were to "Organize and activate sufficient strength to control every fire within the first work period.

If the fire is not controlled in the first work period, the attack each succeeding day (was to) be planned and executed to obtain control before 10 o'clock the next morning" (Forest Service Manual 5130.3--prior to 1978 revision).

In the past, the Superior National Forest has been highly effective at observing this policy. Its detection system is by airplane, with patrol routes based on previous fire occurrence patterns, forest fuel conditions, special risk areas, and fire danger levels. The primary fire suppression agent in the BWCA is water, although hand tools are often used when a mineral soil fireline is needed. Three of the four detection aircraft are float-equipped with water dropping capability to retard fire spread until the arrival of ground forces. As a result, only 5% of the 600 fires reported during the 1960's reached a size of 4 hectares (Haines et al., 1975). Furthermore, since fire control measures were instituted in 1911, the average annual acreage burned in the BWCA has dropped to 4% of that for the 42-year period preceeding this date (Heinselman 1973).

A study of Superior National Forest fires for the 10-year period 1960-1969 by Haines et al. (1975) shows that, on the average, 60 fires per year occur on 40 days and burn only 120 hectares. All but 1% of these fires occur between April 2 and November 4. This is one of the few national forests in the eastern United States with an essentially unimodal fire season. Summer fires, though, generally require more severe burning conditions than spring or autumn fires to achieve similar intensities and spread rates. This is due to the presence of green surface vegetation during the summer season.

Lightning is the single most prevalent ignition source (Haines _et al_. 1975), yet the combined man-caused sources outnumber lightning by roughly 5 to 1. Conifer forest types account for 66% of all fires, but only 50% of the area burned. In contrast, grass and sedge types account for only 16% of the fires, but due to high fire spread rates, 32% of the area burned. The percentages are 12 and 3 respectively for hardwood fuel types (Haines _et al_., 1975).

Despite the noted success in controlling most wildfires, the record shows that large fires are still possible when fuels are dry, relative humidity is low (below 30%), and winds exceed 7 to 9 meters per second (Sando and Haines 1972). Under these conditions escaped fires become large and are ultimately "controlled" more often by exhaustion of fuel or by weather changes than by efforts of man. Such fires, of course, are rare--and were rare even before the fire suppression era. Heinselman (1973) found that 73% of all remaining virgin stands in the BWCA date from just five fire years--1863, 1864, 1875, 1894, and 1910.

Between 1960 and 1977, 13 man-caused fires and 12 lightning fires were reported in the study area. All but two of these fires were less than 4 hectares in size. One was just 6 hectares, and the other--the Fraser fire of 1976--spread from 25 to 250 hectares overnight and was controlled several days later at 415 hectares. The fire history maps of Heinselman (1973) show several relatively large fires in the study area between 1800 and 1960. Significant fire years were 1692, 1801, 1854, 1863, 1864, 1875, 1894, 1910, and 1925. Most of the area burned in 1863-64 and again in 1875, resulting in a dominant stand age of about 100 years (Figure 4).

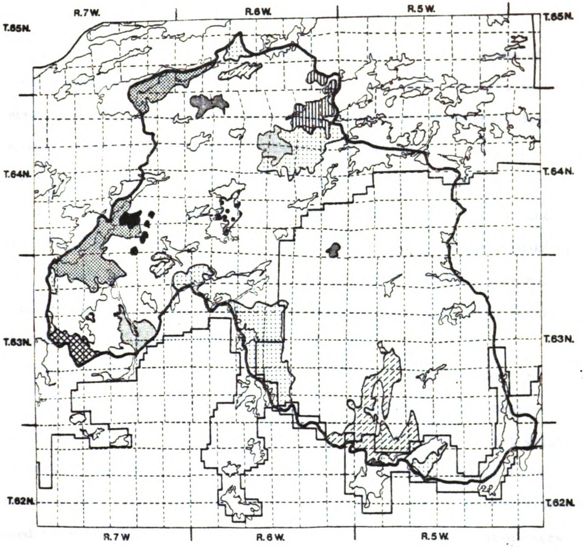


Figure 4. Stand origin map for fire management pilot study area.[1/]

1692		1875	
1801		1875/80	
1854		1894	
1864		1910	
1864/75		1925	

[1/] After Heinselman (1973).

FUEL INVENTORY AND FUEL MODEL DEVELOPMENT

Forest fuels are of interest to land managers only in terms of their flammability characteristics--the way they burn. Efforts to quantitatively describe or classify fuel conditions, then, must deal directly with those physical and chemical properties of potential fuelbeds that influence their burning behavior. Two structural levels are recognized for defining these properties--(1) that of the individual fuel particles (branches, twigs, needles, etc.) that make up the fuelbed, and (2) the aggregate fuelbed itself. In this section, concern is focused exclusively on the latter. Individual fuel particle characteristics are treated subsequently.

Several intensive and localized studies have involved complete physical descriptions of selected fuel complexes in the Lake States. Sando and Wick (1972) measured the vertical distribution of fuel weight in several Minnesota conifer and mixed conifer-hardwood stands in order to model fuel conditions throughout the stand. Similar techniques were used to quantify fuels in red pine plantations and natural oak-hickory stands in Lower Peninsula Michigan.[1/] Johnson[2/] has described a mature

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1/ Roussopoulos, Peter J. 1973. A quantative appraisal of a variety of wild-land fuel conditions in the Northeastern United States. (Unpublished study plan, North Central Forest Exp. Stn.).

2/ Johnson, Von J. 1975. The fuel dynamics and site effects of specific silvicultural treatment in jack pine. (Unpublished study plan, North Central Forest Exp. Stn.).

jack pine stand in central Michigan before and after prescribed burning, while in nearby Ontario, Walker and Stocks (1975) inventoried aerial, surface, and ground fuels in both mature and immature jack pine. Work such as that by Kiil (1965, 1968), Brown (1968, 1970a, 1976), McNab et al. (1976), Hough and Albini (1976), Muraro (1971), Fahnestock (1968), and Habeck (1973), although not directly applicable to the Lake States, provide examples of research methodology in natural forest fuels.

At the bulk fuelbed level, fire behavior is influenced strongly by the amount, spatial distribution or arrangement, and "fineness" or size distribution of organic materials available for combustion. Loading or mass of fuel per unit land area (gm/m^2) is the conventional means of expressing fuel amounts. Packing ratio (β)--the proportional volume of the fuelbed occupied by fuel (1-porosity)--is a useful measure of spatial arrangement in relatively uniform fuelbeds (Rothermel 1972). When packing ratios are spatially variable, a "characteristic" packing ratio is required. Fuelbed fineness is conventionally expressed as the ratio of fuel surface area to fuel volume (σ, cm^{-1}) (Rothermel 1972).

The only effective way to evaluate the net influence these factors have on fire potential, though, is with mathematical models of fuel and fire behavior (Philpot 1977, Rothermel and Philpot 1973). Perhaps the most widely used fire model is that developed by Rothermel (1972) and refined by Albini (1976a) to predict spread rate and intensity based on fuel, weather, and topographic conditions. In addition, an empirical model developed by Van Wagner (1977) in Ontario is available to determine surface fire intensities required for vertical fire development into tree crowns, and spread rates required to produce sustained crowning. Model inputs are the height to crown bases, foliar bulk density, and foliar moisture content. Using these models it is possible to quantitatively appraise measured fuel conditions in terms of potential flammability, and to classify forest communities on this basis. It is toward this end that a broad-scale inventory of forest fuels was conducted on upland sites of the study area. The inventory was designed to satisfy the input requirements of the above models with regard to bulk fuelbed properties. Specifically, it was designed to measure the loading of potential fuel materials (gm/m^2) by plant species, condition (living or dead), size class, and height stratum (for use with the Van Wagner (1977) model). Height strata were delineated in increments of 30.5 cm above the litter surface. Size classes relate to the moisture timelag classes of Deeming et al. (1972) as follows:

Size Class	Description	Timelag
F	Foliage	1 hr.
I	Woody, 0-.64cm dia.	1 hr.
II	Woody, .64-2.54cm dia.	10 hr.
III	Woody, 2.54-7.62cm dia.	100 hr.
IV	Woody, >7.62cm dia.	1000 hr.

Inventory Methods

Sources of organic materials that may become fuel for forest fires include the L, F, and H layers of the forest floor, mosses and lichens that grow on the forest floor, herbaceous plants, downed deadwood of various sizes lying above the litter layer, understory shrubs and tree reproduction, and tree crown materials--either living or dead. Inventory techniques differ for the various fuel components, due both to physical differences and efficiency considerations, and to differences in fire model sensitivity to sampling errors. In the interest of sampling effeciency, a double-sampling or allometric inventory procedure was used for all fuel components. Only relatively easily quantified dimensional characteristics of vegetation and detritus materials were measured in the field--and pre-established theoretical or statistical relationships were utilized to convert measurements to estimates of the needed loadings by size class, height, etc. For example, to estimate litter loadings, only the vertical depth of the litter layer was measured at each inventory site. Supplementary bulk density determinations (Loomis 1977) facilitated conversion of these depths to fuel loadings in grams per square meter. Without such measures, fuel inventories would necessarily involve tedious extractive sampling methods, and in remote areas this would be economically prohibitive.

Inventory Sample Design

Due to the unavailability of a suitable cover type map for the study area at the onset, prestratification of the inventory sample by vegetative type was not feasible. Hence, a two-stage random sampling scheme was chosen for this survey to minimize travel time.

The primary sampling units were individual land survey sections (or portions thereof) containing 64 hectares or more of land area. Sampled sections were chosen randomly with equal probability. Ten secondary sampling units were located in each chosen section.

Secondary sampling units consisted of two subsamples, the first located randomly within the section, rejecting points falling in water or on lowland sites, and the second spaced 80 meters away at a randomly chosen azimuth from the first. Again, a rejection technique was used to assure that only upland sites were sampled.

The plot design of each subsample is shown in Figure 5. It consists of a central point with four 30.5 meter transects radiating outward at right angles to one another, each ending in a 2 x 2 meter square quadrat. One of two orientations for the transects was assigned with equal probability, the first corresponding to the cardinal directions (orientation 1) and the second being a 45° clockwise rotation of the first (orientation 2).

On-Site Procedure

Details of the plot inventory process are described below for each of the recognized fuel components.

General Site Description

A general description of each plot location was recorded upon arrival at each designated sample point. Cover types (Society of American Foresters 1954), Grigal-Ohmann Community Type (Grigal and Ohmann 1975), and physiographic characteristics of the site were described. Any natural or man-caused disturbance to the site was also noted, estimating the time lapsed since the disturbance occurred. An increment boring was taken on a dominant of the cover-type species for site index determination using locally derived curves. Slope, aspect, soil texture, elevation above the nearest body of water, and percent of crown closure were also recorded. These measurements provide a mechanism for investigating relationships between fuel flammability and more conventional land classification criteria.

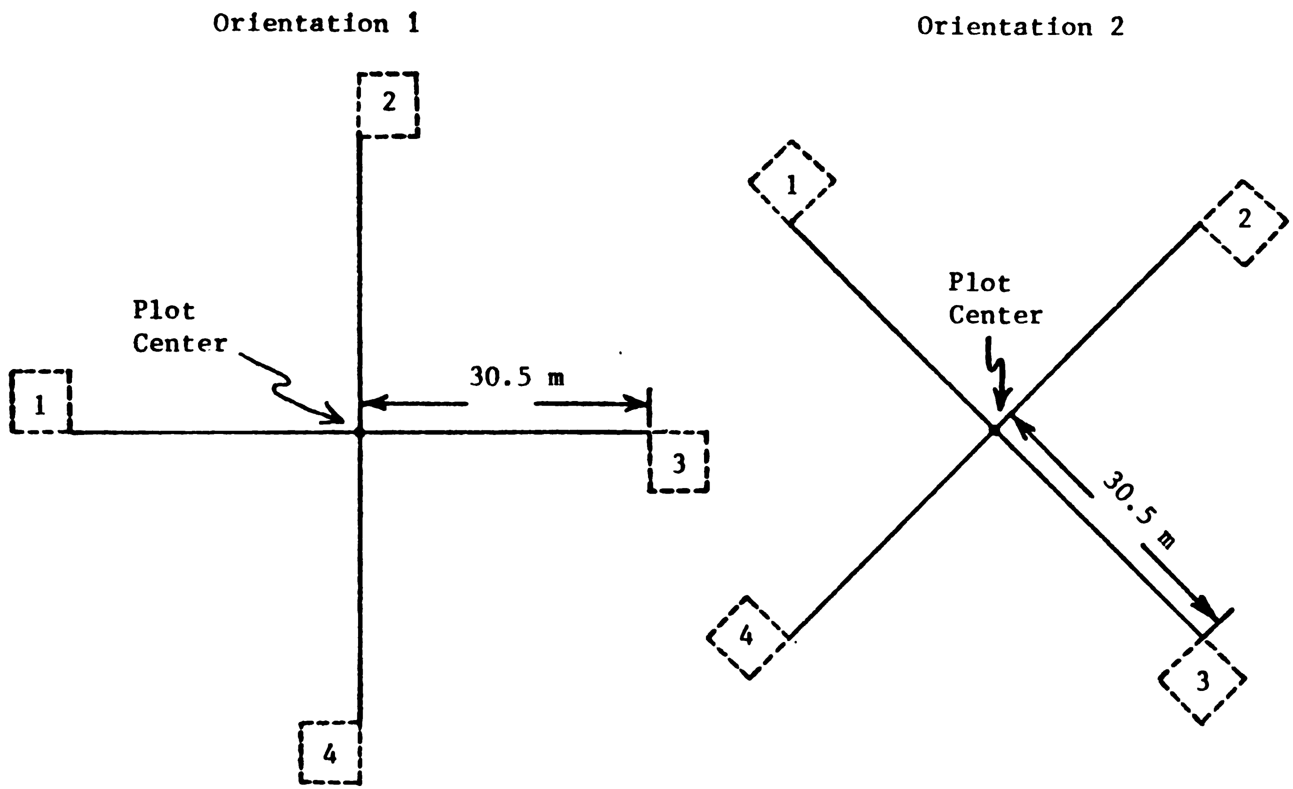

Figure 5. Standard sample plot and orientation.

Downed Deadwood

Dead twigs, limbs, and boles of woody plants that have fallen to the forest floor can provide a highly significant source of fuel material. These fuels were sampled using the planar intersect technique (Van Wagner 1968, Brown 1971, Brown and Roussopoulos 1974), observing tally-rules given by Brown (1974).

Each of the transects radiating from the sample point (Figure 5) was used to define a conceptual 30.5 meter sample plane that extended vertically from the litter surface to 2 meters above that level. The ground-level edge of each plane was delineated by stretching a measuring tape between two chaining pins placed at the ends of each transect. Individual dead and down woody particles intersecting designated segments of each sample plane were tallied by species and size class.

Transect tally zones, expressed in distance from the central sample point, were established separately for each size class as follows:

Diameter Class	Diameter Range (cm)	Transect Tally Zone (m)
I	0-.64	28.0-30.5
II	.64-2.54	24.4-30.5
III	2.54-7.62	18.3-30.5
IV	>7.62	0-30.5

The actual diameter of each particle at the point of intersection with the sample plane determined its size class. When particle diameters were borderline, they were classified using a go-no-go gauge with openings of 0.64cm, 2.54cm, and a length of 7.62cm, similar to that described by Brown (1974). Diameters of class IV material intersecting any portion of the 30.5 meter transect were measured with a diameter tape or caliper to the nearest 0.25cm and recorded as rotten or sound. All other classes were simply dot-tallied if they intersected within their designated tally zone.

The number of particle intersections over 30.5cm above ground level was recorded separately by size class, as was the height of the highest particle intersected. These data provide a means of representing the vertical distribution of deadwood fuel materials--facilitating estimation of a characteristic packing ratio.

Finally, the topographic slope along each sample transect was measured with a clinometer. Auxiliary data needs and procedures for analyzing the planar intersect data are discussed in a subsequent section.

Minor Vegetation

Grasses, forbs, and small woody plants such as twinflower and blueberry, as well as shrub and tree reproduction under 30.5cm tall were clipped and weighed using a ranked-set sampling procedure (McIntyre 1952). The 2 x 2 meter plot at the distal end of each transect was divided into four sub-plots; one square meter each. These sub-plots were ranked visually in terms of total qualifying plant biomass. On the first transect, the sub-plot rated highest was clipped at ground level. Using a spring scale accurate to 1 gram, green weights were obtained individually for all species contributing at least two grams to the total sample weight. Species contributing less than this were pooled and weighed as a composite miscellaneous (other) category. On the second transect, the sub-plot rated second in biomass was clipped and weighed as above. This process was continued on sub-plots three and four so that the ranking of the clipped sub-plot corresponded to the number of the transect to which it belonged.

Periodically, a subsample of each clipped species was weighed, bagged, labeled, and returned to the laboratory for moisture content determination. Moisture content estimates were applied to convert from green to dry biomass (gm/m^2).

Organic Mantle

Forest floor loadings were determined by measuring the individual depths of the L layer (the surface layer of the forest floor consisting of freshly fallen leaves, needles, twigs, stems, bark, and fruits) F layer (partially decomposed litter with portions of plant structures still recognizable) and H layer (well decomposed organic matter of unrecognizable origin). These depths were measured to the nearest 0.25 cm at the center of each square-meter quadrat and averaged for each transect arm. Bulk densities from a concurrent study (Loomis 1977) were applied to convert average depths to weight estimates.

Mosses and Lichens

Ground cover plants were characterized by occular estimates of "percent cover" and average height for each of the three unclipped square-meter plots on each transect. These estimates were made separately for each of four groups represented:

1. *Dicranum* spp.
2. *Cladonia* spp.
3. *Plurosium schreberi*
4. "other"

Again, conversions from volume to loadings were accomplished using bulk density values obtained from supplemental samples.

Shrubs and Seedlings

Woody shrubs and tree seedlings greater than 30.5cm tall but less than 2.54cm dbh were sampled by a "ranked-set, double-sampling" procedure using regression analysis. The square-meter sub-plots at the end of each transect were ranked occularly according to shrub and seedling biomass and sub-plots were chosen as for herbaceous material. Within each sampled sub-plot, stem diameters of all shrubs and seedlings were measured 15cm above ground level and tallied by species and condition (living or dead).

A supplementary study near the study area provided regression statistics for estimating the amount and distribution of shrub and seedling biomass from the relatively simple basal diameter measurements made in the actual field inventory.

Crown Fuels

Finally, tree crowns were described by a technique similar to that of Sando and Wick (1972). The distal end of each transect served as a "sampling point" for a 20- factor Bitterlich sample (Bitterlich 1947). Trees qualifying for sampling or "in" trees were described by the following independent variables:

a. Species

b. D.B.H.

c. Total height

d. Height to base of live crown

e. Height to the point where unpruned branches predominate the bole of the tree

f. Live crown width

g. Average width of the cylinder comprised of dead branches below the live crown

h. Generalized geometric shape of the live crown in the following categories:

   (1) Cylinder

   (2) Cone

   (3) Spheroid

   (4) Hemispheroid

   (5) Truncated Spheroid

   (6) Paraboloid of Rotation

   (7) Inverse Paraboloid

i. Condition of tree (living or dead)

j. Number of dead branches below the live crown by diameter class at the point of exit from the bole.

A double-sampling approach termed "dimensional analysis" by Whittaker and Woodwell (1968, 1971) or "allometry" by Kira and Shidei (1967) was applied to estimate total and component tree biomass for each species and condition category from the above descriptors. Furthermore, the simple models of crown geometry allowed estimation of the volume within the canopy that is occupied by tree crowns as well as the vertical distribution of biomass within the canopy.

Auxiliary Fuel Characterization and Inventory Data Analysis

The indirect fuel inventory approach used in this study made it necessary to secure information on the relationships between measured fuel and vegetation properties and fuel loadings (gm/m^2) by condition and size class, as well as vertical distributions of these materials. In this section, the various sources and uses of this information in analyzing the raw inventory data are discussed. Again the fuel component classes are treated separately.

Downed Deadwood

Theoretical development of the planar intersect sampling technique has been discussed thoroughly by Van Wagner (1968), Brown and Roussopoulos (1974), and DeVries (1973). When cylindrical fuel particles are oriented randomly within a horizontal plane, the established deadwood fuel loading (l) is computed as:

$$L = \frac{\pi^2 \sum_{i=1}^{n} d_i^2 \rho_i}{8\ell} \qquad 4.1$$

where:

L = estimated fuel loading (gm/m^2)

d_i = diameter of the i^{th} intersected particle (m)

ρ_i = density of the i^{th} intersected particle (gm/m^3)

ℓ = horizontal length of the sample plane (m)

n = number of intersected particles

When the plane is positioned along a slope, the horizontal length is computed as:

$$\ell = \ell'(1 + \phi^2)^{-1/2} \qquad 4.2$$

where:

ℓ' = slope length of the sample plane (m)

ϕ = topographic slope tangent along plane

Adapting Equation 4.1 for simple counts of intersected particles by species and size class, rather than actual diameter measurements, produces Equation 4.3:

$$L_{ij} = \frac{\pi^2 q_{ij}^2 n_{ij} \rho_{ij}}{8\ell_j} \qquad 4.3$$

where:

q_{ij} = quadratic mean diameter of particles from the i^{th} species and j^{th} diameter class (m)

n_{ij} = the number of intersected particles of the ij^{th} species-size class combination

ρ_{ij} = the density of particles from the ij^{th} species-size class combination (gm/m^3)

ℓ_j = the horizontal length of the tally zone for the j^{th} diameter class

L_{ij} = the estimated loading of the ij^{th} species-size class combination (gm/m^2)

If q_{ij} is in centimeters, ρ_{ij} in gm/cm^3 (specific gravity), and ℓ'_j in meters, the combined Equations 4.2 and 4.3 become:

$$L_{ij} = 0.01234 \frac{q^2_{ij} n_{ij} \rho_{ij} \sqrt{1 + \phi^2}}{\ell'_j} \qquad 4.4$$

The values of ℓ'_j were 2.5, 6.1, 12.2, and 30.5 meters, respectively for size classes I, II, III, and IV. Values for ϕ and n_{ij} (or Σd_i^2 for class IV particles) were determined at the inventory plots, while q_{ij} and ρ_{ij} are constants to be established by species and size class. Data from earlier fuel studies on the Superior National Forest[1/]

1/ Roussopoulos, P. J. 1971. Results of four prescribed burns at Virginia, MN. Paper presented at USDA Forest Service R-9 Fire Control Meeting, Combined Air Officers and Fire Staff, Theodosia Springs, Missouri, April 26-30, 1971.

(Roussopoulos and Johnson 1973, Brown and Roussopoulos 1974) provided the required estimates (Table 2).

In addition to loading by species and size class, the vertical distribution of this loading is useful in appraising fire behavior potential (Sando and Wick 1972). Measurements of fuelbed depth are the conventional means of determining fuel packing ratios, but highly skewed vertical loading distributions have made depth measurements both difficult and questionable (Brown 1970a, Albini 1975). In this study, an attempt is made to represent the vertical distribution of fuel loadings as a first step in establishing a characteristic fuel packing ratio.

Desired properties for a theoretical probability function, to adequately represent the vertical distribution of downed deadwood, are that it be bounded at both ends and be capable of representing high positive skewness, since most deadwood particles are on or near the ground. Its parameters must also be easily evaluated from relatively simple on-site measurements. A special case of the beta distribution satisfies these requirements. Over the finite interval (0, 1), the beta probability density function (Hahn and Shapiro 1967) is given as:

$$f(x) = \begin{cases} \frac{\Gamma(\gamma+\eta)}{\Gamma(\gamma)\Gamma(\eta)} x^{\gamma-1}(1-x)^{\eta-1}, & 0 \le x \le 1,\ 0 < \gamma,\ 0 < \eta \\ 0, & \text{elsewhere} \end{cases} \quad 4.5$$

where:

x is a random variable

γ and η are beta distribution parameters

$\Gamma(y) = \int_0^\infty x^{y-1} e^{-x}\, dx$, or $\Gamma(y) = (y-1)!$, when y is an integer

Table 2. Quadratic mean diameters (q_{ij}) and particle specific gravities (ρ_{ij}) for downed deadwood materials by species and size class. 1/

	Diameter Class (cm)						
	0-.64		.64-2.54		2.54-7.62		>7.62
Species	q_{ij} (cm)	ρ_{ij}	q_{ij} (cm)	ρ_{ij}	q_{ij} (cm)	ρ_{ij}	ρ_{ij} 2/
Balsam fir	.180	.690	1.118	.405	3.937	.360	.360
Jack pine	.371	.550	1.311	.590	4.549	.490	.430
Red pine	.450	.610	1.250	.529	4.031	.490	.440
White pine	.279	.550	1.067	.509	4.064	.490	.350
Black spruce	.203	.674	1.245	.647	3.759	.486	.400
Northern White cedar	.203	.560	1.194	.491	3.759	.429	.310
Trembling aspen	.376	.590	1.290	.440	4.318	.400	.380
Paper birch	.320	.690	1.039	.537	4.318	.550	.550
Red maple	.424	.650	1.013	.576	4.039	.550	.500
Other	.424	.650	1.179	.576	4.267	.550	.500

1/ Values obtained from both published (Roussopoulos and Johnson 1973, Brown and Roussopoulos 1974) and unpublished data sources (Roussopoulos 1971, op. cit.; Roussopoulos 1973, op. cit.).

2/ Values obtained from Wood Handbook (U.S.D.A. 1955).

When $\gamma < 1$ and $\eta > 1$, this function displays the desired "reverse J" shape (Hahn and Shapiro 1967). The cumulative beta distribution is:

$$F(x) = \begin{cases} 0, \ x < 0, \\ \frac{\Gamma(\gamma+\eta)}{\Gamma(\gamma)\Gamma(\eta)} \displaystyle\int_0^x t^{\gamma-1}(1-t)^{\eta-1}\, dt, \ 0 \le x \le 1, \\ 1, \ x > 1 \end{cases} \qquad 4.6$$

where:

t is simply a dummy variable of integration

For a special case of this function, when $\eta=2$, equation 4.6 can be simplified considerably:

$$F(x) = \frac{\Gamma(\gamma+2)}{\Gamma(\gamma)} \int_0^x t^{\gamma-1}(1-t)\, dt, \ 0 \le x \le 1$$

$$= \gamma(\gamma+1) \left[\frac{t^{\gamma}}{\gamma} - \frac{t^{\gamma+1}}{\gamma+1} \right]_{t=0}^{t=x}, \ 0 \le x \le 1$$

$$= x^{\gamma}\left(1+\gamma(1-x)\right), \ 0 \le x \le 1 \qquad 4.7$$

In this form, the function can easily be solved numerically for γ given just one value of $F(x)$ at a known fractional height within the fuel bed (x). The proportion of deadwood intersections below a height of 30.5 cm (p_j) and the height in centimeters of the highest intersected particle (h_j), determined by particle size class at each inventory plot, provide the required information. For the j^{th} size class, the value of γ_j can be found by fixed-point iteration as follows:

For n = 0, 1, 2,....., until convergence criteria are satisfied, compute:

$$\gamma_{j(n+1)} = \left(\frac{30.5}{h_j}\right)^{\gamma_{j(n)}} \left[1 + \gamma_{j(n)} \left(1 - \frac{30.5}{h_j}\right)\right] - p_j + \gamma_{j(n)} \qquad 4.8$$

For this application, iteration was terminated if $\gamma_{j(n+1)} - \gamma_{j(n)} < 10^{-6}$. Convergence was normally achieved in less than 10 iterations. With estimates of γ_j determined in this manner, the deadwood fuel loading for each size class was distributed vertically up to a height of h_j according to:

$$F(x)_j = \left(\frac{x}{h_j}\right)^{\gamma_j} \left[1 + \gamma_j\left(1 - \left(\frac{x}{h_j}\right)\right)\right] \qquad 4.9$$

where:

x = height above the litter layer (cm)

$F(x)_j$ = the estimated proportion of the total j^{th} size class loading occurring below a height of x cm.

The above procedure was validated using unpublished data on the vertical distribution of cutting slash in nine Michigan clearcut areas (Table 3). These data were obtained using the planar intersect sampling method, but tallying intersections by height stratum as well as species and size class. Height strata were defined as 0-.30m, .30-.61m, .61-.91m, .91-1.22m, 1.22-1.52m, 1.52-1.83m, and 1.83-2.13m. Represented in the sample were four clearcuts in the jack pine-oak type in central Lower Peninsula Michigan (Roscommon 1-4), three clearcuts in the black spruce-northern white cedar type in Upper Peninsula Michigan (Shingleton 1-3), and two mixed-oak harvests in the west-central lower Peninsula (White Cloud 1 & 2). Table 3 shows the measured cumulative distribution percentage points by size class for each of these areas, along with the derived estimate of γ_j using Equation 4.8.

Table 3. Measured vertical slash distributions by particle size class on nine Michigan clearcuts,[1/] and the derived beta distribution parameter γ_j.

Fraction of Slash Volume Below Datum Height

Sample Area	Size Class	Datum Height (m) .30	.61	.91	1.22	1.52	1.83	2.13	γ_j
Roscommon 1	I	.871	.956	.988	.997	1.000			.16111
	II	.846	.932	.973	.990	.998	1.000		.16577
	III	.898	.978	.985	.993	1.000			.12719
	IV	1.000							------
Roscommon 2	I	.929	.972	.995	1.000				.11032
	II	.916	.979	.989	.998	1.000			.10492
	III	.898	.983	.994	1.000				.15828
	IV	.958	.992	1.000					.09523
Roscommon 3	I	.781	.928	.954	.973	.979	1.000		.23936
	II	.804	.911	.958	.982	.993	1.000		.21341
	III	.779	.919	1.000					.48112
	IV	.950	.971	1.000					.11157
Roscommon 4	I	.851	.920	.954	.989	.998	1.000		.16036
	II	.734	.900	.954	1.000				.42172
	III	.917	.988	.988	1.000				.12976
	IV	.412	.570	.844	.976	.976	1.000		.77237
Shingleton 1	I	.811	.889	.958	.984	1.000			.23940
	II	.628	.885	.965	.988	1.000			.49642
	III	.829	.926	.974	.989	1.000			.21476
	IV	.647	.856	.933	.987	1.000			.46875
Shingleton 2	I	.741	.829	.924	.981	.989	1.000		.28644
	II	.558	.767	.919	.972	.998	1.000		.53003
	III	.588	.809	.958	.979	1.000			.55922
	IV	.334	.572	.978	1.000				1.27362
Shingleton 3	I	.380	.526	.705	.863	.942	.997	1.000	.75299
	II	.362	.547	.769	.851	.940	1.000		.87187
	III	.320	.586	.786	.961	1.000			1.09928
	IV	.225	.542	.879	.976	.993	.997	1.000	1.11123
White Cloud 1	I	.974	.987	.987	.987	1.000			.03236
	II	.943	.986	1.000					.12736
	III	.923	.962	.962	1.000				.11982
	IV	.835	.976	1.000					.35985
White Cloud 2	I	.880	.960	1.000					.26386
	II	.674	.859	.989	1.000				.52364
	III	.649	.865	.973	.973	.973	1.000		.40329
	IV	.825	.907	.907	1.000				.27273

1/ Data obtained from an unpublished study of wildland fuel conditions in the Northeastern United States (Roussopoulos 1973, Op. Cit.).

In Figure 6, the form of the cumulative distribution function is shown in comparison with measured values for the first entry in Table 3, while Figure 7 (a-d) plots the predicted cumulative percentage points against the corresponding measured values for all entires in Table 3. The 45° lines in Figure 7 indicate the loci of perfect agreement between predicted and actual values. Points falling below these lines represent over-estimates of the proportional volume of slash material below the indicated height. Agreement between predicted and actual values appears quite good for the smaller diameter classes-especially at the lower datum heights where most of the slash is found. Agreement deteriorates somewhat for the larger size classes, though, principally above the .91 meter datum height. The increased scatter with size class is not surprising, due to poorer representation of larger diameter fuels in the samples, while the apparent increased scatter in the upper right portion of each graph is due more to the scaling of axes than to absolute prediction errors. Furthermore, the four most serious underestimates in Figure 7d are attributable to the Shingleton 3 sample area where trees were felled but crowns were left intact and no products were removed. All other sample areas were commercial harvests. The Shingleton 3 area was the only case showing a significant difference (at the .05 level of confidence) between predicted and actual vertical distributions by the Kolmogorov-Smirnov nonparametric test for goodness-of-fit. When the Shingleton 3 data are deleted, Figure 7d shows reasonable agreement.

Despite the noted discrepancies between the predicted and actual vertical distributions, the fact that the plotted points are scattered roughly evenly about the "perfect agreement" line, and the fact that the larger diameter particles--where poorer agreement was found--are of

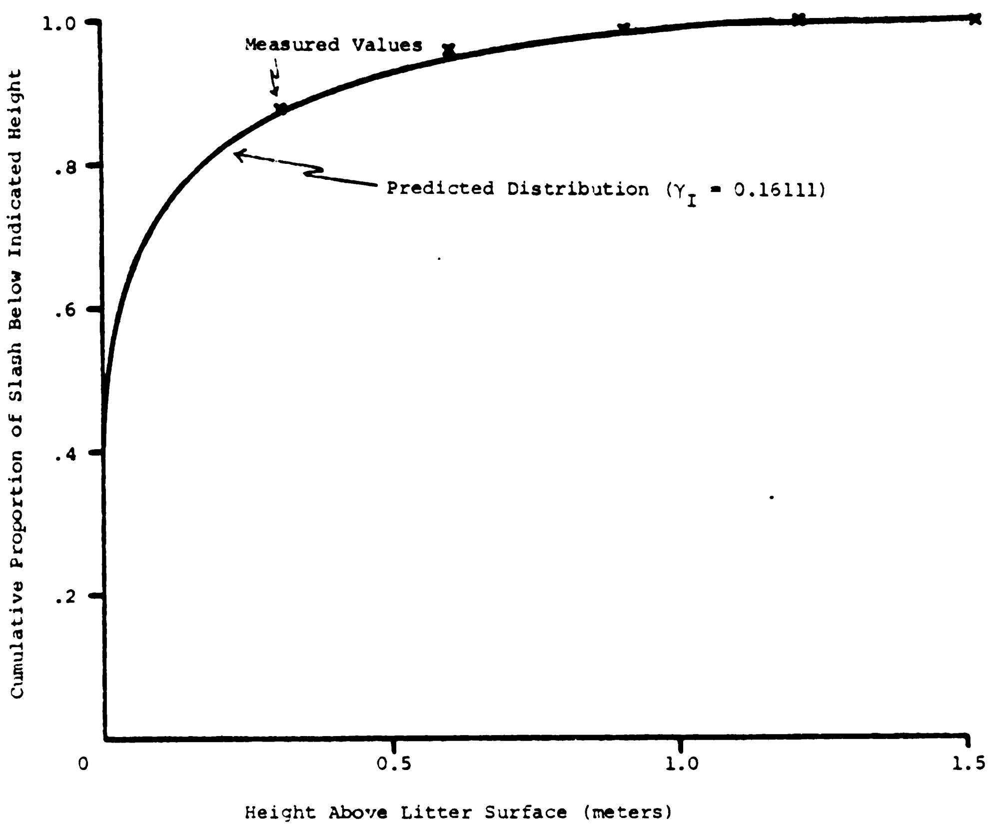

Figure 6. Relationship between predicted and measured vertical slash distribution for size class I in the Roscommon 1 sample area.

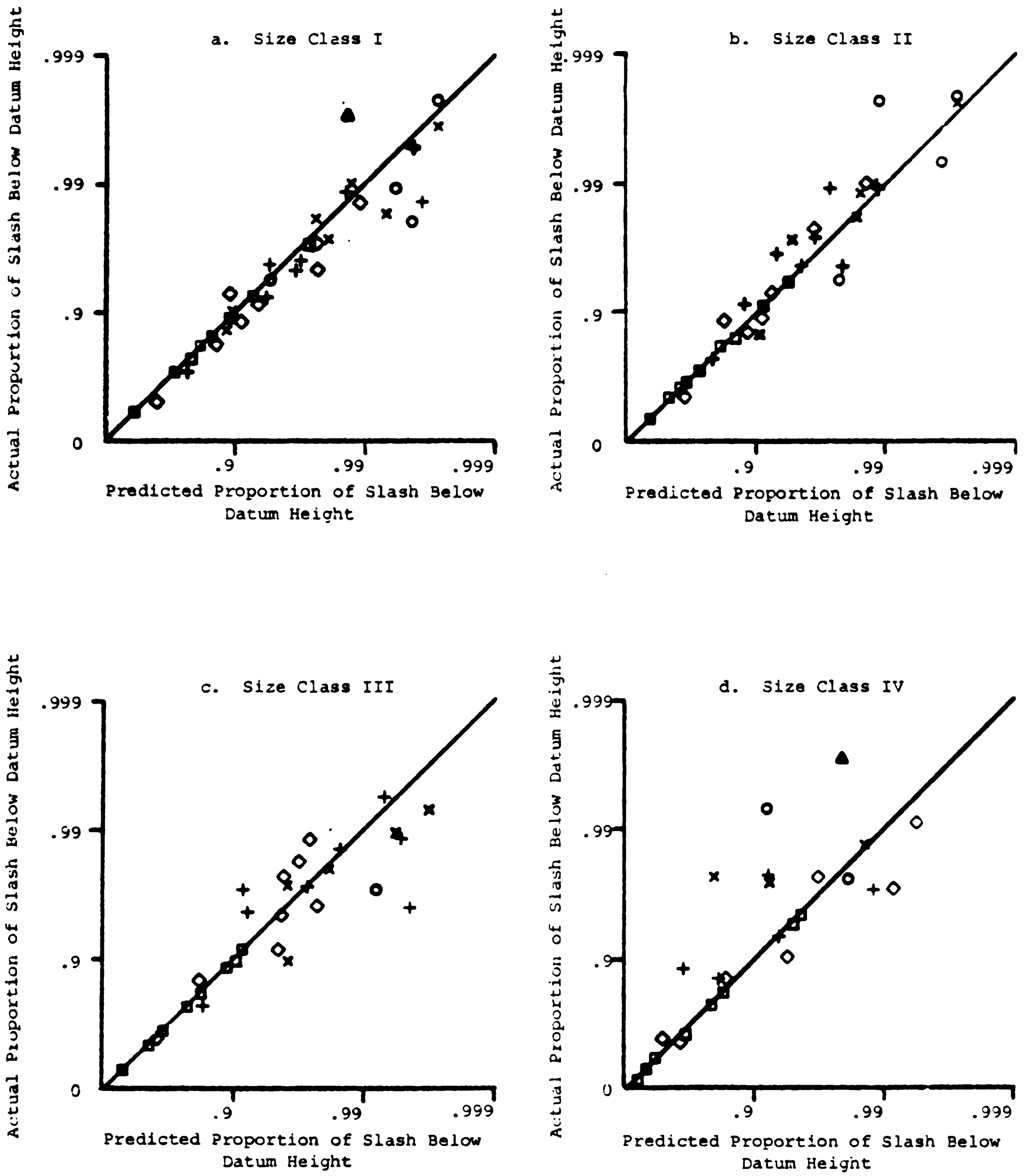

Figure 7. Predicted versus actual cumulative percentage points for vertical slash distributions on nine Michigan clearcuts. 1/ Cumulative percentage points are shown by particle size class for datum heights of .30 m (□), .61 m (◇), .91 m (+), 1.22 m (x), 1.52 m (O), and 1,83 m (Δ).

1/ Data obtained from an unpublished study of wildland fuel conditions in the Northeastern United States (Roussopoulos 1973, op. cit.).

minor importance in a fire behavior context, suggest that Equation 4.9 yields suitable vertical distribution estimates in untreated logging slash. In non-slash fuels like those encountered in the BWCA study area, this algorithm is yet untested. Nevertheless, since the distribution of particle inclination angles in one-year-old and older slash has been found to be similar to that of naturally fallen branch material (Brown and Roussopoulos 1974), it seems likely that the general form of the vertical distribution function would also be similar.

Minor Vegetation

Because herbaceous and small woody plants (including shrub and tree seedlings less than 30.5cm tall) were actually clipped and weighed in the field, only three supplementary data items were required: plant moisture content and associated dry weight conversion factors, the fractional distribution of biomass between foliar and woody parts, and the vertical distribution of these materials. These will be discussed in turn.

Dry Weight Conversion

Using the ranked set sampling procedure of McIntyre (1952), the arithmetic mean loading for all clipped plots provides an efficient, unbiased estimate of the fresh biomass of these materials per unit area. Since actual determination of plant moisture content was not feasible in this study, an indirect approach was taken to convert the fresh weight estimates to oven-dry values in grams per square meter. Two concurrent sampling efforts were established during the period June 24 to August 26, 1976--while the field fuel inventory was underway.

One of these efforts involved the periodic subsampling of clipped vegetative material during the field inventory process. Subsamples were weighed in the field, bagged, and transported via fire detection aircraft to the Kawishiwi Field Laboratory near Ely, Minnesota within five days. At the laboratory they were oven-dried for 24 hours at 105°C and reweighed. The dry weights were divided by the field fresh weights to obtain the dry weight conversion factor (CF) for the sample.

The second sampling effort was conducted at the Kawishiwi Field Laboratory where plant moisture contents could be monitored more continuously.[1/] Plants representing 21 species or related species groups found commonly in the BWCA study area were collected at intervals of one to several days (excluding non-work days and days with rain) throughout the sample period. Forty-two subsamples were taken between 1400 and 1600 CDT each sample day (3 subsamples each from 14 species), with individual species or species groups being represented in proportion to their occurrence. The number of sample days for any given species or species group ranged from 3 for starflower to 22 for large-leaved aster (Table 4). All above-ground plant parts were included in each sample. Moisture contents and dry weight correction factors were determined gravimetrically as described previously and each subsample triplet was averaged for the day.

At the end of the sample period, the time series of daily correction factors were examined and compared on the basis of magnitude and seasonal

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[1/] Loomis, Robert M., Peter J. Roussopoulos, and Richard W. Blank. 1978. Summer dry weight conversion factors and associated moisture contents of some herbaceous and other plants in northeastern Minnesota (Manuscript in preparation for publication).

Table 4. Seasonal average dry weight conversion factors (C.F.), standard errors (S.E.), number of sample collection days, and species composite membership for some grasses, forbs, and small woody plants collected near the Kawishiwi Field Laboratory. 1/

Plant Group	n	C.F.	S.E.	Species Composite
Labrador Tea (*Ledum groenlandicum*)	11	.422	.012	1
Blueberry[2] (*Vaccinium* spp.)	18	.402	.009	1
Club Moss[3] (*Lycopodium* spp.)	18	.397	.011	1
Grasses[4]	10	.378	.018	1
Rubus[5] (*Rubus* spp.)	4	.330	.024	2
Spreading Dogbane (*Apocynum androsaemifolium*)	6	.323	.024	2
Twinflower (*Linnaea borealis*)	3	.303	.035	2
Bracken Fern (*Pteridium aquilinum*)	13	.291	.009	2
Wild Sarsaparilla (*Aralia nudicaulis*)	22	.285	.005	2
Strawberry[6] (*Fragria* spp.)	10	.283	.014	2
Bunchberry (*Cornus Canadensis*)	18	.277	.005	2
Bush Honeysuckle (*Diervilla lonicera*)	5	.264	.024	2
Pearly Everlasting (*Anaphalis margaritacea*)	4	.250	.032	2
False Solomon's Seal (*Smilacina racemosa*)	3	.250	.017	2
Other Ferns[7]	5	.240	.018	2
Wood Horsetail (*Equisetum sylvaticum*)	4	.228	.005	3
Large-Leaved Aster (*Aster macrophyllus*)	22	.212	.007	3
Starflower (*Trientalis borealis*)	3	.213	.003	3
Dwarf Solomon's Seal (*Maianthemum canadense*)	17	.205	.006	3
Sweet Coltsfoot (*Petasites* spp.)	4	.158	.019	3
Bluebead-Lily (*Clintonia borealis*)	15	.090	.003	4

1/ After Loomis et. al. (1978) (Op. Cit.)

[2] *Vaccinium myritilloides* and *V. angustifolium* are predominant.
[3] *Lycopodium clavatum* and *obscurum* are predominant.
[4] *Carex* spp. and *Oryzopsis asperifolia* are predominant.
[5] *Rubus strigous* and *R. pubescens* are predominant.
[6] *Fragria vesca* and *F. virginiana* are predominant.
[7] *Athyrium* spp., *Onoclea sensibilis* and *Osmunda cinnamomea* are predominant.

trend. Seasonal CF averages ranged from .090 for Clinton's lily to .422 for labrador tea (Table 4). Four species composites were identified by graphic comparison. The membership of each composite is also shown in Table 4. For each sample day the samples representing each species composite were averaged, obtaining four time-series of composite correction factors (Figure 8), covering most of the field inventory period. Correction factor estimates for non-sample days were derived by linear interpolation between sample days, as indicated in Figure 8.

Four observations concerning Figure 8 are worthy of note. First and most obvious, is the wide range of CF values, corresponding to moisture contents from 122 to 1150 percent, and consistent ranking of the four composite groups. Both the most and least succulent species apparently retain these distinctions throughout the season. Second, the general parallelism exhibited by these four signatures indicates that, though the moisture content levels vary considerably among the four groups, their relative moisture responses to environmental stimuli are quite similar. Third, a net upward trend in CF values is apparent for all composites, reflecting the impact of the 1976 summer drought throughout the upper midwest. In fact, termination of sampling on August 26 was due in part to the conscription of inventory personnel to fight several large forest fires attributable to the lower moisture conditions. Finally, the absolute range of fluctuation in the four series is noticeably higher at higher CF levels. In relative terms, though, they are similar. The range of CF values as a percentage of range mid-points is nearly constant for all species composites (37, 42, 40, and 40 percent respectively for composites 1, 2, 3, and 4). These observations suggest that 1) it is necessary to account for seasonal

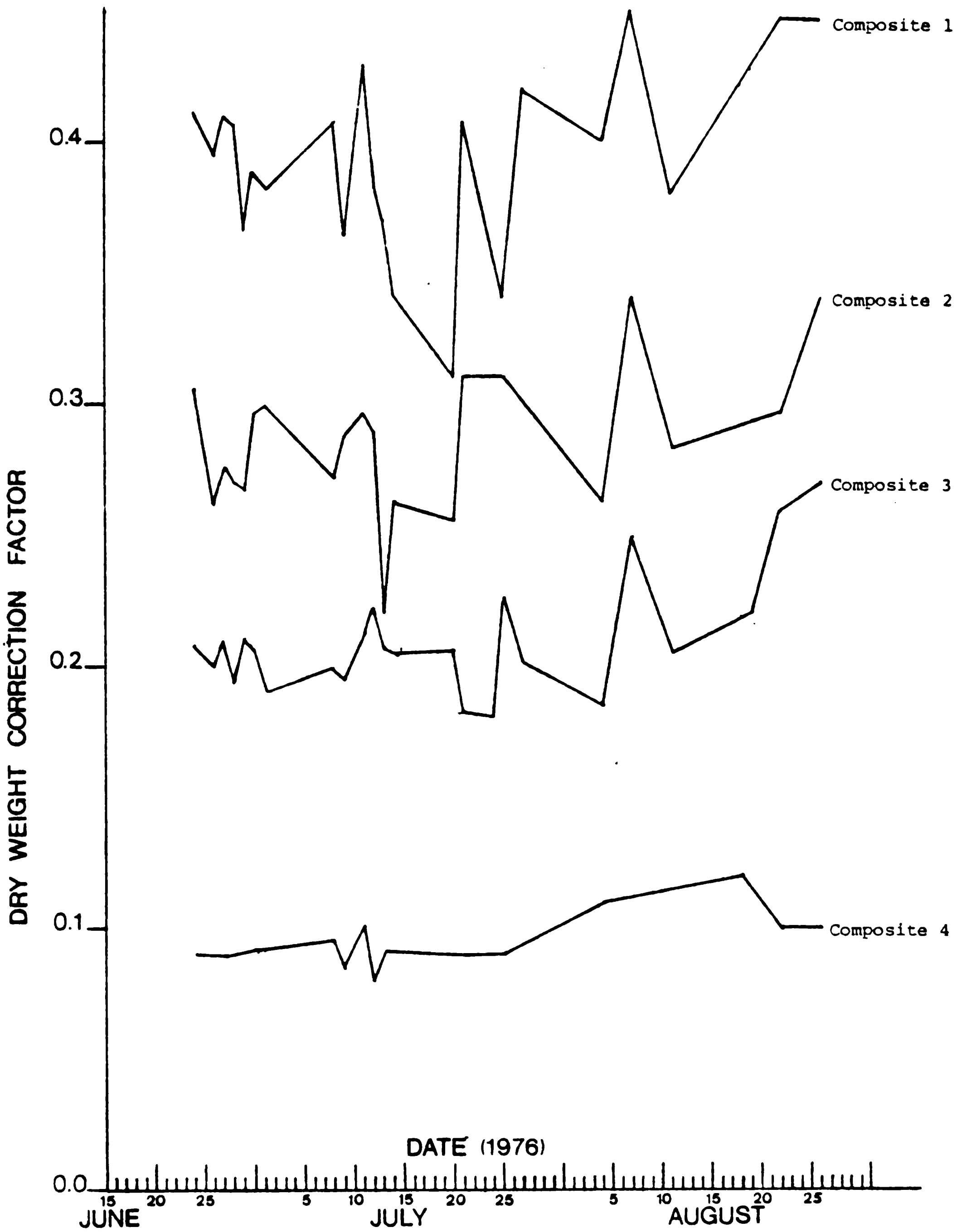

Figure 8. Time series of measured dry weight correction factors for composite groups of grasses, forbs and small woody plants collected near the Kawishiwi Field Laboratory during 1976.

plant moisture content trends in converting fresh biomass estimates to dry-weight equivalents, and 2) these seasonal trends can be represented using a moisture content analog if calibrated properly for differences in general CF levels among species and locations.

In this study, the CF measurements at the Kawishawi Laboratory provide a suitable analog for study area values. Calibration was achieved by linear regression of correction factors for samples extracted from the study area against the corresponding values from Figure 8. The resulting regression equation is:

$$CF_i = 0.00817 + 0.86059\ (KCF_i)$$

where:

CF_i = dry weight correction factor for the i^{th} species composite in the BWCA study area

KCF_i = corresponding dry weight correction factor for the i^{th} species composite obtained at the Kawishawi Field Laboratory.

Additional regression statistics are: n=269, $s_{y \cdot x}$=0.0869, F=264.5, and r^2=0.50. Although the coefficient of determination (r^2) is not overly impressive, the F statistic indicates an extremely high level of significance for the regression.

The regression estimates of CF_i were computed for each fuel inventory sample day and used to convert measured field fresh weights of minor vegetation to oven-dry fuel loadings. Loadings were expressed in grams per square meter by species for each inventory sample.

Component Biomass

For small woody plants, a rough estimate of the distribution of plant biomass among woody and foliar components was needed to define a representative surface area-to-volume ratio for the fuelbed. These estimates were obtained by clipping a few stems (less than 30.5cm tall) of each prominant species, separating the foliar and woody components, and determining the fresh weight of each. This was done in late summer following the period of major plant growth. The percentage of total fresh weight attributable to foliage was computed for each species and rounded to the nearest 10%. Resulting values averaged 30% for labrador tea; 40% for blueberry, sweet fern (*Comptonia peregrina*), *Rubus* spp., *Ribes* spp., and bog rosemary (*Andromeda glaucophylla*); and 50% for all other shrubs less than 30.5cm tall. For small tree seedlings, results were 40% for balsam fir and red pine, 50% for black spruce and northern white-cedar, and 30% for all other species. These proportions were assumed to be representative of the dry weight distribution as well. All woody parts were less than 0.64cm in diameter.

Vertical Distribution

Due to the definition of minor vegetation in this study, most of these plants were confined to the lowest height stratum (0-30.5cm), making it unnecessary to establish vertical biomass distributions. A few of the herbaceous and low shrub species, though, would frequently exceed 30.5cm in height. For these species, field inventory personnel were asked to subjectively estimate the overall percentage distribution of above-ground biomass among the 0-30.5, 30.5-61.0, and 61.0-91.5cm height strata. The consensus of these estimates (Table 5) provided a means of representing the vertical loading distribution for these species.

Table 5. Consensus estimates of percentage biomass distributions among three height strata for taller minor vegetation species.

	Height Stratum (m)		
	0-.30	.30-.61	.61-.91
Species		PERCENT	
Blueberry *(Vaccinium* spp.)	90	10	0
Wild Sarsaparilla *(Aralia nudicaulis)*	30	60	10
Spreading Dogbane *(Apocynum androsaemifolium)*	90	10	0
Bracken Fern *(Pteridium aquilinum)*	20	60	20
Sweet Fern *(Comptonia peregrina)*	40	40	20
Wild Raspberry *(Rubus* spp.)	60	40	0
Wild Pea *(Lathyrus* spp.)	70	30	0
Current *(Ribes* spp.)	60	40	0
Labrador Tea *(Ledum groenlandicum)*	70	30	0
Bog Rosemary *(Andromeda glaucophylla)*	80	20	0

Organic Mantle

To convert litter and duff layer depths to oven-dry loadings (gm/m^2), dry-weight bulk densities are required. Loomis (1977) reports forest floor weights, depths, and bulk densities for nine jack pine and six aspen stands near the Kawishawi Field Laboratory. Measured bulk densities and standard errors in the jack pine stands were 18.2 ± 1.67, 48.2 ± 1.85, and 66.6 ± 3.14 kg/m^3 for the L, F, and H layers respectively. In the aspen stands, corresponding values were slightly lower: 15.1 ± 1.03, 42.0 ± 2.27, and 54.1 ± 2.40 kg/m^3. The jack pine values were applied to all inventories in conifer types, while aspen values were applied in all hardwood types. Loading estimates were expressed in grams per square meter.

In keeping with the National Fire Danger Rating System (Deeming _et al._ 1977) the upper 0.64cm of litter was classified as 1 hr. timelag fuel, the next 1.9cm was 10 hr., and the remainder 100 hr. timelag.

Mosses and Lichens

Bulk densities were also needed for ground cover plants to derive loadings from estimates of percent cover and height. These values were obtained by a procedure similar to that of Loomis (1977) for forest floor materials. Four 0.2 hectare sample plots were established near the Kawishawi Field Laboratory--two in mature jack pine, one in a dense stand of spruce-fir, and one in a rock outcrop community within a jack pine stand. The plots showed no evidence of recent disturbance and were representative of much of the area in the BWCA.

In each sample plot, an eight point by eight point systematic sampling grid was established. At each point, a 12.7cm diameter circular sample of moss or lichen was extracted and bagged. Samples were located as close to the sample point as possible, but such that the entire area within the 12.7cm diameter circle was covered by a continuous mat of mosses or lichens. If no suitable ground cover was found within a 3 meter radius of the grid point, no sample was taken. Sample material was extracted by cutting around a 12.7cm metal cylinder at the ground with a knife. The thickness of the extracted ground cover mat was measured to the nearest 0.25cm at the time of sampling.

Samples were bagged and removed to the Kawishawi Field Laboratory where soil particles were separated from vegetative material using a water bath, and dry weights were obtained to the nearest 0.1 gram by oven-drying at 105°C for 24 hours. Sample volumes were computed from the field depth measurements and resulting dry-weight bulk densities were expressed in kg/m^3.

In all, 227 samples were obtained on the four plots. Samples were post-stratified into two groups--mosses and lichens. The moss group included 100 samples, comprised mainly of *Plurosium schreberi* with minor representation from *Dicranum* spp. The mean and standard error of the bulk density measurements for this group were 14.954 ± 0.420 kg/m^3. For the remaining 127 lichen samples (*Cladonia* spp.), both the mean and standard error were roughly twice that for the mosses--26.873 ± 0.839 kg/m^3.

These bulk densities were used to compute ground cover loadings from inventory observations by:

$$L_{gc} = 0.1\ C\ D\ \rho_b \qquad 4.10$$

where:

L_{gc} = ground cover fuel loading in gm/m^2

C = field estimate of percent cover

D = field estimate of ground cover mat depth in cm

ρ_b = appropriate bulk density estimate (kg/m^3)

Shrubs and Tree Seedlings

Estimation of the amount and distribution of biomass for shrubs and small trees from field measurements of stem diameter required the development of regression equations. Although a few studies have produced relevant estimators for total and component above-ground plant biomass (Ohmann *et al*. 1976, Crow 1977, Telfer 1969), they provide little insight into the size distribution of dry matter as desired for fire modeling. Brown (1976) reported similar equations for 25 shrubs of the northern Rocky Mountains. In addition to the biomass equations, though, he included a table of stemwood weight percentages attributable to specific fuel size classes. A sampling effort similar to that of Brown (1976) was undertaken at the Kawishawi Field Laboratory to provide the needed functions.[1/]

Methods

Sample stems of 17 species of shrubs and tree reproduction (<2.5cm dbh) were collected during July and August of 1976. At least 20 stems

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1/ Roussopoulos, Peter J. and Robert M. Loomis. 1978. Biomass and dimensional properties of shrubs and small trees in northeastern Minnesota. (Manuscript in preparation for publication. North Central Forest Experiment Station, E. Lansing, Mich.).

per species were cut at ground level and were taken to the Kawishawi Field Laboratory for processing. For each sample stem, the following measurements were recorded: stem diameter at ground level and at 15cm above ground level to the nearest 0.25cm (measurement of diameter at 15cm above ground avoids the region of high stem taper normally found at ground level), plant height, and length (depth) of crown to the nearest 15cm. Each plant was divided into components of foliage and woody parts. Dead and live woody parts were also separated. All woody parts were further separated into size classes by diameters. Each component group was weighed to the nearest 0.1 gram and its moisture content determined by subsampling and ovendrying for 24 hours at 105°C. All fresh weights were converted to ovendry in this manner.

Analysis

Total plant weight, foliage weight, total wood weight (live and dead), and live woody weight all in grams dry weight (Y), were regressed with the 15cm stem diameter (X) in cm using the allometric model:

$$Y = a\ X^b \qquad 4.11$$

Regression statistics were evaluated in linearized form using natural logarithm transformations of X and Y. The "a" coefficient was adjusted for bias inherent in this procedure (Baskerville 1972).

For each stem, the dry weights of all woody material less than 2.5cm inclusive, were divided by the overall weight for total wood and for live wood only. These ratios (Y) represent the proportional contribution of size classes 0 to 0.6cm and 0 to 2.5cm to the weight of the live and the total woody components. They were regressed against the stem diameter at 15cm (X) using the hyperbolic model:

$$Y = X/(a + bX) \qquad 4.12$$

The regressions were accomplished using the following linearized form:

$$X/Y = a + bX \qquad 4.13$$

To help evaluate the vertical distribution of these fuels, linear regression equations were also developed for plant height and crown length on the 15cm diameter.

Results

In all, 460 stems were collected and processed representing 14 deciduous species of trees and shrubs and three coniferous trees (Table 6). For all species, the range of sampled stem diameters was 0.3 to 5.1 cm at 15 cm above ground. All species were represented over the bulk of this interval except *Diervilla lonicera, Lonicera canadensis,* and *Rosa acicularis.* These small shrubs rarely attain stem diameters outside the range sampled. Total above ground biomass ranged from 1 to 2,714 grams dry weight per stem for all species.

Component Weights

Regression statistics were calculated for dry weights of all above-ground components, foliage, total wood, and live wood (Table 6). Examination of the coefficients of determination (r^2) shows reasonably good fits for all species except *Diervilla lonicera* and *Lonicera canadensis.* These low r^2 values may be partially due to the narrow range (0.2cm for *Diervilla*) of sampled stem diameters compared to the measurement precision (± 0.12cm).

These equations agree quite well with those of Ohmann et al. (1976) except for *Corylus cornuta,* where their estimates show somewhat lower weights--especially at the larger stem diameters. Because their samples were also collected in the vicinity of the Kawishawi Field Laboratory,

Table 6. Sample size and regression coefficients[1/] for estimating component dry-weights of shrubs and small trees (<2.5cm dbh).

Species	Stems Collected	Range of Stem Diameters	Total				Foliage				All wood				Live wood			
			a	b	r^2	Syx	a	b	r^2	Syx	a	b	r^2	Syx	a	b	r^2	Syx
Abies balsamea	25	0.5-3.3	72.715	2.250	0.96	80	29.319	2.011	0.94	38	42.904	2.404	0.97	50	41.330	2.394	0.97	49
Acer rubrum	36	0.3-4.1	60.367	2.342	.94	278	13.082	1.840	.91	25	45.947	2.505	.93	274	45.085	2.480	.92	246
Acer spicatum	25	0.3-4.3	73.182	2.259	.95	141	17.305	1.696	.89	26	54.779	2.407	.95	122	52.384	2.417	.95	127
Alnus spp.	28	0.8-4.1	63.280	2.380	.93	164	14.725	1.828	.90	18	48.762	2.509	.90	164	48.077	2.484	.90	160
Amelanchier spp.	27	0.5-4.1	71.534	2.391	.93	174	10.478	1.988	.83	21	60.997	2.445	.94	160	58.333	2.458	.91	160
Betula papyrifera	23	1.3-3.6	76.316	2.279	.93	73	14.717	1.529	.66	17	62.830	2.378	.93	75	61.956	2.376	.92	77
Cornus rugosa	27	0.3-3.6	74.114	2.457	.96	124	17.131	2.093	.93	13	55.886	2.591	.96	136	54.629	2.551	.95	132
Corylus cornuta	36	0.3-2.5	62.819	2.420	.89	46	12.115	2.010	.81	8	50.154	2.523	.90	47	49.245	2.503	.90	44
Diervilla lonicera	21	0.3-0.5	14.211	1.217	.45	4	3.082	.613	.19	1	12.269	1.608	.53	3	9.276	1.445	.59	1
Lonicera canadensis	25	0.3-1.0	33.900	1.793	.68	5	5.319	1.275	.39	2	28.899	1.942	.67	4	28.017	2.020	.69	4
Picea spp.	25	0.5-3.3	65.757	2.287	.97	68	36.288	2.047	.95	42	28.670	2.566	.98	38	27.806	2.543	.97	34
Populus spp.	27	0.5-3.3	46.574	2.527	.96	52	10.828	2.052	.87	19	35.264	2.657	.97	41	34.906	2.655	.97	41
Prunus spp.	25	0.8-3.8	68.041	2.237	.90	155	12.382	2.024	.77	42	55.076	2.306	.87	152	54.235	2.253	.86	143
Rosa acicularis	23	0.3-1.3	83.240	2.837	.83	9	22.853	2.282	.79	3	63.140	3.224	.82	9	60.282	3.214	.83	8
Salix spp.	25	0.5-3.0	55.925	2.594	.96	113	12.280	2.120	.94	32	43.316	2.726	.95	96	42.495	2.721	.95	95
Sorbus americana	24	0.5-3.8	44.394	3.258	.95	350	8.083	2.601	.93	11	35.960	3.427	.95	407	35.585	3.425	.95	398
Thuja occidentalis	38	0.3-5.1	68.423	1.863	.94	86	35.288	1.442	.90	36	30.800	2.244	.94	62	30.632	2.232	.94	59

[1/] Regressions are of the form $Y = aX^b$ where Y is the component weight in grams, X is the stem diameter in centimeters measured 15 centimeters above ground, and a and b are regression coefficients from the table. Weights are expressed in grams of total above ground material (Total), foliage (Foliage), dead and live woody parts (All wood), and live woody parts only (Live wood) for 17 species or genera.

and because they also used stem diameter measured at 15cm as the independent variable, close agreement is not surprising. Brown (1976) and Telfer (1969), on the other hand, used stem diameter at ground level. To facilitate comparision with the results of these studies, the relation between the 15cm stem diameter and basal stem diameter was examined. Scatter diagrams suggested that ground diameter could be predicted from the 15cm diameter using simple linear regressions. The resulting coefficients were remarkably similar for all species (Table 7). Telfer's (1969) predictions for woody plants in eastern Canada, after diameter adjustment, were also in close agreement. Brown's (1976) equations, on the other hand, yielded lower weight estimates for most species, perhaps partially due to the different environmental conditions of the northern Rocky Mountains. Both Brown and Telfer predicted greater weights for *Lonicera* spp. at larger diameters (Brown's weights were lower than Telfer's). Brown had the broadest diameter range for *Lonicera* (0.3 to 1.7cm); Telfer's was similar to this study (0.1 to 0.7cm).

Size Distribution

Examination of scatter diagrams revealed that the proprotional contributions of the 0 to 0.6cm (I) and 0 to 2.5cm (I + II) size classes to total woody weight are discontinuous functions of stem diameter. They equal 1.0 at low stem diameters and fall quickly away from this value above some "critical stem diameter" near the upper size class limit. To ensure realistic size class predictions on both sides of this discontinuity, two measures were necessary. First, for each size class the smallest sample stem was found that contained woody material in the next larger size class. Naturally, its stem diameter at 15cm was

Table 7. Regressions through origin (y = bx) for height and crown length, and linear regressions (y = a + bx) for basal stem diameter versus stem diameter (cm) at 15 cm above ground level.

Species	Height (meters)			Crown length (meters)			Basal diameter (cm)				
	b	Sy·x	n	b	Sy·x	n	a	b	r^2	Sy·x	n
Abies balsamea	0.7094	0.2902	25	0.6455	0.2876	25	0.0684	1.1302	0.9216	0.2929	25
Acer rubrum	1.3761	.5851	33	.9522	.6927	33	.0003	1.1675	.9649	.2039	36
Acer spicatum	1.2100	.4989	22	.7443	.4093	22	.1645	1.0485	.9499	.2488	25
Alnus spp.	1.1289	.8339	6	.5331	.9089	6	.1409	1.0225	.9592	.1695	28
Amelanchier spp.	1.3176	.3496	17	.8061	.3114	17	.0142	1.1037	.9815	.1569	27
Betula papyrifera	1.5720	.5564	21	.9837	.7265	21	.1713	1.0452	.9376	.1968	23
Cornus rugosa	1.1728	.6782	29	.6860	.4204	27	.0243	1.0828	.9714	.1505	27
Corylus cornuta	1.5314	.3192	36	.9510	.3085	36	.1894	.9226	.9476	.1214	36
Diervilla lonicera	1.3268	.1389	21	.8179	.1520	21	.1062	.8818	.5216	.1126	21
Lonicera canadensis	1.2184	.2402	25	.7488	.1876	25	.0809	.9780	.7346	.1188	25
Picea spp.	.5772	.1769	25	.5050	.1389	25	.0715	1.1241	.9711	.1858	25
Populus spp.	1.2515	.5219	27	.8136	.6473	27	.1294	1.0517	.9643	.1752	27
Prunus spp.	1.2183	.5750	19	.7943	.3435	19	.1151	1.0676	.9417	.2094	25
Rosa acicularis	1.4505	.1967	23	.8661	.1609	23	.0338	1.0412	.8412	.1092	23
Salix spp.	1.2747	.5282	17	.7497	.4044	17	.0502	1.1730	.9810	.1543	25
Sorbus americana	1.5018	.4470	24	.9532	.4532	24	.0263	1.1373	.9735	.1370	24
Thuja occidentalis	.6290	.2256	38	.6063	.2124	38	.1853	1.0906	.9556	.2925	38

always close to the upper diameter limit--about 0.5cm for the 0 to 0.6cm class and 2.1cm for the 0 to 2.5cm class. These diameter values varied little among species. Stems with diameters below these values were deleted from the respective size class regressions. This eliminated samples from the "flat" section of the curve where the proportional size class contribution is 1.0 and allowed separate mathematical representation of the "flat" and "falling" curve sections. Second, the critical stem diameter--the point separating the two sections--was defined from the coefficients of each hyperbolic regression as a/(1-b). The regression equation applies only to stem diameters above this value, which results in the following expression for the fractional contribution of each size class (Y) in terms of stem diameter (X):

$$Y = \begin{cases} 1.0, \text{ for } 0 < X < \dfrac{a}{(1 - b)} & (\text{"flat" section}) \\ \dfrac{X}{(a + bX)}, \text{ for } \dfrac{a}{(1 - b)} < X & (\text{"falling" section}) \end{cases} \qquad 4.14$$

Regression coefficients were calculated for use with equation 4.14, both for all wood and for live wood only (Table 8). For the <0.6cm size class regressions, *Diervilla lonicera* was the only species that had no samples with stem diameters more than 0.5cm. Data for all other species were subjected to regressions. *Diervilla, Corylus cornuta, Lonicera canadensis, Rosa acicularis,* and *Sorbus americana* were exempted from the 0.0 to 2.5cm size class regression analysis because each had less than five sampled stems that were 2.1cm or more in diameter. Good fits were obtained for most of the remaining species with this model (Table 8).

Actual weight estimates for each size class are obtained by multiplying the appropriate fractional weight contribution estimate (equation

Table 8. Regression statistics for estimating fractional weight contributions of woody components by size class and condition (live or dead) for 17 species of northern Minnesota shrubs and small trees.

Species	All woody parts < 0.6 cm divided by all woody parts					Live woody parts < 0.6 cm divided by live woody parts					All woody parts < 2.5 cm divided by all woody parts					Live woody parts < 2.5 cm divided by live woody parts				
	a	b	r^2	Syx	n	a	b	r^2	Syx	n	a	b	r^2	Syx	n	a	b	r^2	Syx	n
Abies balsamea	-0.8141	2.3989	0.924	0.6129	25	-1.0298	2.6303	0.911	0.7324	25	-4.2677	2.8728	0.940	0.3290	9	-4.7586	3.0867	0.928	0.3887	9
Acer rubrum	-6.2520	10.3120	.718	5.9481	33	-7.4744	11.5724	.734	6.5710	33	-6.0540	3.5985	.805	1.1121	8	-6.2718	3.7192	.687	1.3304	8
Acer spicatum	-4.7664	7.6075	.925	2.1277	23	-5.3703	8.5717	.913	2.6055	23	-8.6441	4.1621	.939	.7271	6	-8.8463	4.2436	.940	.7397	6
Alnus spp.	-4.2928	6.9640	.854	2.3184	28	-5.0621	7.7270	.821	2.9061	28	-3.8505	2.8249	.946	.5092	6	-3.9024	2.8765	.940	.5463	6
Amelanchier spp.	-4.0400	6.8436	.918	2.1167	27	-4.4118	7.2891	.905	2.4477	27	-6.4998	4.0315	.911	.7414	6	-7.0820	4.2563	.906	.8053	6
Betula papyrifera	-5.8830	7.7092	.915	1.7199	23	-7.1140	8.5998	.898	2.1135	23	-6.0057	3.5414	.973	.2942	10	-6.4097	3.7084	.972	.3138	10
Cornus rugosa	-2.6090	5.6040	.752	2.1095	24	-3.2924	6.4142	.788	2.2932	24	- .4652	1.1927	.978	.1039	7	- .4892	1.2027	.976	.1092	7
Corylus cornuta	-2.0501	4.6178	.896	.8202	33	-2.5036	5.2050	.904	.8849	33	*	*	*	*	*	*	*	*	*	*
Diervilla lonicera	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Lonicera canadensis	- .8217	2.6503	.939	.1054	15	- .8217	2.6503	.939	.1054	15	*	*	*	*	*	*	*	*	*	*
Picea spp.	- .7873	2.5976	.964	.4800	25	- .9063	2.8078	.952	.6046	25	-4.0003	2.7137	.922	.3528	9	-4.2958	2.8364	.938	.3236	9
Populus spp.	-4.8321	8.2591	.841	3.1064	27	-4.5801	8.3773	.829	3.2937	27	-6.3969	3.7164	.910	.5263	9	-6.4176	3.7228	.911	.5235	9
Prunus spp.	-2.0843	5.1685	.721	1.6514	24	-2.4157	5.8313	.694	2.1243	24	-4.7809	3.1011	.984	.6872	5	-4.7984	3.1078	.987	.6857	5
Rosa acicularis	-1.1971	3.3862	.911	.2203	17	-1.1971	3.3862	.911	.2203	17	*	*	*	*	*	*	*	*	*	*
Salix spp.	-4.1190	7.4681	.760	4.4845	23	-4.1282	7.7257	.792	4.2844	23	-6.0504	3.5769	.760	1.1493	9	-6.1529	3.6205	.772	1.1484	9
Sorbus americana	-10.0310	15.1988	.932	2.9887	24	-9.9149	15.4869	.929	3.1181	24	*	*	*	*	*	*	*	*	*	*
Thuja occidentalis	-4.8576	5.8264	.843	3.0684	36	-6.3768	6.9339	.797	4.2709	36	-8.3000	4.3000	.940	1.1477	13	-9.4581	4.7387	.935	1.3232	13

1/ The regression model is $X/Y = a + bX$, where independent variable X is stem diameter (cm) measured 15 cm above ground level and Y is the fraction by weight attributed to each indicated size class.

4.14, Table 8), times the corresponding predicted wood weight (equation 4.11, Table 6). Weights of the 0.6 to 2.5cm and > 2.5cm size classes, as well as dead wood weights are found by subtraction.

Vertical Distribution

Knowledge of the total heights and crown lengths of understory vegetation is useful in representing vertical distributions and packing ratios for these fuels. Equations were developed to predict these dimensions using stem diameter at 15cm as the predictor variable in a forced zero-intercept regression model (Table 6). Plant heights for the conifers were roughly half those of deciduous plants with the same stem diameter. The crown length ratios for coniferous samples (crown length/total height) were characteristically 1 1/2 times those of deciduous species.

Estimated biomass for each shrub tallied in the field fuel inventory was distributed vertically according to the following assumptions:

1. The crowns are cylindrical in shape with uniform bulk density throughout.
2. The proportional contribution of each size class is uniform throughout the crown volume.
3. Below the crown base (plant height minus crown length), stem taper is represented by a paraboloid of rotation with altitude equal to estimated total plant height and diameter at a height of 15cm equal to the field measurement.

The vertical distribution of shrub layer loadings for the bulk fuelbed was obtained by summing the vertical distributions for individual tallied stems.

Crown Fuels

As for the shrub layer fuels, the analysis of crown fuel inventory data required auxiliary estimators for total crown weight, distribution of weight among components and size classes, and vertical fuel distribution. Methods patterned after those of Sando and Wick (1972) were employed.

Weight of Living and Dead Crown Components

Crown weight regressions were obtained entirely from the plant biomass and forest fuel literature, exploiting published information from other regions and for exotic species where necessary. Table 9 displays published regressions used in this analysis for the weight of live and dead crown components.[1/] Also included in Table 9 are reported coefficients of determination (r^2), literature sources, and species for which equations were originally developed. Dead crown weight regressions were not available for the pine species, northern white cedar, paper birch, and red maple. For the conifers, equations developed for taxonomically and structurally similar western species were adapted from Brown (1978). No attempt was made to differentiate between living and dead components of paper birch and red maple. These compromises, and the fact that the equations of Brown (1963), Young *et al*. (1964), and Ribe (1973) were derived from data collected some distance from Minnesota, introduced substantial uncertainty concerning the canopy fuel models. However, their use was confined to evaluating potential crown fire behavior under extreme burning

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1/ Tree crown materials are defined here as living or dead foliage, twigs, and branches less than 7.62cm in diameter.

Table 9. Dry weight regression equations and sources for live and dead crown components. (W = component weight in kg, D = stem diameter at breast height in cm, H = tree height in meters).

Species	Component	Regression Equation	r^2	Source	Subject Species
Abies balsamea	Total crown	$W=0.1848\ D^{1.845}$	.96	Sando 1/	*Abies balsamea*
	Live crown	$W=0.2148\ D^{1.697}$	.95	Sando & Wick (1972)	*Abies balsamea*
Pinus banksiana	Live crown	$W=0.1091\ D^{2.0270}$	.91	Sando & Wick (1972)	*Pinus banksiana*
	Dead crown	$W=\begin{cases}(0.0102\ D-0.025)(\text{Live weight}), & D \leq 25.4\text{cm}\\ 0.235(\text{Live weight}), & \text{otherwise}\end{cases}$	---	Brown (1978)	*Pinus contorta*
Pinus resinosa	Live crown	$W=3.663\ e^{0.985\ D}$	.91	Brown (1963)	*Pinus resinosa*
	Dead crown	$W=0.0008\ D^{2.8376}$	.87	Brown (1978)	*Pinus ponderosa*
Pinus strobus	Total crown	$W=0.0447\ D^{2.1679}H^{0.4292}-0.0127\ D^{2.0215}H^{0.9670}$	.98	Young et. al. (1964)	*Pinus strobus*
	Dead crown	$W=0.0005\ D^{2.6076}$	.80	Brown (1978)	*Pinus Monticola*
Picea mariana	Total crown	$W=0.2407\ D^{1.7052}$	.90	Sando 1/	*Picea mariana*
	Live crown	$W=0.2905\ D^{1.5259}$	.86	Sando & Wick (1972)	*Picea Mariana*
Thuja occidentalis	Total crown	$W=0.0152\ D^{1.41}H^{1.59}-0.0034\ D^{1.39}H^{2.06}$	.93	Dyer (1967)	*Thuja occidentalis*
	Dead crown	$W=0.0003\ D^{3.0}$	.98	Brown (1978)	*Thuja plicata*
Populus tremuloides	Total crown	$W=0.0182\ D^{2.5094}$	.98	Loomis & Roussopoulos (1978)	*Populus tremuloides*
	Live crown	$W=0.0079\ D^{2.1012}+0.0084\ D^{2.6746}$	.97	Loomis & Roussopoulos (1978)	*Populus tremuloides*
Betula papyrifera	Total crown	$W=0.0571\ D^{2.1679}H^{0.4292}-0.0157\ D^{2.0215}H^{0.9670}$	.97	Young et. al. (1964)	*Betula papyrifera*
Acer rubrum	Total crown	$W=0.0555\ D^{2.1679}H^{0.4290}-0.0157\ D^{2.0215}H^{0.9670}$	.97	Young et. al. (1964)	*Acer rubrum*
Others	Total crown	$W=0.0228\ D^{1.7450}+0.0575\ D^{1.6711}$	.82	Ribe (1973)	Combined species

1/ Unpublished secondary analysis of data from Sando and Wick (1972).

conditions--when even relatively large errors in fuel inputs are of small consequence. Use of relationships derived elsewhere to represent BWCA species with similar form and growth habit appears reasonable for this application.

Because variable radius plot sampling was employed for crown fuels, the crown weight estimates for each tallied tree were expanded to areal loadings by:

$$L = 140.45\ W/D^2 \qquad 4.15$$

where:

L = crown component loading (gm/m^2)

W = crown component weight for individual tree (kg)

D = tree diameter at breast height (cm)

For standing dead trees, an occular estimate of the proportion of the crown remaining intact was used to calculate an appropriate dead fuel weight from the crown weight regressions.

Size Class Distribution

The combustion of standing tree crowns, either by torching or continuous crowning, notably involves little but the finest fuel elements--principally foliage (Van Wagner 1977). It is important, then, that these crown components be distinguished from the heavier, less flammable branches and limbs.

Little information is available concerning the size distribution of crown materials for BWCA species. Data for balsam fir and black spruce were provided by Sando[1/], with regressions for quaking aspen

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1/ Unpublished secondary analysis of data from Sando and Wick (1972).

size class distributions adapted from Loomis and Roussopoulos (1978). For other species, reasonably representative estimators were sought from studies alien to the BWCA. Selected functions for live crown size class contributions are given in Table 10, while corresponding functions for dead materials are given in Table 11. These relationships were used to apportion the live and dead crown weight estimates among component size classes.

Vertical Distribution

The proximity of crown fuels to the surface fuelbed and the bulk density of materials (especially foliage) within the canopy space are of crucial importance to the development of torching and crowning fire behavior (Van Wagner 1977). A geometric approach similar to that described by Sando and Wick (1977) provided means for modeling these features. In this model, the vertical distribution of live fuel materials was represented using the live crown dimensions and shape designations assigned in the field. Crowns of individual tallied trees were considered uniform in bulk density of all components throughout the crown volume. With this assumption, the model vertically distributes live component weight estimates for each tallied tree and sums for all trees in the sample.

Dead crown components were distributed within and below the live crown according to the field records of the height to the point where unpruned dead branches predominate the hole, and the number of dead branches tallied by size class. Size class weights for tallied dead branches, regardless of species, were computed from equations reported by Loomis and Roussopoulos (1978). These weights were distributed uniformly from the base of the conceptual cylinder containing unpruned

Table 10. Statistical estimators and sources for live crown dry weight by size classes. (W = dry weight of size class (Kg), L = total live crown weight (Kg), D = tree diameter at breast height (cm), H = tree height (m)).

Species	Size class	Predictor Equation	r^2	Source	Subject species
Abies balsamea	F	$W=0.273\ L$	---	Sando [1/]	*Abies balsamea*
	F+I	$W=0.518\ L$	---	Sando [1/]	*Abies balsamea*
	F+I+II	$W=\begin{cases}(1.027-0.0059\ D)L, & D>7.4cm\\ L, & otherwise\end{cases}$	.94	Brown (1978)	*Abies grandis*
Pinus banksiana	F	$W=(0.493-0.0046\ D)L$	.76	Brown (1978)	*Pinus contorta*
	F+I	$W=(0.777-0.0057\ D)L$	.70	Brown (1978)	*Pinus contorta*
	F+I+II	$W=\begin{cases}(1.049-0.0055\ D)L, & D>10cm\\ L, & otherwise\end{cases}$	.55	Brown (1978)	*Pinus contorta*
Pinus resinosa	F	$W=0.558\ L\ e^{-0.187\ D}$	.89	Brown (1978)	*Pinus ponderosa*
	F+I	$W=(0.558\ e^{-0.187\ D}+0.01)L$	---	Brown (1978)	*Pinus ponderosa*
	F+I+II	$W=\begin{cases}0.985\ L\ e^{-0.0122\ D}, & D\geq 2.54\\ L, & otherwise\end{cases}$	.85	Brown (1978)	*Pinus ponderosa*
Pinus strobus	F	$W-0.550\ L\ e^{-0.0136\ D}$	.95	Brown (1978)	*Pinus monticola*
	F+I	$W=(0.914-0.0614\ D^{0.5})L$	.91	Brown (1978)	*Pinus monticola*
	F+I+II	$W=\begin{cases}1.056\ L\ e^{-0.0071\ D}, & D>10cm\\ L, & otherwise\end{cases}$	.87	Brown (1978)	*Pinus monticola*

1/ Unpublished secondary analysis of data from Sando and Wick (1972).

Table 10. (Cont.)

Species	Size class	Predictor Equation	r^2	Source	Subject Species
Picea mariana	F	$W=0.367\ L$	---	Sando [1/]	*Picea Mariana*
	F+I	$W=0.598\ L$	---	Sando [1/]	*Picea Mariana*
	F+I+II	$W=\begin{cases}(1.038-0.0061\ D)L, & D>10cm\\ L, & \text{otherwise}\end{cases}$	.95	Brown (1978)	*Picea engelmannii*
Thuja occidentalis	F	$W=0.617\ L\ e^{-0.0092\ D}$	.98	Brown (1978)	*Thuja plicata*
	F+I	$W=0.756\ L\ e^{-0.0095\ D}$	.98	Brown (1978)	*Thuja plicata*
	F+I+II	$W=\begin{cases}1.06\ L\ e^{-0.0088\ D}, & D>7.4cm\\ L, & \text{otherwise}\end{cases}$	.98	Brown (1978)	*Thuja plicata*
Populus tremuloides	F	$W=0.0079\ D^{2.1012}$	.97	Loomis & Roussopoulos (1978)	*Populus tremuloides*
	I (only)	$W=0.0155\ D^{1.9041}$	.92	Loomis & Roussopoulos (1978)	*Populus tremuloides*
	II (only)	$W=\begin{cases}0.0525\ D^{1.8905}, & D>10.35cm\\ 0.0084\ D^{2.6746}, & \text{otherwise}\end{cases}$	.87 .98	Loomis & Roussopoulos (1978)	*Populus tremuloides*
	III (only)	$W=\begin{cases}0.0159\ D^{2.4728}, & D>23.6cm\\ 0.0084\ D^{2.6746}, & \text{otherwise}\end{cases}$	.86 .98	Loomis & Roussopoulos (1978)	*Populus tremuloides*
Betula papyrifera	F	$W=0.0295\ D^{1.702}$	.89	Ribe (1973)	*Betula papyrifera*
	I (only)	$W=1.85\ D^{-0.77}$ (Total live crown-foliage)	---	Loomis & Roussopoulos (1978)	*Populus tremuloides*
	F+I+II	$W=0.0481\ D^{3.5204}H^{-2.0449}$	.61	Yount et. al. (1964)	*Betula papyrifera*

1/ Unpublished secondary analysis of data from Sando and Wick (1972).

Table 10. (cont.)

Species	Size class	Predictor Equation	r^2	Source	Subject Species
Acer rubrum	F	$W=0.0248\ D^{1.8015}$	.85	Ribe(1973)	*Acer rubrum*
	I(only)	$W=1.85\ D^{-0.77}$(Total live crown-foliage)	---	Loomis & Roussopoulos(1978)	*Populus tremuloids*
	F+I+II	$W=0.211\ D^{0.8616}H^{0.2486}$	.29	Young et. al.(1964)	*Acer rubrum*
Others	F	$W=0.0228\ D^{1.7450}$	.81	Ribe(1973)	Combined species
	I(only)	$W=1.85\ D^{-0.77}$(Total live crown-foliage	---	Loomis & Roussopoulos(1978)	*Populus tremuloids*

Table 11. Statistical estimators and sources for dead crown dry weight by size classes. (W = dry weight (Kg), C = total dead crown weight (Kg), D = tree diameter at breast height (cm), H = tree height (m)).

Species	Size class	Predictor Equation	r^2	Source	Subject Species
Abies balsamea	F	$W=\begin{cases} 1.434\ C\ e^{-0.0717\ D}, & D \geq 7.6cm \\ C, & otherwise \end{cases}$	.77	Brown (1978)	*Abies grandis*
	F+I	$W=\begin{cases} 1.502\ C\ D^{-.353}, & D \geq 11.3cm \\ C, & otherwise \end{cases}$	.61	Sando[1/]	*Abies balsamea*
	F+I+II	$W=\begin{cases} C(1.249-0.014\ D), & D \geq 17.8cm \\ C, & otherwise \end{cases}$	---	Sando[1/]	*Abies balsamea*
Pinus banksiana	F	$W=\begin{cases} 0.139\ C, & D \geq 50.8cm \\ 2.743\ C\ D^{-0.758}, & 3.8cm \leq D < 50.8cm \\ C, & otherwise \end{cases}$	.95	Brown (1978)	*Pinus contorta*
	F+I	$W=\begin{cases} 0.226\ C, & D \geq 50.8cm \\ 2.798\ C\ e^{-0.05\ D}, & 22.9cm \leq D < 50.8cm \\ C, & otherwise \end{cases}$	.77	Brown (1978)	*Pinus contorta*
Pinus resinosa	F	$W=\begin{cases} 0.004\ C, & D \geq 76.2cm \\ C(3.584/D-0.0434), & otherwise \end{cases}$	.60	Brown (1978)	*Pinus ponderosa*

1/ Op. cit.

Table 11. (Cont.)

Species	Size class	Predictor Equation	r^2	Source	Subject Species
	F+I	$W=\begin{cases} 0.06\ D, & D\geq 76.2\text{cm} \\ C(1.062-0.0131\ D), & \text{otherwise} \end{cases}$	.69	Brown (1978)	*Pinus ponderosa*
Pinus strobus	F	$W= 1.5415\ C\ D^{-0.456}$	.49	Brown (1978)	*Pinus monticola*
	F+I	$W=\begin{cases} C(1.029-0.002\ D), & D\geq 17.8\text{cm} \\ C, & \text{otherwise} \end{cases}$	.12	Brown (1978)	*Pinus monticola*
Picea mariana	F	$W=\begin{cases} 2.6746\ C\ D^{-0.645}, & D\geq 4.6\text{cm} \\ C, & \text{otherwise} \end{cases}$	.77	Brown (1978)	*Picea engelmannii*
	F+I	$W= 1.0027\ C\ e^{-0.0337\ D}$	.68	Sando 1/	*Picea mariana*
	F+II	$W=\begin{cases} C(1.339-0.0099\ D), & D\geq 13.6\text{cm} \\ C, & \text{otherwise} \end{cases}$	---	Sando 1/	*Picea mariana*
Thuja occidentalis	F	$W=\begin{cases} C(3.726\ D-0.0158), & D\geq 3.8\text{cm} \\ C, & \text{otherwise} \end{cases}$	.87	Brown (1978)	*Thuja plicata*
	F+I	$W=\begin{cases} 1.453\ C\ e^{-0.021\ D}, & D\geq 20.3\text{cm} \\ C, & \text{otherwise} \end{cases}$	.66	Brown (1978)	*Thuja plicata*

1/ Op. Cit.

Table 11. (Cont.)

Species	Size class	Predictor Equation	r^2	Source	Subject Species
Populus tremuloides	I	$W = 0.0232\ C\ D^{1.847}$ - (Live class I)	.95	Loomis & Roussopoulos (1978)	*Populus tremuloides*
	I+II	$W = \begin{cases} 0.0665\ C\ D^{1.8697} & \text{-(Live class I+II), } D \geq 10.3\text{cm} \\ 0.0125\ C\ D^{2.5874} & \text{-(Live class I+II), otherwise} \end{cases}$	.88	Loomis & Roussopoulos (1978)	*Populus tremuloides*
	I+II+III	$W = \begin{cases} 0.0224\ C\ D^{2.4026} & \text{-(Live class I+II+III), } D \geq 23.5\text{cm} \\ 0.0125\ C\ D^{2.5874} & \text{-(Live class I+II+III), otherwise} \end{cases}$	---	Loomis & Roussopoulos (1978)	*Populus tremuloides*

dead branches to the base of the live crown. Additional dead material (from Table 11) not accounted for by tallied branches (if any) was distributed uniformly throughout the live crown space.

Resulting representations of vertical crown fuel distribution were used to evaluate conditions required for the initiation of torching and crowning fire behavior.

Inventory Results

In all, 210 subsample units were inventoried within the pilot study area. Figure 9 shows the locations of land survey sections in which sampling was conducted and Table 12 indicates the distribution of subsamples among management zones and Grigal-Ohmann (1975) community types. Thirty subsamples were inventoried in one of the ten selected sections that was drawn twice in the sample. Logistical problems, though, prevented completion of the remaining ten subsamples within that section--hence a total of 210 subsamples.

The distribution of inventory subsamples between the two management zones closely reflects the actual proportion of the study area within each zone. Sample allocation between community types differs little between zones, with the aspen-birch type accounting for 86% and 76% of the Portal and Interior subsamples respectively. Overall, 80% of the inventory subsamples were classified within the aspen-brich community type. This striking predominance of broadleaf types is apparently atypical of the BWCA on the whole (Table 1), and is likely attributable to the 19th century fire history of the study area (Heinselman 1973).

For all 210 subsamples, there was no evidence of fire disturbance since the major fire of 1875. Only four subsamples showed evidence of

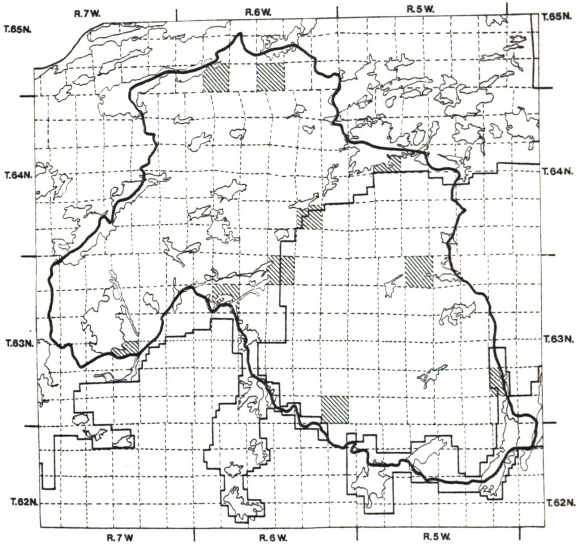

Figure 9. Locations of land survey sections randomly selected for fuel inventory.

Table 12. Land survey sections selected for sampling and distribution of subsample units among management zones and community types.

Legal Descript			No.	Subsamples by Mgt Zone		Subsamples by Community Type 1/								
Sec	Town	Range	Subsamples	Portal	Interior	MA-A-B-Fir	Fir-Birch	Aspen-Birch	JP-Bal Fir	Asp-Bir-Wp	Red Pine	Bsp-F-Moss	No W Cedar	Jp-B Spruce
26	64N	6W	30	26	4	1	5	23	1	---	---	---	---	---
32	65N	6W	20	--	20	---	---	10	2	7	1	---	---	---
34	65N	6W	20	--	20	---	---	18	---	---	---	2	---	---
3	63N	6W	20	--	20	---	---	20	---	---	---	---	---	---
17	64N	5W	20	--	20	---	4	11	1	---	---	---	4	---
36	63N	6W	20	20	--	---	---	17	---	---	---	1	---	2
25	63N	5W	20	20	--	---	---	16	---	---	---	4	---	---
8	63N	6W	20	--	20	---	---	20	---	---	---	---	---	---
22	63N	7W	20	--	20	---	---	13	---	---	4	1	---	2
4	63N	5W	20	20	--	---	---	20	---	---	---	---	---	---
All			210	86	124	1	9	168	4	7	5	8	4	4

1/ Grigal and Ohmann (1975)

other noteworthy disturbance in the past 25 years. Two were harvested in 1971 within the Portal zone, while the other two, also in the Portal zone, were cut in 1956.

Despite the area's relatively uniform upland forest cover and disturbance history, though, several stand and site measurements showed considerable variation among inventory subsamples. The ages of dominant trees ranged from 32 to 117 years (Figure 10a), with a mean value of 80. Also quite variable was tree basal area. It ranged from 3.4 to 34.4 m^2/ha (Figure 10b) with a mean and standard deviation of 16.6 ± 6.3. Site index averaged 14 meters at age 50 and ranged from 9 to 21.

Floristic Composition

The noted over-representation of broadleaf community types in the fuel inventory sample indicates that the chosen study area is not representative of the BWCA in general. Since hardwood types are notably less prone to severe fire behavior than conifers, it will be difficult to extrapolate results of the pilot program to the BWCA in general--where coniferous types are more prevalent. Comparing the floristic composition of the fuel inventory sample with that of a more extensive survey of BWCA vegetation offers further detail on this anomaly.

Ohmann and Ream (1971b) report measurements of basal area of trees, stem density of tall shrubs and tree seedlings, and percent cover of low shrubs, herbaceous plants, and ground cover species for 106 randomly selected natural stands throughout the BWCA. Similar values are reported by Grigal and Ohmann (1975) for 77 of the original 106 natural stands combined with 50 randomly located stands in areas that have been logged. The natural stands of Ohmann and Ream (1971b) should be directly comparable to the fuel inventory subsamples of the Interior zone. Furthermore,

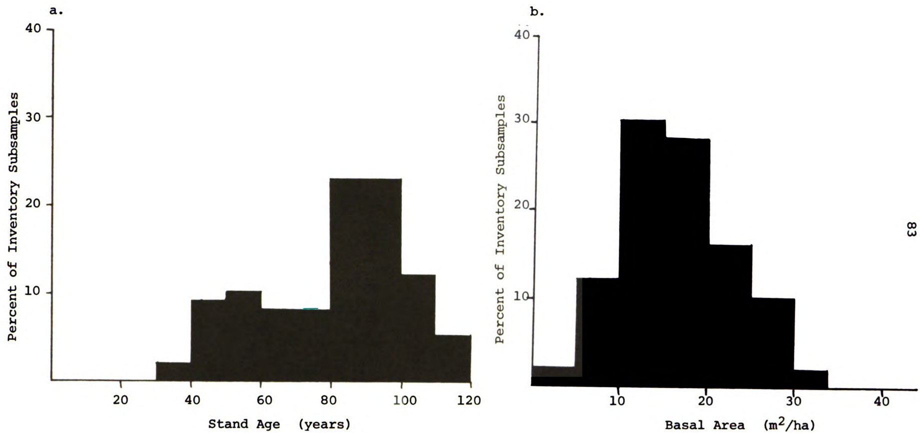

Figure 10. Probability distribution histograms for a.) age of dominant overstory component, and b.) tree basal area at fuel inventory plots.

since the proportional representation of natural stands in the Grigal-Ohmann data set (61%) is nearly identical to that for Interior zone subsamples in the study area (59%), the values reported by Grigal and Ohmann (1975) should be comparable with those for the aggregate fuel inventory subsamples.

Table 13 summarizes these values by vegetative stratum for all four data sets, while Table 14 shows the percentage contribution of individual species (Ohmann (1973) calls this relative dominance or relative density). Note in Table 13 that tree basal area is considerably lower for the study area than for the extensive BWCA. Furthermore, it appears that tree seedlings within the pilot study area have been largely displaced by tall shrubs. The low shrub and herbaceous strata cannot be compared directly, since percent cover was not measured in the fuel inventory. Comparison of relative dominance for these strata (Table 13), therefore, may be questionable. Ground cover percentages in the study area are only slightly lower than found elsewhere.

The most striking observation in Table 14 concerns the relative contribution of aspen and paper birch to sample basal area. In the Interior zone of the study area these species account for 47%, and they account for 55% in the aggregate sample. Respective values for the BWCA in general are only 17 and 18%. Coniferous species make up much of the difference, reflecting the noted contrast in community type distributions. Except for the relative density of red maple and balsam fir tree seedlings in the general BWCA stands, though, and some minor rank reversals in species density for tall shrubs, there are few additional differences among the data sets. Even in the herbaceous stratum, the small variations apparent here can be partially attributed to

Table 13. Summary data for vegetative surveys in the study area and the BWCA in total.

Vegetative Stratum	Pilot Study Area		BWCA in Total	
	Interior Zone	All Subsamples	Natural Stands 1/	All Stands 2/
Tree Basal Area (m^2/ha)	17.8	16.8	30.8	30.9
Seedling Density (stems/ha)	4999	7275	27,308	46,169
Tall Shrub Density (stems/ha)	60,772	63,446	25,358	26,042
Low Shrub:				
% cover			5.6	5.9
gm/m^2	4.7	4.4		
Herbaceous Plants:				
% cover			59.2	31.7
gm/m^2	19.5	18.3		
Ground Cover:				
% cover	15.8	14.6	23.4	22.6

1/ Data from Ohmann and Rean 1971b.

2/ Data from Grigal and Ohmann 1975.

Table 14. Relative species dominance or density by stratum for the study area and the BWCA in total.

Stratum	Fire Management Pilot Study Area				Entire BWCA			
	Interior Zone Only		All Subsamples		Natural Stands Only (Ohmann and Ream 1971b)		Both Natural and Logged Stands (Grigal and Ohmann 1975)	
	Species	Relative Dom(%)	Species	Relative Dom(%)	Species	Relative Dom(%)	Species	Relative Dom(%)
Trees (> 2. 5cm dbh)	*Populus tremuloides*	30.0	*Populus tremuloides*	37.1	*Pinus banksiana*	23.2	*Populus tremuloides*	17.5
	Betula papyrifera	16.8	*Betula papyrifera*	17.8	*Populus tremuloides*	16.9	*Pinus banksiana*	17.1
	Pinus banksiana	15.4	*Picea mariana*	13.3	*Picea mariana*	12.7	*Picea mariana*	11.0
	Picea mariana	10.6	*Pinus banksiana*	12.6	*Pinus strobus*	11.0	*Pinus strobus*	8.9
	Abies balsamea	8.8	*Abies balsamea*	6.8	*Abies balsamea*	7.3	*Thuja occidentalis*	8.8
	Pinus strobus	5.7	Other	12.4	*Thuja occidentalis*	7.2	*Abies balsamea*	8.5
	Thuja occidentalis	5.7			*Acer rubrum*	2.3	*Acer rubrum*	3.2
	Acer rubrum	1.5			Other	19.4	Other	25.0
	Other	5.5						
Tree Seedlings (< 2.5cm dbh)	*Populus tremuloides*	30.7	*Betula papyrifera*	27.5	*Acer rubrum*	40.9	*Acer rubrum*	61.4
	Abies balsamea	28.0	*Populus tremuloides*	19.2	*Abies balsamea*	38.6	*Abies balsamea*	22.7
	Thuja occidentalis	18.0	*Abies balsamea*	16.3	Other	20.5	Other	15.9
	Acer rubrum	10.7	*Picea mariana*	11.4				
	Betula papyrifera	10.0	*Acer rubrum*	9.8				
	Other	2.6	*Thuja occidentalis*	9.2				
			Other	6.6				
Tall Shrubs	*Corylus cornuta*	46.4	*Corylus cornuta*	53.4	*Corylus cornuta*	42.9	*Corylus cornuta*	41.4
	Alnus crispa	20.5	*Alnus crispa*	16.9	*Acer spicatum*	25.9	*Acer spicatum*	28.3
	Acer spicatum	9.9	*Acer spicatum*	11.2	*Alnus crispa*	11.1	*Alnus crispa*	8.5
	Other	23.2	Other	18.5	Other	20.1	Other	21.8
Low Shrubs	*Vaccinium* spp.	35.7	*Vaccinium* spp.	38.2	*Vaccinium angustifolium*	29.8	*Vaccinium angustifolium*	26.8
	Diervilla lonicera	19.5	*Diervilla lonicera*	17.1	*Diervilla lonicera*	19.6	*Diervilla lonicera*	18.5
	Rubus spp.	15.0	*Rubus* spp.	10.6	*Gaultheria procumbens*	12.9	*Gaultheria procumbens*	9.4
	Other	29.8	Other	34.1	Other	37.7	Other	45.3
Herbaceous Plants	*Aster macrophyllus*	24.5	*Aster macrophyllus*	24.8	*Aster macrophyllus*	17.8	*Aster macrophyllus*	41.5
	Lycopodium spp.	14.6	*Lycopodium* spp.	19.1	*Cornus canadensis*	4.5	*Malanthemum canadense*	6.9
	Aralia nudicalis	13.4	*Aralia nudicalis*	12.4	*Malanthemum canadense*	3.4	*Cornus canadensis*	6.7
	Pteridium aquilinum	9.8	*Pteridium aquilinum*	9.2	*Clintonia borealis*	3.3	*Clintonia borealis*	5.3
	Other	37.7	*Clintonia borealis*	5.3	Other	71.0	Other	39.6
			Other	29.2				
Ground Cover	*Plurosium schreberi*	22.83	*Plurosium schreberi*	16.4	*Plurosium schreberi*	49.9	*Plurosium schreberi*	43.7
	Cladonia spp.	13.9	*Cladonia* spp.	12.3	*Dicranum* spp.	15.8	*Dicranum* spp.	13.9
	Other	63.3	Other	71.3	*Cladonia rangiferina*	2.3	*Cladonia rangiferina*	2.7
					Other	32.0	Other	39.7

disparate measures of species abundance used in the two sampling efforts. Apparently, the study area's major distinction is its comparatively low representation from coniferous tree species, possibly due to the loss of seed sources in the fire of 1875.

The community type and relative species composition of the fuel inventory sample, along with the visual appearance of the landscape, leaves one with an impression of a broadly uniform, but floristically diverse forest community (often called the "Minnesota mix") occupying most of the study area's upland sites. The "patchwork" character of other BWCA landscapes, on the other hand, could present very different fire management problems when prescribed natural fire programs are initiated elsewhere.

Fuelbed Properties

In spite of the floristic homogeneity of upland communities in the study area, biomass and fuel loading estimates are quite variable among fuel inventory subsamples. Table 15 shows the mean loading of major fuel components in grams dry weight per square meter area, as well as the maximum value, minimum value, and standard deviation by community type (Grigal and Ohmann 1975).

Similar values are given by fuel size class and condition (live or dead) for surface fuel materials in Table 16, and for crown fuels (above 1.8m in height) in Table 17. In Table 16, H and F layer fuels have been deleted. Total loading of organic material ranged nearly an order of magnitude from 3186 to 17,220 gm/m^2 (Table 15). Of the ten fuel components listed, humus shows the greatest range of variation among subsamples--from 172 to 11,219 gm/m^2, while downed deadwood had the

Table 15. Summary of fuel loading means ($\bar{x}$), ranges, and standard deviations (s) by fuel component and community type.

Fuel Component		Grigal-Ohmann (1975) Community Type: MA-A-B-Fir	Fir-Birch	Aspn-Birch	JP-Bal Fir	Asp-Bir-Wp	Red Pine	Bsp-F Moss	No N Cedar	JP-B sprc
		grams per square meter								
H Layer	$\bar{x}$	825	2201	2250	3704	2982	2658	6937	3651	4339
	Max	825	4360	7565	5291	4470	2963	11219	6603	6138
	Min	825	1312	172	1989	1169	2370	2540	1101	2116
	s	0	892	1252	1603	1273	253	3332	2813	1791
F Layer	$\bar{x}$	667	827	852	827	812	839	1501	659	1111
	Max	667	1256	2055	1409	1070	1133	2604	950	2083
	Min	667	153	133	582	507	705	429	460	337
	s	0	340	452	390	208	174	838	209	814
L Layer	$\bar{x}$	960	280	410	390	373	377	461	185	486
	Max	960	416	1056	648	528	440	752	254	636
	Min	960	69	115	243	278	312	81	139	393
	s	0	114	179	189	99	51	284	50	110
Ground Cover	$\bar{x}$	11	109	63	95	46	24	423	256	76
	Max	11	325	860	160	76	57	1128	661	162
	Min	11	0	0	23	0	11	102	57	11
	s	0	135	94	56	30	19	414	278	68
Herbaceous Plants-	$\bar{x}$	20	25	29	9	17	24	43	6	19
	Max	20	42	89	13	24	42	157	10	37
	Min	20	8	8	4	6	15	13	1	12
	s	0	11	15	4	6	12	48	4	12
Downed Deadwood	$\bar{x}$	3636	1595	1268	1137	1926	1665	1903	2262	1472
	Max	3636	3562	5589	1389	3052	2990	3991	4199	1952
	Min	3636	495	85	901	372	862	435	1175	864
	s	0	1100	841	225	1066	888	1411	1102	504
Shrubs (live)	$\bar{x}$	559	454	480	227	295	285	230	320	227
	Max	559	1204	6259	501	587	388	613	743	709
	Min	559	28	24	20	64	127	2	49	9
	s	0	351	577	212	182	108	208	298	325

Table 15. (cont.)

Fuel Component		Grigal-Ohmann (1975) Community Type								
		MA-A-B-Fir	Fir-Birch	Aspn-Birch	JP-Bal Fir	Asp-Bir-Wp	Red Pine	Bsp-F Moss	No W Cedar	JP-B sprc
		grams per square meter								
Shrubs (dead)	$\bar{x}$	71	79	99	15	66	74	38	20	19
	Max	71	187	1329	39	146	130	164	48	61
	Min	71	2	1	0	21	23	0	1	3
	s	0	69	138	17	41	51	58	21	28
Trees (live)	$\bar{x}$	1653	2020	1729	2240	2361	2245	2154	1862	2735
	Max	1653	3505	3816	3414	2960	3119	2752	2146	4098
	Min	1653	1030	258	1253	1549	1113	1045	1342	1182
	s	0	801	664	900	540	787	566	359	1529
Trees (dead)	$\bar{x}$	147	503	271	407	400	387	663	315	603
	Max	147	1083	805	494	521	682	1127	364	1008
	Min	147	151	28	283	237	141	438	259	253
	s	0	313	152	92	99	215	210	43	397
All Components	$\bar{x}$	8549	8094	7452	9052	9278	8580	14354	9536	11086
	Max	8549	10348	13928	10705	12176	9954	17220	11949	13463
	Min	8549	5413	3816	6463	5555	6253	10000	7397	9423
	s	0	1473	1933	1821	2370	1385	2619	1954	1819

Table 16. Summary of surface fuel loadings (below 1.8 m) by size class, condition, and community type.

Condition	Size	Grigal-Ohmann (1975) Community Type								
		MA-A-B-Fir	Fir-Birch	Aspn-Birch	JP-Bal Fir	Asp-Bir-Wp	Red Pine	Bsp-F Moss	No W Cedar	JP-B Sprce
		Grams per square meter								
Live	F $\bar{x}$	100	143	112	104	87	117	160	140	69
	Max	100	235	290	192	138	219	351	264	105
	Min	100	56	34	37	44	50	66	104	44
	s	0	63	52	65	33	64	96	73	30
	I $\bar{x}$	120	115	110	60	72	86	83	150	29
	Max	120	234	372	105	115	113	210	222	64
	Min	120	40	10	12	20	64	2	78	8
	s	0	66	68	38	32	19	66	73	24
	II $\bar{x}$	257	293	225	170	150	129	258	303	129
	Max	257	666	918	234	255	187	568	443	223
	Min	257	90	15	76	63	45	107	162	93
	s	0	177	163	69	80	57	159	115	63
	III $\bar{x}$	7	45	52	26	21	14	243	185	47
	Max	7	255	1893	60	66	44	743	531	130
	Min	7	0	0	0	0	0	0	11	7
	s	0	84	160	31	29	20	295	235	56
	IV $\bar{x}$	0	0	0	0	0	0	0	0	0
	Max	0	0	3	0	0	0	0	0	0
	Min	0	0	0	0	0	0	0	0	0
	s	0	0	0	0	0	0	0	0	0
Dead	F $\bar{x}$	93	92	83	110	89	111	75	55	104
	Max	93	124	116	118	95	119	117	98	119
	Min	93	37	7	102	74	107	15	25	80
	s	0	30	22	6	7	5	38	32	19
	I $\bar{x}$	126	105	95	61	64	105	57	84	41
	Max	126	158	289	103	90	196	88	120	77
	Min	126	52	29	19	46	40	31	57	26
	s	0	36	39	40	18	59	19	32	24

Table 16. (Cont.)

Condition	Size	MA-A-B-Fir	Fir-Birch	Aspn-Birch	JP-Bal Fir	Asp-Bir-Wp	Red Pine	Bsp-F Moss	No W Cedar	JP-B Sprce
		Grigal-Ohmann (1975) Community Type								
		grams per square meter								
II	$\bar{x}$	489	348	392	362	387	413	331	200	394
	Max	489	527	782	487	567	488	616	267	500
	Min	489	64	99	262	308	327	82	98	318
	s	0	156	124	111	91	67	180	72	77
III	$\bar{x}$	698	326	315	297	224	381	361	771	287
	Max	698	901	1317	543	287	776	538	1793	475
	Min	698	71	1	132	136	156	128	211	92
	s	0	261	217	176	50	241	154	699	177
IV	$\bar{x}$	3301	1139	882	746	1608	1101	1588	1402	1164
	Max	3301	2774	5139	980	2826	2489	3659	2258	1592
	Min	3301	196	0	404	207	307	338	545	689
	s	0	844	773	248	1047	912	1336	856	384
All	$\bar{x}$	5191	2606	2267	1935	2701	2457	3155	3342	2264
	Max	5191	5229	6252	2127	3987	3575	5239	5345	2647
	Min	5191	1687	989	1550	1125	1722	1994	2309	1917
	s	0	1286	920	262	1063	769	1161	1363	323

Table 17. Summary of crown fuel loadings (above 1.8 m) by size class, condition, and community type.

Condition	Size	MA-A-B-Fir	Fir-Birch	Aspn-Birch	JP-Bal Fir	Asp-Bir-Wp	Red Pine	Rsp-F Moss	No W Cedar	JP-B Sprce
		Grigal-Ohmann (1975) Community Type								
		grams per square meter								
Live	F $\bar{x}$	272	504	372	559	548	629	633	490	1024
	Max	272	857	1240	796	785	882	959	625	1513
	Min	272	237	48	341	287	283	276	378	453
	s	0	238	190	188	168	258	205	128	562
	I $\bar{x}$	265	396	329	448	430	389	440	293	694
	Max	265	657	1021	681	580	615	649	360	1018
	Min	265	238	57	255	239	166	205	237	291
	s	0	137	144	183	129	202	128	51	377
	II $\bar{x}$	325	609	466	554	669	547	613	431	778
	Max	325	1043	2205	895	913	981	811	562	1158
	Min	325	310	87	368	361	174	217	304	351
	s	0	218	237	233	180	323	189	115	425
	III $\bar{x}$	874	488	608	640	708	658	413	394	286
	Max	874	889	1542	1043	902	1101	686	820	439
	Min	874	166	34	289	475	322	78	82	56
	s	0	251	279	322	174	306	189	309	163
	IV $\bar{x}$	23	16	25	11	35	9	7	8	0
	Max	23	66	140	33	56	28	26	19	0
	Min	23	0	0	0	2	0	0	0	0
	s	0	20	27	15	19	13	9	10	0
Dead	F $\bar{x}$	0	110	49	89	113	56	198	92	186
	Max	0	298	271	142	179	108	291	142	289
	Min	0	8	0	52	63	26	75	41	101
	s	0	95	48	45	38	34	77	51	93
	I $\bar{x}$	25	113	65	98	100	166	123	84	250
	Max	25	412	351	127	132	257	267	101	444
	Min	25	23	6	61	68	24	65	51	66
	s	0	119	50	20	20	109	63	22	206

Table 17. (Cont.)

Condition	Size	MA-A-B-Fir	Fir-Birch	Aspn-Birch	JP-Bal Fir	Asp-Bir-Wp	Red Pine	Rsp-F Moss	No W Cedar	JP-B Sprce
		Grigal-Ohmann (1975) Community Type								
		grams per square meter								
II	$\bar{x}$	63	181	134	152	150	157	253	75	148
	Max	63	506	504	212	231	314	474	105	281
	Min	63	47	17	95	107	71	167	25	52
	s	0	137	74	49	47	95	100	33	106
III	$\bar{x}$	18	42	33	35	31	12	77	15	6
	Max	18	153	163	58	51	50	318	32	13
	Min	18	5	0	12	10	0	12	3	2
	s	0	44	23	19	16	21	101	13	5
IV	$\bar{x}$	0	0	1	0	0	2	3	3	0
	Max	0	1	11	1	1	11	14	12	0
	Min	0	0	0	0	0	0	0	0	0
	s	0	0	1	0	0	5	5	6	0
All	$\bar{x}$	1866	2460	2083	2586	2784	2625	2760	1884	3372
	Max	1866	3553	5952	3862	2504	3579	3878	2374	5103
	Min	1866	1701	390	1531	1820	1115	1628	1577	1383
	s	0	614	817	970	632	1030	653	342	1892

next largest range (85 to 5589). Most of the deadwood variation, though is attributable to the size class IV material (Table 16). Except under extreme drought conditions, humus and large diameter deadwood have only minor influence on forest fire behavior. The more influential surface fuel components (L layer, ground cover, herbaceous plants, and class F and I downed deadwood), although highly variable in a relative sense, have a somewhat narrower range of absolute variation.

Among the community types, variability of loading means is for the most part minor. As might be expected, the black spruce-feather moss community has notably higher H layer, F layer, and ground cover loadings, while stands with high representation from black spruce have an unusual amount of dead material in the canopy space (Tables 15 and 17). These results are substantiated by experience. Beyond this, though, the only major anomalies in community type averages concern the maple-aspen-birch-fir type that is represented by a single subsample--hardly adequate for meaningful comparison. It is apparent that little, if any, of the dispersion of loading estimates for fuel inventory sub-samples can be attributed to differences among community types. Variation seems considerably higher within these types than it is among them.

Besides fuel loading, the distribution of that loading must also be considered. Figure 11 presents vertical fuel distribution histograms for two contrasting stands. In the first (Figure 11a), representing an aspen-birch stand in the central portion of the study area, fuel bulk density is quite high in the first 30.5cm stratum above the litter--5815 gm/m^3. This gradually decreases upward through a balsam fir under-story and aspen canopy to zero at a height of roughly 10 meters, the

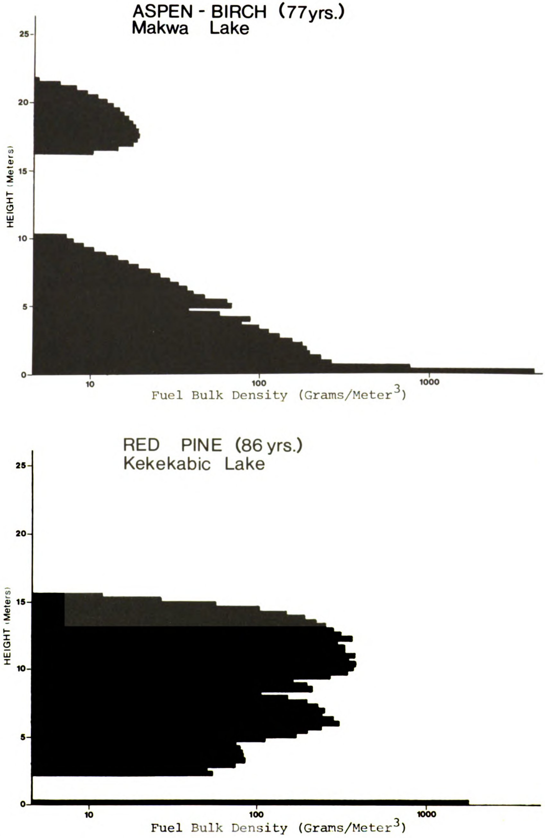

Figure 11. Vertical distribution of fuel materials for two contrasting stands.

height of the aspen trees. Above this, a few decadent remnants of an earlier jack pine stand are shown as a sparse "super-canopy". Note that the boles of these trees are not shown. Boles of standing trees seldom constitute an important fuel source, and have been ignored in the representation of inventoried stands. A surface fire could easily produce torching of the balsam fir understory and provide the necessary conditions for fire-brand generation. Crowning, however, is not likely in an aspen canopy (Van Wagner 1977).

The situation is somewhat different in a relatively pure red pine stand in the northern part of the study area (Figure 11b). Again the surface stratum is quite dense, but above this is a fuel-free region about two meters deep. A relatively high intensity surface fire would be required to ignite crown fuels in this stand, but once ignited, sustained crowning could possibly be achieved.

To preserve and utilize these differences among inventory subsamples, loading estimates were summarized by species, size class, condition, and height in 30.5cm increments for each inventory subsample. These data, together with appropriate data concerning physical and chemical properties of fuel components, provided the basic inputs for subsequent efforts to appraise fire behavior potential and classify upland fuels of the study area.

CHEMICAL AND PHYSICAL FUEL PROPERTIES

In addition to the aggregate physical properties of the fuel array, forest fire behavior is also influenced by the character of individual fuel particles that comprise the fuelbed. These may include needles, cones, twigs, branches, leaves, fruiting structures, etc. Combustion characteristics of these particles are related both to chemical and physical particle properties.

Chemical Properties

The two primary chemical attributes related to combustion are inorganic mineral content and solvent extractable materials (Philpot 1977) which dramatically influence heat of combustion (Shafizadeh *et al*. 1977).

In a flammability study of differentially weathered corn plants, Broido and Nelson (1964) found that the susceptibility of samples to flaming combustion was inversely related to sample ash content. This finding was qualified by Mutch and Philpot (1970), who produced evidence that silica is chemically inert to the combustion process and suggested that it be discounted from the ash fraction when evaluating wildland fuel flammability. Thermal analyses of a variety of plant materials (Philpot 1968, 1970) have established quantitative relationships between silica-free ash content and rates of fuel volatilization that have been incorporated into the Rothermel (1972) fire behavior model.

Heat of combustion has an obvious influence on fire behavior, and is also an input to the Rothermel model.

To apply this model in the appraisal and classification of forest flammability within the study area, an attempt was made to characterize important BWCA fuel elements with respect to these properties.

Methods

Samples of prominent BWCA plant species were collected near the Kawishawi Field Laboratory during August of 1976. They were identified by species, size class, and condition (live or dead), dried for 72 hours at 70°C, and ground to pass a 1mm screen. After being sealed in plastic bags they were transported to Michigan State University where total ash content and silica-free ash content were determined using standard methods.[1/] [2/] High heat of combustion was determined with a Parr adiabatic bomb calorimeter (Model 1241) by the method described in Parr Manual No. 153. These were converted to low heats of combustion by subtracting 302 cal/gm (Byram 1959).

Results

In all, 373 samples were processed for total and silica-free mineral content, while 214 were subjected to calorimetry. These samples were allocated among fuel component categories, size classes, and condition classes as shown in Tables 18, 19, and 20. Total ash (fraction

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1/ ASTM Standards: Method of Test for Ash in Wood, D 1102-56.

2/ Assoc. Official Agr. Chemists. 1965. Methods of Analysis, 6.005: Sand and Silica.

Table 18. Summary of total ash content determinations by fuel component, size class, and condition. (n = sample size, $\bar{x}$ = mean ash fraction, max = maximum, min = minimum, s = standard deviation).

Fuel Component		Live Fuel Size Class				Dead Fuel Size Class			
		F	I	II	III	F	I	II	III
Conifer trees	n	12	12	14	12	8	9	11	9
	$\bar{x}$	.037	.031	.015	.011	.038	.029	.014	.009
	max	.058	.063	.020	.016	.056	.046	.018	.014
	min	.020	.020	.010	.008	.026	.021	.010	.005
	s	.012	.016	.003	.003	.010	.008	.003	.003
Hardwood Trees	n	14	14	21	15	7	5	7	6
	$\bar{x}$	.054	.018	.013	.010	.056	.024	.013	.009
	max	.063	.026	.022	.018	.063	.038	.019	.005
	min	.046	.010	.006	.004	.041	.016	.011	.012
	s	.006	.006	.004	.004	.008	.010	.004	.003
Shrubs	n	46	33	28	14				
	$\bar{x}$	.071	.022	.015	.014				
	max	.103	.032	.020	.033				
	min	.030	.014	.010	.008				
	s	.015	.004	.003	.006				
Herbaceous Plants and Low Shrubs	n	58	8			4			
	$\bar{x}$	.077	.026			.093			
	max	.197	.056			.122			
	min	.025	.010			.056			
	s	.040	.015			.033			
Ground Cover	n	6							
	$\bar{x}$	.049							
	max	.079							
	min	.027							
	s	.020							

Table 19. Summary of silica-free ash content determinations by fuel component, size class, and condition. (n = sample size, $\bar{x}$ = mean silica-free ash fraction, max = maximum, min = minimum, s = standard deviation).

Fuel Component		Live Fuel Size Class				Dead Fuel Size Class			
		F	I	II	III	F	I	II	III
Conifer Trees	n	12	12	14	12	8	9	11	9
	$\bar{x}$	.027	.019	.011	.008	.026	.018	.011	.006
	max	.037	.026	.013	.013	.034	.022	.017	.011
	min	.014	.012	.008	.004	.020	.012	.005	.003
	s	.007	.004	.001	.003	.006	.004	.004	.003
Hardwood Trees	n	14	14	21	15	7	5	7	6
	$\bar{x}$	.037	.014	.010	.008	.029	.020	.010	.007
	max	.054	.023	.018	.016	.034	.035	.016	.011
	min	.028	.007	.003	.003	.018	.012	.006	.003
	s	.008	.006	.004	.004	.005	.010	.004	.004
Shrubs	n	45	33	29	14				
	$\bar{x}$	.058	.019	.012	.012				
	max	.092	.028	.022	.014				
	min	.026	.013	.008	.006				
	s	.015	.004	.003	.006				
Herbaceous Plants and Low Shrubs	n	58	8			4			
	$\bar{x}$	.053	.020			.015			
	max	.130	.047			.022			
	min	.011	.006			.009			
	s	.029	.013			.006			
Ground Cover	n	6							
	$\bar{x}$	.018							
	max	.033							
	min	.009							
	s	.009							

Table 20. Summary of low heat of combustion (cal/gm) determinations by fuel component, size class, and condition.

Fuel Component		Live Fuel Size Class				Dead Fuel Size Class			
		F	I	II	III	F	I	II	III
Conifer Trees	n	9	8	6	8	4	6	4	7
	$\bar{x}$	4710	4340	4490	4647	4851	4764	4462	4622
	max	5048	4954	4740	5823	5110	4945	4880	4721
	min	4530	3287	3805	4298	4721	4551	3946	4465
	s	566	747	350	281	178	146	401	90
Hardwood Trees	n	3	6	3	3	4	3	2	1
	$\bar{x}$	4552	4451	4413	4072	4663	4590	3962	4555
	max	4671	5064	4787	3755	4762	4803	4291	4555
	min	4428	4236	4123	4316	4536	4326	3633	4555
	s	122	312	340	288	103	243	465	0
Shrubs	n	27	23	19	11				
	$\bar{x}$	4207	4168	4155	4224				
	max	4607	4505	4569	4864				
	min	3516	3534	3565	3742				
	s	250	233	286	285				
Herbaceous Plants and Low Shrubs	n	40	4			4			
	$\bar{x}$	4211	4648			4227			
	max	5021	4821			4846			
	min	3397	4561			3686			
	s	361	117			477			
Ground Cover	n	9							
	$\bar{x}$	3983							
	max	4178							
	min	3731							
	s	171							

dry-weight) ranged from 0.004 for a sample of size class III aspen to 0.197 for horsetail (*Equisetum* spp.). Silica-free ash, of course, was slightly lower, ranging from 0.003 for several large diameter tree materials to 0.130 for Clinton's lily. As might be expected, ash contents are highest in foliar materials and lowest in large diameter roundwood. The conifers have generally lower mineral contents than hardwood trees and shrubs, contributing to their more flammable nature, while herbaceous plants have the highest values. These findings appear consistent with what is known about the disposition of plant nutrients in forest ecosystems (Morrison 1973, Carter and White 1971, Reiners and Reiners 1972, Gerloff et al. 1964). Furthermore, the values compare favorably with studies of fuel chemistry in other regions (Philpot 1970, Hough 1969). There seems to be little difference in the ash content between living and dead materials.

Low heat values displayed a similar relationship to size class, with foliage having high values and branchwood materials slightly lower. Conifer trees show slightly higher calorific values than hardwoods, shrubs, and herbaceous plants, due to their higher resin and lignin contents (Howard 1973). Reported calorific values of ecological and fuel materials for other areas, when corrected for the latent heat of vaporization for the water of reaction, are generally consistent with these results (Van Wagner1972, Hough 1969, Susott et al. 1975, Reiners 1972, Telitsyn and Sosnovshchenko 1969, Reiners and Reiners 1970, Hughes 1971). Although heat of combustion is seasonally variable (Madgwick 1970, Hughes 1971), it is considered constant in this study.

For both ash content and heat of combustion, individual species determinations were preserved in the analysis. Appropriate average values from Tables 18, 19, and 20 were applied to species and components not represented in the sample. Dead shrub materials were not available in large quantities, and since little difference is noted between live and dead tree materials, the values for live shrubs were applied to both condition categories.

Physical Properties

Physical fuel particle properties required by the Rothermel (1972) fire model include surface area-to-volume ratio (cm^{-1}), fuel particle density (gm/cm^3), and moisture content (fraction of dry weight). Of these, the last is highly variable in time and space, especially for dead fuels, and is considered a manifestation of meteorological conditions rather than a fuel property. The National Fire Danger Rating System (Deeming et al. 1977) provides methods for computing these values from daily observations of temperature, relative humidity, and precipitation. Particle density and surface area-to-volume ratio, on the other hand, are considered fuel particle constants.

Particle densities for tree branchwood have already been discussed (Table 2). A density of 0.5 gm/cm^3 was assigned for all other woody fuel components. For foliar materials, though, density is more variable, and actual measurement was required. Samples of selected foliar materials were collected and taken to the Kawishawi Field Laboratory where green volume and oven-dry weight were measured. Volumes of long narrow particles were found by repeating cross-section measurements at appropriate intervals along the longitudinal axis of the piece. For flat pieces, mean thickness and surface area were measured with a micrometer and polar planimeter, respectively. Oven drying at 105°C for 24 hours provided dry weights of measured particles.

The surface area-to-volume ratio (σ) is a measure of particle "fineness" and is related to the time response of a fuel element to the fire environment. For large woody size classes (II, III, and IV), surface area-to-volume ratios are relatively constant among all tree species. Representative values of σ=3.58 and σ=0.98cm^{-1}, proposed by Albini (1976b) were applied to size class II and III branchwood, respectively. A σ value of 0.33cm^{-1}, corresponding to a diameter of 12cm (σ=4.0/diameter for a cylinder), was used to represent size class IV material. Values of σ for class I branchwood and foliage, though, are quite variable among species. Since the fire spread model is highly sensitive to this parameter, individual species values were obtained for the finer fuels. Sources contributing to Table 2 provided values for tree branchwood. Size class I values ranged from 8.66cm^{-1} for red pine to 25.07cm^{-1} for balsam fir. Intermediate values were: jack pine, 15.35; white pine, 15.75; black spruce, 21.92; northern white cedar, 10.50; aspen, 11.09; paper birch, 12.89; and red maple, 13.12.

Surface area-to-volume ratios for foliar materials were measured using a minature planar intersect sampling procedure. Foliage samples of tree, shrub, and herbaceous species were collected near the Kawishawi Field Laboratory during August of 1976. For each species, a sample of at least 200 grams fresh weight was spread over a flat surface immediately following collection. A randomly placed string served to delineate the sampling plane. Each intersected particle was described as follows:

1. Geometric shape of the particle cross-section was identified at the point of intersection (e.g. circle, ellipse, triangle, rectangle, etc.)
2. Dimensions of the cross section were measured at the point of intersection with a micrometer caliper.
3. Cross-sectional area and cross-sectional perimeter were calculated from the characteristic shape and measured dimensions. The estimated surface area-to-volume ratio was defined as the ratio of cross-sectional perimeter to cross-sectional area (cm/cm^2).

For the entire sample, a characteristic surface area-to-volume ratio was computed, first for each shape category in the sample as the arithmetic mean of measured values, then for the entire sample as a weighted mean (weighted by surface area) of the individual shape category means.

Measured surface area-to-volume ratios and particle densities for sampled foliar materials are given in Table 21. Surface area-to-volume ratios for balsam fir, jack pine, and red pine compare favorably with values given by Brown (1970b) for grand fir (*Abies grandis* Dougl. Lindl.), lodgepole pine (*Pinus contorta* Dougl.), and ponderosa pine (*P. ponderosa* Laws.), respectively. Eastern white pine, though, has a value half again that reported for western white pine (*P. monticola* Dougl.). In contrast, the aspen estimate reported by Brown (1970b) was considerably higher than shown in Table 21, ($139.8cm^{-1}$).

Species not represented in the sample were assigned the sample mean values for the appropriate vegetative stratum.

Table 21. Fuel particle densities (ρ) and surface area-to-volume ratios (σ) for selected foliar materials.

Species	ρ (gm/cm³)	σ (cm⁻¹)
Herbaceous		
Anaphalis margaritacea	0.12	52.07
Apocynum androsaemifolium	0.17	71.52
aralia nudicalis	0.11	87.17
Aster macrophyllus	0.08	53.87
Clintonia borealis	0.07	47.11
Cornus canadensis	0.20	105.18
Lathyrus palustris	0.18	79.36
Malanthemum canadense	0.15	100.85
Osmunda clatoniana	0.09	77.69
Pteridium aquilinum	0.19	98.46
Average	0.14	77.33
Low Shrubs		
Diervilla lonicera	0.15	93.34
Lonicera canadensis	0.27	117.95
Average	0.21	105.64
Tall Shrubs		
Acer spicatum	0.20	78.41
Amelanchier spp.	0.21	95.67
Alnus crispa	0.14	73.65
Cornus rugosa	0.16	92.45
Corylus cornuta	0.17	85.73
Prunus pensylvanica	0.18	121.69
Salix spp.	0.29	89.83
Sorbus decora	0.25	110.63
Average	0.20	93.51
Deciduous Trees		
Acer rubrum	0.22	110.02
Betula papyrifera	0.16	82.02
Populus tremuloides	0.36	94.72
Average	0.25	95.59
Coniferous Trees		
Abies balsamea	----	72.54
Pinus banksiana	----	79.13
Pinus resinosa	----	49.28
Pinus strobus	----	147.05
Thuja occidentalis	----	39.47
Average	0.50 1/	77.49

1/ A density of 0.5 gm/cm^3 was assigned to all conifer foliage.

FUEL TYPE CLASSIFICATION

Because forest fuel is merely forest vegetation and its associated detritus viewed from a specialized standpoint (Davis 1959), efforts to classify fuels lap decidedly onto the well-developed field of plant community classification. Early attempts to classify plant communities involved simple subjective methods and assumed that natural vegetation existed in a mosaic of discrete, well-defined "types" (McIntosh 1967). Gleason (1946), however, disputed this assumption and introduced what is known as the "continuum concept", stimulating a lengthy controversy among plant ecologists. Most ecologists now lean toward the continuum concept recognizing that discontinuities may be produced through environmental disturbance and the activities of man (Poole 1974). Whittaker (1962) presents a summary of early literature dealing with community classification.

More recently, a large variety of objective classification techniques have been developed, involving defensible statistical analysis of field data. A vast literature dealing with these techniques has been reviewed by Cormak (1971) and Whittaker (1973). Most of these algorithms are best applied under the "community type" viewpoint, while a group of techniques involving direct ordination or "gradient analysis" (Whittaker 1967) are commensurate with the continuum concept.

Despite the availability of objective classification techniques for many years, only recently have any been applied to forest fuel classification (Habeck 1973, 1976, Kessel 1976). This may be due in part to the need to classify fuel communities not by floristic composition, but instead by their less tenable flammability characteristics.

In the past, there have been a number of broad fuel type classifications for northeastern fuels. One of the most notable of these consisted of 14 fuel types recognized in former Forest Service Region 7 for many years (Banks and Frayer 1966). Empirical studies of fire behavior in these fuel types have been summarized and published by Abell (1937), Jemison and Keetch (1942), and Banks and Frayer (1966). This classification was closely patterned after that of Hornby (1936) for northern Rocky Mountain fuels. Both of these classifications were based on fire behavior potential; that is, rate of spread and resistance to control. Their empirical basis, though, restricted their applicability to regions and conditions from which observations were taken. In 1952 Forest Service Region 9 initiated a fuel type classification that involved a simple cover type classification with slash, blowdown, and burned areas superimposed.[1/] Because fuel conditions were not described physically or quantitatively, though, none of these early classifications is compatible with modern fire modeling and fuel appraisal techniques.

A fuel type key was published by Fahnestock (1970) "to provide means for recognizing and tentatively evaluating, in the field, the fire spread potential and the crowning potential of fuels on the basis of readily observed characteristics...". Although the dichotomous key approach appears good for use by field personnel, its qualitative nature limits its usefulness in quantitative studies of forest flammability.

1/ Price, Jay H. 1952. Correspondence with R-9 National Forests dated January 18, 1952.

Only with the development of the Rothermel spread model (Rothermel 1972), has our understanding of wildland fuel combustion been sufficient to predict fire behavior--hence fuel flammability--from quantitative descriptions of weather, fuels, and topography. The fuel parameters required by this model include moisture content, calorific value, total and silica-free ash content, total fuel weight per unit ground area, representative surface area to volume ratio (σ), fuel particle density, and fuel bed depth or packing ratio. Model outputs are forward rate of fire spread (R) and reaction intensity (I_R). From these, a variety of additional fire behavior descriptors may be derived (Albini 1976a), while Van Wagner (1977) offers a means of determining the potential for crown fire development. Hence, using Rothermel's model, wildland fuel complexes may be appraised and classified objectively on the basis of expected fire behavior under predefined conditions of weather and topography (Anderson 1971, Roussopoulos and Johnson 1975).

One outstanding application of techniques of quantitative ecology to fuel appraisal and fire modeling problems is offered by Kessel (1975, 1976). Direct ordination methods were used to describe fuel conditions in terms of spatial and temporal environmental gradients in Glacier National Park. This gradient analysis forms the basis of an information retrieval system for rapid "turn-around" fire behavior prediction and fire management decision-making. Unfortunately, recent efforts to quantitatively classify upland forest communities in the BWCA (Grigal and Ohmann, 1975), and to relate observed fire intensity on the Little Sioux Fire (Sando and Haines 1972) to a variety of site factors (Nordin and Grigal 1976) have suggested that direct ordination of BWCA plant communities may not be feasible. Instead, a discrete-type approach to fuel classification is more appropriate.

The present attempt to develop a fuel type classification for the fire management study area proceeded in three phases: 1) appraisal of fire potential (fuel appraisal) at inventoried plots, 2) cluster analysis on the basis of fire behavior potential to identify natural groupings, and 3) discriminant analysis of clusters and comparison with an existing forest type classification for the study area. These will be discussed in turn.

Fuel Appraisal

In keeping with the idea that fuels should be rated or classified on the basis of the way they burn, an attempt was made to appraise the potential fire behavior for all inventoried plots. Predicted surface fire spread rates and intensities for standard weather conditions, as well as requirements for torching and crowning formed a state vector for each inventory plot. These state vectors became a basis for subsequent efforts to quantitatively classify study area fuels. Methods and models used in appraising fire behavior potential are described briefly in the following sections.

Surface Fire Behavior

The Rothermel (1972) fire model provided estimates of forward rate of spread (m/sec) and reaction intensity (cal/m^2-sec), intermediate values needed to compute fireline intensity (cal/m-sec) and flame length (m) (Byram 1959) for fires burning in surface fuels only (fuels within one meter of the ground).

The formulation for this model is theoretically based, but its embodiment includes a series of empirically derived relationships where underlying physical principles have yet to be established. It envisions fire spread as a sequence of ignitions in a spatially uniform fuelbed that is contiguous with the ground. Energy derived from a burning fuelbed volume contributes to the ignition of adjacent unburned fuelbed volumes, which in turn contribute energy to yet other volumes, etc. If these fuelbed volumes are relatively small, but identical in composition, the rate at which the process takes place is governed by the equation of Frandsen (1971), based upon the law of conservation of energy:

$$R = \frac{I_P}{\rho_b \varepsilon Q_{ig}} \qquad 6.1$$

where:

R = forward rate of fire spread (m/sec)

ρ_b = bulk density of the fuelbed (gm/m^3)

I_P = propagating intensity of the fire, i.e. the rate at which energy is absorbed by the unburned fuel (cal/m^2-sec)

ε = the fractional fuel loading that must be heated to ignition temperature for ignition to take place (dimensionless)

Q_{ig} = heat of preignition--the energy required to bring a unit mass of fuel to ignition temperature (cal/gm).

Since only part of the heat energy released by the burning fuelbed volume is absorbed by unburned fuel, the propagating flux (I_P) can be expressed as:

$$I_P = \xi I_R \qquad 6.2$$

where:

I_R = the reaction intensity, the rate of heat release per unit of ground area (cal/m^2-sec)

ξ = propagating flux ratio, the proportion of the heat released by burning fuel that is absorbed by unburned fuel (dimensionless). This is a function of fuelbed geometry, windspeed, and topographic slope (Albini 1976b).

Furthermore, reaction intensity (I_R) can be expressed as:

$$I_R = \Gamma' w h \eta_s \eta_m \qquad 6.3$$

where:

Γ' = potential reaction velocity, the proportion of fuelbed loading consumed per unit time when the moisture content and mineral content of the fuel is zero (sec^{-1}).

w = fuel loading (gm/m^2)

h = heat content of fuel (cal/gm)

η_s = mineral damping coefficient, the reduction in reaction velocity due to inorganic fuel constituents (dimensionless)

η_m = moisture damping coefficient, the reduction in reaction velocity due to fuel moisture (dimensionless).

Combining equations 6.1, 6.2, and 6.3 we have the theoretical formulation of the Rothermel spread model:

$$R = \frac{\xi \Gamma' w h \eta_s \eta_m}{\rho_b \varepsilon Q_{ig}} \qquad 6.4$$

Of the above variables, only w, h, and ρ_b are measured directly. All others have been empirically related to more or less measurable fuel and environmental factors through wind tunnel, combustion chamber, and laboratory experiments at the Northern Forest Fire Laboratory (Rothermel 1972). Important independent variables are identified below:

ξ = f (surface area-to-volume ratio (σ), fuel packing ratio (β), windspeed (U), and topographic slope tangent (tan ϕ)) 6.5

Γ' = f (σ, β) 6.6

η_s = f (silica-free mineral content (s_e)) 6.7

η_m = f (fuel moisture content (M_f), and moisture of extinction (M_x)) 6.8

ε = f (σ) 6.9

Q_{ig} = f (M_f) 6.10

Since β is simply bulk density (ρ_b) divided by particle density (ρ_p), and since ρ_b is fuel loading divided by fuelbed depth (δ), the list of independent input parameters for the Rothermel model is reduced to:

1. w_0, oven-dry fuel loading (gm/m^2)
2. σ, surface area-to-volume ratio (cm^{-1})
3. S_T, mineral content (fraction dry weight)
4. S_e, silica-free mineral content (fraction dry weight)
5. h, low heat value (cal/gm)
6. ρ_p, oven-dry particle density (gm/cm^3)
7. M_f, fuel moisture content (fraction dry weight)
8. M_x, moisture of extinction (fraction dry weight)
9. δ, fuelbed depth (m)
10. tan ϕ, topographic slope tangent
11. U, windspeed at midflame height (m/sec)

Most wildland fuelbeds are comprised of both living and dead materials representing a variety of plant species and a range of particle size classes. When this is the case, the first seven inputs are determined for each fuel category - size class combination and the model computes a surface area-weighted mean for each. In this manner, heterogeneous fuelbeds can be modeled as though they were homogeneous, as long as assumptions concerning spatial uniformity and surface contiguity hold true. Field tests of the model have shown that it is reasonably accurate when these assumptions are valid (Brown 1972, Sneeuwjagt 1974, Sneeuwjagt and Frandsen 1977), and it has enjoyed routine operational use in a variety of applications including fire management planning, fire danger rating, and "real-time" fire behavior prediction. Though several modifications to the model have been considered for spatially variable fuels (Bevins 1976, Kourtz et al. 1977, Frandsen 1978), none has yet been applied to the extent of the above formulation.

The "species by condition by size class by height" data storage format used in this study was chosen for its compatibility with the Rothermel model. Processing of the inventory data for surface fuels (materials below a height of one meter), using this model, is relatively straightforward. Only inputs 7-11 require specific comment. The moisture of extinction (M_x) for living fuels was represented by the method of Albini (1976a), while for dead fuels, a uniform value of 0.25 was assigned, complying with the 1972 version of the National Fire Danger Rating System (Deeming et al. 1972). For each inventory plot, the on-site slope measurement provided the value for tan ϕ. Representative fuelbed depths (δ) for individual inventory plots were computed according to the observations of Sneeuwjagt (1974), as the height above ground that includes 90% of the surface fuel loading. Three combinations of wind speed (U) and fuel moisture (M_f) were used to represent low, moderate, and high burning conditions (Table 22).

Spread rate (R) and reaction intensity (I_R) were evaluated by the Rothermel model for measured surface fuel conditions on each of the 210 inventory plots, under all three standard weather conditions. These predicted values were further transformed to fireline intensity (I) and flame length (FL) as follows:

$$I = RI_R\tau \qquad 6.11$$

where:

I = fireline intensity (Byram 1959) (cal/m-sec)--the energy released per meter of fire front per second

τ = fire residence time (sec), computed as 756/σ according to Anderson (1969), and

$$FL = .006\ I^{.46}\ \text{(Byram 1959)} \qquad 6.12$$

where:

FL = flame length in meters

The predicted values of R, I, and FL for each of the three weather conditions formed the surface fire portion of the state vector describing each inventory plot.

Torching and Crowning Requirements

Besides potential surface fire behavior, threshold surface fire intensities required for torching individual trees and threshold spread rates required for continuous crowning were predicted using the model proposed by Van Wagner (1977). Torching, according to the model, can occur only when the fireline intensity (I) of a surface fire exceeds

Table 22. Fuel moisture and windspeed conditions used in appraising potential fire behavior.

	Fire Weather Condition		
	Low	Moderate	High
Windspeed (m/sec)	2.24	4.47	6.71
Fuel Moisture (%)			
Dead Class F	15	10	3
Class I	15	10	5
Class II	15	12	8
Class III	15	13	10
Class IV	15	13	11
Live Class F	200	150	100
Class I	120	80	60
Class II	120	70	50
Class III	100	70	50
Class IV	100	70	50

some critical threshold value (I_0). This threshold intensity is a function of the height to the base of conifer crowns and needle moisture content:

$$I_0 = [Z(177.38 + 1002.04M)]^{3/2} \qquad 6.13$$

where:

I_0 = threshold fireline intensity (cal/m-sec)

Z = height to conifer crown bases (m)

M = needle moisture content (fraction dry weight)

Once torching occurs, continuous crowning can take place only if fire will spread through the crowns at a rate that equals or exceeds the threshold value (R_0). R_0, according to the model, depends solely on the bulk density of conifer foliage in the canopy:

$$R_0 = 50.04/\rho_{bf} \qquad 6.14$$

where:

R_0 = threshold spread rate for continuous crowning (m/sec)

ρ_{bf} = foliar bulk density (gm/m^3)

Constants for equations 6.13 and 6.14 were evaluated empirically by Van Wagner (1977) using data from field-scale experimental fires in red pine and jack pine stands in Ontario. For fuel classification in the BWCA, independent variables Z and ρ_{bf} were derived from the crown fuel inventory data, while M was assigned a value of 1.0--a common midsummer moisture content. The height to crown bases (Z) was determined using the vertical crown fuel distribution for each individual plot. It was defined as the height separating the lower 5% of the total needle loading from the upper 95%. For needle bulk density (ρ_{bf}), total needle loading was divided by the volume of canopy space containing 90% of the conifer foliage.

Resultant estimates of I_0 and R_0 completed the state vector for each inventory plot.

Fire Behavior Ordination and Classification

As was found for the fuel loading estimates, there was considerable variation in fire behavior potential among inventory plots. Flame length estimates for the high fire danger condition (Table 22) ranged over ±50% of the midrange value. Torching threshold intensities (I_0) ranged from 0 cal/m-sec, where balsam fir crowns extended to the ground, to infinity, where no conifers were found at all. Obviously, this range of variation indicates a high level of uncertainty about how a fire will behave within the study area.

From a management standpoint, it is desirable to reduce this uncertainty as much as physically possible or economically justifiable. Fuel classification is one means of doing this. The object is to classify the landscape so that the "within-class" variation in fire behavior potential is small compared to the "among-class" variation. Of course, the usefulness of this approach depends upon the ease with which resulting fuel types may be recognized and mapped. If one cannot assign appropriate fuel type designations to vegetative units without an on-site inventory, there is little point in classifying.

In this study, an attempt was made to classify inventory plots on the basis of fire behavior potential. The resulting classification was then examined to determine its usefulness to BWCA fire managers.

Classification Methods

Since fire behavior potential cannot be represented by a single variable, attempts to quantitatively classify wildland fuels must involve multivariate statistical methods. Cluster analysis is the most direct means available for numerical classification (Radloff and Betters 1978). A number of studies concerning BWCA vegetation have involved various means of cluster analysis (Grigal and Arneman 1970, Ohmann and Ream 1971b, Grigal and Ohmann 1975, Noble et al. 1977). Advantages of cluster analysis in the context of several natural resource problems are discussed by Turner (1974).

In essence, cluster analysis searches for "natural" groupings of observed subjects. It produces groups or clusters of observations that have similar properties. In this study, a hierarchical agglomerative clustering procedure, based on simple Euclidean distance, was used to classify all inventory plots. The method begins by considering each inventory plot as an individual fuel type. Each of these types is characterized by a set of n variables (fire behavior predictions), that collectively describe a point in n-dimensional space. That is, the position occupied by an inventory plot in the fire behavior state space is determined uniquely by the state vector for the plot.

If the n observations or predictions used to characterize each plot are statistically independent and appropriately scaled, the difference between any two plots can be represented by the Euclidean distance between their respective locations in state space. This is computed as:

$$D_{jk} = \left[\sum_{i=1}^{n} (x_{ij} - x_{ik})^2 \right]^{1/2} \qquad 6.15$$

where:

D_{jk} = distance between points representing the jth and kth inventory plots in state space.

x_{ij} = value of the ith variable on the jth inventory plot

n = the number of variables used to characterize each plot

Clustering can be accomplished by successively combining the closest pair of plots or group of plots until the desired number of clusters is obtained.

In this application, clusters were aggregated according to a single linkage algorithm. That is, intercluster similarity was determined by the distance between the nearest pair of individuals shared by the two clusters. Although a large number of linkage rules have been proposed for various applications, single linkage is by far the simplest.

The main difficulty encountered in this procedure concerned scaling differences and statistical correlation among the fire behavior predictions comprising the state vectors. To obtain meaningful distance or similarity measures by Equation 6.15, axes defining the state space must be both uniformly scaled and orthogonal. Since spread rate, intensity, and flame length are highly correlated and expressed in disparate units of measure, transformation was required before clustering.

The problem of scale was alleviated by normalizing all fire behavior estimates. That is, each value was transformed as follows:

$$x'_{ij} = \frac{x_{ij} - x_{i,min}}{x_{i,max} - x_{i,min}} \qquad 6.16$$

where:

x'_{ij} = the normalized value of the i^{th} fire behavior estimate describing the j^{th} inventory plot

x_{ij} = the raw value of the i^{th} fire behavior estimate describing the j^{th} inventory plot

$x_{i,min}$ = the minimum value of the i^{th} fire behavior estimate among all plots

$x_{i,max}$ = the corresponding maximum value.

This resulted in a set of dimensionless values, ranging over the interval (0,1).

Correlation among components of the transformed state vectors was eliminated using principal components analysis (Seal 1964). The basic purpose of this procedure is to reduce a large number of correlated variables to a relatively small number of significant, uncorrelated principal components, that preserve most of the original variation in the system. First, the axis is found in the original n-dimensional state space that accounts for the maximum possible variance; then the second axis is determined, orthogonal to the first, such that as much of the remaining variation is removed as possible; then the third axis is located orthogonal to the first two; and so forth. Each additional axis accounts for successively smaller amounts of the original variation. The resulting axes or principal components form an orthogonal coordinate system that can be used to redefine the original state vectors for clustering.

The relationship between the original state vectors and the new principal components can be shown in matrix notation:

$$P = XA \qquad 6.17$$

where:

X = the row vector containing values of the n normalized fire behavior estimates--the original state vector.

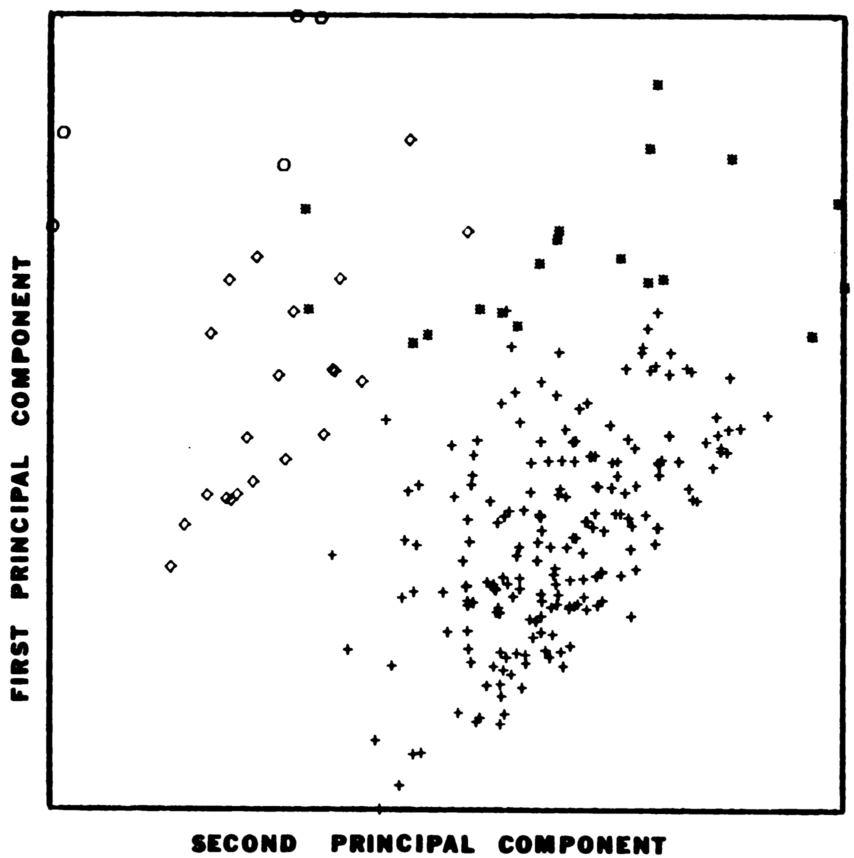
P = the row vector containing corresponding values for the $p \leq n$ principal components--the revised state vector.

A = the n x p matrix whose columns are the normalized eigenvectors of the correlation matrix (R) for the original normalized fire behavior estimates.

Principal component scores (P vectors) were computed for each inventory plot and used as input to the hierarchical agglomerative clustering routine based on Euclidean distance. Resulting clusters were taken to represent invididual fuel types with distinct burning characteristics.

Classification Results

The original 11 fire behavior estimates describing each inventory plot (surface rate of spread, intensity, and flame length for three weather conditions, as well as threshold torching intensity and threshold spread rate for crowning) were reduced, via the principal component analysis, to three statistically independent components. Hence, a three-dimensional state space was obtained that accounted for 87% of the variation in the system. Figure 12 shows the location of all inventory units within the principal component space based on their burning characteristics. The plane of the first two components



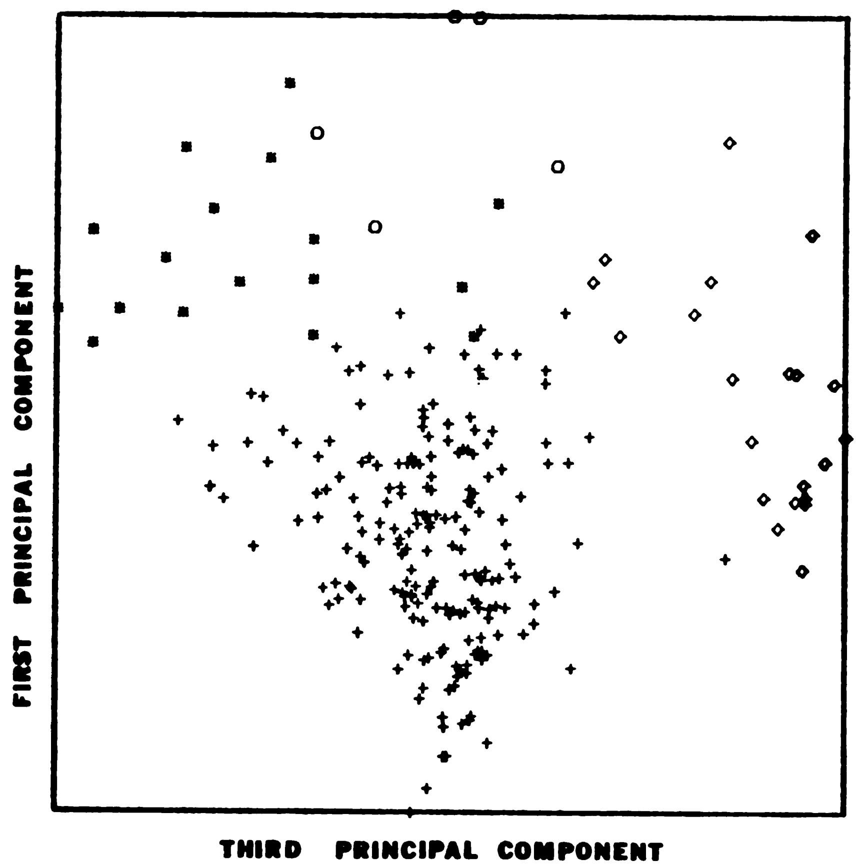


Figure 12. Principal components ordination of fuel inventory units in the pilot study area. a.) Location of subsampling units in the plane of the first two components. b.) Location of subsampling units in the plane of the first and third components.[1/]

1/ Symbols show the subsequent numerical grouping of subsamples into four clusters: type I (+), type II (◊), type III (*), and type IV (O).

accounts for 83% of the variation (Figure 12a), while the third principal component accounts for an additional 4% (Figure 12b).

Figure 12 also shows the results of the cluster analysis. Four fuel types were identified and designated types I, II, III, and IV. Groups that do not clearly separate in the plane of the first two principal components (Figure 12a) can be distinguished in the plane of the first and third (Figure 12b). Eighty-one percent of all sampling units were grouped as type I, 9% as type II, 8% as type III, and 2% as type IV. The number and plotted density of the type I samples reflects the visually apparent homogeneity of upland stands in the pilot study area, as well as the noted predominance of a single community type (aspen-birch) in the sample.

The dendrogram resulting from this analysis also shows the relative sizes of the four groups (Figure 13). This is a diagrammatic representation of the hierarchical relationships among inventory plots. At the bottom of the graph, each inventory plot is represented individually. As the clustering process begins, grouping of similar plots or clusters is represented by the merging of branches. The height at which the lines merge corresponds to the distance separating the groups in the principal component space (the distance function). The shortest distance function between any two plots was 0.0041, while all but eight individual plots had been combined below the 0.1 level. The final combination of clusters occurred at a distance function of 0.3722. Chaining, a common problem in cluster analysis that involves the systematic addition of small groups to larger groups in the clustering process, does not appear to have been a problem. Units of generally equal size were joined together at each level in the dendrogram.

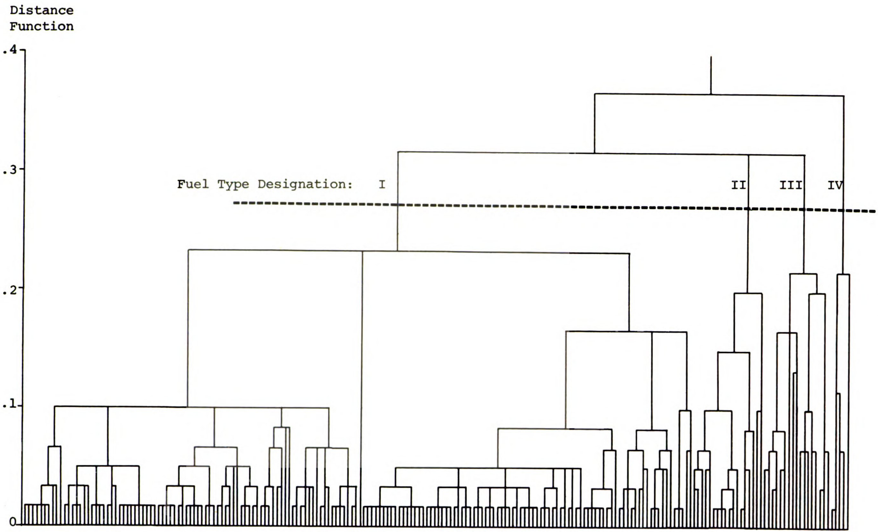


Figure 13. Clustering dendrogram showing the hierarchical relationships among the inventoried plots and the level of dissimilarity (distance) chosen to define fuel types.

As is apparent in Figure 13, the number of fuel types identified could range from 210 to 1, depending on the level of intercluster distance chosen to define them. A distance function of 0.27 was chosen in this analysis (dashed line in Figure 13), primarily for operational convenience. More than five or six types would be cumbersome for fire management decision makers. Fuel types I through IV, described previously, were identified at this level of dissimilarity.

Discriminant Analysis and Relationship to Cover Type

Following clustering, the data were subjected to a discriminant analysis (Cooley and Lohnes 1962) to allow classification of uninventoried stands on the basis of readily observed site and stand characteristics. In this procedure, a set of discriminant functions was computed, based on the composition of the four fuel types. Undesignated stands can be assigned to the most appropriate fuel type according to the discriminant function scores.

Forty-two site and stand variables were subjected to a stepwise discriminant analysis that, at each step, selects the variable that minimizes Wilks' lambda (Rao 1952). If the matrix W is defined as the within-groups cross-products matrix and T is the total sample cross-products matrix, the elements of W and T are computed as follows:

$$w_{ij} = \sum_{k=1}^{g} \left[\sum_{n=1}^{N_k} (x_{ikn} - \bar{x}_{ik})(x_{jkn} - \bar{x}_{jk}) \right] \qquad 6.18$$

$$t_{ij} = \sum_{n=1}^{N} (x_{in} - \bar{x}_i)(x_{jn} - \bar{x}_j) \qquad 6.19$$

where:

g = the number of fuel types

N_k = the number of plots included in type k

N = total number of plots

i and j run from 1 to p, the total number of variables

Wilks' lambda (Λ) is defined as:

$$\Lambda = \frac{|W|}{|T|} \qquad 6.20$$

This ratio of determinants decreases as the discriminating power of the included variables is improved. At each step in the process, then, the variable is selected that contributes most to the reduction of Λ. The coefficients of the discriminant functions produced by this algorithm are simply the normalized eigenvectors of the matrix $W^{-1}(T - W)$.

Table 23 lists the 42 stand and site variables in order of their contribution to reducing Λ. Maximum tree height for upland black spruce, jack pine, and balsam fir, the most prominent conifers in the study area, were by far the most important variables. This makes intuitive sense, since torching is dependent on the height to conifer crown bases, and crowning depends on the density of conifer foliage in the canopy. Other noteworthy variables were site index, and basal area of all conifer species. Resulting discriminant functions, when all 42 variables were included, were able to correctly classify 91% of the measured inventory plots. A relationship exists, therefore, between fire behavior potential and general site properties.

Although 91% success is an impressive figure, it must be remembered that 81% success could be achieved simply by assigning all inventory plots to fuel type I. Furthermore, use of the discriminant functions to classify uninventoried stands involves estimates of variables that require at least brief on-site examination. For only 10%

Table 23. Entry sequence for the 42 stand and site variables in a stepwise discriminant analysis of fuel types.

Step Number	Variable Entered	Wilks' Lambda
1	Height of spruce	0.83992
2	Height of jack pine	0.69891
3	Height of balsam fir	0.66101
4	Site index for dominant species	0.64360
5	Basal area of all conifer species	0.62547
6	Management history code	0.60942
7	Density of dead paper birch stems	0.59597
8	Soil texture code	0.58320
9	Basal area of jack pine	0.56857
10	Topographic slope	0.55673
11	Aspect code	0.54571
12	Density of dead aspen stems	0.53521
13	Stand age	0.52550
14	Time since last fire	0.51273
15	Density of dead maple stems	0.50317
16	Height of paper birch	0.49515
17	Height of maple	0.49001
18	Basal area of maple	0.48009
19	Basal area of miscellaneous species	0.47520
20	Basal area of paper birch	0.47020
21	Height above water	0.46657
22	Height of red pine	0.46232
23	Height of white pine	0.45684
24	Density of dead balsam fir stems	0.45361
25	Density of dead jack pine stems	0.45041
26	Basal area of red pine	0.44758
27	Density of dead red pine stems	0.44207
28	Height of northern white cedar	0.43889
29	Height of aspen	0.43583
30	Density of dead white pine stems	0.43348
31	Basal area of aspen	0.43131
32	Physiographic class	0.42925
33	Basal area of white pine	0.42784
34	Depth to bedrock	0.42647
35	Percent crown closure	0.42495
36	Basal area of northern white cedar	0.42367
37	Height of miscellaneous species	0.42262
38	Density of dead hardwood stems	0.42168
39	Density of dead northern white cedar	0.42080
40	Basal area of spruce	0.42018
41	Time since last disturbance	0.41978
42	Density of dead conifer stems	0.41957

improvement in efficiency, the additional effort appears questionable. Hopes to classify and map study area fuels on the basis of general site and stand characteristics were thus abandoned.

As a second alternative, the relationship between fuel types and an existing covertype classification was examined (Table 24). Since the classification of sites according to the community type classification of Grigal and Ohmann (1975) also requires on-site description, it was deemed unsuitable for this purpose. Instead, the vegetation type map prepared for the study area by the University of Minnesota College of Forestry (Appendix)[1/] was used. An overlay of inventory plot locations on the vegetative type map facilitated assignment of type designations to each plot. A key to the type designations is given in Table 24 and on the type map (Appendix).

Note that for all types, at least 50% of the assigned subplots belonged to the cluster representing fuel type I. By maximum likelihood, then, all upland types should be represented by fuel type I. Apparently, in this area the distinctions among identified fuel types are due to variations in fuel properties that take place <u>within</u> forest types, and in general, do not vary significantly among forest types. This observation suggests that a single fuel type may be sufficient to represent upland fuels for the entire study area.

1/ Vegetative type map prepared for the North Central Forest Experiment Station, USDA Forest Service, by the University of Minnesota College of Forestry using 1:15840 Aerochrome infrared photography flown August 17 and September 16, 1976.

Table 24. Distribution of sample plots among cover types and fuel types.

Overstory			Understory			Map	Percent	Percentage Distribution Among Fuel Types			
Species	Size	Density	Species	Size	Density	Designation	All Plots	I	II	III	IV
Upland brush	---------	-------	----------------	---------	-------	1h	3.721	100.0	--	--	--
Aspen-birch	Pole	Poor	Upland brush	---------	-------	Ac'/1h	1.395	66.7	--	--	33.3
Aspen-birch	Pole	Medium	----------------	---------	-------	Ac"	11.629	60.0	32.0	8.0	--
Aspen-birch	Pole	Medium	Upland brush	---------	-------	Ac"/1h	1.860	75.0	--	25.0	--
Aspen-birch	Pole	Poor	Rock outcrop	---------	-------	Ac'/R	1.395	66.7	--	33.3	--
Aspen-birch	Pole	Medium	Rock outcrop	---------	-------	Ac"/R	0.930	50.0	50.0	--	--
Aspen-birch	Pole	Good	----------------	---------	-------	Ac"'	3.721	62.5	12.5	12.5	12.5
Aspen-birch	Sawtimber	Poor	Upland brush	---------	-------	Ad'/1h	1.395	100.0	--	--	--
Aspen-birch	Sawtimber	Medium	----------------	---------	-------	Ad"	23.722	76.4	11.8	9.8	2.0
Aspen-birch	Sawtimber	Medium	Aspen-birch	Pole	Poor	Ad"/Ac'	1.860	75.0	--	25.0	--
Aspen-birch	Sawtimber	Medium	Aspen-birch	Pole	Medium	Ad"/Ac"	6.048	61.5	7.7	15.4	15.4
Aspen-birch	Sawtimber	Medium	Jack pine	Sawtimber	Poor	Ad"/5d'	0.930	100.0	--	--	--
Aspen-birch	Sawtimber	Medium	Jack pine	Sawtimber	Medium	Ad"/5d"	0.930	100.0	--	--	--
Aspen-birch	Sawtimber	Medium	Spruce-fir	Pole	Poor	Ad"/6c'	0.465	100.0	--	--	--
Aspen-birch	Sawtimber	Medium	Spruce-fir	Pole	Medium	Ad"/6c"	5.582	91.7	8.3	--	--
Aspen-birch-pine	Sawtimber	Poor	Spruce-fir	---------	-------	3d'	0.465	100.0	--	--	--
Cedar	Sapling	Medium	----------------	---------	-------	4b"	2.326	100.0	--	--	--
Jack pine	Pole	Poor	Rock outcrop	---------	-------	5c'/R	0.465	100.0	--	--	--
Jack pine	Sawtimber	Poor	----------------	---------	-------	5d'	0.465	100.0	--	--	--
Jack pine	Sawtimber	Poor	Upland brush	---------	-------	5d'/1h	2.326	80.0	--	20.0	--
Jack pine	Sawtimber	Medium	----------------	---------	-------	5d"	5.117	90.9	--	9.1	--
Jack pine	Sawtimber	Medium	Aspen-birch	Pole	Poor	5d"/Ac'	0.930	100.0	--	--	--
Jack pine	Sawtimber	Medium	Aspen-birch	Pole	Medium	5s"/Ac"	0.930	100.0	--	--	--
Jack pine	Sawtimber	Medium	Aspen-birch	Sawtimber	Poor	5d"/Ad'	0.930	100.0	--	--	--
Jack pine	Sawtimber	Medium	Aspen-birch	Sawtimber	Medium	5d"/Ad"	0.930	100.0	--	--	--
Jack pine	Sawtimber	Medium	Cedar	Sapling	Medium	5d"/4b"	0.930	100.0	--	--	--
Jack pine	Sawtimber	Medium	Spruce-fir	Pole	Medium	5d"/6c"	2.791	100.0	--	--	--
Spruce-fir	Pole	Medium	----------------	---------	-------	6c"	4.186	88.9	--	11.1	--
Spruce-fir	Pole	Medium	Aspen-birch	Pole	Poor	6c"/Ac'	0.930	100.0	--	--	--
Spruce-fir	Sawtimber	Medium	----------------	---------	-------	6d"	1.860	100.0	--	--	--
Spruce-fir	Sawtimber	Medium	Jack pine	Sawtimber	Poor	6d"/5d'	1.395	100.0	--	--	--
Lowland conifer	Pole	Medium	----------------	---------	-------	7c"	1.860	100.0	--	--	--
Red pine	Sawtimber	Medium	----------------	---------	-------	8d"	0.930	100.0	--	--	--
White pine	Sawtimber	Medium	----------------	---------	-------	9d"	3.256	85.7	--	14.3	--
White pine	Sawtimber	Medium	Aspen-birch	Sawtimber	Medium	9d"/Ad"	0.465	100.0	--	--	--
White pine	Sawtimber	Medium	Spruce-fir	Pole	Medium	9d"/6c"	0.465	100.0	--	--	--
White pine	Sawtimber	Medium	Spruce-fir & Aspen-birch	Pole Pole	Medium Poor	9d"/6c"/Ac'	0.465	100.0	--	--	--
ALL PLOTS								100.0	81.4	8.4	2.3

Further examination of the four fuel types adds support to this notion. Samples representing types II and IV were found to be entirely void of coniferous tree species. Since vertical fire development is extremely unlikely in pure hardwood stands of this area (Van Wagner 1977), and since these two types accounted for only 11 percent of the sampling units, they may be deleted from consideration without concern. Types I and III, however, include conifers at least as an understory component, enabling fire development into the crown space. The primary differences between these two types are the amount of dead and downed branchwood on the forest floor, amount of leaf litter, and abundance of herbaceous growth. Table 25 presents average fuel properties for types I and III. Mainly due to the high dead/live ratio, type III fuels burn with slightly greater intensity and offer greater opportunity for torching and spotting behavior. Little guidance can be given, though, in distinguishing between these types on the ground. There is little use, then, in recognizing any difference between them. It is recommended that one or the other be chosen to represent burning conditions for the entire study area.

The choice between fuel models I and III is perhaps best left a matter of administrative discretion. Type I is more representative of the area on the whole, but type III offers more conservative (more severe) estimates of fire behavior. Since torching and spotting is most commonly associated with jackpots or concentrations of fuel, rather than average conditions for broad areas, it may be argued that the more severe of these two models would be preferred for anticipating these phenomona.

Table 25. Summary of fuel properties for BWCA fuel types I and III.

	Fuel Type I	Fuel Type III
Fuel Loadings (gm/m^2)		
Litter	449	651
Live + Dead Foliage	112	135
Live + Dead Class I	179	202
Live + Dead Class II	359	381
Live + Dead Class III	920	853
Surface Area-to-Volume Ratio (cm^{-1})	84	83
Dead/Live Ratio	3.73	8.65
Height to Conifer Crown Base (m)	1.83	1.83
Surface Fuel Packing Ratio	0.0242	0.0255

APPLICATION AND VALIDATION OF RESULTS

Even though efforts to classify and map fuels on the basis of fire behavior potential were not entirely successful, and a high level of uncertainty concerning fire behavior at a specific location still exists, the results of the fuel appraisal remain useful for anticipating general fire behavior for the area on the whole. In this section, tools are presented for identifying conditions that will likely produce torching and long-distance spotting, as well as predicting surface fire spread rates and intensities. Predicted versus actual fire behavior is compared for three project-scale fires that occurred in or near the study area in 1976, and historical weather records are examined to determine the frequency and seasonal distribution of spotting conditions. Suggestions are offered for applying the results of this study.

Fire Behavior Prediction

To provide simple means for identifying conditions when natural fires could escape the study area, fire behavior nomographs were developed for fuel types I and III. Methods of Albini (1976b) were employed to display predicted surface fire intensities and spread rates in a nomograph format. Threshold surface fire intensities required for vertical fire development (Van Wagner 1977) were incorporated directly into the nomographs.

Figure 14 displays the resulting fire behavior nomographs for types I and III in the form developed by Albini (1976b). These are graphical aids for computing surface fire intensities and spread rates by the Rothermel (1972) model under a wide variety of conditions. They

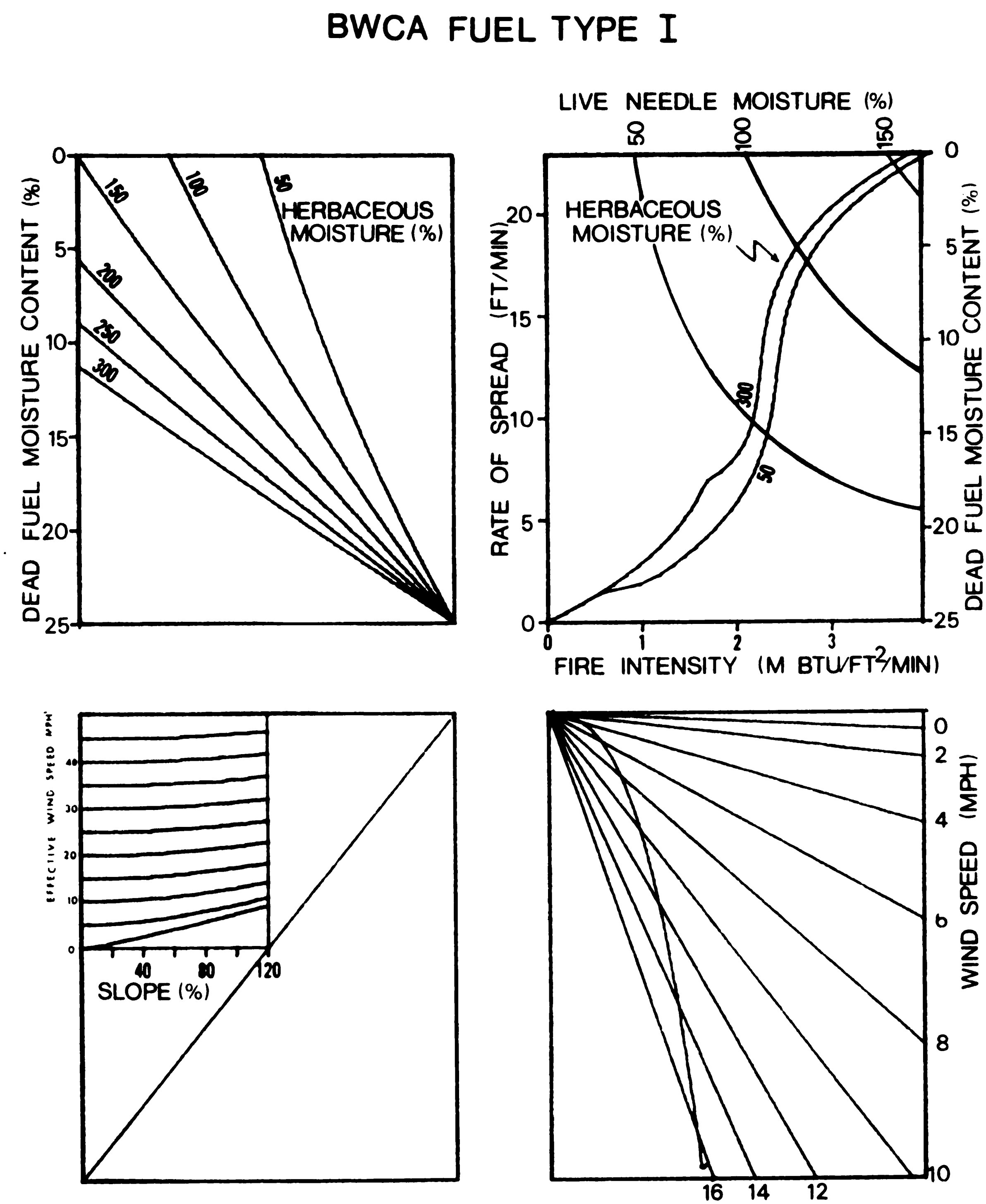


Figure 14a. Fire behavior nomograph for fuel type I.

BWCA FUEL TYPE III

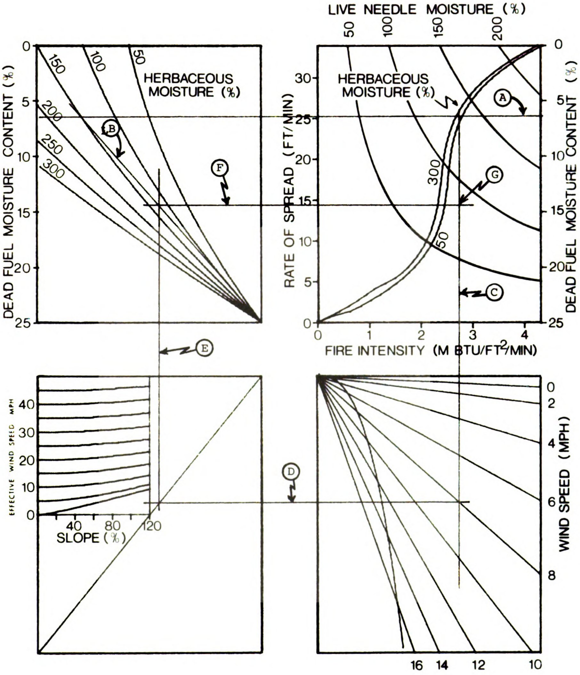


Figure 14b. Fire behavior nomograph for fuel type III.

also show threshold surface fire intensities required for vertical fire growth into the crowns (Van Wagner 1977). Using these graphs, one can evaluate burning conditions with regard to the likelihood of torching and subsequent spotting. For operational convenience, English units were used in these graphs.[1/]

Input variables include (1) dead fuel moisture content; (2) live fuel moisture content for surface (herbaceous) fuels; (3) wind speed; (4) topographic slope; and (5) foliar moisture content of coniferous trees. Periodic measurements or estimates of live fuel moistures are required, while dead fuel moisture content is computed as a weighted average of National Fire Danger Rating System (Deeming et al., 1972) 1-hour, 10-hour, and 100-hour timelag moistures. Appropriate weighting coefficients are given in Table 26.

The noted differences in potential fire behavior for types I and III are readily seen by comparing the scaling of the two nomographs.

Use of the nomographs is explained in detail by Albini (1976b). The only noteworthy departure from Albini's explanation occurs after the fire intensity and rate of spread have been graphically determined. These values serve as coordinates of a point in the upper right graph that corresponds to the surface fire line intensity (Byram 1959). Upper right locations (high fire intensity and high rate of spread) indicate high fire line intensities, while lower left locations indicate low ones. The hyperbolic curves corresponding to various needle moistures

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1/
1 foot/minute=0.3048 meters/minute
1 $BTU/foot^2/minute$=0.2713 $calories/cm^2/minute$
1 mile per hour=0.447 meters/second

Table 26. Weighting coefficients for dead fuel moisture calculation.

Time-lag Class	Fuel Type	
	I	III
1-hour (class I)	0.77	0.40
10-hour (class II)	0.18	0.32
100-hour (class III)	0.05	0.28

in the upper right graph are lines of equal fire line intensity. They identify torching threshold values from the Van Wagner (1977) model. If the point determined by the rate of spread and fire intensity is below and to the left of the appropriate torching threshold intensity curve (interpolate if necessary), the fire is expected to remain on the surface. On the other hand, if the point is above the appropriate threshold intensity curve, periodic flaming of tree crowns is predicted.

Consider a fire reported in fuel type III on a day with the following conditions: 5% 1-hour timelag moisture, 7% 10-hour timelag moisture, 10% 100-hour timelag moisture, 150% herbaceous moisture, 8 mile per hour wind speed, 0% topographic slope, and 100% needle moisture content. The circled letters in Figure 14b refer to the steps listed below:

A. Dead fuel moisture is computed using the coefficients in Table 26. (.40 x 5%) + (.32 x 7%) + (.28 x 10%) = 7.04%
This value is found on the vertical axis of the upper right graph, and a horizontal line is extended from this point across both upper graphs.

B. As described by Albini (1976b), a "turning line" is drawn on the upper left graph by extending a straight line through the graph origin and the intersection of line A with the curve representing 150% herbaceous moisture.

C. The herbaceous moisture curves in the upper right graph ("s" curves) are interpolated for 150% herbaceous moisture at their intersection with line A. A vertical line is dropped from this point through the lower right graph. Estimated surface fire intensity (reaction intensity) can now be read on the horizontal axis of the upper right graph. In this case, it is about 2700 BTU/ft^2/min (733 cal/cm^2/min).

D. No slope correction is required in this example so the line corresponding to an 8 mph wind in the lower right graph is sought directly. At the intersection of this line with line C, a horizontal line is drawn to the diagonal turning line in the lower left graph.

E. A vertical line is drawn from this intersection to turning line B in the upper left graph.

F. From this intersection, a final horizontal line is drawn back through the upper right graph. Estimated forward rate of spread can now be read--about 14 feet per minute (4.27 m/min).

G. The intersection of lines F and C (point G) corresponds to the surface fire line intensity (Byram 1959). If point G is below and to the left of the appropriate torching threshold intensity curve, the fire is expected to remain on the surface. On the other hand, if point G is above the appropriate threshold intensity curve, periodic flaming of tree crowns is predicted. In this example, point G falls below the 100% needle moisture curve so a surface fire is expected. Depending on other circumstances, suppression could probably be deferred without jeopardy.

A relatively small change in wind speed can produce very different results though. For example, with all other values held constant, a 10-mile per hour wind would increase the spread rate to 20 feet per minute and place the intersection point above the threshold surface intensity, suggesting that torching is likely and spotting possible.

Solving the nomograph in reverse under these moisture conditions, we find that a 9 mile per hour wind speed is required to produce a fireline intensity exactly at the threshold level. This, then, may be viewed as a threshold wind speed for the given moisture and slope conditions. When winds are expected to exceed the threshold value, managers should be aware that torching is likely and, depending on moisture conditions, spotting is possible. Fires occurring under these conditions should be examined closely to determine whether spotting fire behavior could jeopardize the perimeter of the study area or other critical values within the study area.

Validation

To determine the reliability of the nomograph predictions, weather and fire behavior data were examined for three actual fires that occurred in or near the study area during August and September of 1976. Actual fire behavior, with emphasis on long-distance spotting, was compared with predictions obtained from the nomographs.

The three fires chosen for this exercise were the Roy Lake Fire (August 21 to August 27, 1976), the Rice Lake Fire (August 30 to September 2, 1976), and the Fraser Lake Fire (September 7 to September 12, 1976). The Roy Lake Fire occurred just west of the end of the Gunflint Trail, about 12 km northeast of the study area. The Rice Lake Fire occurred near Forest Center Landing, a roughly equal distance to the southwest, and the Fraser Lake Fire burned within the northwestern part of the study area.

Since these were all project scale fires, weather observations in the general vicinity of the fires were taken at roughly hourly intervals throughout each burning day. These observations provided the dead fuel moisture and wind speed inputs required by the nomographs. Additional inputs were assumed constant and assigned the following values, as appropriate for local conditions:

Herbaceous moisture content:	150%
Needle moisture content:	100%
Topographic slope:	0%

Using the nomograph for fuel model III with the above assumptions, the periodic weather observations were converted to "yes or no" predictions of spotting potential. The prediction was "yes" if the following conditions were met:

1. Observed wind speed $\geq$ 10 mph (4.5 m/sec)
2. 10-hour timelag fuel moisture $\leq$ 8%
3. Predicted torching of conifer crowns from the nomograph

Actual spotting occurrence was determined through examination of maps and records documenting each fire's growth and activity, and through the author's recollection of on-site experience.

A tabulation of the binary (yes or no) scores for both predicted and actual fire behavior, on a daily basis, is given in Table 27. If spotting was predicted or occurred at any time during a given day, the corresponding table entry is "yes". A "no" indicates no spotting (predicted or actual) at any time during the day.

As a general rule, actual spotting occurred between the hours of 1400 and 1900 CDT. Most predicted spotting conditions fell within this period also. Thirteen of the 17 burning days examined showed agreement between predicted and actual spotting behavior. Of the four discrepancies, three involved underprediction. That is, spotting occurred on three days when no spotting was predicted. Two of these

Table 27. Comparison of predicted versus actual spotting occurrence on three project fires in or near the study area.

Fire (area)	Date	Predicted Spotting?	Actual Spotting?
Roy Lake (1368 hectares)	August 21	No	Yes
	22	Yes	Yes
	23	No	Yes
	24	Yes	Yes
	25	Yes	Yes
	26	Yes	Yes
	27	No	No
Rice Lake (435 hectares)	August 30	Yes	Yes
	31	No	No
	September 1	No	Yes
	2	No	No
Fraser Lake (415 hectares)	September 7	Yes	Yes
	8	No	No
	9	No	No
	10	Yes	Yes
	11	Yes	Yes
	12	Yes	No

days occurred on the Roy Lake Fire. Perhaps these differences can be attributed in part to the somewhat sheltered location of the anemometer (at the Seagull Guard Station) and the erratic wind patterns of the area. Wind speeds were found to be characteristically greater at the fire than at the guard station, roughly 8 kilometers to the southeast. The third case involving underprediction occurred on the third day of the Rice Lake Fire. On this day, actual spotting was moderate and the "negative" prediction was marginal. The single case of overprediction took place on the day the Fraser Lake Fire was declared controlled. It is reasonable to expect that a free-burning fire would have produced spotting on this day.

Although this limited comparison is by no means a rigorous test of the model, it does suggest that the approach may be operationally useful in anticipating the behavior of free-burning natural fires, and assessing their potential threat to the study area boundaries. It also suggests that fuel type III provides a more reasonable indication of spotting potential than fuel type I, which produced several additional underpredictions.

Frequency and Distribution of Spotting Conditions

From an operational standpoint it is useful to know how often spotting conditions can be expected, and during what periods they are most likely. Perhaps even more important is information concerning the persistence of spotting conditions once they occur. Decisions regarding specific actions to be taken on naturally-caused fires may depend to a large extent on the expected persistence of spotting behavior. To provide some insight on this matter, an analysis was performed on weather records from the Ely fire danger rating station. Records for the period 1970 to 1977 were obtained from the National Fire Weather Data Library (Furman and Brink 1975) and examined to determine the likelihood of spotting conditions, and of runs of consecutive spotting days by month. Spotting days were defined as days of record showing a wind speed at or above 10 mph (4.5 m/sec), 10-hour timelag fuel moisture at or below 8%, and torching predicted for BWCA fuel type III (from nomograph). The results of this analysis are shown in Table 28.

The first column in Table 28 shows the proportion of all days of record for each month that met the spotting criteria. The month of May had the highest occurrence of spotting conditions (11%) with April and July having only slightly lower values. Only 2% of the September days of record met the criteria.

In the conditional probability columns just to the right, the likelihood of consecutive spotting days is shown for various lengths of run. This may be interpreted as follows. If today (day 0) is a spotting day, it may be useful to know how likely it is that tomorrow and the next day will be spotting days also, that is, that two additional spotting days will follow today. To determine this, look in the column headed "2" and the row for the appropriate month to find the probability of occurrence based on past records. In May, for example, there is an 11% chance that spotting will continue for two additional days. However, there is a 68% chance that there will be no spotting tomorrow--and in no case did spotting conditions prevail for more than two additional days in May.

Table 28. Probability that any day is a "spotting day"[1/] by month, and conditional probability that any spotting day (day 0) is followed by exactly n additional consecutive spotting days.

Month	Probability that any day is a spotting day	Number of Consecutive Spotting Days Following Day 0 (n)				
		0	1	2	3	4
		Conditional Probability				
January	0	-	-	-	-	-
February	0	-	-	-	-	-
March	0	-	-	-	-	-
April	0.10	0.89	0.11	0	0	0
May	0.11	0.68	0.21	0.11	0	0
June	0.06	0.93	0.07	0	0	0
July	0.10	0.61	0.23	0.12	0.04	0
August	0.04	0.89	0.11	0	0	0
September	0.02	1.00	0	0	0	0
October	0.03	0.50	0.17	0.17	0.16	0
November	0	-	-	-	-	-
December	0	-	-	-	-	-

1/

A spotting day is defined as one with wind at or above 10 mph, 10-hour timelag fuel moisture at or below 8%, and torching predicted for BWCA Fuel Type III (from nomograph).

July and October are the only months showing runs of spotting conditions for three days following the first spotting day. The conditional probabilities for October, though, are based on only 6 days meeting spotting criteria for the entire period of record. They should probably be somewhat lower than shown in the table, but the low fire occurrence in October indicates little cause for concern.

From a climatological standpoint, July appears to be the month that is conducive to the development of large fires. Extra caution should be exercised during periods showing high spotting persistence, especially when coincident with a precipitation deficit.

A word of caution is appropriate at this point. Since fire danger rating weather observations are taken at 1300 hrs. daily, and since spotting conditions are most likely between 1400 and 1900, it is likely that Table 28 underestimates both the frequency and persistence of spotting conditions. Nevertheless, it does indicate relative seasonal differences that may prove meaningful.

SUMMARY AND CONCLUSIONS

Mindful of the natural role of fire in the BWCA, the Superior National Forest has proposed a pilot study on the use of natural fire by prescription. The ecological need to restore fire to this wilderness is apparent, but several information needs must be satisfied before a wholesale fire management program may be implemented. Foremost among these needs is a rational and practicable means of deciding when to suppress fires and when to defer control action.

This decision, of course, involves a variety of political, social, and economic, as well as physical and biological considerations. For the pilot study itself, the principal concern of fire managers is that naturally caused fires, if suppression action is deferred, could become uncontrollable, escape the 40,000 hectare pilot study area, and damage non-wilderness resources. Long distance spotting poses the most likely means for this occurrence.

Spotting has been found to occur most frequently when: 1) the 10-hour timelag fuel moisture content is at or below 8%, 2) the windspeed is at least 4.5m/sec (10 mph) above the canopy, and 3) surface fire intensity is sufficient to cause vertical fire development into the canopy space (torching). In this study, an attempt has been made to inventory, appraise, and classify fuel conditions within the pilot study area to facilitate quantitative assessment of the daily potential for torching or crowning -- and ultimately spotting fire behavior. Results may be useful in establishing decision criteria concerning alternative fire suppression or surveillance actions within the study area.

During the summer of 1976, a broad-scale inventory of forest fuels was conducted to provide data on the amount, character, and distribution of organic materials potentially available for combustion on upland sites. A two-stage sampling design was employed, and in all, 210 subsample units were inventoried.

An assortment of established methods, including quadrat, transect, and plotless sampling procedures was used to quantify the various living and dead fuel components for each subsample unit. In the interest of sampling efficiency, double-sampling methods were employed for all fuel components. Biomass regressions, bulk density estimates, and other required constants were evaluated from existing literature or through extractive sampling efforts near the Kawishiwi Field Laboratory. Both surface and aerial fuels were described, expressing fuel amounts in oven-dry grams per square meter by species, condition (live or dead), size class, and height above ground level in 30.5 centimeter increments.

Lowland fuels were not inventoried in this study. Fires that burn in these fuels are generally low in intensity, and seldom produce long-distance spotting. Upland fuels, on the other hand, frequently support extreme fire behavior including crowning in conifer stands and spotting at distances over a kilometer. These burning conditions were observed in upland stands of the pilot study area during the Frazer Lake Fire of 1976.

Upland fuel conditions within the study area range from barren rock outcrops or rock with a thin mantle of mosses and lichens to relatively fresh cutting slash. Total fuel loading ranged from 3.8 to 17.2kg/m^2. Of the 10 fuel component categories recognized, humus showed the greatest range of variation, while downed deadwood had the next largest range. Most of the deadwood variation, though, is attributable to boles and branches greater than 3.6 cm in diameter. Except under extreme drought conditions, humus and large diameter deadwood have only minor influence on forest fire behavior. The more influential surface fuel components (L layer, ground cover, herbaceous plants, and small diameter deadwood), although highly variable in a relative sense, have a somewhat narrower range of absolute variation.

Of the 210 randomly located inventory samples, 168 or 80% were within the aspen-birch community type, reflecting the overall representation of that type within the study area. This is not typical of the BWCA as a whole, where the aspen-birch type makes up less than 30% of the area. The other 20% of the samples were distributed as follows: Maple-aspen-birch-fir (0.5%), fir-birch (4.3%), jackpine-balsam fir (1.9%), aspen-birch-white pine (3.3%), red pine (2.4%), black spruce-feather moss (3.8%), cedar (1.9%), and jackpine-black spruce (1.9%).

Among the community types sampled, the variability of fuel component loadings was for the most part minor. Variation appears to be greater within these types than it is among them. Yet, it is the fire behavior potential, not fuel loading, that concerns BWCA fire managers.

Laboratory analyses of important fuel components were conducted to determine total and silica-free ash contents, low heats of combustion, particle densities, and surface area-to-volume ratios.

These data facilitated the use of existing mathematical fire models to assess fire behavior potential in sampled stands.

The Rothermel (1972) fire model provided estimates of forward rate of spread and reaction intensity which were used to calculate fireline intensity (Byram 1959) and flame length for fires burning in surface fuels only. Three combinations of windspeed and dead fuel moisture content were used to represent a realistic range of burning conditions.

Besides potential surface fire behavior, threshold surface fire intensities required for torching individual trees and threshold spread rates required for continuous crowning were predicted using the model proposed by Van Wagner (1977).

An R-mode principal components analysis was performed on the set of fire behavior predictions for each inventory subsample unit to reduce the dimensionality of the data. Principal component scores were computed for each subsample and used in a Q-mode agglomerative clustering routine based on Euclidean distance in the principal component space. The sampling units comprising each cluster were taken to represent a fuel type with burning characteristics distinct from all other types. Following clustering, the data were subjected to a discriminant analysis to investigate relationships between the fuel type classification and readily observed stand and site characteristics.

As a result of the cluster analysis, four fuel types were identified and designated types I, II, III, and IV. Eighty-one percent of all sampling units were grouped as type I, 9% as type II, 8% as type III, and 2% as type IV. The high representation of type I in the sample reflects the visually apparent homogeneity of upland stands in the study area, and is not surprising considering the representation of community types in the sample (Grigal and Ohmann 1975). Unfortunately, there was no clear relationship between the community type and fuel type classifications.

The discriminant analysis produced a set of functions that were able to correctly classify 91% of the inventoried subsampling units on the basis of general site and stand characteristics alone. Maximum tree height for upland black spruce, jackpine, and balsam fir, site index and basal area of all conifer species were identified as the most important of 42 variables needed to assign stands to the appropriate fuel type. In light of the *a priori* distribution of samples among fuel types, though, use of the discriminant functions to classify uninventoried stands appears questionable. The effort required to quantify all 42 variables approaches that of the fuel inventory itself.

In addition to the discriminant analysis, the relationship between fuel types and an existing vegetation type classification was examined. By maximum likelihood, all upland types should be represented by fuel type I. Apparently, as was found for fuel loadings, the variation in fire behavior potential is greater within forest types than it is among them. The general conclusion drawn both from the analysis of fuel inventory data and from visual inspection of the study area is that in spite of the noted spatial variation in fuel loading and fire behavior potential, a single fuel model should be used to represent upland fuels within the study area.

Fuel types II and IV were inappropriate because they represent pure hardwood stands, and because an understory component of balsam fir is virtually omnipresent in the BWCA. Stands represented by types I and III, on the other hand, include conifers at least in the understory. The primary differences between types I and III are the amount of dead and downed branchwood on the forest floor, amount of leaf litter, and abundance of herbaceous growth. Type III has heavier surface loadings of dead fuel and lighter herbaceous loadings than type I. Type I is more representative of the area on the whole, but type III offers more conservative (more severe) estimates of fire behavior. It may be argued that the more severe of these two models would be preferred for anticipating potential spotting conditions.

For sample clusters representing fuel types I and III, methods of Albini (1976b) were used to construct nomographs that display predicted surface fire intensities and spread rates, as well as threshold conditions for vertical fire development into the crown space. Using the nomographs, one can evaluate burning conditions with regard to the likelihood of torching and subsequent spotting. Predicted occurrence of long-distance spotting, using the fuel type III nomograph, compared favorably with actual conditions on three project fires in or near the study area during 1976. Thirteen of the 17 burning days examined showed agreement between predicted and actual spotting behavior, suggesting that the nomographs may be operationally useful for anticipating spotting conditions and assessing the potential threat of fire spread beyond study area boundaries. Furthermore, since three of the four discrepancies involved under prediction, and since fuel type III represents more severe fire behavior than fuel type I, the nomograph for fuel type III appears more suitable for predicting spotting conditions.

A brief analysis of fire danger rating records from Ely, Minnesota, showed that weather conditions fostering long-distance spotting occur most commonly in April, May, and July. In addition, the expected persistence of these conditions, once they occur, is greatest in May, July, and October. Decision makers should consider historical spotting occurrence and persistence data as well as specific weather forecasts before initiating suppression action on fires that appear to threaten the study area boundary.

Several general comments are in order concerning the scope and complexity of this study in a management decision context, as well as the applicability of study results to the total BWCA. The inventory, appraisal, and classification of fuel conditions in the pilot study area have involved detailed, tedious, and costly measurement and modeling procedures. Yet, the interpretation and "packaging" of study results for application has been guided by a desire to provide an operationally useful decision aid than can be employed at a management cost that is commensurate with resulting improvements in fire management decisions. The fact that identified fuel types could not be discriminated and mapped through simple, cost-effective means indicates that much of the inventory effort was superfluous. Equally useful results could have been produced with considerably less effort.

Careful thought should be given to fuel appraisal needs when the pilot study is expanded to an operational prescribed natural fire program for the whole BWCA. The apparent differences between the vegetation of the pilot study area and that found elsewhere preclude direct application of results of this study to other areas. Whether additional inventory efforts would be fruitful for these areas, though, is uncertain.

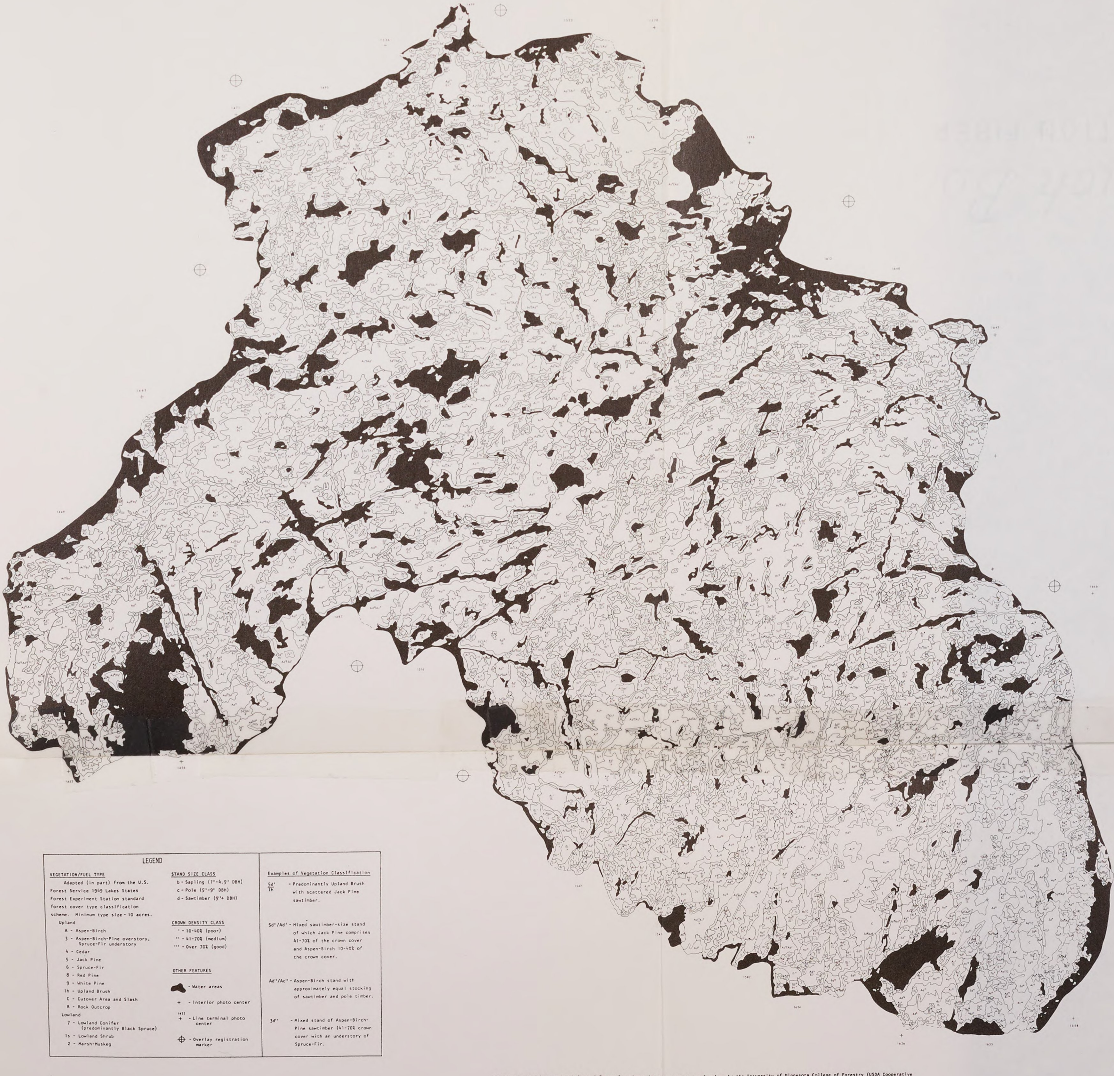
The greater diversity of community types found outside the pilot area may be more conducive to identifying and discriminating communities with meaningful differences in fire behavior potential. Furthermore, the greater representation of conifer types may provide economic justification for additional fuel classification work. Perhaps by the time expansion is considered, additional knowledge of fuel information needs and uses in wilderness fire management will allow explicit consideration of operational costs and benefits in the design of fuel inventory and appraisal activities. This suggests a priority area for future research effort.

In the meantime, results of this study should be applied strictly to the pilot study area. Even here, though, the tools developed in this study are merely first generation prototypes that have not been adequately field tested. Potential users are urged to carefully document their successes and failures so that they may be improved as experience with natural fire in the BWCA accumulates. Furthermore, these tools are by no means substitutes for practical experience or professional judgement. They can only supplement these important attributes.

APPENDIX

VEGETATION/FUEL TYPE CLASSIFICATION

Central Study Area-Boundary Waters Canoe Area
Superior National Forest, Minnesota
1977



LEGEND

VEGETATION/FUEL TYPE

Adapted (in part) from the U.S. Forest Service 1949 Lakes States Forest Experiment Station standard forest cover type classification scheme. Minimum type size - 10 acres.

Upland
- A - Aspen-Birch
- 3 - Aspen-Birch-Pine overstory, Spruce-Fir understory
- 4 - Cedar
- 5 - Jack Pine
- 6 - Spruce-Fir
- 8 - Red Pine
- 9 - White Pine
- 1h - Upland Brush
- C - Cutover Area and Slash
- R - Rock Outcrop

Lowland
- 7 - Lowland Conifer (predominantly Black Spruce)
- 1s - Lowland Shrub
- 2 - Marsh-Muskeg

STAND SIZE CLASS
- b - Sapling (1"-4.9" DBH)
- c - Pole (5"-9" DBH)
- d - Sawtimber (9"+ DBH)

CROWN DENSITY CLASS
- ' - 10-40% (poor)
- '' - 41-70% (medium)
- ''' - Over 70% (good)

OTHER FEATURES
- [water symbol] - Water areas
- + - Interior photo center
- 1622 + - Line terminal photo center
- ⊕ - Overlay registration marker

Examples of Vegetation Classification

- 5d'/1h - Predominantly Upland Brush with scattered Jack Pine sawtimber.
- 5d''/Ad' - Mixed sawtimber-size stand of which Jack Pine comprises 41-70% of the crown cover and Aspen-Birch 10-40% of the crown cover.
- Ad''/Ac'' - Aspen-Birch stand with approximately equal stocking of sawtimber and pole timber.
- 3d'' - Mixed stand of Aspen-Birch-Pine sawtimber (41-70% crown cover with an understory of Spruce-Fir.

Overlay prepared for the North Central Forest Experiment Station, USDA-Forest Service, by the University of Minnesota College of Forestry (USDA Cooperative Research Agreement 13-551) using 1:15,840 scale Aerochrome Infrared photography flown by the Forest Service on August 17 and September 16, 1976. Airphoto interpretation, field checking and map compilation by Mark S. Jensen; detail transfer by Lucinda Hruska-Claeys; drafting by Maurine H. Needham and Mary D. Hagen and project supervision by Dr. Merle P. Meyer.

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