THESIS

FIRE AND BIOMASS IN BANFF NATIONAL PARK CLOSED FORESTS

Submitted by

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In partial fulfillment of the requirements

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We hereby recommend that the thesis prepared under our supervision by Clifford A. White entitled Fire and Biomass in Banff National Park Closed Forests be accepted as fulfilling in part requirements for the degree of Master of Science.

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ABSTRACT

FIRE AND BIOMASS IN BANFF NATIONAL PARK CLOSED FORESTS

Successful fire management in national parks is dependent on knowledge of the ecological role of fire in ecosystems. In Banff National Park (BNP), Alberta, an understanding of the interaction between forest biomass and the fire regime (frequency, intensity and severity (depth of burn)) is necessary to develop a fire management program.

Fire history, biomass and fire behavior descriptors were measured in 220 Banff National Park closed forest stands. Objectives were to: (1) determine if significant quantitative relationships exist between biomass and fire characteristics and closed forest vegetation types classified during an ecological inventory of the park; (2) group vegetation types with similar fire and biomass characteristics into a limited number of "fire groups"; and (3) describe biomass and fire inter-relationships within each group. Cluster and discriminant function analysis were used to aggregate 26 closed forest vegetation types into nine fire groups: warm/dry montane, warm/dry lower subalpine lodgepole pine, montane aspen, mesic montane, cool/moist lower subalpine lodgepole pine, lower subalpine spruce-fir, floodplain spruce-fir, upper subalpine spruce-fir, and upper subalpine spruce-fire underlain with permafrost.

The best discriminating variables between fire groups were elevation, hygrotope, moss cover, crown foliage biomass, and the historic fire intensity/severity index.

Site characteristics (slope, elevation, cosine of aspect and hygrotope) all varied significantly between fire groups. Mean historic fire intervals ranged from <20 years in montane aspen to 173 years in upper subalpine spruce-fir. Pairwise comparisons of group fire interval distributions were made with a chi-square test. One-way analysis of variance yielded significant differences between fire groups for the following biomass components: bolewood, foliage and branchwood in the crown layer, herbs, dwarf shrubs and downed wood in the surface layer, and moss, litter and duff (fermentation and humus layers) in the ground layer. Total stand biomass varied significantly between fire groups, ranging from approximately 225 t/ha in warm/dry lower subalpine lodgepole pine to approximately 425 t/ha in lower subalpine spruce-fir forests. Fire behavior potential descriptors also indicated significant differences between groups for rate of fire spread and crown fire potential.

The fire group classification provided a framework for evaluating time-related changes in fire frequency, biomass and fire behavior potential in warm/dry montane, warm/dry lower subalpine, cool/moist lower subalpine and upper subalpine forests. Since 1880, reduced fire occurrence has increased the time since fire in all BNP forests. Regression

and graphical analysis revealed the importance of time since fire, the intensity/severity (depth of burn) of the last fire, and the length of the last fire interval in explaining change in many biomass and fire behavior potential descriptors. In general, long times since fire resulted in high accumulations in ground, downed wood, and crown foliage and branchwood biomass. Crown bolewood peaked at >150 t/ha in 150-299 year old lower subalpine forests before declining. Total stand biomass accumulates with time since fire in all BNP forests. In warm/dry lower subalpine forests, total biomass increased from approximately 180 t/ha in young stands (<50 years) to >400 t/ha in old (> 300 years) stands. Fire behavior potential descriptors indicated a tendency for high intensity/severity crown fires in old age stands that result in total mortality of the crown layer.

Fire suppression policies in BNP closed forests have resulted in biomass accumulations infrequently attained in the past 300 years. The lower fire frequency will be compensated for by fires of higher intensities and severities. Shifts in the fire regime may result in long term impacts on biomass and plant community characteristics in BNP forests.

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CHAPTER 1

INTRODUCTION

Background

Parks Canada is developing management plans to utilize wildland fire to maintain fire-dependent vegetation within national parks. Parks Canada (1979a) policy will, within the constraints imposed by public safety and facilities protection, allow some randomly ignited (accidental human and lightning started) fires to burn, and where required, use planned ignition (prescribed) fires (Lapoukhine and White 1983).

Banff National Park (BNP) began a fire management planning project in 1980 to evaluate the influence of fire on BNP ecosystems and to implement a plan to restore fire to its ecological role (BNP Warden Service 1980). Project components include analyzing fire history, evaluating fire weather and behavior during recent fires, and describing BNP vegetation development with and without fire. The planning project requires staff training and organization, small planned ignition fires for research purposes, and public information and involvement programs.

Van Wagner and Methven (1979) observe that successful fire management in national parks depends on "a good conceptual grasp of regional ecology and landscape evolution." The Ecological (Biophysical) Land Classification of Banff and Jasper National Parks (Holland and Coen 1982), the framework for ecosystem description in BNP, has mapped the total park into a system of 124 ecosite types based on a hierarchy of climatic, landform and vegetation characteristics (Lacate 1969, Holland and Coen 1982). Parks Canada's Resource Management Planning Process (1979b) states that ecological land classifications will be the basis for developing all resource management plans such as those for vegetation and fire (Lapoukhine and White 1983).

Problem Statement

Forest biomass is the dry weight per unit area of organic material in a forest stand (Ovington 1957, Newbould 1967, Hitchcock and McDonnell 1976, Parde 1980). In northern and Rocky Mountain forests, a strong inter-relationship may exist between biomass and wildland fire (Habeck and Mutch 1973, Wein and MacLean 1983). Van Wagner (1983) observes that fire in northern forests can be characterized by a regime of frequency (occurrence on a point per unit time), intensity (energy released by the advancing fire front) and depth of burning of the forest floor (herein called severity).

In BNP, closed forests (where tree cover is greater than 15%) constitute a significant portion of the park (approximately 35%). Knowledge of the inter-relationship between closed forest biomass and the fire regime is essential both for understanding ecological processes (e.g. nutrient cycling) and effectively managing BNP forests. Biomass may directly influence fire frequency, intensity and severity by affecting the composition and structure of the fuel complex (Brown and Davis 1973). The fire regime in turn may regulate forest biomass through redistributing carbon and nutrients during the fire, and influencing post-fire nutrient cycling (Martin et al. 1979, Olson 1981, Boerner 1982, MacLean et al. 1983).

In the Canadian Rocky Mountains and foothills, several studies have evaluated biomass (Kiil 1968, Hawkes 1979), potential fire behavior (Grigel et al. 1971, Hawkes 1979), and fire history (Van Wagner 1978, Tande 1979, Hawkes 1980). However, none of these studies evaluates the two-way inter-relationship between fire and biomass. In addition, to more fully understand this process in Banff National Park forests, fire and biomass characteristics should be described in terms of the park's ecological land classification system (Holland and Coen 1982).

Objectives

The purpose of this study was to describe the interaction between fire and biomass in BNP forests. Primary objectives were to:

1) determine if significant quantitative relationships exist between biomass and fire characteristics and closed forest vegetation types determined by the ecological land classification;

2) group forest types with similar biomass and fire characteristics into a limited number of "fire groups"; and

3) define biomass and fire inter-relationships within each fire group in terms of spatial and temporal variation.

The objectives of this study were predominantly descriptive, but the information gathered can contribute to the evaluation of a central and two corollary hypotheses of the interaction between fire and biomass in BNP closed forests:

Central hypothesis: The fire regime is a primary regulator of biomass in BNP forests. Biomass characteristics in turn are major determinants of fire intensity and severity.

Corollary 1: The fire regime and biomass characteristics vary in a spatial dimension partially due to site variables that influence the fire and biomass inter-relationship.

Corollary 2: The fire regime and biomass characteristics vary in a temporal dimension partially due to vegetation succession and development processes that influence the fire and biomass inter-relationship.

Thesis Organization

This paper initially provides a description of Banff National Park, emphasizing descriptions of closed forest types and successional sequences. The following section is a literature review--focusing on previous research in biomass, fire history and fire behavior potential relevant to the study area. The methods chapter describes sample plot layout, the types of information collected, and subsequent analysis procedures.

Two chapters deal with study results. The first considers the classification of 26 closed forest vegetation types into nine fire groups. Spatial variation between fire groups is statistically compared utilizing fire history, biomass and fire behavior potential descriptors. The second results chapter presents graphic and regression analysis data of temporal changes of descriptors within four fire groups.

The discussion chapter compares study results in terms of previous research and evaluates potential interactions between fire and biomass characteristics. Preliminary models of the interaction between the fire regime and biomass are presented for four fire groups. Results and discussion are summarized in a concluding chapter.

CHAPTER 2

THE STUDY AREA

Banff National Park occupies 6,640 km^2 of the northern Rocky Mountains in Alberta, Canada (Figure 1). The park extends northwest for 200 km along the eastern side of the continental divide from approximately 50°45'N and 115°30'W to 52°15'N and 117°15'W.

Physiography

BNP is composed of northwest to southeast trending ranges of the Rocky Mountains. The Main Ranges geologic subprovince forms the park's western half, with the Front Ranges predominating in the eastern portion (North and Henderson 1954, Price and Mountjoy 1970). The Main Ranges are massive mountain structures (many peaks exceed 3000 m elevation) spaced by steep walled valleys cut in horizontally banded strata. Icefields and glaciers are common. In contrast, the Front Ranges have less vertical relief, with wide valleys hemmed by thrust faulted ridges that rarely exceed 3000 m elevation.

Eastern flowing drainages of major rivers such as the Bow, Red Deer and North Saskatchewan periodically break the general northwest to southeast lay of the valleys (Figure 1). The valleys of these rivers are broad and U-shaped with areas below 1500 m.

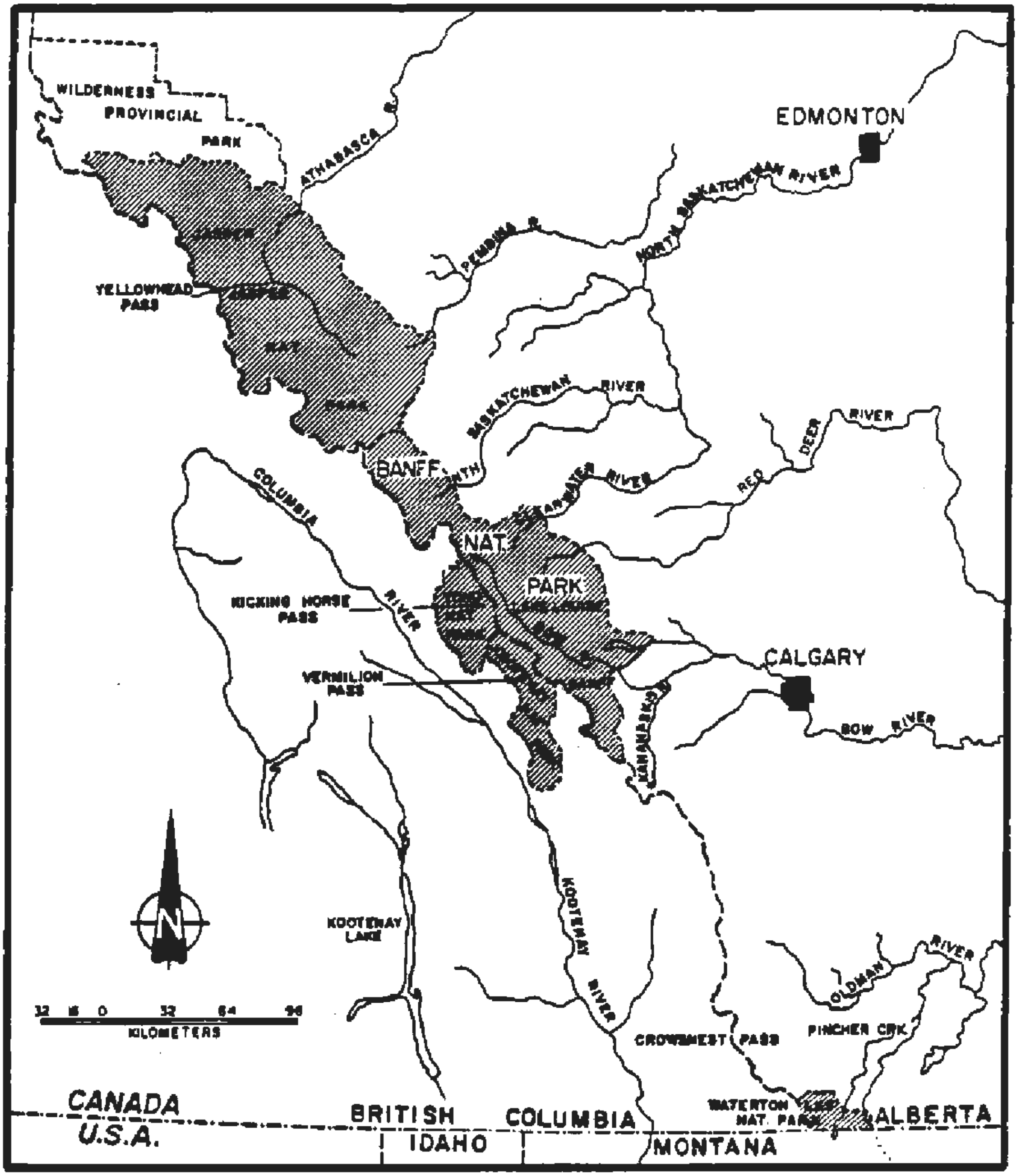

Figure 1: Banff National Park and surrounding lands.

Extensive glaciation shaped most BNP landforms. At least three major Pleistocene glacial advances occurred (Rutter 1972). The last deglaciation of the major valleys probably ended around 9000 B.P. Small neoglacial advances have occurred subsequently, the most recent maximum dating to the mid-nineteenth century (Heusser 1956). The abundant glacial activity resulted in large morainal (till) deposits and the U-shapes of major valleys. Other depositional mechanisms such as water, wind and gravity were often strongly influenced by the glacial activity, and are responsible for the varied surface of the park landscape (Holland and Coen 1982).

Climate

Janz and Storr (1977) provide a climatic analysis for the BNP area. In general, the climate is continental with long cold winters and short cool summers. Wide variations from average conditions occur.

Figure 2 shows profiles for mean monthly temperatures and precipitation at the Banff and Lake Louise (Figure 1) observation stations. The warmest months are July and August with mean monthly temperatures nearing 15°C. Janz and Storr (1977) note that maximum summer temperatures occur most frequently from mid-July to early August. Temperatures in excess of 30°C are uncommon, and pronounced cooling with elevation occurs at most times. However, cold air drainage and inversions are frequent in January, and can occur throughout the year.

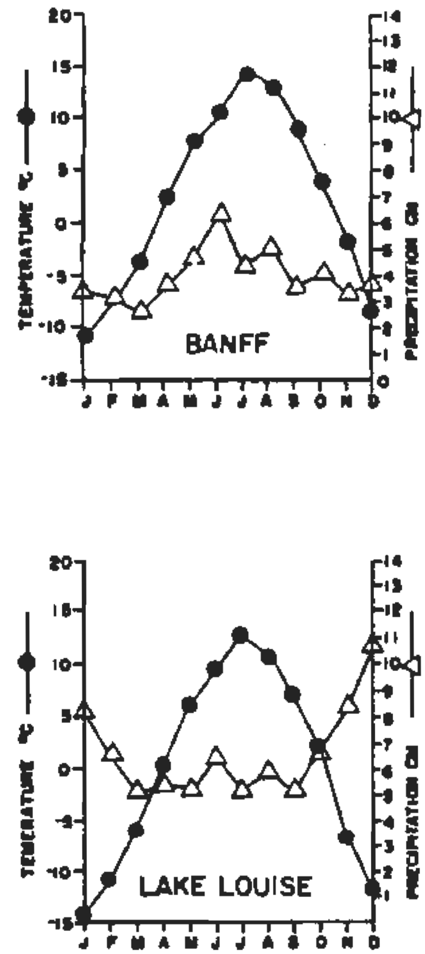

Figure 2: Mean monthly temperatures and precipitation for Banff and Lake Louise, Banff National Park for the period 1951-1981.

Precipitation varies widely in the park, averaging from less than 500 mm in the lower valleys of the Bow and North Saskatchewan to greater than 1250 mm in the Main Ranges of the northern part of the park. In the Banff townsite area, a continental precipitation regime prevails with a winter minima and spring - early summer maxima (Figure 2). Moving northwest to Lake Louise, more maritime conditions occur, and maximum precipitation occurs in winter. July is the driest month.

Winds are mainly westerly, but are channeled by mountain ranges (Janz and Storr 1977). Highest winds are found at upper elevations, and also on the park's east boundary along the low elevation east running valleys such as the Bow and North Saskatchewan.

Vegetation

According to Rowe's (1972) forest classification, BNP lies mostly in the SA1 (East Slope Rockies) Forest Section of the Subalpine Forest Region. Lower elevation areas along the park's eastern boundary are classified in the MS Section of the Montane Forest Region. The majority of the species are common to the boreal forest. A smaller number of species are related to the cordilleran portion of western North America (Ogilvie 1962).

The BNP Ecological (Biophysical) Inventory (Holland and Coen 1982) provides a park-wide classification and description of vegetation types broken down into physiognomic classes of closed forest, open forest, shrubs, low shrub-herb, and herb-dwarf shrub. Closed forest types, the focus of this study, constitute approximately 70% of BNP's vegetated areas. Codes and species defining closed forest types are listed in Table 1, by common and Latin nomenclature.

Ecoregions

In the BNP Ecological Land Classification, vegetation provides the basis for delineating three ecoregions: montane, subalpine and alpine. The subalpine ecoregion is broken into the lower subalpine and upper subalpine. The following descriptions are abstracted from Holland and Coen (1982). Vegetation types are keyed to Table 1.

The montane ecoregion, the most limited ecoregion within BNP (less than 2% of the park area), lies in valley bottoms and on south aspect slopes from 1300 m to 1650 m elevation. The area is distinguished by small grasslands and closed forest vegetation types such as Douglas-fir/hairy wild rye (C1), white spruce/fern moss (C2), lodgepole pine/juniper/bearberry (C3), and aspen/hairy wild rye-peavine (C16). In BNP, two areas of montane ecoregion occur: the Bow River valley from the East Gate to near Castle Mountain, and the North Saskatchewan valley below Mt. Wilson.

The lower subalpine ecoregion lies immediately above the montane, constituting a large portion (approximately 25%) of the park. The area is mainly covered with closed forests. Typical vegetation types are

Table 1: Closed forest vegetation types described by the Banff National Park ecological land classification (Holland and Coen 1982)

Code	Closed Forest Vegetation Type	Code	Closed Forest Vegetation Type
C1	Douglas fir/hairy wild rye (Pseudotsuga menziesii/Elymus innovatus)	C21	Engelmann spruce-subalpine fir/tall bilberry/liverwort (Picea engelmannii-Abies lasiocarpa/Vaccinium membranaceum/Barbilophozia lycopodioides)
C2	White spruce/fern moss (Picea glauca/Thuidium abietinum)	C22	Aspen/hairy wild rye-showy aster (Populus tremuloides/Elymus innovatus-Aster conspicuus)
C3	Lodgepole pine/juniper/bearberry (Pinus contorta/Juniperus communis/Arctostaphylos uva-ursi	C23	Subalpine larch-subalpine fir/grouseberry-everlasting (Larix lyallii-Abies lasiocarpa/Vaccinium scoparium-Antennaria lanata)
C4	White spruce/prickly rose/horsetail (Picea glauca/Rosa acicularis/Equisetum arvense)	C24	Engelmann spruce-subalpine fir/rock willow/white mountain heather (Picea engelmannii-Abies lasiocarpa/Salix vestita/Cassiope tetragona)
C5	White spruce-Douglas fir/feathermoss (Picea glauca-Pseudotsuga menziesii/Hylocomium splendens	C26	White spruce/buffaloberry/fern moss (Picea glauca/Shepherdia canadensis/Thuidium abietinum)
C6	Lodgepole pine/buffaloberry/showy aster (Pinus contorta/Shepherdia canadensis/Aster conspicuus)	C27	White spruce/prickly rose/fern moss (Picea glauca/Rosa acicularis/Thuidium abietinum)
C8	Black spruce-lodgepole pine/willow/sedge (Picea mariana-Pinus contorta/Salix myrtillifolia/Carex vaginata)	C28	Balsam poplar/horsetail (Populus balsamifera/Equisetum pratense)
C9	Lodgepole pine/dwarf bilberry (Pinus contorta/Vaccinium caespitosum)	C29	Lodgepole pine/Labrador tea (Pinus contorta/Ledum groenlandicum)
C10	Lodgepole pine/green alder/feathermoss (Pinus contorta/Alnus crispa/Hylocomium splendens)	C30	Engelmann spruce-subalpine fir/Labrador tea/crowberry) (Picea engelmannii-Abies lasiocarpa/Ledum groenlandicum/Empetrum nigrum)
C11	Lodgepole pine-spruce spp./feathermoss (Pinus contorta-Picea spp./Hylocomium splendens)	C31	Engelmann spruce-subalpine fir/hairy wild rye-heartleaf arnica-twinflower/feathermoss (Picea engelmannii-Abies lasiocarpa/Elymus innovatus-Arnica cordifolia-Linnaea borealis/Hylocomium splendens)
C12	Engelmann spruce-whitebark pine/false azalea (Picea engelmannii-Pinus albicaulis/Menziesia glabella)	C32	Engelmann spruce/horsetail/feathermoss (Picea engelmannii/Equisetum arvense/Hylocomium splendens)
C13	Engelmann spruce-subalpine fir/feathermoss (Picea engelmannii-Abies lasiocarpa/Hylocomium splendens)	C33	Engelmann spruce/hairy wild rye (Picea engelmannii/Elymus innovatus)
C14	Engelmann spruce-subalpine fir/false azalea/grouse berry (Picea engelmannii-Abies lasiocarpa/Menziesia glabella/Vaccinium scoparium)	C34	Engelmann spruce-subalpine fir/heather/feathermoss (Picea engelmannii-Abies lasiocarpa/Phyllodoce glanduliflora/Hylocomium splendens)
C15	Engelmann spruce-subalpine fir/grouseberry (Picea engelmannii-Abies lasiocarpa/Vaccinium scoparium)	C35	Lodgepole pine-(Engelmann spruce)/crowberry/lichen (Pinus contorta-(Picea engelmannii) Empetrum nigrum/Cladonia mitis)
C16	Aspen/hairy wild rye-peavine (Populus tremuloides/Elymus innovatus-Lathyrus ochroleucus)	C36	Lodgepole pine-white spruce/willow/hairy wild rye (Pinus contorta-Picea glauca/Salix glauca/Elymus innovatus)
C17	Balsam poplar/buffaloberry (Populus balsamifera/Shepherdia canadensis)	C37	White spruce/buffaloberry/feathermoss (Picea glauca/Shepherdia canadensis/Hylocomium splendens)
C18	Lodgepole pine/buffaloberry/grouseberry (Pinus contorta/Shepherdia canadensis/Vaccinium scoparium)		
C19	Lodgepole pine/buffaloberry/twinflower (Pinus contorta/Shepherdia canadensis/Linnaea borealis)		
C20	Lodgepole pine/false azalea/grouseberry (Pinus contorta/Menziesia glabella/Vaccinium scoparium)		

lodgepole pine/buffaloberry/showy aster (C6), lodgepole pine/buffaloberry/twinflower (C19), Engelmann spruce-subalpine fir/feathermoss (C13) and Engelmann spruce-subalpine fir/false azalea (C14). Lower subalpine forests occupy almost all BNP valleys up to approximately 2000 m.

The upper subalpine ecoregion is transitional between the closed forests of the lower subalpine and the treeless alpine ecoregion, and covers about 25% of BNP's total area. Shorter, cooler growing seasons than the lower subalpine favor open krummholz forests in many areas. Closed forests in this region include Engelmann spruce-subalpine fir/grouseberry (C15), alpine larch-subalpine fir/grouseberry- everlasting (C23) and Engelmann spruce-subalpine fir/heather/feathermoss (C24). In upper subalpine areas where a shallow snow pack results in permafrost development (Holland and Coen 1982), a common vegetation type is Engelmann spruce-subalpine fir/rock willow/white mountain heather (C24). Lodgepole pine is not commonly found in the upper subalpine.

Above approximately 2350 m in BNP is the alpine ecoregion of meadow and dwarf vegetation that occupies about 5% of Banff's area. The large remaining portion of the park (greater than 35%) is unvegetated rock, talus, moraine and glacier.

Closed Forest Succession

Forest succession and development may cause significant changes in biomass and fire behavior potential. Holland and Coen (1982) provide successional trends for BNP closed forest vegetation types (Figure 3). In general, early successional stages of lodgepole pine forest vegetation types are transitional to mature forest vegetation types of white spruce, Douglas-fir, Engelmann spruce, and subalpine fir.

Successional development in BNP's montane Douglas-fir forests can be described as proceeding through three stages (Stringer and La Roi 1970). In the first stage after fire, an abundance of young lodgepole pine, white spruce and Douglas-fir in the 0-30 cm diameter at breast height (DBH) classes occur, usually mixed with scattered large Douglas-fir showing evidence of surviving past fires. In the second stage (mean stand ages of 47-182 years), numerous medium-sized Douglas-fir dominate and tree reproduction decreases under the closing canopy. Shorter-lived lodgepole pine disappears from the stand. Ultimately a third stage of closed-canopy mature Douglas-fir forest with a hairy wild rye (C1) or feathermoss (C5) forest floor may develop. However, the latter two stages in this sequence probably rarely occur due to fire intervals of less than 40 years in most Douglas-fir forests (Tande 1979). On montane sites where a closed Douglas-fir canopy does not develop, or when disturbance is frequent enough, multi-aged stands of lodgepole pine may occur (Horton 1956, La Roi and Hnatiuk 1980).

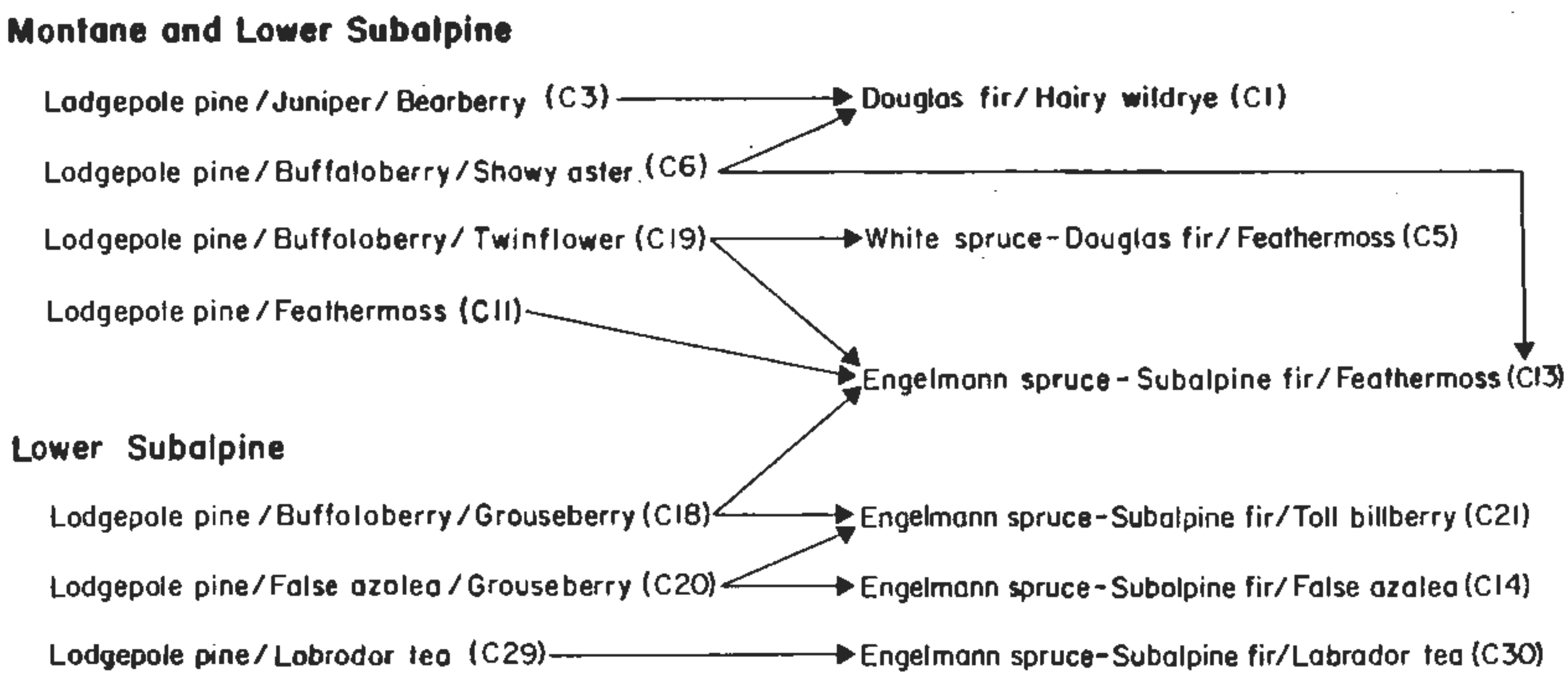

Figure 3: Closed forest succession trends evident in Banff National Park (from Holland and Coen 1982).

Succession in lower subalpine areas of Alberta's Rocky Mountains often results in a subalpine fir-Engelmann spruce mature forest (Bloomberg 1949, Cormack 1956, Beil 1966). Day (1972) describes four stages in development after a stand-destroying fire. In Stage 1 (approximately 55 years) a dense even-aged lodgepole pine overstory develops. Engelmann spruce and subalpine fir reproduction is found in the understory. Stage 2 (approximately 155 years) is characterized by Engelmann spruce beginning to dominate over lodgepole pine. Subalpine fir is aggressively growing below the canopy. In Stage 3 (approximately 255 years) lodgepole pine is decadent and dying out, and spruce is dominating. Subalpine fir is three times as numerous as spruce in the understory. Stage 4 (approximately 355 years) occurs when all original post-fire lodgepole pine and Engelmann spruce have died, and an uneven-age stand of mostly subalpine fir with a minor component of spruce remains. Day (1972) observes that this climax stage of development is characterized by low tree vigor (stagnant and suppressed growth), possibly due to low nutrient cycling.

In the upper subalpine ecoregion, forest development is slow, with only a limited occurrence of lodgepole pine. Forests are dominated by alpine larch, Engelmann spruce and subalpine fir (Holland and Coen 1982).

Current patterns of vegetation types and successional stages in BNP may in many cases be the result of historic human use patterns (Byrne 1964).

Historic Land Uses

Information on human use of the park area is provided by archaeological studies (Reeves 1974, Christenson 1971, Damp et al. 1980) and reviews of historical literature such as Van Kirk (1969) and Byrne's (1964) Man and Landscape Change in Banff National Park Before 1911. Byrne's breakdown of historical periods is utilized in this description.

Pre-European Period: Archaeological evidence indicates occupation of the area by Paleo-Indians by 10,000-9,000 B.C. With some interruptions due to climatic cooling and glacial advances, population densities increased with time. Christenson (1971) reports that the period from 200 A.D. to 1500 A.D. was one of "intensive human occupation of Banff." This aboriginal culture was well adapted to the mountain conditions, probably establishing permanent winter settlements in the lower montane valleys and exploiting subalpine and alpine areas during the summer (Damp et al. 1980). These Paleo-Indians were closely related to the Kootenays of southern British Columbia and northern Montana (Byrne 1964). Barrett (1980) observes that this tribe set purposeful fires to improve horse pasturage and hunting.

The expansion of European occupation across the continent caused the collapse of the long-evolved Paleo-Indian culture by about 1750 A.D. At this time, the Mountain Stoneys (Assiniboines) moved into the area.

Fur Trading Period (c. 1775-1850): The Banff region appears to have been lightly used by Europeans during the early 1800's (Byrne 1964). The hostile Piegan tribe blocked fur traders from using most passes across the Rockies in the park. The North-West and Hudson's Bay Companies established trading posts on the North Saskatchewan and Bow Rivers just outside the mountains. Stoney Indians probably used the Banff area extensively for trapping and hunting. This tribe may have used fire to improve habitat (White 1984).

Prospecting and Early Railroad Period (1850-1887): Despite the large amount of prospecting and gold rushes in other areas of Western Canada after 1850, the Banff region was probably only infrequently visited by prospectors before the coming of the railroad due to mineral-poor sedimentary rock and little known travel routes (Byrne 1964). In 1881 and 1882 the Canadian Pacific Railroad surveyed potential routes through the Howse, Kicking Horse and Kananaskis Passes, and constructed the railroad over Kicking Horse Pass in 1883 and 1884 (Bone 1947, Wilson 1972). Concurrent with the railroad construction (and for several decades after) large areas of the Bow watershed were burned, logged, and much mineral exploration occurred. The boom town of Silver City (between Banff and Lake Louise) grew to some 1500 inhabitants in the early 1880's only to dwindle to a ghost town by 1890 (Byrne 1964).

The Park Period (after 1887): An order-in-council in 1885 and the Rocky Mountain Parks Act of 1887 provided the foundations for today's Banff National Park. Early administrators of the park stressed economic development through tourism and industries such as logging and mining (Byrne 1964). Through the years Parliament made numerous boundary changes to provide for more logical borders and increasing concerns in preservation. In 1930 the National Parks Act was passed which emphasized nature preservation, excluded industrial towns from the park, and finalized park boundaries as they are today (Van Kirk 1969).

Annual visitor use of BNP increased from fewer than 10,000 in 1900 to approximately 180,000 in 1930, to over 3,500,000 in 1980 (Dept. of the Interior 1902, 1932; Parks Canada 1982). Heavy visitation and facility development have provided a strong incentive to suppress forest fires.

Forest Fire Occurrence Since 1880

A detailed account of forest fires occurring in Banff National Park after 1880 is provided by White (1984). Throughout most of this period fire was considered a destructive event. Fire prevention and fuel reduction practices began in the late 1880's. Concern for the need for rapid detection and suppression of fires helped lead to the formation of the Warden Service in 1908. The area burned and number of fires (>40 ha) per decade decreased continuously from 1880 to 1980 (Table 2). Prevention of man-caused fires, suppression actions, and possibly a minor decrease in the frequency of dry seasons are attributed to reducing the area burned.

Since 1880, approximately 35 fires greater than 40 ha burned in the 180,000 ha of subalpine ecoregions of BNP for a ratio of .19 fires per 1000 ha. In the 16,700 ha of montane ecoregion at least 17 fires greater than 40 ha occurred for a ratio of 1.02 fires per 1000 ha. The higher ratio of burning in the montane areas is due to a climate more conducive for fire than in the subalpine ecoregion and more intensive human activity (White 1984).

Man-started fires have been the most numerous and burned the most area since 1880. Of the fires greater than 40 ha with known ignition sources, 78% were man-started and only 22% were lightning ignitions. For the period 1940 to 1980, over 80% of the fires burning from .1 to 40 ha were known to be man-started. In contrast, only 6% were verified lightning ignitions.

Table 2: Burned area and number of fires (>40 ha) per decade (1880-1980) in Banff National Park (from White 1984).

Decade	Area Burned (ha)	Number of Fires
1880-1889	37,050	> 6 [a]
1890-1899	18,600	9
1900-1909	16,050	12
1910-1919	3,300	6
1920-1929	10,950	9
1930-1939	8,050	6
1940-1949	4,200	2
1950-1959	0	0
1960-1969	500	1
1970-1979	45	1
TOTALS	98,745	>52

[a] Poor historical records and reburning by later fires makes determination of actual number of fires difficult.

CHAPTER 3

LITERATURE REVIEW

Several fields of study provide information on fire and biomass characteristics. Studies of ecosystem productivity and nutrient cycling commonly quantify forest biomass (Art and Marks 1971, Krause et al. 1978, Parde 1980). The relationship between biomass and fire characteristics such as rate of spread and intensity is explored in studies of fire behavior potential (Brown and Davis 1973). Fire history research further helps in the interpretation of the relationship between fire and different plant communities (Arno and Sneck 1977). Following is a review of studies on biomass, fire behavior potential and fire history with emphasis on the forests of the northern Rocky Mountains of Canada and the United States.

Forest Biomass

The dry weight of live and dead material in a forest stand results from the differential rates of two processes:

1) net primary production or photosynthetic accumulation remaining after plant respiration, and

2) decomposition, or the breaking down of organic material (Olson 1963).

Biomass estimates, usually expressed as weight per unit area, are thus essential for evaluating ecosystem functions such as nutrient cycling, production and decomposition.

Accumulation of large biomass quantities characterizes forest ecosystems. For example, Whittaker (1975) describes total weights ranging from 60-2000 t/ha for temperate evergreen forests and 60-400 t/ha for boreal forests--compared to only 2-50 t/ha for temperate grasslands. Although net primary productivity estimates by Whittaker (1975) for northern forests (8 t/ha yr) are not particularly high in comparison to temperate grasslands (6 t/ha yr), forest biomass is substantially higher due to continued increments of long-lived woody tissue, and in northern environments, the slow decomposition rates of organic material (Dickenson and Pugh 1974).

Evaluations of biomass can be broken down by components in forest stands including the crown layer, surface (understory) layer, and the ground (soil) layer. Numerous studies have estimated biomass variation and dynamics within these layers in the western and boreal areas of North America.

Crown Layer

Tree boles, branchwood and foliage of the crown layer constitute a major component of forest biomass. Table 3 summarizes crown biomass estimates for forest types similar to those in BNP. Most studies find that

Table 3: Summary of selected studies on foliage bulk density and foliage, branchwood, bolewood, and total crown biomass of the forest crown layer. Values in parentheses refer to the range reported.

Reference, Location	Forest Type	Foliage Bulk Density (Kg/m^3)	Crown Layer Biomass (t/ha)			
			Foliage	Foliage and Branchwood	Bolewood	Total
Alexander (1979), Colorado	lodgepole pine (stand ages of 57-280 years)	.31 (.06-.72)	10.35 (6.18-15.24)	26.99 (17.82-43.04)	92.37 (20.62-157.81)	119.36 (39.35-200.87)
Bella and Franceschi (1980), Alberta	aspen			11.30 (.46-33.05)	74.17 (1.51-239.58)	86.20 (1.96-271.77)
Hawkes (1979), Alberta Rocky Mountains	warm/dry lower subalpine lodgepole pine			26.75		
	cool/moist lower subalpine lodgepole pine			48.28		
	lower subalpine Engelmann spruce			25.36		
	upper subalpine Engelmann spruce, subalpine fir and alpine larch			44.83		
Johnstone (1971), southwestern Alberta	lodgepole pine (stand age of 100 years)		11.50 (7.38-14.61)	28.62 (21.37-38.13)	144.85 (68.22-213.28)	177.06 (91.76-245.07)
Johnstone and Peterson (1980), Alberta	aspen (stand age of 5 years) (stand age of 70 years)					 8.70 325.10
Kill (1968), Alberta	lodgepole pine (stand age of 70 years)			33.92 (25.77-42.36)	60.22 (40.79-75.99)	94.30 (66.57-118.36)
Landis and Mogren (1975), Colorado	Engelmann spruce and subalpine fir		18	29	117	156
Muraro (1971), British Columbia	lodgepole pine (stand ages of 21-200 years)			25.95 (9.66-39.83)		

foliage and branchwood weights are low compared to bolewood, with estimates of total crown layer biomass ranging from approximately 60 to 300 t/ha.

The crown layer is the location of most net primary production in forests. Timber yield studies provide information on productivity. Forests with highest timber increment rates on the eastern slope of the Rocky Mountains in Montana are mid-elevation stands with a potential climax of Engelmann spruce and subalpine fir (Pfister _et al_. 1977). In upper elevation forests, yield falls due to cooler temperatures, shorter growing seasons and poorer soils (Krajina 1970). Productivity may decrease at lower elevations due to drier climatic conditions. The litter and deadfall resulting from crown layer net primary production contribute significantly to the biomass of the surface and ground layers.

Martin _et al_. (1976) and Madgwick (1976) summarize key points of crown biomass production and development:

1) Tree bole, branch and foliage weight increase with age and stem diameter, but the number of trees decreases;

2) Foliage and branch biomass becomes relatively constant after stand crown closure;

3) Tree bole weight per unit area increases for a long period of time.

In northern Rocky Mountain forests, a major effect of fire on the crown layer is the killing of trees. High intensity fires may kill by scorching and consuming needles (Van Wagner 1973a, Ryan 1982). Anderson (1968) and Dube (1976) observe that high intensity fires consume up to 95% fine materials (<.3 cm) in the crown layer. Intense or severe (deep burning) fires may also kill trees by heating tree cambium or roots above lethal temperatures (Fahnestock and Hare 1964, Ryan 1982). Tree resistance to mortality is dependent upon bark thickness, root depth, bark resin, branch and stand foliage habit, and foliage flammability (Flint 1925, Wellner 1970). Douglas-fir has relatively high resistance, lodgepole pine is moderately resistant, and Engelmann spruce and subalpine fir have low to very low resistance to fire mortality (Flint 1925). Lodgepole pine killed by fire may fall to the surface layer within 15 years (Lyon 1977), although some snags remain standing for more than 30 years (Tackle 1959).

Surface Layer

Components of the surface biomass layer are shrubs, dwarf shrubs, herbaceous understory vegetation, and downed branchwood and logs. Table 4 summarizes the results of selected studies of surface layer biomass in montane and subalpine forests.

Herbaceous biomass (often including dwarf shrubs in many studies) is relatively light in most forests. Hawkes (1979) described herbaceous biomass as averaging less than .02 t/ha in lower subalpine Engelmann

Table 4: Summary of selected studies on herbaceous/dwarf shrub, shrub and downed wood biomass of the surface layer. Values in parenthesis refer to range reported.

Reference, Location	Forest Type	Surface Layer Biomass (t/ha) Herbaceous/ Dwarf Shrub	Shrub	Fine Wood	Coarse Wood	Total Wood
Alexander (1979), Colorado	lodgepole pine	.30 (0.00-2.35)	-	2.57[a]	18.34	20.91
Brown and See (1981), eastside Montana Rocky Mountains	dry Douglas-fir	-	-	5.60[b]	23.54	29.14
	lower elevation lodgepole pine and subalpine fir	-	-	5.38	38.11	43.49
	moist lower elevation subalpine fir	-	-	4.26	37.89	42.15
	upper elevation subalpine fir	-	-	4.71	21.07	25.78
Fahnestock (1977) Northern Washington	subalpine stands <100 years years old (mainly lodgepole pine)			6.35[c] (2.69-10.64)	118.96 (13.00-222.37)	
	subalpine stands >100 years old (mainly Engelmann spruce and subalpine fir)			7.65 (1.12-20.46)	125.08 (24.21-237.62)	
Habeck (1976), Montana and Idaho	warm/dry Douglas-fir and ponderosa pine (recent surface fire)	.7	.4	1.0[c]	.3	
	warm/dry Douglas-fir and ponderosa pine (no recent surface fire)	.6	.6	3.0	52.1	
	subalpine fir and lodgepole pine (pioneer stands on open slopes)	1.4	1.9	4.4	7.4	
	subalpine fir and lodgepole pine (developing stands on open slopes)	2.8	1.3	8.8	2.6	
	subalpine fir and lodgepole pine (developing stands on moist sites)	0.8	1.1	4.5	3.6	

Table 4: Cont'd

Reference, Location	Forest Type	Surface Layer Biomass (t/ha)				
		Herbaceous/ Dwarf Shrub	Shrub	Fine Wood	Coarse Wood	Total Wood
Habeck (1976), Montana and Idaho (Cont'd)	subalpine fir and lodgepole pine (mature stands on moist sites)	.71	1.5	6.8	7.8	
Hawkes (1979), Alberta Rocky Mountains	recent burns	.41	.25	1.03[a]	57.52	58.55
	warm/dry lower subalpine lodgepole pine	.21	2.69	2.72	59.25	61.97
	cool/moist lower subalpine lodgepole pine	.07	2.44	1.60	82.11	83.71
	lower subalpine Engelmann spruce	.02	1.44	3.92	102.04	105.96
	upper subalpine Engelmann spruce, subalpine fir and alpine larch	.04	1.02	.62	12.27	12.89
Jeske and Bevins (1976), Glacier National Park, Montana	upright forests (all ages)	.25	1.85			
	0-10 years	.48	4.89	3.19[a]	33.82	
	11-44 years	.45	6.13	2.23	35.88	
	45-69 years	.33	1.75	2.68	12.31	
	70-89 years	.30	2.16	1.90	17.20	
	90-109 years	.34	1.85	2.12	13.16	
	110-129 years	.24	2.04	2.31	18.43	
	130-149 years	.17	1.39	2.51	35.84	
	150-169 years	.36	1.68	3.21	31.35	
	>169 years	.21	.88	2.72	48.41	

Table 4: Cont'd

Reference, Location	Forest Type	Surface Layer Biomass (t/ha) Herbaceous/ Dwarf Shrub	Shrub	Fine Wood	Coarse Wood	Total Wood
Kill (1968), Alberta	lodgepole pine (open stand)	1.41	3.65	.20[d]	.18	.38
	lodgepole pine (moderate density)	1.81	.16	.43	1.14	1.57
	lodgepole pine (dense stand)	1.01	.16	1.03	6.70	7.73
Muraro (1971), Interior British Columbia	lodgepole pine	-	-	8.60[c] (3.14-19.73)	16.37 (2.47-38.78)	24.97
Oberheu and Mutch (1975), Wyoming	recent burn			.77[b]	97.36	
	lodgepole pine			1.45	17.83	
	lodgepole pine to Engelmann spruce-subalpine fir transition			2.20	52.96	
	Engelmann spruce and subalpine fir			2.49	59.90	
Tisdale (1959), Interior British Columbia	aspen	.72				
	lodgepole pine	.47				
	mature Douglas-fir	.17				
	young Douglas-fir	.11				

a. fine wood is <2.54 cm diameter
b. fine wood is <7.6 cm diameter
c. fine wood is <10.16 cm diameter
d. fine wood is <1.3 cm diameter

spruce stands. Kiil (1968) found herbaceous loading less than 2 t/ha in Alberta lodgepole pine forests. Increased crown cover often decreases herbaceous loading due to factors such as blocking of throughfall precipitation (Anderson et al. 1969) and solar radiation (Pyke and Zamora 1982). Thus, recently burned stands in the northern Rocky Mountains may develop high herbaceous biomass which declines over time as the forest canopy develops (Jeske and Bevins 1976, Hawkes 1979).

Shrub biomass estimates (Table 4) vary widely from .16 t/ha in Alberta lodgepole pine stands (Kiil 1968) to over 6 t/ha in 11-44 year old forests in Glacier National Park, Montana (Jeske and Bevins 1976). Shrub biomass decreased with stand age in Glacier Park (Jeske and Bevins 1976). However, Hawkes (1979) observed low shrub biomass (.25 t/ha) in recently burned forests.

Table 4 divides downed wood into a fine component (less than 1.3, 2.54, 7.6 or 10.16 cm diameter, depending on the study) and a coarse component of larger diameter. Fine downed wood biomass is light in most locations, usually averaging less than 2 t/ha. Coarse materials vary widely between areas, with heavy loadings of over 90 t/ha reported for recent burns in Wyoming's Teton Wilderness (Oberheu and Mutch 1975) and Engelmann spruce stands in Alberta (Hawkes 1979). In contrast, most studies of lodgepole pine forests report relatively light coarse downed wood biomass which usually averages less than 50 t/ha.

Total downed wood biomass may be high after fire due to fire-killed tree boles. Wood loading then may decrease to a low at middle stand age due to decomposition, followed by increases as a result of trees succumbing to natural thinning, disease, and insect attack. This pattern is apparent in several studies (Oberheu and Mutch 1975, Brown 1975, Jeske and Bevins 1976, Brown and See 1980). Downed wood biomass is usually highest on the most productive sites (Brown and See 1980).

Decomposition rates for downed wood are slow in northern forests and depend on factors such as diameter, lignin content, and microclimate (McFee and Stone 1966, Fogel and Cormack 1977). Decomposition half times (period required for 50% weight loss) of 10.0 to 20.1 years are reported by Fogel and Cormack (1977) for 10-15 mm diameter Douglas-fir twigs. Over 300 years may be required for incorporation of Douglas-fir logs into the soil profile (Harvey et al. 1981).

Fire in northern Rocky Mountain forests may remove up to 80% of fine (less than 7.6 cm diameter) wood, shrub and herbaceous biomass in the surface layer (Anderson 1968, DeByle 1981). Sound downed logs of larger diameter are usually not significantly burned (Dube 1976), although rotten logs may be partially consumed (Norum 1976). The degree of burning in the surface layer is partially dependent upon biomass moisture content (DeByle 1981) and fire behavior characteristics such as rate of spread (Anderson 1968).

Ground Layer

The forest ground layer refers to moss, litter, and duff (fermentation and humus layers). Table 5 provides ground layer depth and biomass estimates as reported by selected studies of northern Rocky Mountain forests. Comparison between studies is difficult because mineral soil content is included in some reports. Also, several authors do not distinguish litter and moss.

Average duff depths (Table 5) range from .76 cm in Idaho and Montana lodgepole pine forests (Brown 1972) to over 10 cm in subalpine Englemann spruce and subalpine fir stands in the Canadian Rocky Mountains (Dube 1976, Hawkes 1979). Biomass estimates vary from 11.43 t/ha to 129.25 t/ha. In Alberta forests, duff biomass increases as a function of stand age, and on north and east aspects (Kiil unpublished, Hawkes 1979, Hillman and Golding 1981).

Litter biomass estimates (Table 5) generally range from 2 to 5 t/ha with light loadings reported for lodgepole pine forests in Montana and Idaho (Brown 1972) and recently burned areas (Oberheu and Mutch 1975). Litter biomass is often high in trembling aspen forests, averaging more than 4 t/ha in several studies (Lousier and Parkinson 1976, Hillman and Golding 1981, Kiil unpublished).

Numerous researchers have investigated the dynamics of litter accumulation and decomposition in forests. Estimates for annual litter

Table 5: Summary of selected studies on duff depth, and duff litter, moss, and total biomass of the forest ground layer. Values in parenthesis refer to range reported.

Reference, Location	Forest Type	Duff Depth (cm)	Ground Layer Biomass (t/ha) Duff	Litter	Moss	Total
Alexander (1979), Colorado	lodgepole pine	4.22 (2.11-6.83)	58.29 (29.38-95.22)	3.22 (1.14-5.01)	0.00	61.51
Brown (1972), Idaho and Montana	lodgepole pine	.76	11.43	.67	-	12.11
Brown (1974), Idaho and Montana	lodgepole pine	2.29				
Brown (1975), Idaho and Montana	lodgepole pine		- (11.88-65.02)			
Brown and See (1981), eastside Montana Rocky Mountains	dry Douglas-fir	2.54				
	lower elevation lodgepole pine and subalpine fir	3.05				
	moist lower elevation subalpine fir	2.54				
	upper elevation subalpine fir	1.78				
Dube (1976), Canadian Rocky Mountains	subalpine spruce-fir	11.0				
Fahey (1983), southeast Wyoming	lodgepole pine		(13.81-21.89)	(6.66-12.01)		(17.30-33.90)
Fahnestock (1976, 1977) northern Washington	subalpine stands <100 years old (mainly lodgepole pine)					44.85 (13.00-88.77)
	subalpine stands >100 years old (mainly Engelmann spruce and subalpine fir)					88.27 (42.82-112.31)

Table 5: Cont'd

Reference, Location	Forest Type	Duff Depth (cm)	Ground Layer Biomass (t/ha) Duff	Litter	Moss	Total
Hawkes (1979), Alberta Rocky Mountains	recent burns	3.5	28.98		.24	29.22
	warm/dry lower subalpine lodgepole pine	4.7	35.09		2.16	37.25
	cool/moist lower subalpine lodgepole pine	8.5	87.01		6.69	93.70
	lower subalpine Engelmann spruce	10.1	129.25		8.44	137.69
	upper subalpine Engelmann spruce, subalpine fir and alpine larch	2.9	17.95		.47	18.42
Hillman and Golding (1981), Alberta Rocky Mountains and foothills	south aspect lodgepole pine					54.20
	north and east aspect lodgepole pine					55.65
	Engelmann spruce and sub-alpine fir					91.43
	trembling aspen	5.8	87.40	7.70	0.00	95.10
Kill (1968), Alberta foothills	lodgepole pine (open stand)	-	47.18	2.65	.74	
	lodgepole pine (moderate density)	-	45.01	3.23	4.71	
	lodgepole pine (dense stand)	-	45.36	2.40	4.82	
Kill (unpublished), Alberta	aspen	6.86	92.82	4.93[a]		

Table 5: Cont'd

Reference, Location	Forest Type	Duff Depth (cm)	Ground Layer Biomass (t/ha) Duff	Litter	Moss	Total
Kiil (unpublished), Alberta cont'd	lodgepole pine (south aspects)	2.79	39.01	9.86		
	lodgepole pine (north aspects)	5.84	63.38		9.64[b]	
	white spruce	8.13	92.82		14.57	
Lousier and Parkinson (1976), Alberta	aspen		80.4	10.6		91.0
Muraro (1971), interior British Columbia	lodgepole pine	-	-	-	-	26.23 (8.74-93.93)
Oberheu and Hutch (1975), Wyoming	recent burns			1.15		
	lodgepole pine			2.58		
	lodgepole pine and Engelmann spruce-subalpine fir transition			3.34		
	Engelmann spruce and subalpine fir			2.33		

a. includes a small amount of moss
b. includes a small amount of litter

fall include 3.43 to 6.43 t/ha (mostly needles) in Colorado lodgepole pine forests (Moir 1972), 4.15 t/ha (mostly leaves) in an Alberta aspen forest (Lousier and Parkinson 1976), and 1.25 to 2.08 t/ha (mostly needles) for Wyoming lodgepole and pine forests (Fahey 1983). In Alaska aspen stands, litterfall increased from 1.31 t/ha for 10 year old stands to 2.18 t/ha for 50 year old forests (Van Cleve and Noonan 1975). In a west coast subalpine forest, Turner and Singer (1976) found 3.02 t/ha of litter was produced annually, of which nearly 70% was needles.

Litter decomposition half times (time required for 50% weight loss of samples in litter bags) are long in northern forests (Olson 1963) with reported values including 2.5 to 3.5 years for Oregon Douglas-fir needles (Fogel and Cormack 1977), 2.5 to 19.8 years for New Brunswick jack pine (Pinus banksiana) litter (MacLean and Wein 1978) and approximately 2 years for aspen litter in Alaska (Van Cleve 1971). Fogel and Cormack (1977) found Douglas-fir needles decomposed at more rapid rates with higher site moisture and denser cover of mature trees.

Moss (e.g. Pleurozium spp. and Hylocomium spp.) biomass develops with time under northern coniferous forests as nutrients contained in canopy wash are utilized (Tamm 1955). Kiil (1968) and Hawkes (1979) report light moss biomass of less than 1.0 t/ha in open lodgepole pine stands and recently burned areas in Alberta (Table 5). These studies also found relatively heavy moss layer weights (greater than 4 t/ha) in spruce and dense lodgepole pine stands. Moss cover appears to enhance coniferous litter decomposition (Bernier and Roberge 1962) and is an important factor influencing nutrient cycling in northern forests (Krause et al. 1978, Viereck and Schandelmeier 1980).

Fire in northern forests may remove significant quantities of litter, moss and duff biomass (Anderson 1968, Norum 1976, Viereck and Dyrness 1979). Dube (1976) reports average duff depths of 11 cm reduced by fire to 2 cm in a Rocky Mountain subalpine forest. Van Wagner (1972) relates duff consumption in boreal forests to moisture content. Reduction of the crown layer cover and duff depths by fire significantly changes the micro-climate at the ground layer in northern forests (Viereck and Dyrness 1979). Warm temperatures in young stands may increase biomass decomposition and production rates in young stands (Viereck and Schandelmeier 1980).

Fire Behavior Potential

Describing fire behavior potential is the process of relating fire characteristics such as ease of ignition, rate of spread, intensity, and resistance to control to topography, weather, and amount and type of organic material (Hornby 1936, Byram 1959, Brown and Davis 1973). Many properties of organic material affect fire potential including biomass (fuel loading), bulk density, mineral content, vertical continuity and horizontal continuity (Rothermel 1972, Martin et al. 1979, Rundel 1981). Difficulties in measuring and interpreting these properties have led to two general approaches in assessing fire behavior potential (Van Wagner 1971):

1) fire behavior predictions based on field observations of wildland fires (the empirical approach); and

2) fire behavior predictions derived from controlled laboratory analysis of fuel bed combustion (the mathematical modelling approach).

Empirical Approaches

Field measurement of fire characteristics under different fuel and forest cover conditions has provided a basis for many analyses of fire behavior. Show and Kotok (1930) use this approach by evaluating fire perimeter increases in California cover types with information derived from agency fire reports. Barrows (1951) reviewed fire reports to summarize fire rates of spread, perimeter increase and fire suppression effort in the northern Rocky Mountains of United States.

Where fire frequency and numbers of fire records are low compared to the number of fuel conditions, researchers have relied on subjective extrapolations from experienced conditions to predict fire behavior. For example, Hornby's (1936) system required qualitative evaluation of canopy density, aspect, fuel continuity, amount of dead foliage, and snag density. On the basis of these qualities, the observer then assigned potential fire perimeter growth rates and resistance to control to one of four classes: low, medium, high and extreme. The system was originally applied to the northern Rocky Mountains of the United States where over 70 fuel types were recognized.

A weakness in the above studies is the subjectivity and generality in defining fuel complexes (Brown and Davis 1973). To reduce subjectivity, Fahnestock (1970) produced a decision key to help standardize fuel classification. Also of great utility are inventory techniques to measure fuel characteristics such as weight (Brown et al. 1982). Quantitative measurements can be combined with photographic references to provide a quick means of fuel and fire potential evaluation (Maxwell and Ward 1976, Fisher 1981).

A second weakness in many empirical fire potential studies is their failure to integrate the effects of variable weather conditions. Many studies predict fire characteristics on the basis of fixed "average bad" or "extreme" conditions (Hornby 1936, Barrows 1951) whereas fire behavior in a fuel complex will vary widely depending on weather factors such as relative humidity. To alleviate this problem, assessments of fire behavior potential in Waterton Lakes National Park (Grigel et al. 1971) and British Columbia forests (B.C. Ministry of Forests 1979) relate predicted rates of spread and resistance to control to indices of the Canadian Forest Fire Weather Index (Van Wagner 1974).

Fire behavior research in Canada emphasizes an empirical approach. The Canadian Forestry Service has conducted a series of prescribed burns to develop fire behavior indices for common vegetation types and fuel complexes (Lawson 1972, Quintilio et al. 1977, Stocks 1977, Alexander 1982). These experiments require measurements of prefire and postfire fuel complexes, weather conditions, and fire behavior characteristics. Empirical relationships derived from these observations can be used to predict rate of spread (Van Wagner 1973b, Quintilio et al. 1977), duff consumption (Van Wagner 1972) and conditions for the start and spread of crown fires (Van Wagner 1977).

Mathematical Modelling Approach

An alternate approach to predicting fire behavior emphasizes relationships derived from the study of fire under controlled laboratory conditions (Hottel 1961, Rothermel 1972). The mathematical model derived by Rothermel (1972) is the most comprehensive to date. Fire characteristics including rate of spread and intensity are predicted by equations utilizing numerous fuel and environmental variables. The United States Forest Service has measured fuel variables in common vegetation types to develop fuel models for input into the equations (Albini 1976, Deeming et al. 1977). Graphs (Albini 1976, Rothermel 1983) and hand calculators (Burgan 1979) use the Rothermel equations to predict fire behavior for fuel models under variable weather conditions.

The Rothermel model works well to predict fire behavior in single level fuel types such as grasses, shrubfields and slash (Andrews 1980). However, the equations represent only those fires that are contiguous to the ground in a single uniform stratum where fine fuels carry the flame and spotting does not occur (Rothermel 1972). Thus, there are limitations for predicting fire behavior in northern forests where crowning, spotting and massive wind turbulence may occur (Van Wagner 1971, 1983).

Fire Behavior Potential in Rocky Mountain Forests

Numerous studies have evaluated fire behavior and control potential for vegetation types similar to those in BNP. Table 6 summarizes rate of spread, surface fire intensity, crown fire potential and resistance to control ratings from selected studies (Barrows 1951, Grigel et al. 1977, British Columbia Ministry of Forests 1979, Hawkes 1979). Differences in evaluation procedures and fuel conditions make overall comparisons difficult.

Ease of ignition, evaluated on the basis of fire occurrence (Barrows 1951) or the Canadian Fire Danger Rating System (British Columbia Ministry of Forests 1979) shows that grass fuels in the understory facilitate ignition. Similarly, fires in forest types with high grass cover tend to spread the most rapidly. Surface fire intensity is often evaluated as highest in mature spruce-fir forests that have high downed wood biomass (Hawkes 1979). In addition, the British Columbia Ministry of Forests (1979) rates the crowning potential as extreme in spruce-fir forests compared to other forest types.

Table 6: Summary of selected studies on fire behavior and control characteristics in forests.

Reference, Location	Forest Type	Fire Behavior/Control Characteristic: Ease of Ignition	Rate of Spread		Surface Fire Intensity	Crowning Potential	Resistance to Control	
Barrows (1951), Montana, Idaho	Douglas-fir	extreme	extreme		-	-	-	
	lodgepole pine	moderate	high		-	-	-	
	subalpine	high	low		-	-	-	
	fir/larch	low	moderate		-	-	-	
British Columbia Ministry of Forests (1979), British Columbia	lodgepole pine/litter	very easy	fast		high	moderate to high	moderate to high	
	lodge pine-Douglas fir/grass	moderately easy	very fast		high	high	high	
	lodgepole pine-spruce-fir/litter	moderately easy	fast		high	moderate to high	high	
	spruce-fir/moss	moderate to easy	very fast		extreme	extreme	extreme	
			spring/fall	summer			spring/fall	summer
Grigel et al. (1977), Waterton Lakes National Park, Alberta	deciduous	-	high	low	-	-	low	low
	lodgepole pine	-	extreme	extreme	-	-	high	high
	open conifer	-	extreme	high	-	-	low	low
	mixed pine-spruce-fir	-	high	high	-	-	moderate	low
Hawkes (1979), Kananaskis Provincial Park, Alberta	60 year old lodgepole pine, little downed wood	-	low		low	low	moderate	
	90-120 year old lodgepole pine, little downed wood	-	moderate		low	moderate	moderate	
	150-300 year old lodgepole pine-spruce, much dead wood	-	high		moderate	moderate	high	
	300+ year old spruce	-	high		high	moderate	high	
	300+ year old spruce-fir-larch (upper subalpine)	-	low		low	moderate	low	

Fire History

Fire history studies provide information on frequencies, sizes and intensities of past fires (Arno and Sneck 1977, Stokes and Dieterich 1980). Many researchers utilize tree ring counts from cross-sections, wedges, or increment cores from live trees, snags, stumps, and downed logs to estimate years when fires occurred (Heinselman 1973, McBride and Laven 1976, Arno and Sneck 1977, Johnson 1979, Tande 1979, Hawkes 1979). Chronologies for fire scars and tree ring widths from sample trees should be plotted and cross-dated to improve dating accuracy (Arno and Sneck 1977, Stokes 1980).

Analysis of fire year information can follow approaches similar to life table demographic techniques introduced by Pearl (1928). Where multiple fires can be dated in sample stands, analysis focuses on the length of intervals to evaluate fire frequency (Rowe et al. 1975, Johnson 1979). The technique is analogous to deriving life tables from a known age at death. Alternatively, the time since fire on sample points can be used to determine fire frequencies (Van Wagner 1978). This method of analysis is particularily useful in northern forests where high fire intensities may eliminate evidence of multiple fires (Yarie 1981), and is similar to constructing life tables from the age-class structure of a population.

Fire history information for the northern Rocky Mountains (Idaho, Wymong, Montana and Canada) is available from both fire interval and time since fire analyses. Results from both approaches are presented here.

Fire Intervals

Fire history information in the northern Rocky Mountains, reviewed by Arno (1980), has emphasized mean fire intervals (average time between fires) for small (approximately 40 ha) stands. Table 7 shows pre-European era mean fire interval estimates for forest types similar to those found in BNP.

Low elevation montane forests of Douglas-fir and lodgepole pine have relatively short mean fire intervals of usually less than 40 years (Table 7). The higher frequency of fire can be attributed to a warm/dry climate with long periods of favorable burning conditions (Tande 1979, Arno 1980). Also, native peoples utilizing these areas may have started many fires in the pre-European period (Arno 1980, Barrett 1980). Many historic fires in montane areas were low intensity surface burns that did not kill all trees (Tande 1979, Arno 1980, Davis *et al*. 1980, Fisher and Clayton 1983).

Upper subalpine forests, commonly dominated by Engelmann spruce and subalpine fir, may have long mean fire intervals exceeding 300 years (Table 7). Arno (1980) states that small fires of low to moderate intensity were the most common in upper elevation forests.

Table 7: Mean fire intervals (years) for small forest stands (approximately 40 ha) in northern Rocky Mountains of United States and Canada

	Forest Type			
Reference Location	montane Douglas-fir	montane lodgepole pine	lower subalpine lodgepole pine	upper subalpine spruce-fir lodgepole pine
Arno (1980) Montana	13[a] 26[b]	22[a] 40[b]		63
Arno and Gruell (1983), SW Montana	35-40			
Gabriel (1976), Montana		40		
Hawkes (1980), Alberta			101	304
Houston (1973), NW Wyoming	22			
Romme (1980), NW Wyoming				300
Tande (1979), Alberta	18	27	74	

[a] southern Bitterroot Valley
[b] northern Bitterroot Valley

Emphasis on mean fire intervals in the Rocky Mountains has precluded detailed analysis of the frequency distributions of intervals. In contrast, Rowe _et al_. (1975) and Johnson (1979) have investigated fire interval distributions for Canadian boreal forests. By evaluating the fit of fire interval data to Weibull and negative exponential distributions, assumptions on stand flammability with time can be made (Johnson 1979).

Time Since Fire

As Harper (1977) observes, "the past population dynamics of a forest may be inferred from the age structure of the present population." Thus, a useful method to determine the historic frequency of stand regenerating fires is to evaluate age-class (time since fire) distributions, often available from forest inventory data (Van Wagner 1978, Suffling 1980, Yarie 1981). Where fires of lower intensity occur, fire scars can be used to estimate the time since fire (Van Wagner 1978).

Figure 4 illustrates forest stand age distributions of four areas in Alberta's Rocky Mountains derived from Mackenzie (1973), Tande (1977), Van Wagner (1978) and Hawkes (1979). The low percentage of stands in the young (0-40 year) age class in the four areas studied may be attributed to fire suppression efforts begun in the 1900's. Byrne (1964) and Day (1972) state that the high percentage of Canadian Rocky Mountain stands in the 40 to 80 year class is the result of abnormally widespread fires caused by Europeans about 1900. However,

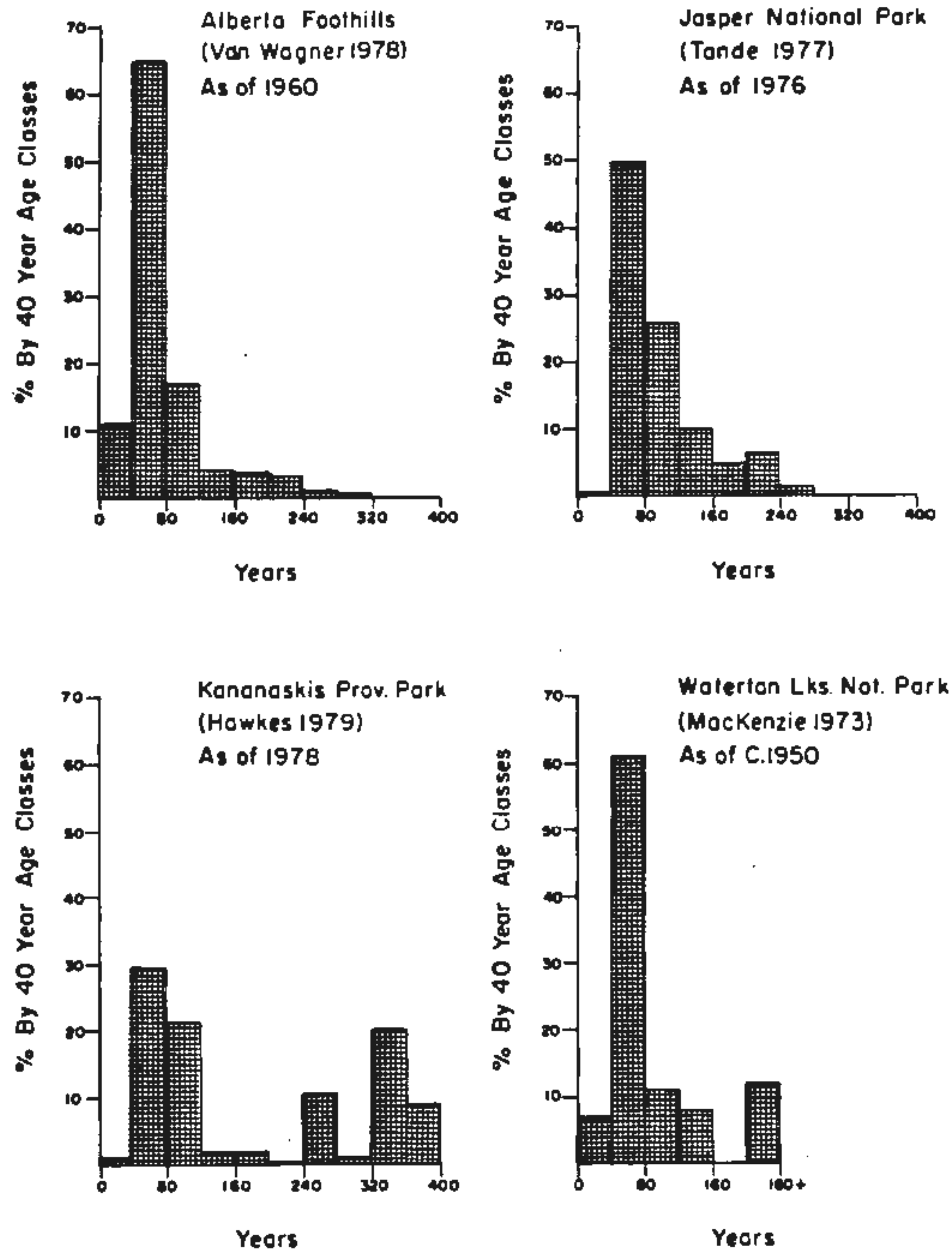

Figure 4: Stand age distributions from selected studies of Alberta Rocky Mountain and foothill forests.

MacKenzie (1973) points out that this interpretation may be incorrect because later burns could have eliminated much evidence of earlier widespread fires. The Kananaskis stand age structure (Figure 4) is not similar to other locations. Hawkes (1979) concludes that the bimodal stand age distribution results from grouping lower subalpine forests that have had frequent fires with old high elevation forests with a low fire frequency (see Table 7).

Van Wagner (1978) shows that if flammability remains constant with stand age, the fire climate remains relatively equal from year to year, and ignition occurs randomly, the time since fire distribution will fit a negative exponential curve. The Alberta foothill forest's age structure (Figure 4) as of 1915 (the beginning of fire suppression activities) closely approximates this distribution (Van Wagner 1978) with an annual probability of burning (p) of .02. The mean age of the foothill stands as of 1915 was 50 years (or 1/p) and equals the average fire interval or what Van Wagner calls the "fire cycle"--the number of years required to burn over an area equal to the whole area of the forest. Some areas may burn more than once during the time of a cycle. Assuming a negative exponential distribution, 36.8% of the stands should escape burning for a period longer than the fire cycle, thus exceeding the mean stand age.

The negative exponential age-class distribution has long been recognized as applicable to biological populations with a constant rate of mortality independent of age (Pearl 1928). In contrast, Yarie (1981) uses Weibull functions to represent age-class distributions of Alaska spruce forests where flammability (and hence fire-caused mortality) may be dependent on age.

Fire and Biomass Interaction

One-way effects of fire on biomass or fire on fire behavior potential have been evaluated by numerous researchers (as reviewed above). Integrated approaches emphasizing the two-way relationships between biomass and fire behavior/history are few (Martin et al. 1979). Olson (1981) proposes that in many ecosystems, the biomass and fire inter-relationship may, in the long term, yield an equilibrium where "frequent fires with low fuel availability and hence low CO_2 (biomass) release per fire may give nearly the same product as lower frequency multiplied by higher average CO_2 (biomass) release per fire." In other words, the product, (frequency) x (biomass released), may be relatively constant in a given forest type despite wide variability in fire frequencies, severities and intensities.

In concurrence with Olson's hypothesis, many researchers of Rocky Mountain forests believe that short fire intervals favor low intensity understory fires whereas longer intervals usually result in stand-replacing fires of high intensity (Habeck and Mutch 1973, Tande 1977, Martin et al. 1979, Fisher and Clayton 1983). Unfortunately, quantitative information on this relationship is limited. Martin et al. (1979)

observe that in the intermountain region of the United States "the frequency of fire affects the severity of fire in that less fuel build-up of material greater than 3 inches (7.6 cm) occurs on short fire cycles than on long cycles."

Similarly, observations on the influences of biomass on fire history (e.g. probability of burning) are also relatively limited for Rocky Mountain forests. Habeck and Mutch (1973) state that "a physical deterioration over time is often the factor that finally induces high flammability in lodgepole pine, spruce and north-slope communities in the Northern Rocky Mountains." In Yellowstone National Park, Romme (1980) found that fire-free intervals of over 300 years were required to permit downed wood biomass to accumulate to a level that would sustain another fire. In contrast, Van Wagner's (1978) study of Alberta foothill forests (reviewed above) indicates that stand age may not have influenced the historical probability of burning. Forest stands in this area appear to burn randomly with a probability of burning that remains constant with stand age.

Thus, for the northern Rocky Mountains, information is not adequate enough to develop relatively holistic models of the interaction between fire and biomass. However, for the mixed-conifer communities of Yosemite National Park van Wagtendonk (1972) developed a computer model that simulates interactions between fire intensity, fire frequency and biomass (measured as total fuel energy). The model incorporates several subsystems including: biomass accumulation and decomposition, lightning ignitions, weather conditions and fire behavior/energy release. Biomass and fire behavior potential can be predicted with the model for various management strategies such as no fire suppression, complete fire suppression, or a prescribed burning program.

CHAPTER 4

METHODS

Methods of study were designed to gather and evaluate biomass, fire behavior potential and fire history information over a broad range of closed forest areas in Banff National Park.

Sample Plot Location and Layout

The Ecological (Biophysical) Land Classification of Banff and Jasper National Parks (Holland and Coen 1982) provided the mapping scheme for locating plots. The land classification recognizes 124 ecosite types (map unit types) each representing a unique combination of parent material, landform, soil and vegetation conditions (Appendix A). Several factors guided sample plot location:

1) plots were located in at least 2 ecosites for each of 70 ecosite types that are composed mostly of closed forest;

2) ecosites throughout the park were selected for sampling to provide park-wide information;

3) wherever possible, a range of stand ages was sampled; and

4) sample ecosites were located relatively accessible to roads, trails and backcountry cabins for logistical reasons. These criteria were used to select tentative sample ecosites on air photographs prior to each of two field seasons.

When the general plot location was reached on the ground, field crews chose an exact plot site to represent stand conditions. Plot layout (Figure 5) was based upon McRae et al. (1979). The triangular shape minimizes sampling biases due to possible downed wood arrangement on slopes or with direction of windfall. Plot size and layout did not vary with stand conditions; a standard plot minimized field crew errors and increased efficiency.

Data Collection and Calculation

Site Information

In the northern Rocky Mountains, site variables such as aspect, elevation and slope may have significant effects on biomass production (Krajina 1970, Pfister et al. 1977), fire behavior potential (Grigel et al. 1971, British Columbia Ministry of Forests 1979) and fire history (Arno 1980). At each plot field crews obtained information for the following site descriptors:

1) Elevation (meters) - Contours on National Topographic Series 1:50,000 scale maps provided elevation above sea level.

2) Slope (degrees) - Clinometers were used to measure slope angle to the nearest degree.

3) Cosine of aspect - Plot aspect (as measured to the nearest degree by compass) was transformed using an equation similar to that presented by Beers et al. (1966):

$$A' = \cos (A - A_{max})$$

where A is the measured azimuth and A_{max} is the azimuth of coolest and/or wettest conditions. This value was assumed to be in the northeast

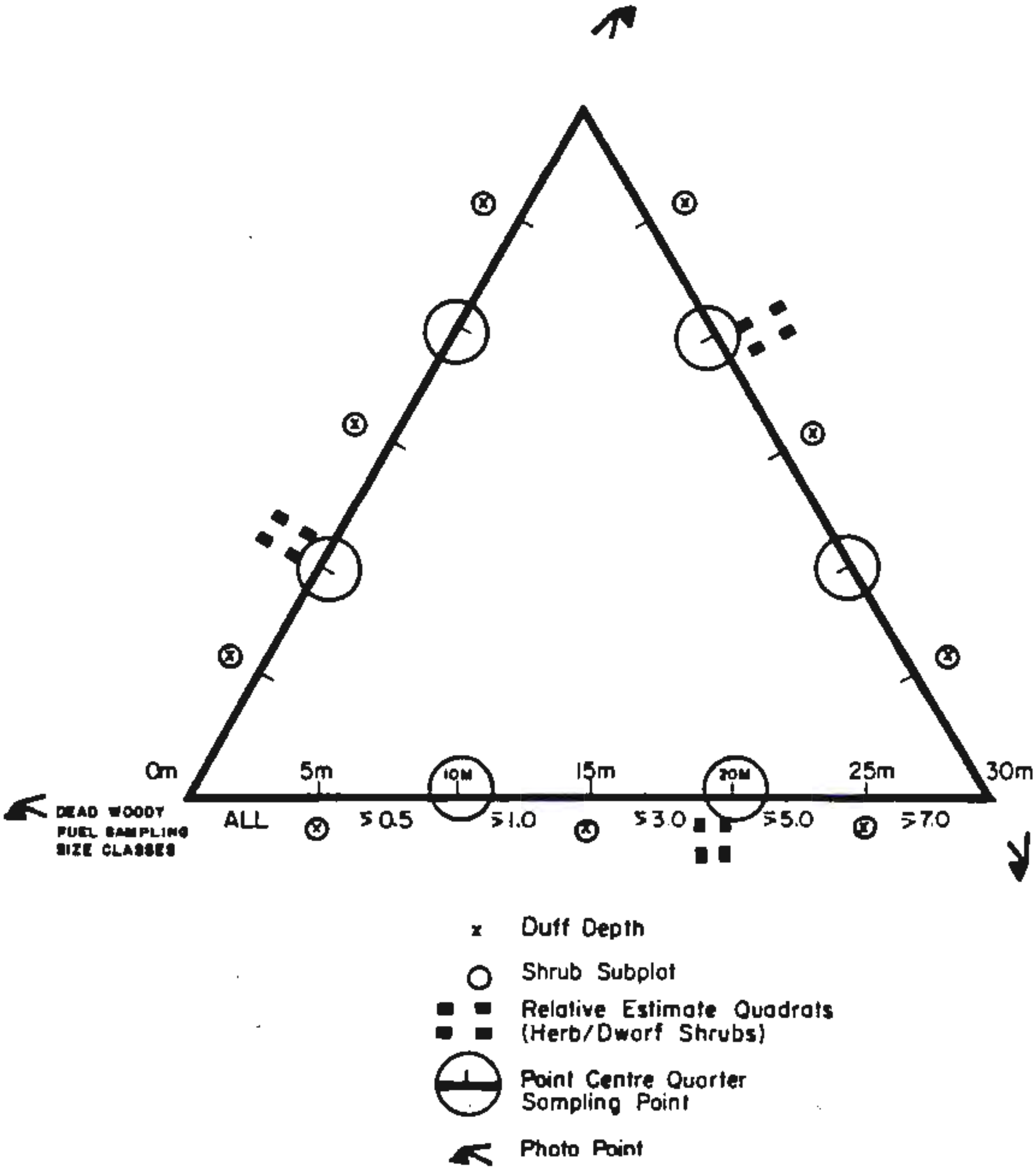

Figure 5: Biomass sample plot layout.

quadrant at 45° (Beers _et al._ 1966). The resulting variable (A') is in the range of -1.0 to 1.0 with negative values indicating southern warm/dry aspects, and positive values indicating northern cool/moist aspects.

4) Vegetation Type - Crews recorded coverage percentage of vegetation species (within the plot triangle). The vegetation type (Table 1) was obtained from the key provided by Holland and Coen (1982).

5) Hygrotope - A moisture regime value (Table 8) was recorded (Walmsley _et al._ 1980) for each sample plot based upon the vegetation type description (Holland and Coen 1982).

In addition, field crews determined Universal Transverse Mercator location coordinates from National Topographic series maps and took photographs along sample lines from each corner of the plot triangle (Figure 5).

Fire History Information

This study required detailed fire history information for each sample plot to evaluate potential fire and biomass interactions. Thus field crews collected increment cores, cross sections and wedges from live trees, snags, stumps and downed logs within a radius of approximately 250 m around the plot triangle similar to methods described by Tande (1977, 1979), Arno and Sneck (1977), and Hawkes (1979, 1980). As Arno and Peterson (1983) observe, mean fire intervals decrease as the area of fire history sample stands is increased. Larger stand areas increase the probability of more historic fires occurring within sample

Table 8: Hygrotype (ecological moisture regime) classes (Walmsley *et al.* 1980) described for Banff National Park by Holland and Coen (1982)

Value	Class	Usual Soil Drainage
1	xeric - very dry, little precipitation or high evapotranspiration, very low available water storage capacity (AWSC)	very rapid
2	subxeric - dry, low AWSC	rapid
3	mesic - moist, intermediate to high AWSC	well to moderately well
4	subhygric - moist to wet, variable AWSC, seasonal seepage	imperfect
5	hygric - wet, variable AWSC, permanent seepage	poor
6	subhydric - wet, variable AWSC, excess water most of time	very poor
7	hydric - very wet, standing water	-

units. The size of sample units in this study (approximately 20 ha) is appropriate for fire history sampling in lodgepole pine and Oouglas-fir forests where fire-scarred trees and other evidence may be scattered (Arno and Peterson 1983).

Wherever possible, wedges of fire-scarred trees were obtained. However, determining the date of the last fire year in even-aged lodgepole pine stands with no fire scars often required counting rings on cross sections obtained from trees at 30 cm above ground and adding 8 years (derived from data in Hamer and Herrero 1983). In even-aged stands with snags and deadfall, the second to last fire year could be estimated by counting rings on several logs or snags, adding 8 years, and subtracting this figure from the last fire year. Errors with this method occur due to weathering of outer rings, rot, and difficulties in determining which fire killed the tree (Hawkes 1980). In old forests dominated by white spruce, Engelmann spruce or subalpine fir where no fire-scar evidence was found, 30 years were added to the oldest ring counts obtained to approximate the origin year of these unevenly-aged stands.

Rough estimates of fire history in the field were refined in the lab by sanding and staining samples, preparing a master chronology, and cross-dating to fire scars from nearby sample plots (Arno and Sneck 1977). A study by Hamer and Herrero (1983) in the Cascade Valley north of Banff townsite provided additional fire history information. Also, park records, newspaper clippings and old photographs (White 1984) helped date BNP fires since 1880.

Fire history information provided values for the following descriptors for each plot:

1) Fire intervals (years) - Where two or more fires could be dated for a sample plot, fire intervals were calculated for each period between fires.

2) Time since fire (years) - Values of time since fire (or stand origin where no fires could be dated) were calculated for each plot as of 1980, 1930 and 1880.

3) Fire intensity/severity index (unitless) - Whenever possible a historical fire intensity/severity index value for past fires was estimated from the amount of trees surviving burns (Kessell 1979) where 1 = no survival of trees, 2 = 5-50% of trees survived, 3 = 51-95% of trees survived, and 4 = trees only scarred.

4) Stand age (years) - The time (as of 1980) since stand origin or the last fire (with an intensity/severity index greater than 3) was calculated for each plot. This value represents the age of the majority of dominant trees within the plot.

5) Mean fire-free interval (years) - To compare plots with dateable fires to a limited number of plots with little or no fire evidence, the mean fire-free interval was calculated for each plot. This value equals the 1980 time since fire (or stand origin) averaged with any fire intervals determined for the plot.

Crown Layer Information

The crown layer is a major component of biomass in Rocky Mountain forests (Brown 1978, Hawkes 1979). Crown layer characteristics such as tree density, bolewood biomass, and foliage biomass may strongly influence biomass characteristics in the surface and ground layers (Alexander 1979). Fire behavior can also be substantially controlled by crown layer characteristics such as height to live crown, and foliage bulk density (Van Wagner 1977). In this study all live trees greater than 7 cm basal diameter were considered to form the crown layer. The point-centered quarter method (Cottam and Curtis 1956) was the basis for gathering tree information with six sample points located at 10 m and 20 m on each triangle side (Figure 5). The following information was recorded in the field for each closest tree in each quarter (n = 24): distance to tree center, species, diameter at breast height (DBH), condition class (dominant, intermediate, suppressed), height to live crown, height to dead crown and total height.

Measurements were used to calculate values for several crown descriptors:

1) Tree density (stems/ha) - The method described by Cottam and Curtis (1956) and Mueller-Dombois and Ellenberg (1974) was used to calculate tree density from point-centered quarter distance measurements.

2) Stand basal area (m^2/ha) - By multiplying the average basal area of the sample trees by stand density, the stand basal area was derived.

3) Foliage biomass (t/ha) - Regression equations (Brown 1978) were used to estimate foliage weight for each sample tree based on DBH, condition class and live crown length. Foliage biomass was obtained by multiplying average foliage weight of sample trees by stand density.

4) Foliage and branchwood biomass (t/ha) - Regression equations (Brown 1978) were used similarly to the procedure for calculating foliage biomass.

5) Bolewood biomass (t/ha) - A weighted mean DBH was calculated from the average basal area of sample trees. Regression equations for prairie province trees (Singh 1982) were used to determine the average tree bolewood (stump and stem greater than 2 cm diameter) weight from the calculated DBH value. Stand bolewood biomass was derived by multiplying average tree bolewood weight by stand density. This method is similar to that described by Madgwick (1971) and Parde (1980).

6) Height to live crown (m) - The average of all sample trees height to a continuous layer of branches with live foliage was calculated.

7) Height to dead crown (m) - The average of all sample trees height to a continuous layer of dead branches was calculated.

8) Foliage bulk density (kg/m^3) - Foliage biomass was divided by average live crown length to obtain foliage bulk density (Van Wagner 1977).

Surface Layer Information

Components measured in the surface layer include downed wood, herbaceous plants, dwarf shrubs, shrubs, and tree regeneration (less than 7 cm basal diameter). These components may constitute a significant portion of biomass in some Rocky Mountain forests (Hawkes 1979, Brown et al. 1982), and influence fire behavior (Rothermel 1983). Values were determined for the following surface layer descriptors:

1) Herb/dwarf shrub biomass (t/ha) - The relative weight estimate technique (Hutchings and Schmautz 1969, Brown et al. 1982) was used to evaluate herbaceous plant and dwarf shrub biomass. Field crews placed quadrats at 20 m on each plot side (Figure 5). Clipped material was placed in marked paper bags and oven-dried at 100°C for 24 hours before weighing.

2) Herb/dwarf shrub cover (%) - An ocular estimate was made of herb/dwarf shrub cover within the plot triangle.

3) Shrub biomass (t/ha) - Shrub biomass (including tree regeneration less than 7 cm diameter at ground height) was determined by tallying stems by basal diameter class and species within 9 circular 1 m^2 subplots at the 4, 15 and 25 m marks on each plot side (Figure 5). Biomass was calculated from stem counts using equations developed by Brown (1976) and Kessell (1979).

4) Shrub cover (%) - An ocular estimate was made of shrub and tree regeneration cover within the plot triangle.

5) Downed wood biomass (t/ha) - Downed wood was tallied along each 30 m plot side with the line intercept method (Van Wagner 1968,

Brown 1974) using Canadian size classes and methods described by McRae et al. (1979). Constants utilized in calculations included the theoretical quadratic-mean diameter for each size class[1], specific gravities (USDA Forest Service 1974 and Brown 1974), and the non-horizontal correction factors described by Brown and Roussopoulos (1974). For descriptive purposes, downed wood biomass was broken into two groups: fine materials including all size classes less than 3 cm in diameter, and coarse materials including all size classes greater than or equal to 3 cm diameter.

Ground Layer Information

Substantial biomass may accumulate in the ground layer of northern and Rocky Mountain forests (Kiil 1968, Kiil unpublished, Hawkes 1979, Viereck and Schandelmeier 1980). Organic material in the ground layer may constitute a significant portion of fuel consumed by fire (Van Wagner 1972). To gather information on this layer, field crews measured depths of the litter, moss, fermentation (F) layer, and humus (H) layer at the 5, 15 and 25 m marks on each triangle side (n = 9). Values were obtained for several ground layer descriptors:

1) Moss cover (%) - An ocular estimate was made of the moss cover within the plot triangle.

2) Moss biomass - Average moss depth was converted to biomass assuming an oven-dry bulk density of 15.44 kg/m^3 as determined by Kiil (1968) for Alberta lodgepole pine stands.

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[1] Personal written communication from C. E. Van Wagner, Canadian Forestry Service May, 1980.

3) Litter cover (%) - An ocular estimate was made of litter cover (needles and dead leaves) within the plot triangle.

4) Litter biomass - Average litter depth was utilized to calculate biomass based on an oven-dry bulk density of 27.35 kg/m^3 measured by Kiil (unpublished) in Alberta lodgepole pine forests.

5) Duff depth (cm) - The average duff depth was calculated from F and H layer depth measurements.

6) Duff biomass (t/ha) - An estimate of 116.99 kg/m^3 was derived from the bulk density of oven-dried duff (F & H layers) from data in Kiil (unpublished) for Alberta lodgepole pine forests. Duff biomass was calculated from the average of duff depth measurements.

Fire Behavior Potential

An important element of this study was to evaluate fire behavior potential at each sample plot. This information is essential to assess the potential inter-relationship between biomass and fire. For example, variables such as surface fire intensity and crown fire potential influence the degree of fire-caused plant mortality and the consumption of organic matter (Anderson 1968, Wellner 1970, Van Wagner 1972, Wein and MacLean 1983). In addition, park managers require information on fire resistance to control for planning purposes. In this study, evaluation of fire behavior potential and resistance to control emphasized use of empirically based relationships and keys. The following descriptor values were obtained for each sample plot:

1) Resistance to handline construction rating (unitless) - A measure of fire resistance to control was obtained by rating sample plots for potential handline construction rates with a key developed for Alberta forest conditions by Murphy and Quintilio (1978). The resistance rating is increased by deep duff, high shrub cover, dense stands and high quantities of logs, roots and rocks. Murphy and Quintilio (1978) calibrate the resistance to control value obtained with the key to an estimate of meters of fire line constructed per person per 45 minute hour (Table 9).

2) Rate of spread rating I (unitless) - A decision key for describing potential rate of spread for surface fires (Fahnestock 1970) was utilized. To obtain key values nine 1 m^2 subplots at the 5, 15 and 25 m marks on each triangle side were visually evaluated for fine fuel size, shape, compactness, vertical position and horizontal continuity. A mean plot value was then calculated. Table 10 provides rates of spread estimates (m/min) for key values calculated by Fahnestock (1970) using the Rothermel (1972) fire model.

3) Rate of spread rating II - An additional indicator of potential surface fire rate of spread was the biomass (t/ha) of fine (<3 cm diameter) litter, herb/dwarf shrubs, shrubs, and downed wood similar to the method used by Hawkes (1979). The quantity of fine materials is an important determinant of rate of fire spread (Fahnestock 1970, Rothermel 1972, Van Wagner 1983). Fine material quantities were totalled from biomass estimates described above.

Table 9: Rates of line construction (meters/45 min. h/person) for resistance to handline construction key values (Murphy and Quintilio 1978)

Value	Rate of Handline Construction (m/45 min. h/person)	Value	Rate of Handline Construction (m/45 min. h/person)
1	140	15-16	9
2	70	17-18	8
3	47	19-22	7
4	35	23-27	6
5	28	28-32	5
6	23	34-48	4
7	20	49-62	3
8	17	>62	2
9	15		
10	14		
11	13		
12	12		
13	11		
14	10		

Table 10: Rates of spread estimated by Fahnestock (1970) for rate of spread key values

Rate of Spread Key Value	Estimated Rate of Spread (m/min.)
100	2.28
18	.42
6	.13
4	.09
3	.07
2	.05
1	.01
<1	.00

4) Surface fire intensity rating - Potential surface fire intensity was rated by calculating the ground and surface biomass (t/ha) available for burning by the advancing fire front. Biomass available was assumed to be 70% of fine materials (<3 cm diameter) and 40% of coarse materials (≥3 cm diameter). These figures are similar to weight losses reported by Quintilio *et al.* (1977) during a prescribed burn in a jack pine forest. An additional 7.1 t/ha of duff was also assumed to be available from the equation presented by Van Wagner (1972):

$$W = 1.09 + .0473\ DMC \qquad (1)$$

where duff consumption by fire, W (kg/m^2), is related to the Duff Moisture Code (DMC) of the Canadian Forest Fire Weather Index (Van Wagner 1974). A DMC value of 38 was used which represents the lower boundary of the upper 15% of Banff weather station's fire weather index observations for the period 1957-1966 (Simard and Valenzuela 1972).

The sum of 70% of fine materials, 40% of coarse materials, and 7.1 t/ha of duff is only a crude indicator of potential surface fire intensity. A better measure would require predictions of rate of spread (R, m/s), weight of organic matter consumed by the advancing fire front (W, kg/m^2), and the net heat of combustion of organic material (H, kJ/kg) to calculate fire intensity (I, kW/m) by the equation (Byram 1959):

$$I = RWH \qquad (2)$$

However, assuming equal rates of spread and heat content of organic matter in sample plots, the available biomass indicator is useful for comparing potential surface fire intensities between plots.

5) Crown fire potential rating (unitless) - The key developed by Fahnestock (1970) was used to assess potential for crown fire based upon crown layer characteristics such as foliage density and ladder fuels. The values obtained range from zero to 10 where 0 indicates no potential for crown fires, and 10 indicates maximum crown fire potential.

6) Rate of spread required to initiate crown fire (m/min) - Another indicator of crown fire potential was obtained from the relationship proposed by Van Wagner (1977):

$$Io = (Czh)^{3/2} \qquad (3)$$

where Io (kW/m) is the critical surface fire intensity needed to initiate crowning, C is an empirically derived constant that was assumed to equal 0.010 (Van Wagner 1977), z(m) is the height of live crown, and h (kJ/kg) is the heat of ignition of the live crown, or approximately 3060 kJ/kg at 100% foliage moisture (Van Wagner 1977). For each sample plot, the critical intensity to initiate crowning (Io) was solved with equation 3 for 100% foliage moisture content and the measured height to live crown. Byram's (1959) fire intensity relationship (equation 2) was then solved for rate of spread required to attain Io assuming a heat of combustion of 18,700 kJ per kg of fuel, and 70% of fine biomass, 40% of coarse biomass and 7.1 t/ha of duff burned (as described above). The calculated rate of spread to initiate crowning provided a measure of crown fire potential based on the relationship between surface and crown layer characteristics. Low rates of spread to initiate crowning suggest high crown fire potential whereas high rates of spread indicate that crown fires would only occur during extreme conditions.

Data Analysis

Sample plot values for site, fire history, biomass and fire behavior potential descriptors were coded for processing on the University of Calgary and Colorado State University computer systems. Data analyses were made with the Statistical Package for Social Sciences, SPSS, (Nie *et al*. 1977, Hull and Nie 1981), and the Biomedical Computer Programs P-Series, BMDP (Dixon and Brown 1979).

Descriptive Statistics by Vegetation Type

Sample plot data were initially stratified into closed forest vegetation types as classified by Holland and Coen (1982). Descriptive statistics obtained for sample plot variables for each vegetation type included means, standard deviations, ranges and frequency distributions.

Classification of Vegetation Types into Fire Groups

Several procedures were utilized to aggregate vegetation types with similar site, fire history, biomass and fire behavior potential into a limited number of "fire groups." Methods of numerical taxonomy such as cluster and discriminant function analysis were emphasized to insure as objective and repeatable approach as possible in the grouping (Sneath and Sokal 1973). Many researchers have jointly used these techniques in natural resource classification problems (e.g. Radloff and Betters 1978, Omi *et al*. 1979, Laven 1982).

Cluster Analysis - Initially, a cluster analysis procedure was conducted with the sample plot means of selected descriptors for each vegetation type. Cluster analysis is a direct numerical method to evaluate potential groupings of units (Turner 1974, Radloff and Betters 1978). Many variations of the method are possible (Sneath and Sokal 1973). In this case, the BMDP-79 P2M subroutine (Engelman 1979) was selected to form clusters with an average distance method. With this procedure, the similarity between vegetation types (j,l) is based on Euclidean distance (d) such that:

$$d_{(jl)} = [\Sigma_i (X_{ij} - X_{il})^2]^{1/2} \qquad (4)$$

where X_{ij} is the value of the i_{th} descriptor for type j.

The program proceeds by first standardizing all variables to Z scores to preserve equal weighting between descriptors. Next, the Euclidean distance is calculated between initial units (vegetation types). The two most similar units (those separated by the shortest Euclidean distance) are amalgamated to form a cluster whose values are the average of the variables of the original units. The process continues, combining the most similar units and clusters until a single cluster is formed.

The BMDP program plots a dendrogram of the process and Euclidean distances between units and clusters at the point of amalgamation. In this study, the dendrogram gave an initial view of which vegetation types were most similar and could be logically combined into fire groups.

Joint Occupation of Ecosites by Vegetation Types - A second step in classifying vegetation types into fire groups was to evaluate joint occupation of ecosites by different vegetation types. The ecosite types mapped by the BNP ecological inventory (Holland and Coen 1982) often hold two or more vegetation types (Appendix A). Thus, to insure easy applicability of the fire group concept to the existing mapping system, closed forest vegetation types that are common joint occupants of ecosites should be in the same fire group. Table 11, derived from the ecological land classification legend (Holland and Coen 1982), shows the number of ecosites on which vegetation types sampled in this study are common or occasional joint occupants. For example, type C6, lodgepole pine/buffaloberry/showy aster, is found commonly on six ecosite types with vegetation type C19, lodgepole pine/buffaloberry/twinflower, and thus should be in the same fire group if possible.

Discriminant Function Analysis - On the basis of the dendrogram from the cluster analysis and the joint occupancy table, preliminary fire groups were determined. Discriminant function analysis (Cooley and Lohnes 1971) served to test the validity of preliminary groupings and to evaluate which variables are the most important in delineating between types. Based on an existing classification of units into groups, discriminant analysis weighs and linearly combines unit descriptors to

Table 11: Number of ecosite types (Appendix A) jointly occupied by closed forest vegetation types (derived from Holland and Coen 1982). The number of ecosites commonly jointly occupied by vegetation types is shown above the diagonal, and the number of ecosites occasionally jointly occupied is shown below the diagonal. The number of ecosites on the diagonal are only occupied by one vegetation type.

Closed Forest Vegetation Type Code

	1	2	3	4	5	6	9	11	13	14	15	16	18	19	20	21	23	24	26	29	30	31	32	33	34	36	37
1						1																					
2					1														1								
3	3		3			3								4													
4				2																							
5														1													
6	2		3		1			1					1	6													
9					1								1	1													
11			1			1							1	2	1					2							
13									1	7						4					3	3					
14									2							5		1			1						
15											4					5	3										
16												1															
18	1		3			3		2	1	1				7	1					4							
19	3		3		2	3	1	3	1	1			4		2					3							
20							1	3	2	2			3	3						2							
21									1		3				1						1						
23											3					4	6										
24																											
26									1										1								
29									2	2			1			1					1						
30									3	1			2		1					1		2					
31									4	3			1	1					1	1	2						
32									2													1	1				
33											1					1						1					
34									1		6					4	2										
36																											
37																											

Number of ecosites commonly jointly occupied (above diagonal)

Number of ecosites occasionally jointly occupied (below diagonal) tors to derive mutually orthogonal functions which provide the greatest contrast between groups. Discriminant functions are defined as:

$$Di = di_1Z_1 + di_2Z_2 + . . . + dipZp \quad (5)$$

where Di is the score for function i, the d's are weighting coefficients, and the Z's are the standardized values of the p descriptor variables (Klecka 1975).

The SPSS computer package (Nie *et al*. 1975) includes a stepwise program to calculate sets of discriminant functions that best delineate between groups with a minimum of input variables (Klecka 1975). In this study, discriminating variables were selected to maximize the overall multivariate F ratio for the difference between groups.

Successive applications of the SPSS program using individual sample plot cases as classified into preliminary fire group combinations helped refine the classification scheme. A test of the validity of each potential grouping was made by checking the number of sample plots correctly classified by the discriminant functions. As recommended by Morrison (1969), a randomly selected group of sample plots was withheld from the calculation of discriminant functions and then later tested for classification success. Ultimately, a final fire group classification scheme was developed which appeared logical from the cluster analysis, grouped vegetation types that are common joint occupants on ecosites, and gave valid discriminant analysis results.

Spatial Analysis of Fire Groups

The relationship of fire groups to BNP vegetation types and ecosites mapping units (Holland and Coen 1982) allowed a meaningful analysis of spatial variability of biomass, fire behavior potential and fire history. Descriptive statistics (mean, range, standard deviation and frequency distribution) were obtained for all descriptors as aggregated into fire groups. Descriptor values approximating a normal distribution were subjected to a one-way analysis of variance to evaluate differences between fire groups.

Fire interval frequencies are commonly skewed to the right (Johnson 1979). Thus, survival analysis techniques (Elandt-Johnson and Johnson 1980) available on an SPSS subprogram (Hull and Nie 1981) were utilized. Survival analysis examines the time interval between two events (e.g. fires), emphasizing the analysis of the survivorship function calculated in the life tables (Pearl 1928). The survivorship function is the proportion of organisms surviving or in this case, the proportion of forest stands remaining unburned to the start of an age class. The function can be derived from either fire interval or time since fire information (see Chapter 3).

In this study, fire intervals of groups were compared with the survivorship functions of life tables calculated for each group. The SPSS subprogram evaluates the significance of differences between groups with the D statistic (Lee and Desu 1972) which is asymptotically distributed as chi-square with the number of groups-1 degrees of freedom.

Temporal Analysis of Fire Groups

Assuming that the spatial variability of biomass, fire behavior potential and fire history is explained by the fire group classification, much of the remaining variability within groups should be the result of time and stand history events. To analyze these processes, closed forest vegetation types were broken down into four groups of successional sequences that are compatible with Holland and Coen's (1982) descriptions (Figure 3) and the fire group concept.

Initially, time since fire as of 1880, 1930 and 1980 and fire interval distributions were plotted for groups. Data from lower subalpine ecosites were weighted to adjust sampling frequency to the area currently occupied by each type in BNP. This analysis was done to see if time since fire distributions have changed with different human use patterns since 1880 (see Chapter 2).

Regression analysis (Draper and Smith 1966), available as an SPSS subprogram (Kim and Kahout 1975), was utilized to analyze relationships within groups between dependent variables (biomass and fire behavior potential descriptors) and independent fire history descriptors (time since fire, intensity/severity index of last fire, and length of the previous fire interval). Additional independent site information descriptors (slope, cosine of aspect and elevation) were utilized to analyze within fire group spatial variation effects. This approach is similar to that applied by Brown and See (1981) to analyze downed wood biomass in Idaho and Montana forests. To further illustrate changes in biomass and fire behavior potential with time, descriptor means were plotted as a function of time since fire for the following classes: young (<50 years), mature (50-149 years), transitional (150-299 years), and old (≥300 years).

Development of a Preliminary Model of Biomass and Fire Interaction

A primary objective of this study was to describe fire and biomass inter-relationships within fire groups. Information derived from the temporal analysis was therefore integrated to present a preliminary graphic model of biomass and fire interaction in BNP closed forests. To develop the model, biomass accumulation curves for ground, surface, and crown layer components were plotted as a function of theoretical fire regimes (frequency, intensity and severity) for the period 1650-2000. Unlike van Wagtendonk's (1972) simulation model of fire and biomass interaction in Yosemite National Park, information for BNP was inadequate to develop mathematical functions of biomass increment and fuel consumption by fires. Therefore, BNP biomass accumulation patterns illustrated by the preliminary model were simply smoothed and extrapolated from the temporal plots of biomass as a function of time since fire (described above).

CHAPTER 5

RESULTS: FIRE GROUP CLASSIFICATION AND SPATIAL ANALYSIS

Field crews sampled 220 plots requiring 19.8 km of downed wood line transects, 660 herb/dwarf shrub collections, 1980 ground layer depth measurements and 5280 tree measurements. In addition, crews cut over 1000 tree cross sections, returning 615 to the office for sanding and detailed pith and fire scar dating. Plots were sampled in most major BNP watersheds (Figure 6). Plot field sheets and photographs are filed at the Banff National Park Warden Headquarters in Banff, Alberta.

Fire Group Classification

Twenty-six closed forest vegetation types were sampled. Descriptive statistics (sample sizes, means, standard deviations and ranges) for site, fire history, biomass and fire behavior potential descriptions broken down by vegetation type are filed at the Banff Warden Office.

Results of Cluster Analysis

To group vegetation types with similar biomass and fire characteristics, a cluster analysis based on the vegetation type means for 22 descriptors was made with the BMDP-2M subprogram (Engleman 1979). Attributes utilized (Table 12) constitute the majority of those measured. Linearly dependent variables were omitted.

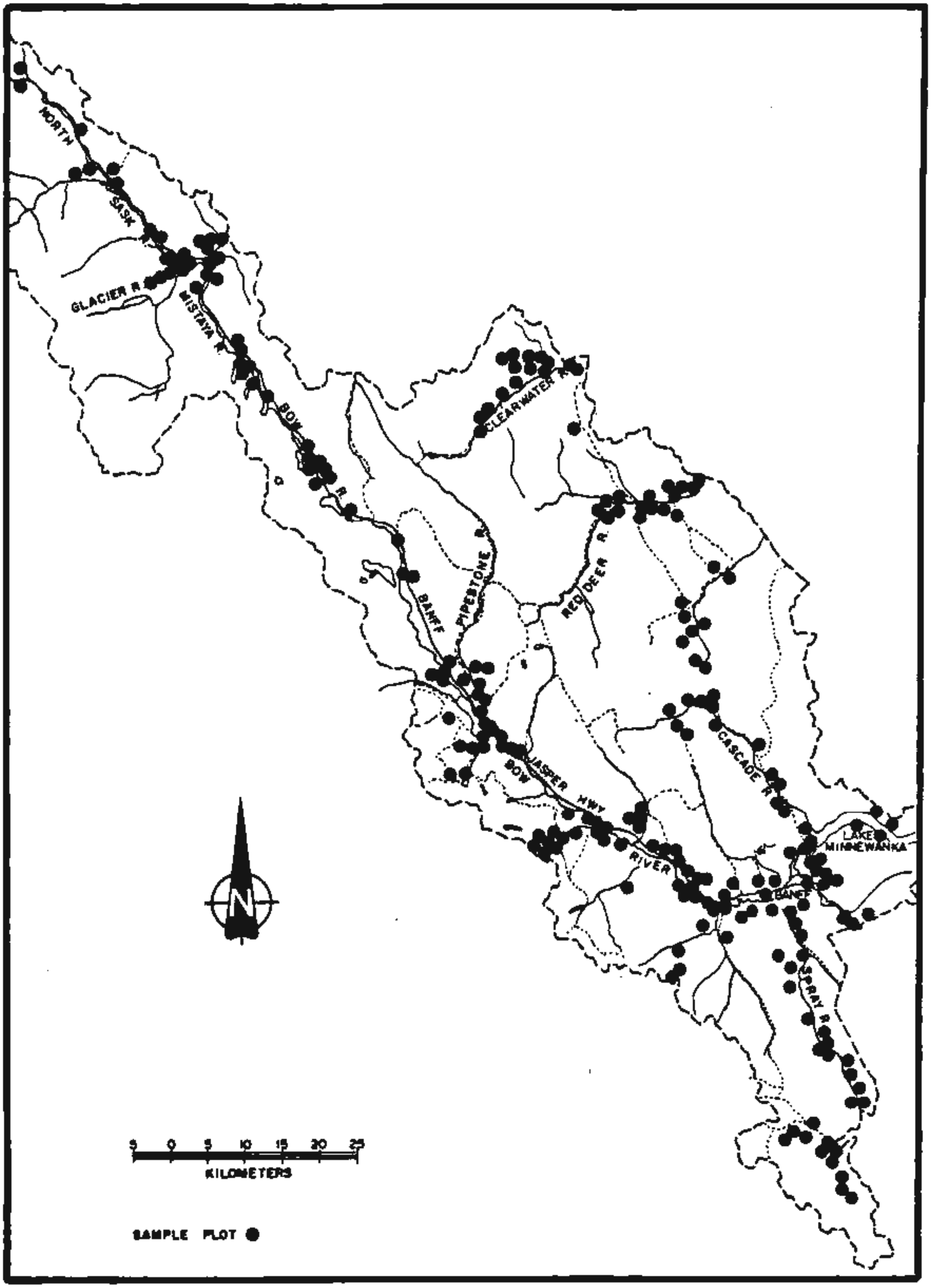

Figure 6: Sample plot locations in Banff National Park.

Table 12: Summarized statistics for descriptors utilized in the cluster analysis of closed forest vegetation types into fire groups.

	Attribute (Units)	Mean	Standard Deviation	Minimum	Maximum
1.	Slope (degrees)	11.22	9.16	0	40.00
2.	Elevation (metres)	1701.23	216.50	1280.00	2240.00
3.	Hygrotope (unitless)	3.12	.84	2.00	6.00
4.	Cosine aspect (unitless)	-.06	.76	-1.00	1.00
5.	Stand age (years)	164.54	106.49	12.00	500.00
6.	Plot mean fire free interval (years)	137.79	104.64	18.00	500.00
7.	Plot mean fire intensity/severity index (unitless)	2.17	1.16	1.00	4.00
8.	Crown foliage biomass (t/ha)	14.99	9.41	0.00	49.20
9.	Foliage bulk density (kg/m^3)	.21	.14	0.00	1.02
10.	Height to live crown (m)	5.81	3.38	0.00	15.00
11.	Height to dead crown (m)	1.62	1.86	0.00	11.20
12.	Herb and dwarf-shrub biomass (t/ha)	.44	.48	0.00	3.07
13.	Shrub biomass (t/ha)	2.01	2.72	0.00	16.84
14.	Coarse downed wood biomass (t/ha)	35.45	34.01	0.00	139.87
15.	Fine downed wood biomass (t/ha)	2.05	1.40	.21	9.75
16.	Litter biomass (t/ha)	2.96	2.46	0.00	16.14
17.	Moss biomass (t/ha)	3.89	3.59	0.00	17.14
18.	Duff biomass (t/ha)	87.26	61.29	8.19	332.28
19.	Resistance to handline construction (unitless)	15.68	7.66	4.00	43.00
20.	Crown fire potential rating (unitless)	4.89	2.15	0.00	9.00
21.	Surface fire intensity	25.43	14.51	9.57	68.06
22.	Rate of spread to initiate crown fire (m/min)	4.86	5.11	0.00	27.77

A dendrogram (Figure 7) illustrates the clustering process. The most similar vegetation types (e.g. C6 and C19) are separated by the shortest Euclidean distance and are clustered first. At Euclidean distance of 4.5, three groups are evident: warm/dry lodgepole pine and Douglas-fir forest types (C1, C9, C6, C19, C3), upper subalpine Engelmann spruce, subalpine fir and larch forest types (C23, C33, C34, C15), and a group of mostly cool/moist lower subalpine forest types of lodgepole pine, Engelmann spruce and subalpine fir (e.g. C29, C11, C18, C20, C13, C14, C31). At Euclidean distances greater than 4.5 several other vegetation types chain into the dendrogram. These types may have extremely different descriptor values (e.g. C3, aspen forests) or have vegetation type means based on a low number of samples (e.g. only 1 sample for C21).

Assessing Potential Groupings in Terms of the Ecological Land Classification

The legend for the ecological land classification (Appendix A) and the joint occupancy table (Table 11) were analyzed to evaluate potential groupings suggested by the cluster analysis. I concluded that the cluster of the warm/dry lodgepole pine and Douglas-fir forest types should be broken down into montane and lower subalpine groups to provide greater resolution. Also, in most cases (Table 11) lower subalpine areas dominated by Engelmann spruce and subalpine fir types (C13, C14, C30, C31) are given a different ecosite classification than lodgepole pine types (C11, C18, C20, C29). For example, C18 and C20 are not commonly associated with C13, C14, C30 or C31 on any ecosites. Thus, a separate fire grouping would be logical.

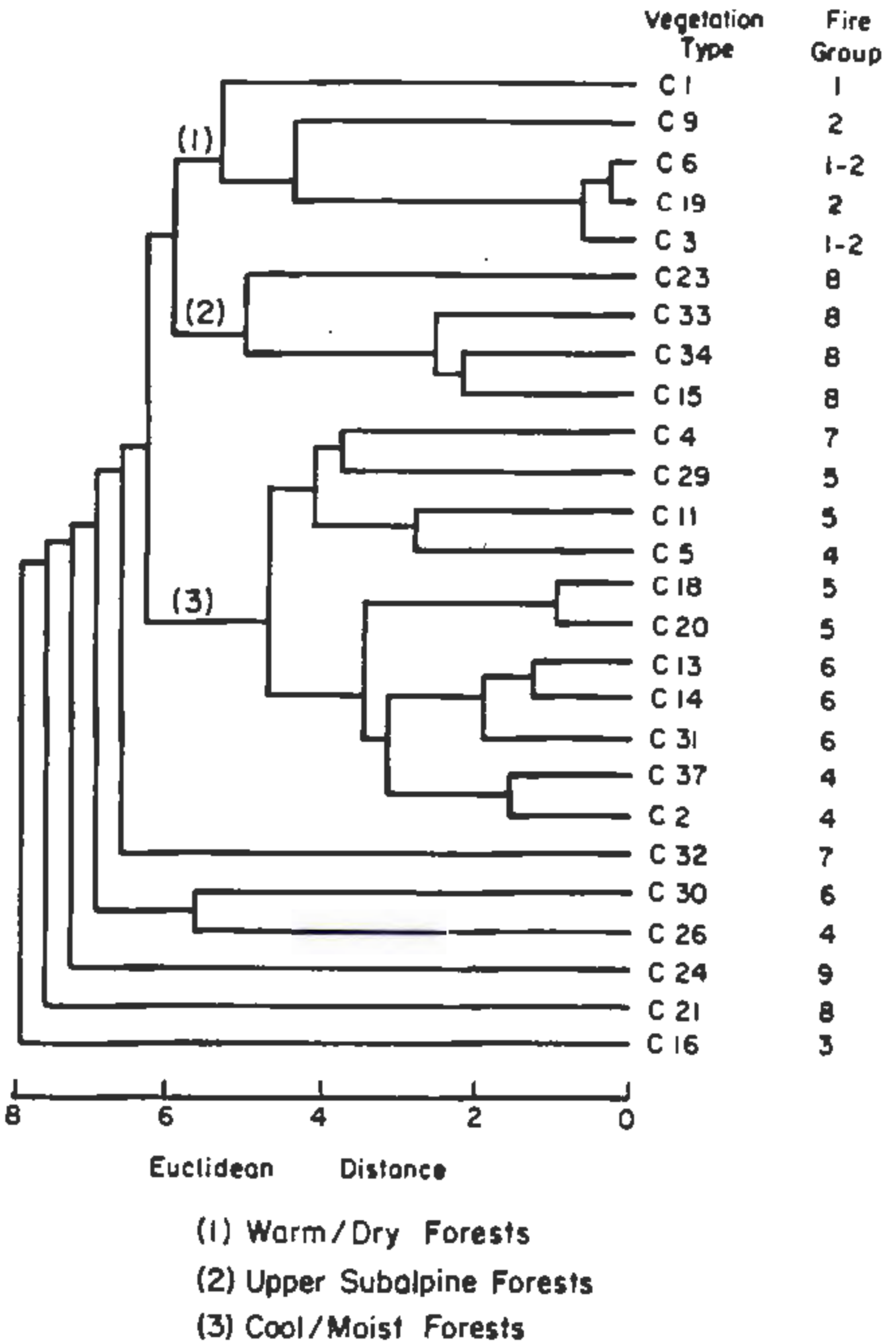

Figure 7: Clustering dendrogram showing relationships of closed forest vegetation types. The fire group classification is also shown.

Results of Discriminant Analysis

Several potential fire group classifications were tested and refined with the SPSS stepwise discriminant analysis program (Klecka 1975). The procedure selected an optimal set of discriminating variables from site, fire history, biomass and fire behavior potential descriptors that gave the greatest F ratio between group centroids. Linear combinations (discriminant functions) were then calculated with the reduced set of variables that maximize the separation between groups. Successive linear functions on orthogonal axes further separate the groups. Function scores were then calculated for each plot and used to predict group membership. The best classification should minimize the number of misclassified cases.

After several potential groupings were tested, a final classification of the 26 vegetation types into 9 fire groups was selected (Table 13). The results of the discriminant analysis procedures discussed below apply to this grouping.

A set of 142 sample plots was selected randomly to derive the discriminant functions. The remaining sample plots were held back to test classification success (Morrison 1969). Table 14 lists the set of descriptors selected and their standardized coefficients for 4 statistically significant discriminant functions. The first function is the most important, accounting for 51% of the discrimination. Elevation, hygrotope and moss cover are the best discriminating variables (highest

Table 13: Classification of closed forest vegetation types into fire groups

Fire Group	Description	Closed Forest Vegetation Types
1	Warm/dry montane lodgepole pine and Douglas-fir (w/d mon)	C1, C3, (montane), C6 (montane)
2	Warm/dry lower subalpine lodgepole pine (w/d ls pine)	C3 (lower subalpine), C6 (lower subalpine), C9, C19, C36
3	Montane aspen (mon asp)	C16
4	Mesic montane spruce and Douglas-fir (mes mon)	C2, C5, C26
5	Cool/moist lower subalpine lodgepole pine (c/m ls pine)	C11, C18, C20, C29
6	Lower subalpine spruce-fir (ls sp-fir)	C13, C19, C30, C31
7	Floodplain spruce-fir (flpl sp-fir)	C4, C32
8	Upper subalpine spruce-fir and larch (us sp-fir)	C15, C21, C23, C33, C34
9	Spruce-fir on permafrost (sp-fir perm)	C24

Table 14: Standardized discriminant function coefficients and relative variation explained by four discriminant functions

Descriptor	Standardized Discriminant Function Coefficients			
	Function 1	Function 2	Function 3	Function 4
Slope	-.14536	-.13144	.14308	-.14987
Elevation	.43549	-.85885	-.13785	-.07060
Hygrotope	.37939	.22018	-.75631	-.23937
Moss cover	.36415	-.12631	.08358	.45179
Herb/dwarf shrub cover	-.24712	-.13584	.32205	-.29659
Shrub biomass	.03174	-.13980	.36950	-.31852
Crown foliage biomass	.29976	.30873	.44840	.21527
Litter biomass	-.12450	.07927	-.15026	-.21836
Duff biomass	.22492	.28266	-.00854	-.25953
Fire intensity/severity index	-.26579	.45406	.13899	-.51305
Mean fire free interval	.02859	.29232	.45006	-.89744
Coarse downed wood biomass	.08015	.39103	.01088	.40768
Fine downed wood biomass	.00423	-.20555	-.29066	.22955
Percent variation explained by function	50.70	20.47	11.65	7.42

standardized coefficients). On this basis, Function 1 can be interpreted as separating sample plots in low elevation dry fire groups from those in moister upper elevation groups.

Function 2 explains an additional 21% of the variance in the discrimination, and weights heavily on elevation, fire intensity/severity index, and coarse downed wood biomass. This function probably serves to separate low elevation fire groups with low coarse downed wood biomass and a history of understory fire from mid-elevation groups that have higher downed wood biomass and are prone to crown fire.

A two-dimensional plot (Figure 8) of discriminant scores for functions 1 and 2 with the initial set of 142 of sample plots shows the relationship between fire groups. Warm/dry montane (Group 1), warm/dry lower subalpine lodgepole pine (Group 2) and montane aspen (Group 3) differ most from upper subalpine spruce-fir with permafrost (Group 9). However, fire groups are not sharply defined, and overlap considerably.

Classification results (Table 15) show that four discriminant functions predicted the correct grouping for 75% of the initial set of 142 sample plots. The most error exists in predicting group membership for cool/moist lower subalpine lodgepole pine stands (Group 5). These forests have similar site, fire history, biomass, and fire behavior potential descriptors to floodplain spruce-fir (Group 7) and upper subalpine spruce-fir stands (Group 8). Figure 8 shows this similarity.

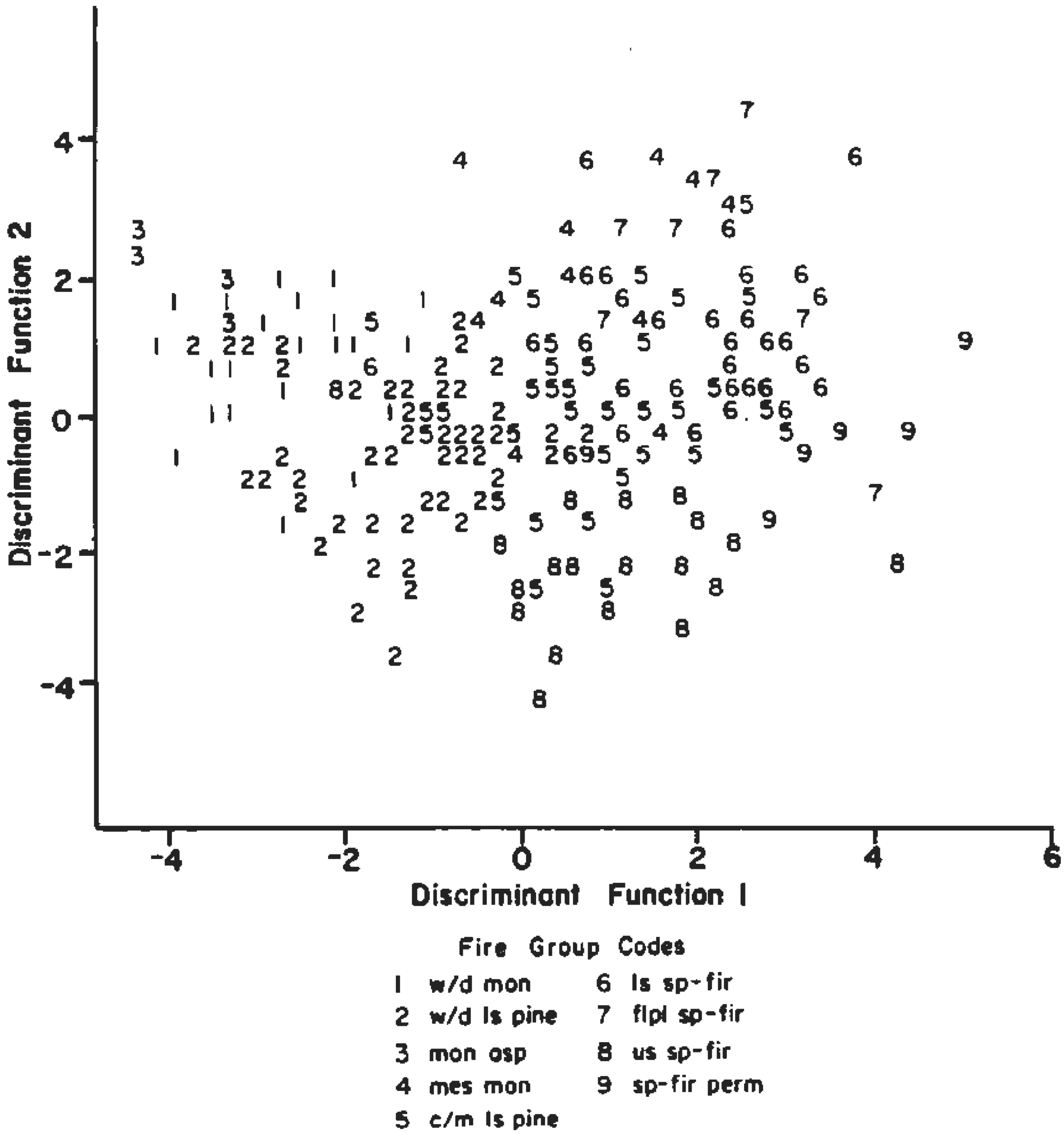

Figure 8: Location of fire group sample plots in two-dimensional discriminant function space. Fire groups are defined in Table 13.

Table 15: Discriminant function classification results for 142 sample plots utilized to derive functions. Fire groups are defined in Table 13.

Actual Group	No. of Sample Plots	Predicted Group Membership (% Correctly and Incorrectly Classified)								
		1	2	3	4	5	6	7	8	9
1 w/d mon	21	15 (71.4)	4 (19.0)	1 (4.8)	1 (4.8)	0	0	0	0	0
2 w/d ls pine	39	7 (17.9)	28 (71.8)	0	1 (2.6)	2 (5.1)	0	0	1 (2.6)	0
3 mon asp	4	0	0	4 (100.0)	0	0	0	0	0	0
4 mes mon	7	0	0	0	6 (85.7)	0	1 (14.3)	0	0	0
5 c/m ls pine	23	1 (4.3)	2 (8.7)	0	1 (4.3)	11 (47.8)	1 (4.3)	3 (13.0)	3 (13.0)	1 (4.3)
6 ls sp-fir	24	0	0	0	2 (8.3)	2 (8.3)	19 (79.2)	0	0	1 (4.2)
7 fipl sp-fir	5	0	0	0	0	0	0	5 (100.0)	0	0
8 us sp-fir	15	0	0	0	0	0	0	0	14 (93.3)	1 (6.7)
9 sp-fir perm	4	0	0	0	0	0	0	0	0	4 (100.0)

Overall correctly classified: 106/142 = 74.6%

Table 16: Discriminant function classification results for 78 sample plots not utilized to derive functions. Fire groups are defined in Table 13.

Actual Group	No. of Sample Plots	Predicted Group Membership (% Correctly and Incorrectly Classified)								
		1	2	3	4	5	6	7	8	9
1 w/d mon	8	3 (37.5)	2 (25.0)	2 (25.0)	0	1 (12.5)	0	0	0	0
2 w/d ls pine	23	4 (17.4)	12 (52.2)	0	2 (8.7)	4 (17.4)	0	0	1 (4.3)	0
3 mon asp	1	0	0	1 (100.0)	0	0	0	0	0	0
4 mes mon	7	1 (14.3)	0	0	3 (42.9)	2 (28.6)	1 (14.3)	0	0	0
5 c/m ls pine	16	1 (6.3)	0	0	2 (12.5)	7 (43.8)	2 (12.5)	2 (12.5)	2 (12.5)	0
6 ls sp-fir	13	1 (7.7)	0	0	2 (15.4)	1 (7.7)	9 (69.2)	0	0	0
7 fipl sp-fir	3	0	0	0	1 (33.3)	0	0	2 (66.7)	0	0
8 us sp-fir	5	1 (20.0)	0	0	0	0	0	0	4 (80.0)	0
9 sp-fir perm	2	0	0	0	0	0	0	0	0	2 (100.0)

Overall correctly classified: 43/78 = 55.1%

A more valid test of the discriminant functions is to classify a set of cases not originally utilized to calculate discriminant functions but where group membership is known (Morrison 1969). The classification results (Table 16) of 78 sample plots held out for this purpose show that only a 55% correct grouping was made. However, this is substantially better than would have been achieved by randomly assigning plots to fire groups.

Spatial Variation Between Fire Groups

Appendix B contains descriptive statistics (sample sizes, means, standard deviations and ranges) for descriptors of sample plots as stratified into fire groups. General descriptions and the results of statistical tests for between-group differences are presented in the following sections.

Site Characteristics

The fire group classification is statistically significant for slope, elevation, cosine of aspect and hygrotope descriptors based on a one way analysis of variance (Table 17).

Fire group slope angles generally increase with elevation. Low elevation, valley bottom areas of montane aspen (Group 3) or floodplain spruce-fir (Group 7) have lowest slope angles. Upper subalpine spruce-fir forests (Groups 8,9) have the steepest slopes and highest elevations.

Table 17: Mean values of selected descriptors for fire groups. Also shown are the one-way analysis of variance significance values for the F statistic. Fire groups are defined in Table 13.

Descriptor	Significance	Fire Group 1 w/d mon	2 w/d ls pine	3 mon asp	4 mes mon	5 c/m ls pine	6 ls sp-fir	7 flpl sp-fir	8 us sp-fir	9 sp-fir perm
Number of Sample Plots	-	29	62	5	14	39	37	8	20	6
Site Characteristics										
Slope (degrees)	.0003	11.28	13.21	3.00	7.85	10.24	10.32	.37	15.15	17.83
Elevation (m)	.0000	1504.21	1689.85	1399.60	1558.15	1716.84	1747.89	1597.62	2032.80	1978.67
Cosine of aspect	.0002	-.38	-.31	-.60	-.35	.21	.01	.03	.14	.56
Hygrotope	.0000	2.55	2.69	3.00	3.08	3.47	3.32	5.50	2.95	4.50
Crown Layer										
Tree density (stems/ha)	.1897	1895.03	1764.23	680.20	1184.85	2104.84	1755.54	1338.12	1266.40	1406.00
Basal area (m^2/ha)	.0011	34.91	31.14	26.62	43.45	41.26	49.65	37.01	39.62	34.97
Bolewood biomass (t/ha)	.0079	107.39	92.76	98.68	136.42	127.38	150.21	110.58	124.36	101.94
Foliage and branchwood biomass (t/ha)	.0000	25.90	25.62	29.20	51.84	38.15	63.92	46.37	50.49	45.73
Foliage biomass (t/ha)	.0000	9.05	8.96	4.64	20.48	15.80	25.14	19.35	18.14	18.73
Foliage bulk density (kg/m^3)	.0000	.14	.14	.08	.24	.24	.31	.24	.22	.31
Height to live crown (m)	.0000	7.34	6.14	7.62	6.29	6.42	5.24	5.94	2.68	2.30
Height to dead crown (m)	.0098	2.07	1.91	3.78	1.57	1.72	1.37	1.28	.51	.47
Surface Layer										
Herb-dwarf shrub cover (%)	.0000	70.69	57.82	90.00	39.00	43.21	31.73	36.87	52.75	27.83
Herb-dwarf shrub biomass (t/ha)	.0001	.67	.51	.81	.37	.33	.18	.23	.66	.22
Shrub cover (%)	.2052	33.07	33.39	30.00	32.54	39.03	36.49	20.88	35.15	49.17
Shrub biomass (t/ha)	.0000	1.51	1.27	.46	1.36	2.24	2.74	1.34	2.80	6.80
Total downed wood (t/ha)	.0441	28.54	36.47	13.00	49.11	39.76	52.14	26.55	27.75	27.71
Fine downed wood (t/ha)	.0184	1.72	1.98	.80	2.73	1.68	2.29	3.06	2.38	2.35

Table 17: (cont'd)

Descriptor	Significance	Fire Group 1 w/d mon	2 w/d ls pine	3 mon asp	4 mes mon	5 c/m ls pine	6 ls sp-fir	7 flpl sp-fir	8 us sp-fir	9 sp-fir perm
Number of Sample Plots	-	29	62	5	14	39	37	8	20	6
Ground Layer										
Moss cover (%)	.0000	29.31	35.73	4.00	69.23	66.79	75.81	63.12	48.00	70.83
Moss biomass (t/ha)	.0000	1.91	2.02	.22	6.34	5.60	6.90	4.46	2.17	5.84
Litter cover (%)	.0000	64.76	57.98	92.00	23.85	27.82	15.54	30.00	43.25	17.50
Litter biomass (t/ha)	.0000	4.12	3.67	10.11	2.74	2.05	1.73	2.09	2.38	1.23
Duff depth (cm)	.0000	4.02	4.43	5.48	11.49	8.84	12.29	10.64	4.62	14.70
Duff biomass (t/ha)	.0000	47.00	51.88	64.12	134.46	103.38	143.85	124.46	54.00	171.99
Total ground biomass (t/ha)	.0000	53.03	57.58	74.45	145.44	111.04	152.48	131.00	58.55	179.06
Total Stand Biomass (t/ha)	.0000	217.05	214.20	216.61	382.64	316.04	421.68	316.07	264.62	361.46
Fire Behavior Potential and Resistance to Control										
Resistance to handline construction	.0000	10.66	11.69	9.20	22.15	17.64	22.84	21.38	11.80	21.17
Rate of spread rating I	.0000	42.65	34.98	75.60	28.31	26.97	24.28	19.75	31.75	23.50
Rate of spread rating II	.0843	6.47	6.06	8.54	6.76	5.57	6.35	5.92	7.28	10.47
Surface fire intensity rating	.1584	22.22	24.51	17.96	29.46	26.09	31.35	20.62	22.20	24.44
Crown fire potential rating	.0000	3.45	3.23	.20	6.88	4.85	6.92	7.25	6.80	6.83
Rate of spread to initiate crown fire (m/min)	.0000	7.09	5.92	6.69	5.22	5.08	3.01	5.48	1.54	.87

Warm/dry montane (Group 1), warm/dry lower subalpine lodgepole pine (Group 2), and montane aspen (Group 3) forests occur predominantly on south aspects with negative cosine of aspects values. Spruce-fir forests underlain by permafrost (Group 9) are found on the most northerly aspects with the highest positive cosine of aspect values. Most other fire groups lie on a variety of north and south aspects.

Hygrotope, or the ecological moisture regime (Table 9), varies significantly between fire groups. Warm/dry montane (Group 1) and warm/dry lower subalpine pine (Group 2) forests are the most xeric with hygrotope values of less than 3. In contrast, floodplain spruce-fir (Group 7) and spruce-fir underlain by permafrost (Group 9) are rated as the wettest with mean values of 5.5 and 4.5 respectively. Most of the other fire groups are rated as mesic (hygrotopes of approximately 3).

<u>Crown Layer</u>

Statistics for one-way analysis of variance show significant differences between fire groups for all selected crown layer descriptors except tree density (Table 17).

Tree density is greatest in forests with a high proportion of lodgepole pine (Groups 1,2,5). Cool/moist lower subalpine lodgepole pine forests (Group 5) have particularly high tree densities, averaging greater than 2000 stems/ha. Aspen forests (Group 3) are the most open, with mean tree densities of less than 700 stems/ha (Table 17).

Basal areas for BNP fire groups average from approximately 25 to 50 m^2/ha. Aspen forests (Group 3) have the lowest basal area, reflecting the low tree density. Lower subalpine spruce-fir forests (Group 6) are characterized by relatively high basal areas. Although tree densities are not exceptionally high, these stands often contain mature lodgepole pine and Engelmann spruce trees with large diameters.

Bolewood biomass of crown layer trees is usually lowest in warm/dry lower subalpine lodgepole pine forests (Group 2), averaging about 90 t/ha. High bolewood biomass is found in mesic montane (Group 4) lower subalpine spruce-fir (Group 6) and upper subalpine spruce/fir (Group 8) forests. Large diameter white and Engelmann spruce trees in these stands are a major component of this bolewood.

Fire groups dominated by spruce and/or subalpine fir have heavy foliage and branchwood biomass (Groups 4,6,7,8,9). In contrast, forests of lodgepole pine, Douglas-fir and aspen (Groups 1,2,3) have relatively low foliage and branchwood biomass. An exception is cool/moist lower subalpine lodgepole forests (Group 5), which have relatively heavy weights, probably due to high tree densities. Foliage bulk density follows a similar pattern to foliage biomass. High bulk densities (>.22 kg/m^3) are found in groups dominated by spruce and/or subalpine fir. Low foliage bulk densities (<.15 kg/m^3) are characteristic of warm/dry montane (Group 1), warm/dry lower subalpine lodgepole pine (Group 2) and montane aspen (Group 3) forests.

Mean heights to live crown range from approximately 3 to 8 m. Warm/dry fire groups at lower elevations have highest heights to live crown (Groups 1,2,3). In comparison, other fire groups which have a high cover of Engelmann spruce and subalpine fir (Groups 6,8,9) are distinguished by low average heights to live crown. The height to dead crown branches follows a similar pattern to the live crown, with dead branches found less than 1 m height in several groups.

Surface Layer

The fire group classification is statistically significant for all surface layer descriptors except shrub cover (Table 17).

Herb/dwarf shrub cover is highest (>50%) in montane aspen (Group 3), warm/dry montane (Group 1) and warm/dry lower subalpine lodgepole pine (Group 2) forests. These stands usually have a high grass cover. Upper subalpine spruce-fir forests (Group 8) also have relatively high cover--usually composed of heathers and heaths. Herb/dwarf shrub biomass follows the same pattern as cover, averaging from less than .20 t/ha in lower subalpine spruce-fir forests (Group 6) to over .80 t/ha in montane aspen stands (Group 3).

Shrub cover and biomass do not vary appreciably between most fire groups. Highest mean cover (approximately 50%) and biomass (approximately 6.7 t/ha) occurs in spruce-fir forests underlain by permafrost (Group 9) due to shrub-like subalpine fir in the understory. Floodplain spruce-fir (Group 7) has the lowest average shrub cover.

Downed wood biomass in the surface layer constitutes a major portion of biomass in BNP forests. Fire group descriptive statistics for individual diameter classes measured are included in Appendix B. Total downed wood biomass is highest in mesic montane (Group 4), cool/moist lower subalpine lodgepole pine (Group 5), and lower subalpine spruce-fir (Group 6) forests, often averaging over 40 t/ha. Montane aspen stands (Group 3) are distinguished by low total downed woods biomass averaging about 12 t/ha. The mean biomass of fine downed wood (<3 cm diameter) is less than 6 t/ha for all fire groups. Aspen stands (Group 3) have the lowest average fine downed wood weights (approximately 1 t/ha) while floodplain spruce-fir has the highest biomass (averaging approximately 3 t/ha).

Ground Layer

Statistics for ground layer descriptors (Table 17) demonstrate significant differences between fire groups. Moss cover and biomass are lowest in montane aspen stands (Group 3) with averages of less than 10% and .5 t/ha respectively. Forests dominated by spruce and/or subalpine fir (Groups 4,6,7,9) or cool/moist lower subalpine lodgepole pine (Group 5) usually have a moss cover exceeding 50% with biomass greater than 5.0 t/ha.

Litter cover and biomass are highest where moss cover is lowest. Aspen (Group 3), warm/dry montane (Group 1) and warm/dry lower subalpine lodgepole pine (Group 2) forests have the highest mean litter cover

(>50%) and biomass (>3 t/ha). In moister forests at upper elevations, litter cover is often less than 50% and biomass less than 2.5 t/ha.

Aspen (Group 3), warm/dry montane (Group 1) and warm/dry lower subalpine lodgepole pine (Group 2) forests have relatively low average duff depths (<6 cm) and biomass (<75 t/ha). Generally, fire groups with moister hygrotopes and higher elevations (Figure 9) have greater duff depths and biomass, with the exception of upper subalpine spruce-fir (Group 8) where duff biomass averages only about 50 t/ha. Because duff makes up most of the ground layer biomass, total ground weight estimations for fire groups are similar to those for duff. Warm/dry montane forests (Group 1) have the lowest ground layer biomass (approximately 50 t/ha). Spruce-fir forests underlain by permafrost (Group 9) hold the heaviest ground layer of all BNP forests, averaging nearly 180 t/ha.

Total Stand Biomass

Total stand biomass (crown, surface and ground layer total weight) estimates for fire groups are given in Table 17. The classification into groups is statistically significant based on a one-way analysis of variance. Heaviest mean total stand biomass (>400 t/ha) is found in lower subalpine forests of Engelmann spruce and subalpine fir (Group 6). Warm/dry montane, warm/dry lower subalpine lodgepole pine, and montane aspen (Groups 1,2,3) have comparatively low total stand biomass, averaging less than 250 t/ha.

Fire Behavior Potential and Resistance to Control

Table 17 summarizes information on fire behavior potential and resistance to control descriptors for fire groups. The resistance to handline construction rating (Murphy and Quintilio 1978) varies significantly between fire groups. Because of the importance of duff depth in the rating, forests with the deepest duff (Groups 4,5,6,7,9) yield the highest resistance to handline construction ratings. Conversely, lower elevation forests of Douglas-fir, lodgepole pine, and aspen (Groups 1,2,3) have shallow duff depths that allow easy digging to mineral soil and rapid handline construction. Upper subalpine spruce-fir forests (Group 8) also have low resistance ratings due to low duff depths. Key values can be converted to estimated rates of line construction (m/person/45 min. hr.) with Table 9.

Application of Fahnestock's (1970) rate of spread key also shows significant differences between fire groups. Forests with high grass cover such as montane aspen, warm/dry montane, and warm/dry lower sub-alpine lodgepole pine (Groups 1,2,3) are given the highest key values. Using the biomass of fine (<3 cm diameter) materials as an indicator of potential rate of spread does not show major differences between fire groups. Montane aspen (Group 3) may have high rates of spread due to a high biomass of grass. Surface fire spread could be high under some conditions in spruce-fir forests underlain by permafrost (Group 9). These forests have a high biomass of shrub-like subalpine fir in the surface layer.

Potential surface fire intensity, as approximated by the ground and surface biomass available for burning, is not significantly different between groups. However, aspen forests (Group 3) appear to have the lowest biomass available for surface fire (<20 t/ha) and lower subalpine spruce-fir forests (Group 6) the highest biomass available (>30 t/ha).

Both crown fire potential descriptors, Fahnestock's (1970) key and the rate of spread to initiate crown fire, show similar differences between fire groups. Forests dominated by dense-crowned trees with abundant ladder fuels such as spruce and subalpine fir (Groups 4,6,7,8,9) are given high crowning potential ratings with Fahnestock's (1970) key. Similarly, spruce-fir forests often have a low height to live crown and heavy ground and surface biomass available for burning (Table 17). Thus relatively low rates of spread could generate fire intensities high enough to initiate crown fire. In contrast, montane aspen (Group 3), warm/dry montane (Group 1) and warm/dry lower subalpine lodgepole pine (Group 2) forests are characterized by more open-crowned trees, fewer ladder fuels, higher heights to live crowns, and relatively light ground and surface biomass available for burning. Crown fire potential ratings are therefore lower, and higher rates of spread are required to initiate crowning.

Fire History

Means, sample sizes and frequency distributions of historic fire intervals for fire groups are illustrated by Figure 9. Montane aspen

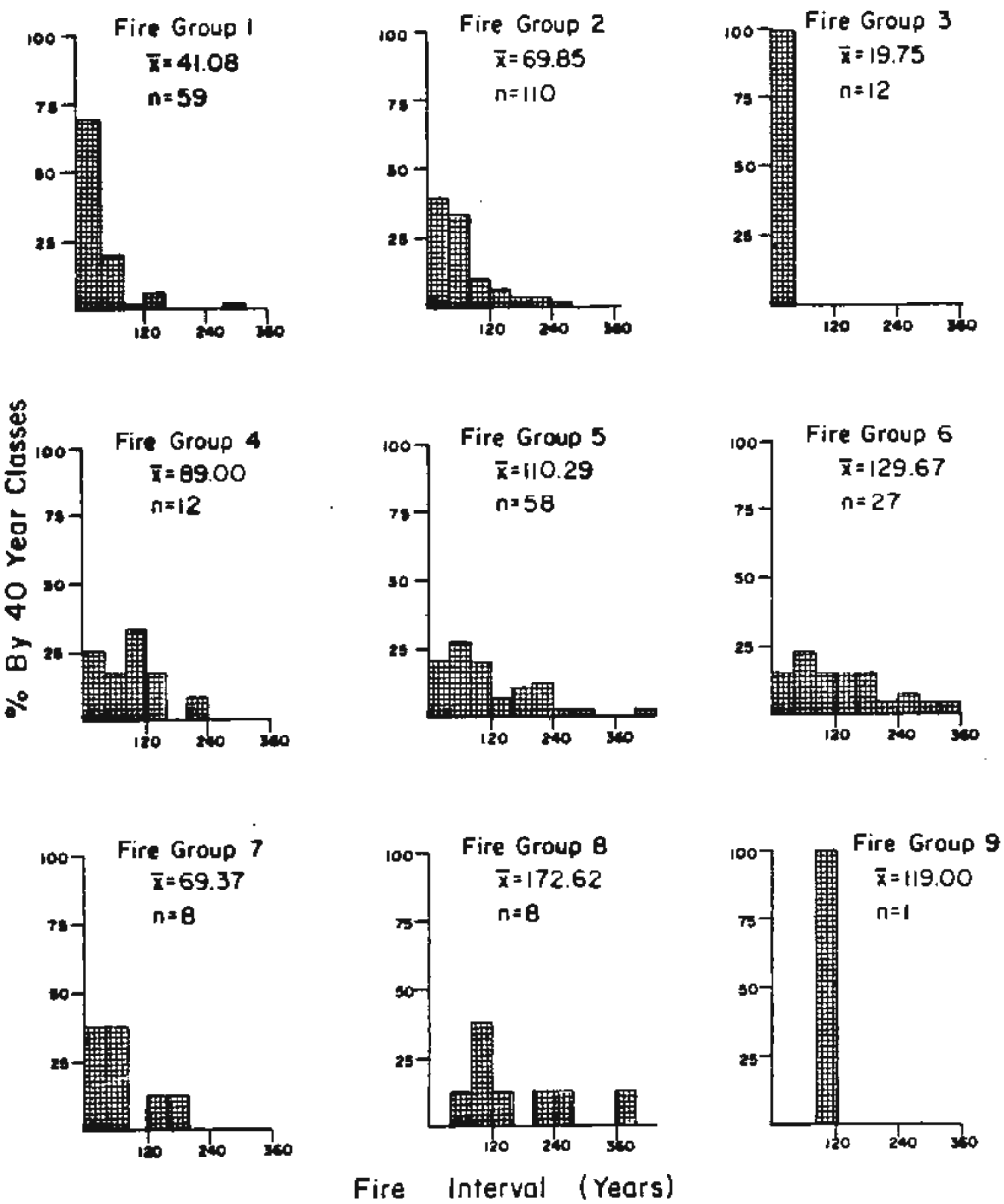

Figure 9: Means, sample sizes and distributions of fire intervals for fire groups.

forests (Group 3) have the shortest intervals with a mean of approximately 20 years. Warm/dry montane (Group 1) and warm/dry lower subalpine lodgepole pine (Group 2) forests also have evidence of relatively frequent fires with mean intervals of less than 70 years. The longest fire intervals occur in upper subalpine spruce-fir (Group 8) forests with a mean exceeding 150 years. Only one interval of 119 years was determined for spruce-fir forests underlain by permafrost (Group 9). However, the mean stand age in these forests as of 1980 was 337 years (Appendix B), suggesting longer mean fire intervals in this group.

Pairwise Lee-Desu statistics (Table 18) were calculated for life table survivorship functions derived from fire intervals. The statistics show that the majority of differences between fire group intervals are significant at the .05 level. Mesic montane, cool/moist lower subalpine pine, lower subalpine spruce-fir, and upper subalpine spruce-fir (Groups 4,5,6,9) statistically have the most similar historic fire intervals. Warm/dry montane forests and montane aspen (Groups 1,3) are the most dissimiliar from other groups (and from each other).

Means and frequency distributions of the intensity/severity index for historic fires also vary widely between fire groups (Figure 10). Montane aspen (Group 3) and warm/dry montane (Group 1) forests historically had fires of relatively low intensities or severities that left much of the crown surviving (intensity/severity index values of 3 or 4). Cooler and moister forests at higher elevations (Groups 5,6,7,8,9) are

Table 18: Lee-Desu statistics and probabilities for pairwise comparisons of fire group survivorship functions derived from fire intervals.

Fire Group	1	2	3	4	5	6	7	8	9[a]
1 w/d mon		15.15 (p=.000)	4.23 (p=.040)	11.15 (p=.001)	36.66 (p=.000)	30.92 (p=.000)	4.53 (p=.033)	15.12 (p=.000)	
2 w/d ls pine			14.35 (p=.000)	2.78 (p=.095)	13.06 (p=.000)	13.90 (p=.000)	.07 (p=.789)	10.38 (p=.001)	
3 mon asp				12.42 (p=.000)	22.90 (p=.000)	21.54 (p=.000)	9.06 (p=.003)	13.73 (p=.000)	
4 mes mon					.13 (p=.714)	1.13 (p=.287)	1.17 (p=.280)	4.03 (p=.045)	
5 c/m ls pine						1.24 (p=.265)	1.97 (p=.160)	3.34 (p=.068)	
6 ls sp-fir							4.02 (p=.045)	1.17 (p=.279)	
7 flpl sp-fir								4.41 (p=.035)	
8 us sp-fir									
9 sp-fir perm									

[a]Due to fire return interval size of 1 in Firegroup 9 statistical comparisons are impossible.

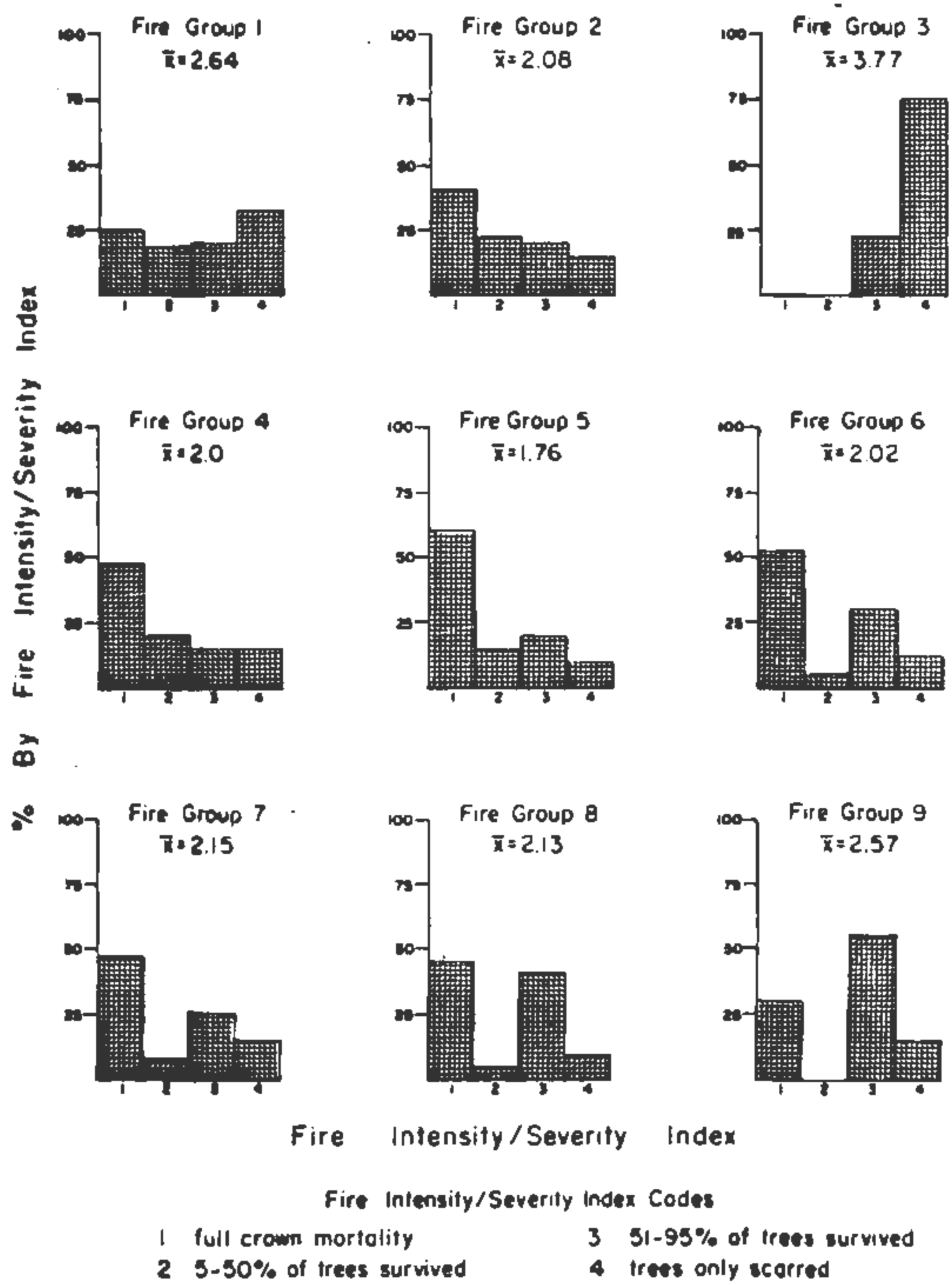

Figure 10: Means and distributions of fire intensity/severity index values for fire groups.

characterized by intense and severe fires that killed most of the canopy (intensity/severity index values of 1 or 2). Forests dominated by Engelmann spruce and subalpine fir (Groups 6,7,8,9) appear to have a history of fires that either left much of the crown surviving, or alternatively killed it completely (index values of 1, 3 or 4). Very few fires left from 5-50% of the canopy surviving (index value of 2).

CHAPTER 6

RESULTS: TEMPORAL ANALYSIS OF FIRE GROUPS

The fire group classification provided a general framework for evaluating time-related changes in fire frequency, biomass and fire behavior potential. Sample size permitted analysis of the following groups:

1) Warm/dry montane forests (Fire Group 1) - stands of Douglas-fir and lodgepole pine on warm/dry montane ecosites dominated by C1, C3, and C6 vegetation types;

2) Warm/dry lower subalpine forests (Fire Groups 2 and 6)-lodgepole pine stands (C3, C6, C9, C11, C18, C19 vegetation types) and Engelmann spruce-subalpine fir stands (C13, C31 vegetation types) that are successionally related on warm/dry lower subalpine ecosites (Figure 3);

3) Cool/moist lower subalpine forests - (Fire Groups 5 and 6) - lodgepole pine stands (C20, C29 vegetation types) and Engelmann spruce- subalpine fir stands (C14, C21, C30 vegetation types) that are successionally related on cool/moist lower subalpine ecosites (Figure 3);

4) Upper subalpine forests (Fire Groups 8 and 9) - stands of Engelmann spruce, subalpine fir, and alpine larch (C15, C23, C24, C33, C34 vegetation types) on upper subalpine ecosites.

Insufficient samples were collected in other fire groups to allow temporal analysis.

Time Since Fire and Fire Intervals

Means and frequency distributions for time since fire as of the years 1880, 1930 and 1980 and fire intervals are shown by Figures 11 to 14. Frequent fires since 1880 eliminated evidence of time since fire as of 1880 in seven warm/dry montane sample plots. In several upper subalpine plots no evidence of fire was found--thus time is since stand origin.

The mean time since fire increased for all fire groups between 1880 to 1980. For example, in warm/dry lower subalpine forests the average time since fire increased from approximately 85 years in 1880 to 130 years in 1980. The time since fire frequency distributions for each group show substantially fewer stands as of 1980 in the young (0-39 years) time since fire classes compared to 1930 and 1880. As of 1880, warm/dry montane and warm/dry lower subalpine forests had substantially more stands in the young time since fire/stand origin classes than cool/moist lower subalpine and upper subalpine forests.

Mean fire intervals range from 41.08 years for warm/dry montane stands to 166.67 years for upper subalpine stands. Lee-Desu statistics for pairwise comparisons of group survivorship functions derived from fire intervals (Table 19) show differences significant at the .05 level, except between cool/moist lower subalpine and upper subalpine stands.

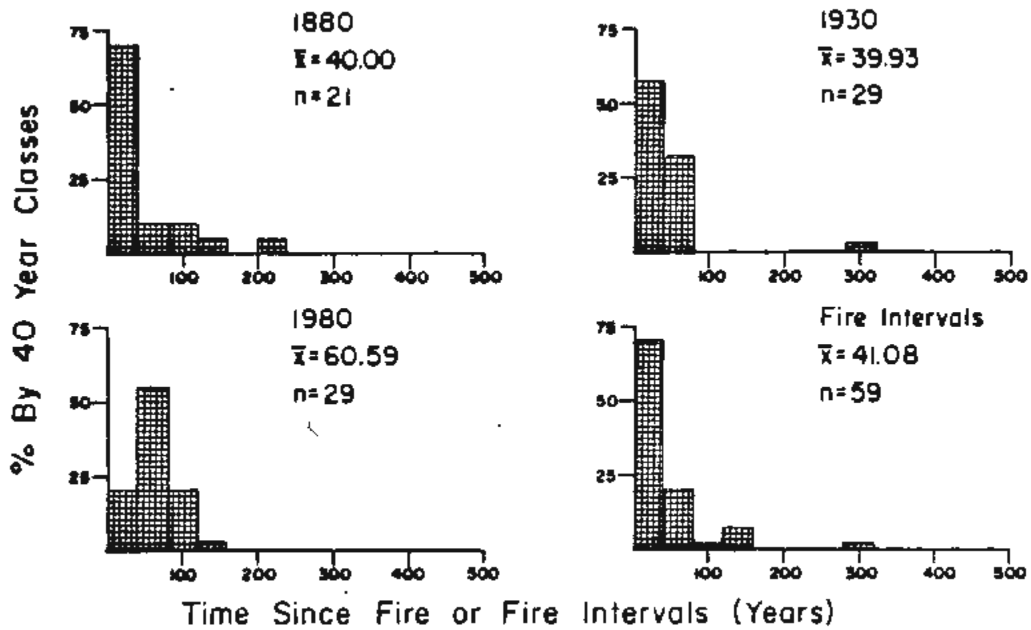

Figure 11: Time since fire as of 1880, 1930, and 1980 and fire interval distributions for warm/dry montane sample plots.

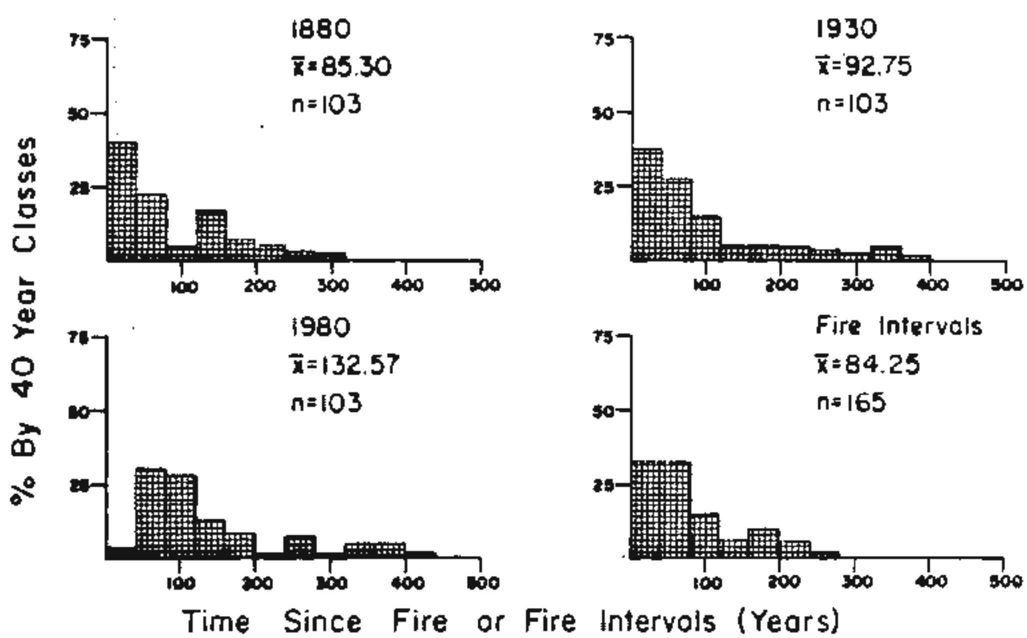

Figure 12: Time since fire as of 1880, 1930, and 1980 and fire interval distributions for warm/dry lower subapline sample plots.

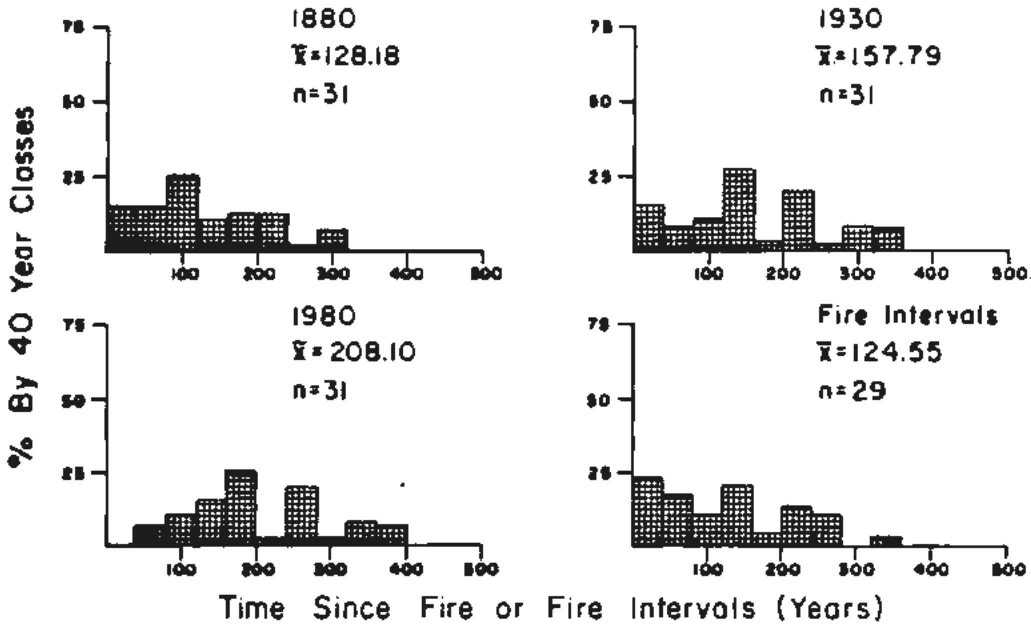

Figure 13: Time since fire as of 1880, 1930 and 1980 and fire interval distributions for cool/moist lower subalpine sample plots.

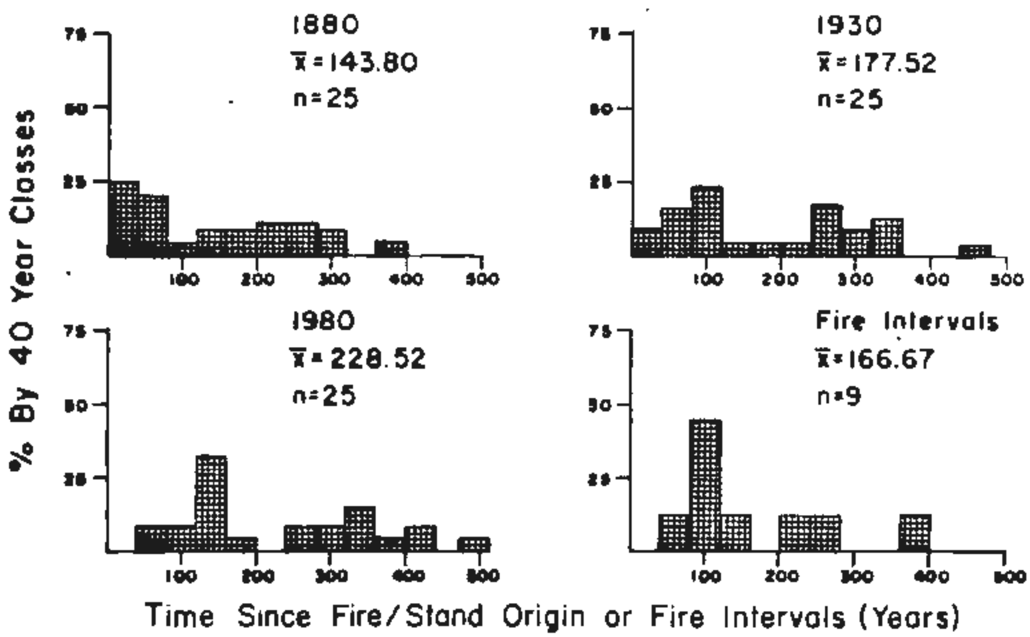

Figure 14: Time since fire as of 1880, 1930 and 1980 and fire interval distributions for upper subalpine sample plots.

Table 19: Lee-Desu statistics and probabilities for pairwise comparisons of fire group survivorship functions derived from fire intervals (as arranged for temporal analysis).

Fire Group	warm/dry montane	warm/dry lower subalpine	cool/moist lower subalpine	upper subalpine
warm/dry montane	-	28.43 p=0.00	26.80 p=0.00	16.67 p=0.00
warm/dry lower subalpine		-	5.55 p=0.02	8.50 p=0.00
cool/moist lower subalpine			-	1.44 p=0.23
upper subalpine				-

Table 20: Mean time since fire (years) and sample sizes for fire groups stratified into time since fire classes.

Time Since Fire Class	Fire Group			
	warm/dry montane	warm/dry lower subalpine	cool/moist lower subalpine	upper subalpine
Young (0-49 years)	37.6 (n=14)	34.8 (n=18)	-	-
Mature (50-149 years)	82.0 (n=15)	95.0 (n=70)	102.6 (n=11)	115.2 (n=11)
Transitional (150-299 years)	-	202.7 (n=18)	209.2 (n=12)	206.5 (n=4)
Old (300+ years)	-	381.7 (n=8)	363.4 (n=5)	362.0 (n=10)

Temporal Variation of Biomass and Fire Behavior Potential

Regression analysis (Table 21) showed only a partial ability to explain changes in biomass and fire behavior potential descriptors as a function of stand history. Further understanding of the patterns of temporal variation was obtained by plotting mean values of descriptors for the following time since fire/stand origin classes: young (<50 years), mature (50-149 years), transitional (150-299 years), and old (≥300 years). Table 20 summarizes the mean time since fire/stand origin and sample size of fire groups for each class. Descriptor values for each class were tabulated only if the sample size is four or more. The results of regression analysis and plots as a function of time since fire are reported below. Statistics for regression analysis are included in Appendix D.

Crown Layer Change with Time

Time since fire, usually in combination with other stand history variables such as the intensity/severity index and the length of the last fire interval, is a significant variable explaining crown biomass descriptors in most BNP forests (Table 21). Figure 15 shows a general pattern of increasing foliage, branchwood and bolewood biomass with time since fire in all fire groups. Foliage and branchwood biomass appears to increase to approximately 60 t/ha before levelling off in old (≥300 years) lower subalpine forests. In contrast, bolewood biomass in these forests accumulates to a peak of over 140 t/ha in transitional (150-299 years since fire) stands, but thereafter begins to decline. Foliage bulk density shows a tendency to increase with time since fire, but the pattern is not consistent in all groups.

Table 21: Summarized results of regression analysis of selected dependent crown, surface and ground layer descriptors on independent site and stand history variables. Significant variables are listed in order of their additional contribution to the regression sum of squares. Dashes indicate that no significant regressions were found.

Descriptor	warm/dry montane n = 28		warm/dry lower subalpine n = 95		cool/moist lower subalpine n = 20		upper subalpine n = 26	
	R^2	Variables[a]	R^2	Variables[a]	R^2	Variables[a]	R^2	Variables[ab]
Crown layer								
Foliage biomass	-	-	.25	tsf,int,lfi	.22	elv	.38	tsf
Foliage and branchwood biomass	.37	int,tsf	.24	tsf,int,lfi	.34	tsf	.15	tsf
Bolewood biomass	.37	tsf,int	.14	tsf,int	-	-		
Surface layer								
Herb dwarf shrub cover	.25	asp	.12	tsf	-	-	.48	slp,tsf,asp
Herb dwarf shrub biomass	-	-	.07	tsf	-	-	-	-
Shrub cover	.21	lfi	.14	slp,int	-	-	.41	elv,asp
Shrub biomass	.65	lfi,asp,slp	-	-	-	-	.32	tsf,slp
Coarse downed wood biomass	.51	lfi,int	.10	lfi	-	-	.23	slp
Fine downed wood biomass	.34	asp	.15	lfi,int	-	-	-	-
Ground layer								
Moss cover	.37	tsf,elv	.39	tsf,elv,asp,int,lfi	-	-	.30	tsf
Moss biomass	.31	elv,tsf	.44	tsf,asp,elv,int,lfi	-	-	.40	tsf
Litter cover	.30	elv,tsf	.43	tsf,lfi,elv,asp,int	.28	elv,tsf	.37	tsf
Litter biomass	.32	asp,slp	.13	asp,slp	-	-	.29	slp
Total ground biomass	.35	tsf,int,asp	.28	lfi,int,tsf,asp	-	-	.30	tsf
Total stand biomass	.36	tsf	.32	lfi,int,tsf,asp	.27	tsf	.19	tsf

a. Variable codes: time since fire (tsf), last fire interval (lfi), fire intensity/severity index (int), slope (slp), cosine of aspect (asp), elevation (elv)

b. Last fire interval and fire intensity/severity index not included in regressions.

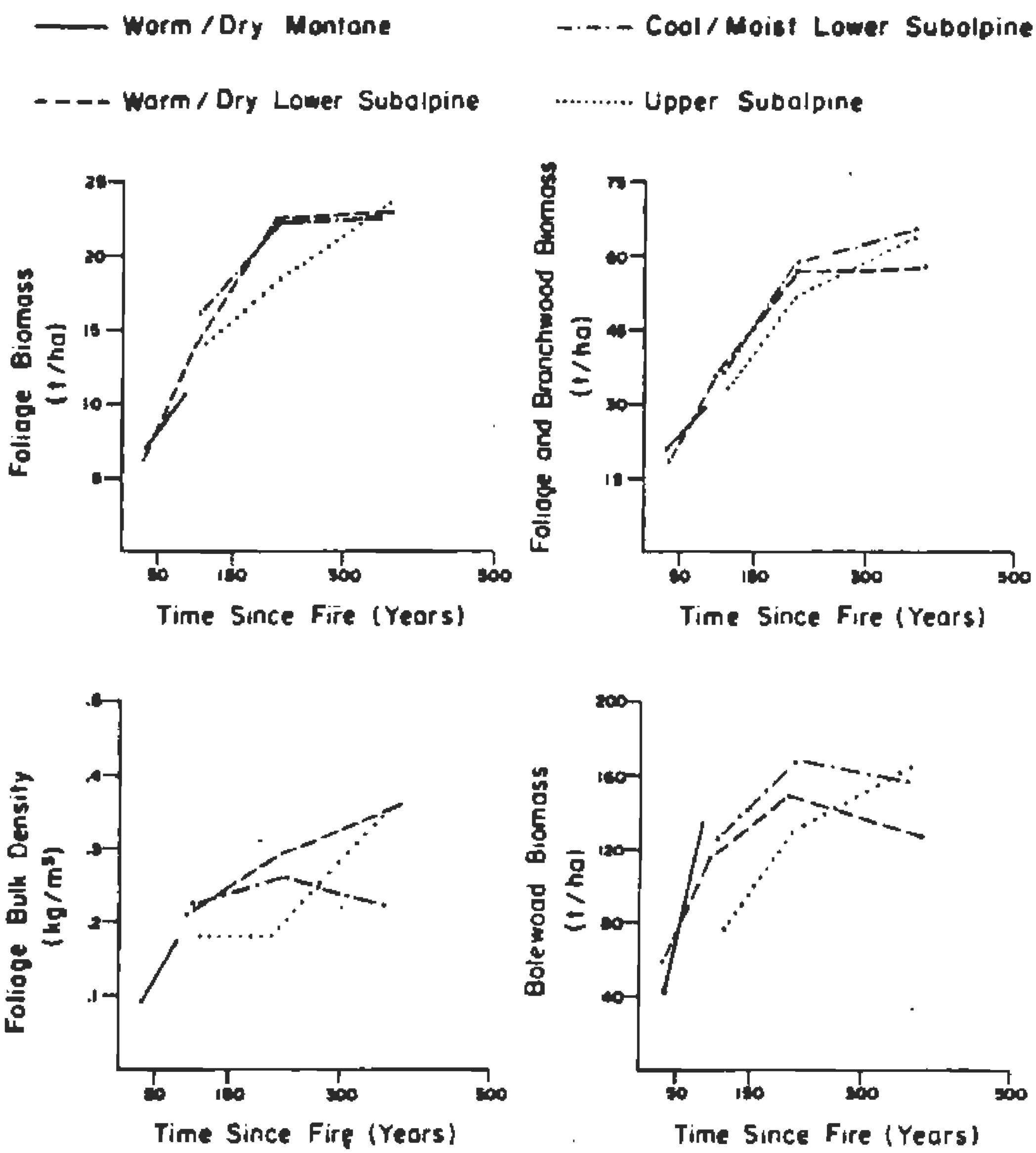

Figure 15: Selected crown layer descriptors for fire groups plotted as a function of time since fire classes.

In warm/dry montane and warm/dry lower subalpine forests, where low intensity and severity fires (index values of 3 or 4) are common (Figure 11), the fire intensity/severity index is a significant regression coefficient explaining crown layer descriptors (Table 21). Stands with high crown cover surviving the last fire generally have a different pattern of crown layer development in the current time since fire period. This will be described in a subsequent section.

Surface Layer Change with Time

Changes in surface layer descriptors are often not correlated to stand history variables--particularly in cool/moist lower subalpine forests (Table 21). Only in warm/dry lower subalpine forests do both herb/dwarf shrub cover and biomass appear to be significantly related to time since fire. In these forests, herb/dwarf shrub cover and biomass decrease steadily as time since fire increases (Figure 16).

No consistent changes of shrub cover and biomass are apparent as a function of time since fire. Possibly the length of the last fire interval may be an important variable explaining shrub cover and biomass in warm/dry montane forests (Table 21). Regression coefficients (Appendix D) indicate that the longer the last fire interval the greater shrub cover and biomass may be in current warm/dry montane forests.

In warm/dry montane and lower subalpine forests a significant relationship exists between the length of the last fire interval and coarse downed wood biomass. The longer the last fire interval, the

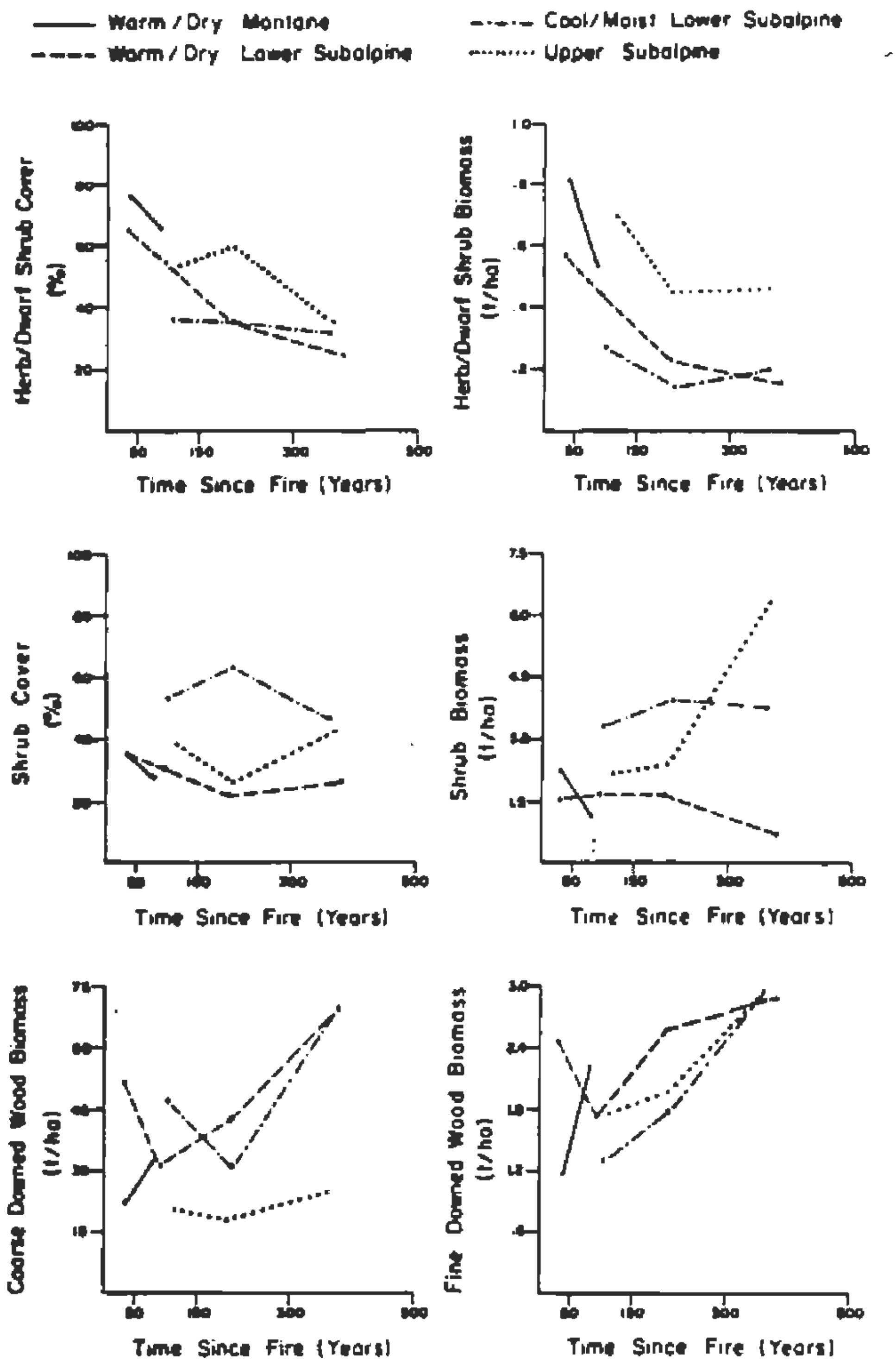

Figure 16: Selected surface layer descriptors for fire groups plotted as a function of time since fire classes.

greater the coarse downed wood biomass should be in the current stand. In warm/dry montane forests, the fire intensity/severity index of the last fire is also important. Low fire intensities and severities that leave high canopy coverage (index values of 3 and 4) create the least amount of coarse downed wood. The relationship of coarse downed wood biomass and time since fire is not consistent (Figure 16). Warm/dry and cool/moist lower subalpine forests appear to have low biomass at mid stand ages, but this pattern is not apparent in montane and upper subalpine stands.

Fine downed wood biomass (<3 cm) appears to have a slight tendency to increase with time since fire in most BNP forests (Figure 16), although this variable was not statistically significant in the regression analysis.

Ground Layer Change with Time

Time since fire, often in combination with other site and stand history variables, is significantly related to ground layer descriptors in 14 of 20 regression analyses of four groups of closed BNP forest types (Table 21). Litter cover tends to decrease with time since fire (Figure 17). Conversely, moss cover increases with time since fire. However litter and moss biomass patterns with time since fire are not consistent in the fire groups analyzed.

Duff depths increase markedly with time since fire in BNP forests. For example, in young (<50 years) warm/dry lower subalpine forests

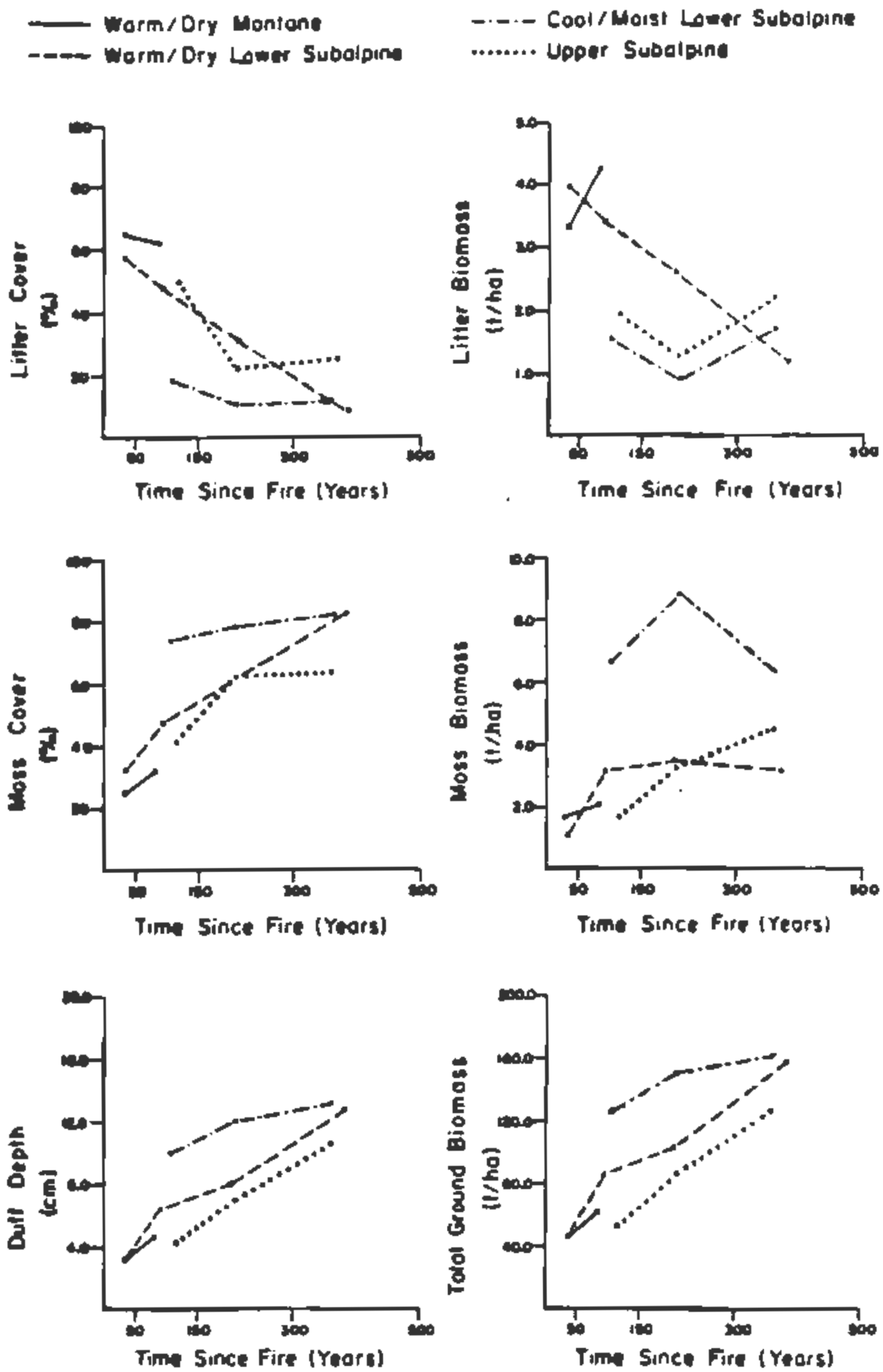

Figure 17: Selected ground layer descriptors for fire groups plotted as a function of time since fire classes.

depths average less than 4 cm, but rise to over 12 cm in old (≥300 years) stands (Figure 17).

Time since fire, particularly in combination with the historic fire intensity/severity index and the last fire interval, is a significant variable explaining total ground biomass in all fire groups except cool-/moist lower subalpine forests (Table 21). As illustrated in Figure 17, mean ground biomass in warm/dry lower subalpine forests increases from approximately 40 t/ha in young (<50 years) stands to nearly 160 t/ha in old (>300 years) stands. In warm/dry montane and warm/dry lower subalpine forests, the intensity/severity index of the last fire is also an important independent variable related to ground layer biomass. Regression coefficients (Appendix D) indicate that less severe or intense fires (index values 3 and 4) result in higher ground biomass in the current stand. This relationship is described more fully in a subsequent section. An additional variable of high significance to ground biomass in warm/dry lower subalpine forests is the length of the last fire interval. In combination with several other variables, increasing the length of the last fire interval can result in higher ground biomass in the current stand.

Total Stand Biomass Change with Time

Regression analysis (Table 21) indicates that time since fire is the only significant variable related to total stand biomass in warm/dry montane, cool/moist lower subalpine, and upper subalpine forests. A much more complex relationship is suggested in the regression for warm/dry lower subalpine forests where the last fire interval, intensity/severity index of the last fire, time since fire, and cosine of aspect in combination are all significant. This complex relationship results from each variable's differential effect in each layer (as discussed above) and the relative importance of each layer in the composition of total stand biomass.

Plotting mean stand biomass by time since fire class (Figure 18) reveals that accumulation rates may be relatively high in young and mature stands (<150 years). Biomass accumulation rates then begin to decrease in older forests. For all stand ages total biomass is highest in cool/moist lower subalpine stands, and lowest in upper subalpine forests.

Fire Behavior Potential Changes with Time

Figure 19 illustrates fire behavior and resistance to control descriptors as a function of time since fire. The resistance to handline construction rating increases with time in most fire groups. Deeper duff depths (Figure 17) and higher quantities of coarse downed wood (Figure 16) cause the ratings to be higher in older forests. The rate of spread rating I, which is based upon Fahnestock's (1970) key, shows a tendency for slower potential spread rates as time since fire increases in most forests. This is mostly attributable to decreases in dwarf shrub/herb cover upon which the key is sensitive. In contrast, the rate

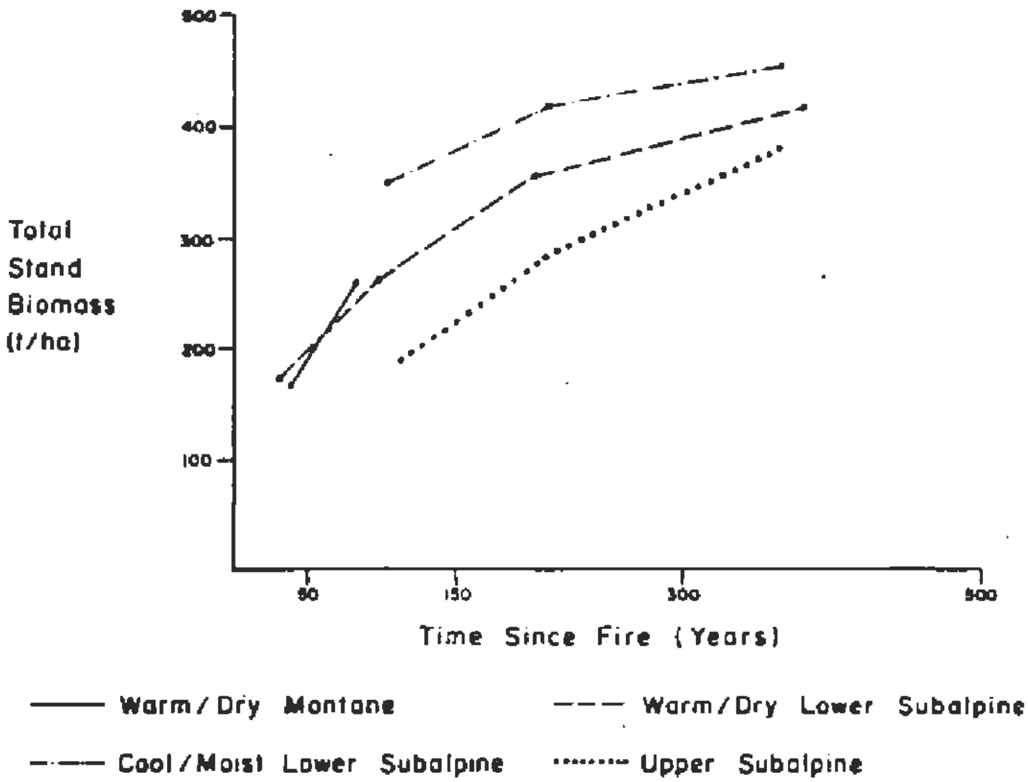

Figure 18: Total stand biomass for fire groups plotted as a function of time since fire classes.

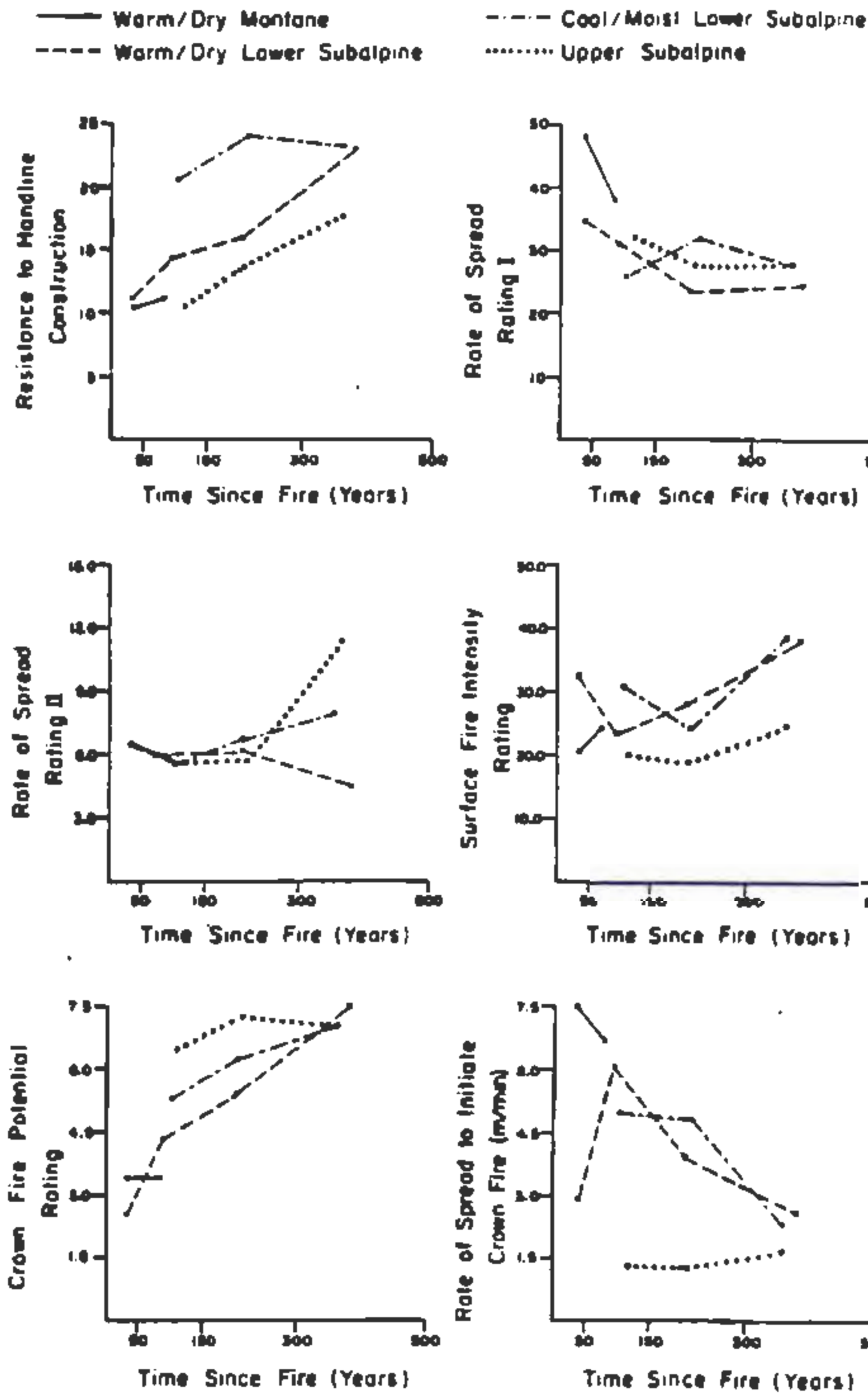

Figure 19: Fire behavior potential descriptors for fire groups plotted as a function of time since fire classes.

of spread rating II, which is derived from the quantity of fine biomass (<3 cm) shows no consistent patterns.

The surface fire intensity rating, as approximated by the weight of available fuel, shows trends which are mostly due to biomass changes of downed wood (Figure 16). Potential surface fire intensity is often high in young stands with abundant dead wood material, decreases to a low in mid-aged stands, then begins to rise again in old forests.

Crown fire potential, estimated with Fahnestock's (1970) key, generally increases with time since fire, particularly in warm/dry lower subalpine forests. The key gives low crowning potential ratings to young lodgepole pine stands with open crowns. Older forests of densely crowned spruce and subalpine fir with ladder fuels receive higher ratings. Crowning potential was also evaluated by calculating the rate of spread required to initiate crowning. As Figure 19 reveals, the rate of spread required to start crown fire is low (3 m/min) in young warm/dry lower subalpine forests, but must be relatively high (6 m/min) as these forests reach maturity. Then, as time since fire increases, greater surface layer biomass available for burning and lower heights to the live crown layer of spruce and subalpine fir trees decrease the rate of spread required to initiate crown fire.

A further evaluation of fire behavior variability with time was obtained by plotting the intensity/severity index of past fires as a function of the fire interval preceding the burn (Figure 20). For all BNP forests, this graph shows that fires ending short fire-free periods (<50 years) often left a substantial portion of trees surviving. However, fires terminating intervals of longer than 100 years were usually intense and severe enough to leave little of the crown layer alive.

Fire Behavior Effects on Biomass Change

Results of regression analysis of biomass components with stand history and site descriptors (Table 21) reveal the importance of the intensity/severity index of the last fire in explaining biomass. Thus, warm/dry montane and warm/dry lower subalpine fire groups were aggregated to evaluate this effect. These fire groups are similar (Figure 8), characterized by a wide range of historic fire intensity/severity index values (Figure 9). Sample plots were then divided by the intensity/severity index of the last fire into two strata: 1) those in which the last fire was of relatively low intensity or severity, killing less than 50% of the crown layer, and 2) those in which the last fire was of relatively high intensity or severity, killing more than 50% of the crown layer.

Figure 21 provides graphs of the two strata as a function of time since fire. Lines connect mean values for young (<50 years), mature (50-149 years), transitional (150-299 years) and old (≥300 years) time since fire classes. A minimum of four samples for each strata in each class was utilized to calculate means.

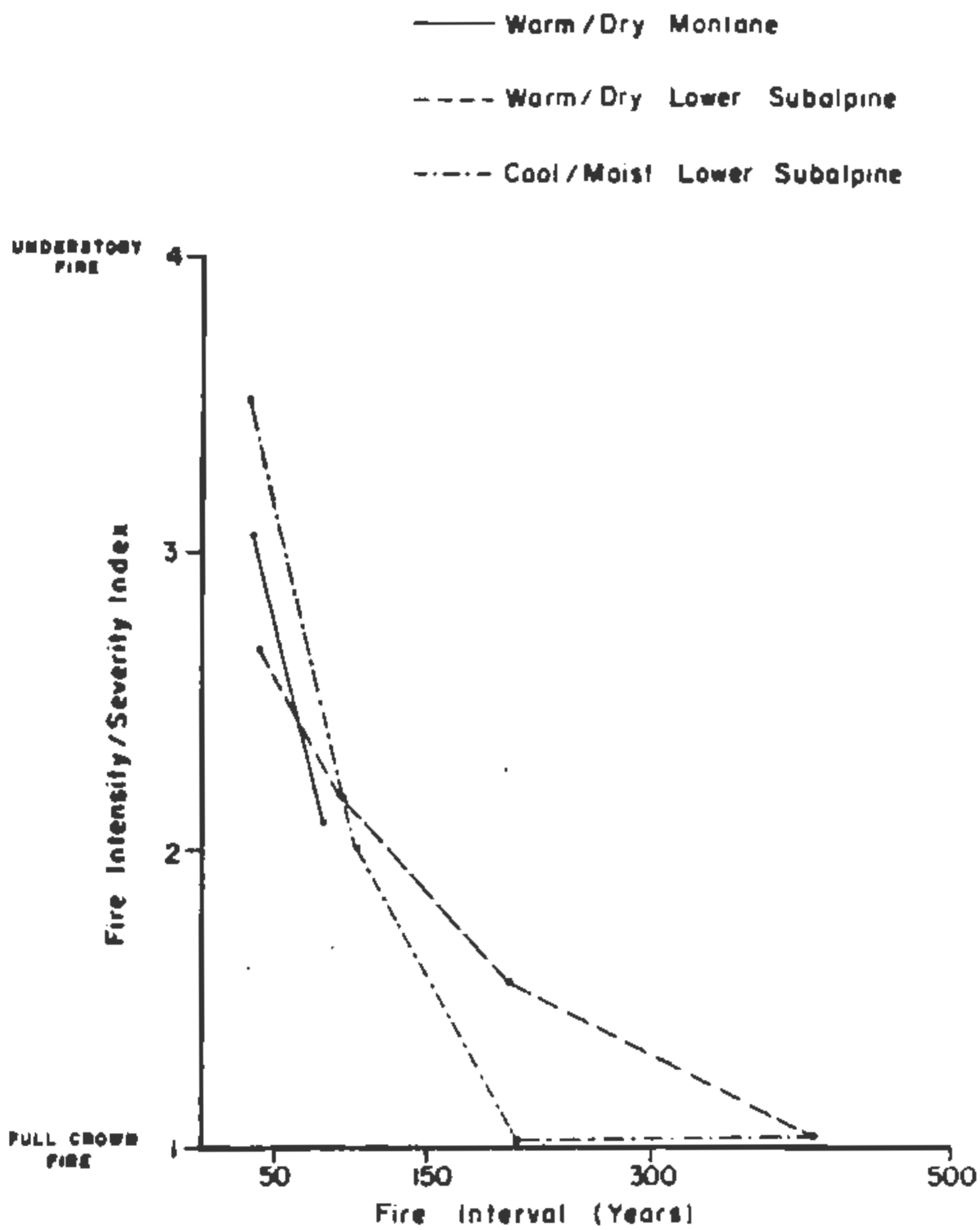

Figure 20: Fire intensity/severity index values for fire groups plotted as a function of length of the proceeding fire interval (time since fire) classes.

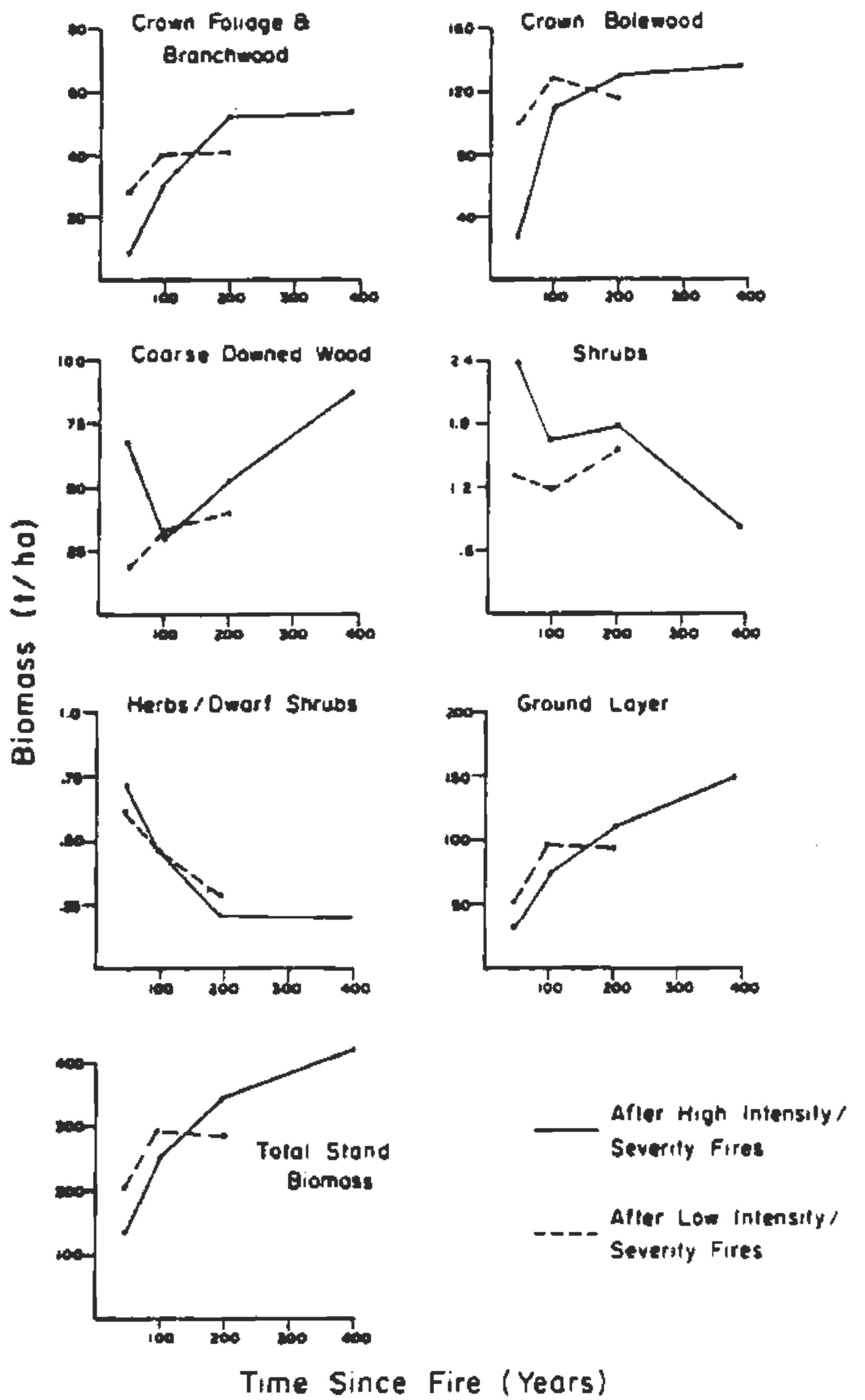

Figure 21: Selected biomass descriptors for warm/dry lower subalpine and montane forests plotted as a function of time since classes and the intensity/severity index of the last fire.

By definition, low intensity/severity fires leave more than 50% of the crown layer surviving; therefore foliage/branchwood and bolewood biomass is higher in young stands after these fires than after more severe or intense burns (Figure 21). However, by 150 years after fire, the crown layer biomass in the high intensity/severity stands becomes greater than in the low intensity/severity forests.

In the surface layer, downed wood biomass is high (approximately 70 t/ha) in young stands where the last fire killed most of the crown layer--leaving a high quantity of dead bolewood to fall to the forest surface. In addition, shrub biomass is highest in young stands created by high intensity/severity fires.

The trends in ground biomass following fires of differential intensities and severities are logical. More severe fires remove the greatest amount of duff, litter and moss leaving a low (approximately 30 t/ha) ground layer biomass in young stands. However, ground biomass inincreases rapidly in these forests (probably due to rotting logs) to exceed that of low intensity/severity stands by 150 to 300 years after fire.

Total stand biomass follows a similar pattern to bolewood and ground layer biomass. After extreme fires, total biomass is low (approximately 135 t/ha) but continues to increase to over 400 t/ha in old forests (≥300 years). In comparison, total stand biomass appears to level out in mature forests after milder fires at approximately 300 t/ha.

CHAPTER 7

DISCUSSION

Results of this study show that significant quantitative relationships exist between biomass and fire characteristics and closed forest vegetation types determined by the ecological land classification (Holland and Coen 1982). Closed forest types with similar characteristics can thus be meaningfully clustered into fire groups to provide a framework for explaining spatial and temporal variation in fire history, biomass and fire behavior potential. In addition, study results indicate that the fire regime is a primary regulator of biomass in BNP forests. Biomass characteristics in turn are major determinants of fire intensity and severity (depth of burn).

This chapter will discuss application of these results to the ecological land classification for fire management purposes, interpret characteristics of fire groups, and evaluate the interaction between fire and biomass in BNP forests.

Application of the Ecological Land Classification

The relationship between closed forest vegetation types as clustered into nine fire groups and fire history, biomass and fire behavior potential is moderately strong. The classification success obtained with discriminant analysis (Tables 15, 16) and the statistically significant results from the one-way analysis of variance tests (Table 17) show that measured descriptors vary appreciably between fire groups. The relationships between vegetation type, fire history, biomass and fire behavior potential are to be expected. For example, fire history often dictates vegetation type. Areas burned most frequently in the Rocky Mountains are maintained in early seral forests such as lodgepole pine and aspen (Horton 1956, Holland and Coen 1982). Forest types such as aspen and lodgepole pine in turn have significantly different crown and understory biomass characteristics from older forests of subalpine fir and Engelmann spruce.

A practical test of the validity of clustering vegetation types into fire groups is to illustrate group occurrence in BNP's landscape. The ecological land classification (Holland and Coen 1982) mapped the park with a system of 124 ecosite types. Applying the fire group classification to the ecosite mapping scheme was facilitated by clustering vegetation types that often occupy the same ecosite (see key in Appendix A) into the same fire groups whenever possible. Ecosite types can thus be easily designated to a fire group on the basis of vegetation (Table 22).

Figure 22 shows the patterns of fire groups in the lower Bow Valley of Banff National Park illustrated on the ecological land classification

Table 22: Ecosite types classified by the Ecological Land Classification (Holland and Coen 1982) broken down by fire groups.

Fire Group	Description	Ecosite Types[a]
1	warm/dry montane lodgepole pine and Douglas-fir	AT1, FR1, NY1, NY3 (south aspects), PT1, PT3
2	warm/dry lower subalpine lodgepole pine	AL1, GT1, GT2, PR2, SB3, SB4, VD2
3	montane aspen	HD1, PT4
4	mesic montane spruce and Douglas-fir	HD3, NY3 (north aspects), TA3
5	cool/moist lower subalpine lodgepole pine	BK1, BK4, CA4, IB1, MC1, ML2, PR1, PR3, PR6, SP1
6	lower subalpine spruce-fir	AL2, BK6, BY1, BY2, BY4, CA1, CA2, CV1, FV1, FV2, IB3, ML1, SB1, SB2, VD1
7	floodplain spruce-fir	HC1, VL3, VL4
8	upper subalpine spruce-fir and larch	BP2, EG2, EG3, LV1, LV3, MQ1, NG1, PL1, PL3, PL5, WF1, WF4, WH1, WH2, WH3
9	spruce-fir on permafrost	SF1

[a] described in Appendix A

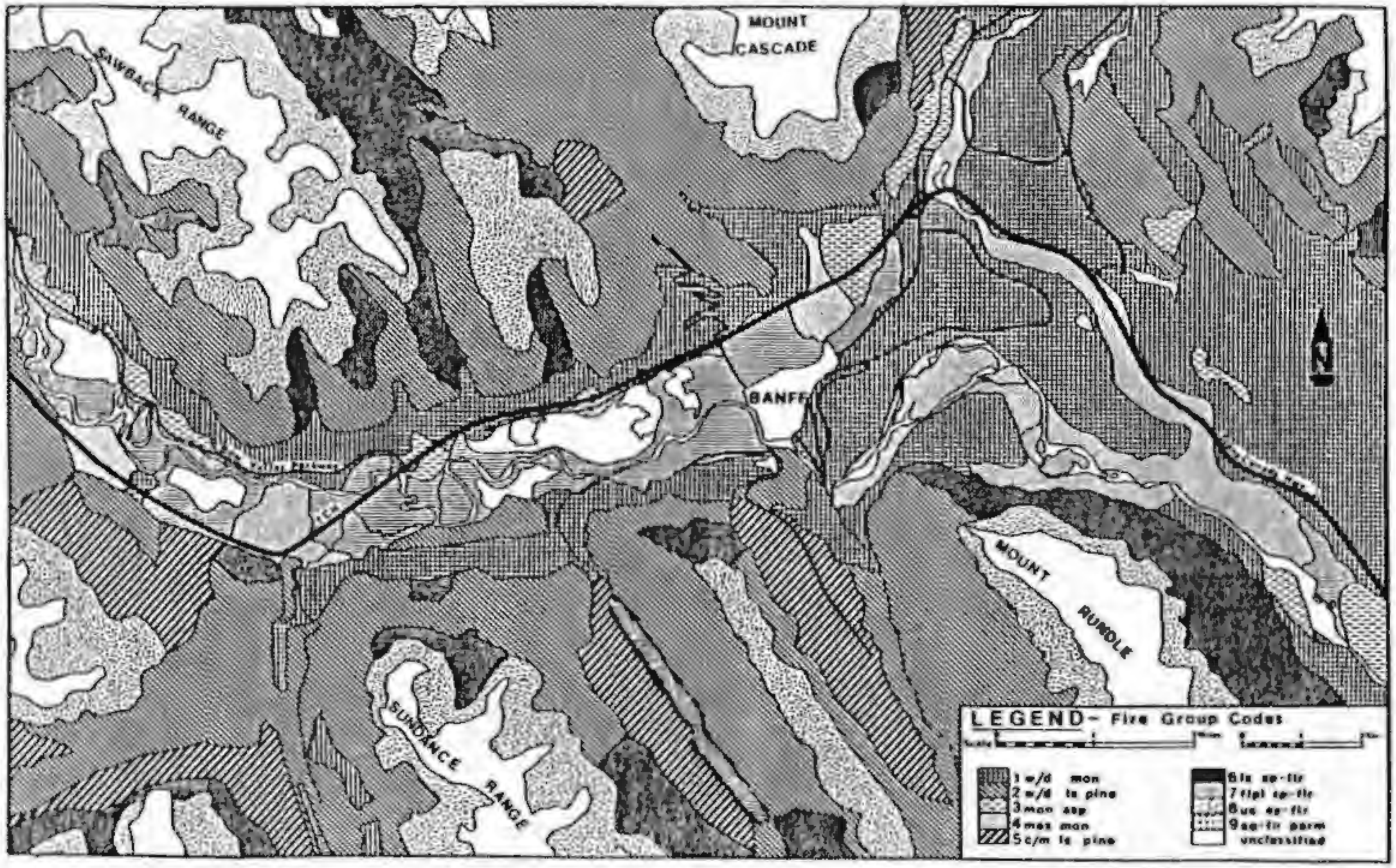

Figure 22: Fire groups in the lower Bow Valley of Banff National Park. Fire groups are defined in Table 13 and Table 22.

base map. The pattern is logical. South and southwest aspect slopes at low elevations are mapped as the warm/dry montane fire forests (Group 1). Often immediately adjacent to these areas, but at higher elevations lie warm/dry lower subalpine lodgepole pine forests (Group 2). Northern aspect slopes at mid-elevation are dominated by cool/moist lower subalpine lodgepole pine forests (Group 5). Upper subalpine spruce-fir forests (Group 8) occupy higher elevation areas near tree line.

Fire History of Fire Groups

Fire interval and time since fire distributions and evaluations of historic fire intensities and severities in BNP provide evidence for a variety of fire regimes similar to those reported by other researchers for northern Rocky Mountain forests (Habeck and Mutch 1973, Tande 1979, Hawkes 1980, Davis *et al*. 1980, Arno 1980, Fisher and Clayton 1983). These fire regimes range from relatively frequent fires in warm/dry montane and warm/dry lower subalpine forests that may be of low intensity and severity to infrequent fires in cool/moist lower subalpine and upper subalpine forests that are severe and intense enough to kill all overstory trees.

Fire Intervals

Mean fire intervals calculated for BNP forests (Figure 10) are similar to adjacent Jasper National Park (Tande 1979) and Kananaskis

Provincial Park (Hawkes 1980). The mean interval of 41 years in BNP warm/dry montane forests is longer than the 18 and 27 years reported by Tande (1979) for these forests in Jasper (Table 7). Possible explanations include a drier climate in the Jasper area (Janz and Storr 1977) and the larger size of Tande's sample stands (50 ha compared to 20 ha in this study). Mean fire intervals may be inversely related to the area of sample units (Arno and Peterson 1983).

BNP montane forests of aspen (Fire Group 3) and warm/dry Douglas-fir and lodgepole pine (Fire Group 1) have the shortest mean fire intervals (less than 50 years). Factors influencing the high fire frequency include climate and human use. These forests occupy the warmest and driest areas of the park (Holland and Coen 1982) which average less than 500 mm annual precipitation (Janz and Storr 1977). In addition, the montane ecoregion had the greatest human activity in the pre-European and European periods (Byrne 1964, Damp et al. 1980).

Since the establishment of the park, fires greater than 40 ha occurred five times more frequently per 1000 ha in montane forests compared to subalpine areas (White 1984). Of these fires, approximately 80% of known ignition sources were due to man's activities. Short fire intervals in the montane ecoregion during the pre-European period may be partially attributed to Kootenay and Stoney Indians who utilized the area (Byrne 1964). Barrett (1980) and White (1984) provide evidence that these native tribes purposely and accidentally started many fires.

Increased precipitation, cooler temperatures and less human use can explain longer fire intervals (>80 years) at higher elevations. Cool/ moist lower subalpine lodgepole pine forests (Group 5) and spruce/fir forests (Group 6) have mean fire intervals of 110 to 130 years (Figure 10). These estimates compare well to Hawkes' (1979) estimate of 101 years for lower subalpine stands in Kananaskis Provincial Park (Table 7). In contrast to fires in BNP's montane ecoregion, which may occur even during relatively wet years, fire occurrence in the subalpine is dependent on long periods of low precipitation. White (1984) calculated that since 1890, the frequency of these conditions was approximately two times per decade.

Time Since Fire

Time since fire distributions as of 1980 (Figures 11 to 14) show trends comparable to distributions reported by MacKenzie (1973) for Waterton Lakes National Park, Tande (1977) for Jasper National Park and Van Wagner (1978) for Alberta foothills (Figure 4). Time since fire distributions as of 1980 for all areas studied suggest that few Rocky Mountain forests stands have been burned in the last 40 years. As observed in Chapter 2, the primary reasons for the decrease in burned area in BNP are prevention of man-caused fires and fire suppression efforts (White 1984). The low frequency of recently burned stands in today's forests indicates the major impact of current fire control policies on BNP stand age distributions compared to pre-1880 conditions.

Tande (1977) points out that similar management programs begun in Jasper National Park in 1910 have dramatically altered fire frequencies that existed at least since the late 1600's.

Byrne (1964) and Day (1972) conclude that fire frequency in the Canadian Rocky Mountains was abnormally high between 1880 and 1920 due to the activities of railroad builders, prospectors and loggers. However this is not supported by Banff's stand history information. The comparison of 1880 and 1930 time since fire distributions for BNP fire groups (Figures 11 to 14) shows few differences. Therefore the frequency of fire from 1880 to 1930 must have been similar to the pre-1880 period. The predominance of man-caused fires between 1880 and 1930 (White 1984), and the evidence that these fires did not dramatically change 1880 time since fire distributions, suggests that man-caused fires were also frequent prior to 1880. The Kootenay and Stoney Indian tribes may have been the major source of these man-caused fires (Barrett 1980, White 1984).

A Comparison of Time Since Fire and Fire Intervals

Time since fire and fire interval distributions can both be analysed through life table techniques to interpret fire frequency. However, as Merrell (1947) and Caughley (1966) observe, the results will be identical only if the environment does not change and the populations are at equilibrium. Thus 1930 and 1980 time since fire distributions for BNP cannot be used for comparison because they reflect changing environments due to European influence (e.g. fire suppression). However, the time since fire distribution as of 1880 could reflect a relatively stable environment prior to that time.

In the case of random burning of forest stands with a time since fire structure at equilibrium, the fire interval and time since fire distributions will be equal. This occurs because fires in essence randomly sample forest's time since fire distribution. Caugley (1966) describes analagous situations for sampling ages of wildlife populations. Figure 23 shows plots of the fire interval and 1880 time since fire distributions on semilog graphs. A similarity is evident. Comparing mean time since fire to mean fire interval values, respectively, for each fire group yields: 40.0 and 41.1 years for warm/dry montane forests, 84.2 and 85.3 years for warm/dry subalpine forests, 124.5 and 128.2 years for cool/moist lower subalpine forests, and 166.7 and 143.8 years for upper subalpine forests.

Points descending a straight line on the semi-log paper fit a negative exponential distribution. As Rowe et al. (1975), Van Wagner (1978) and Johnson (1979) show, negative exponential time since fire and fire interval distributions result when forest stands are randomly burned and flammability is uniform with stand age. The mean of the negative exponential distribution (average time since fire or fire interval) is the fire cycle (C) or years required to burn over an area equal to the whole area of the forest type in question (Van Wagner

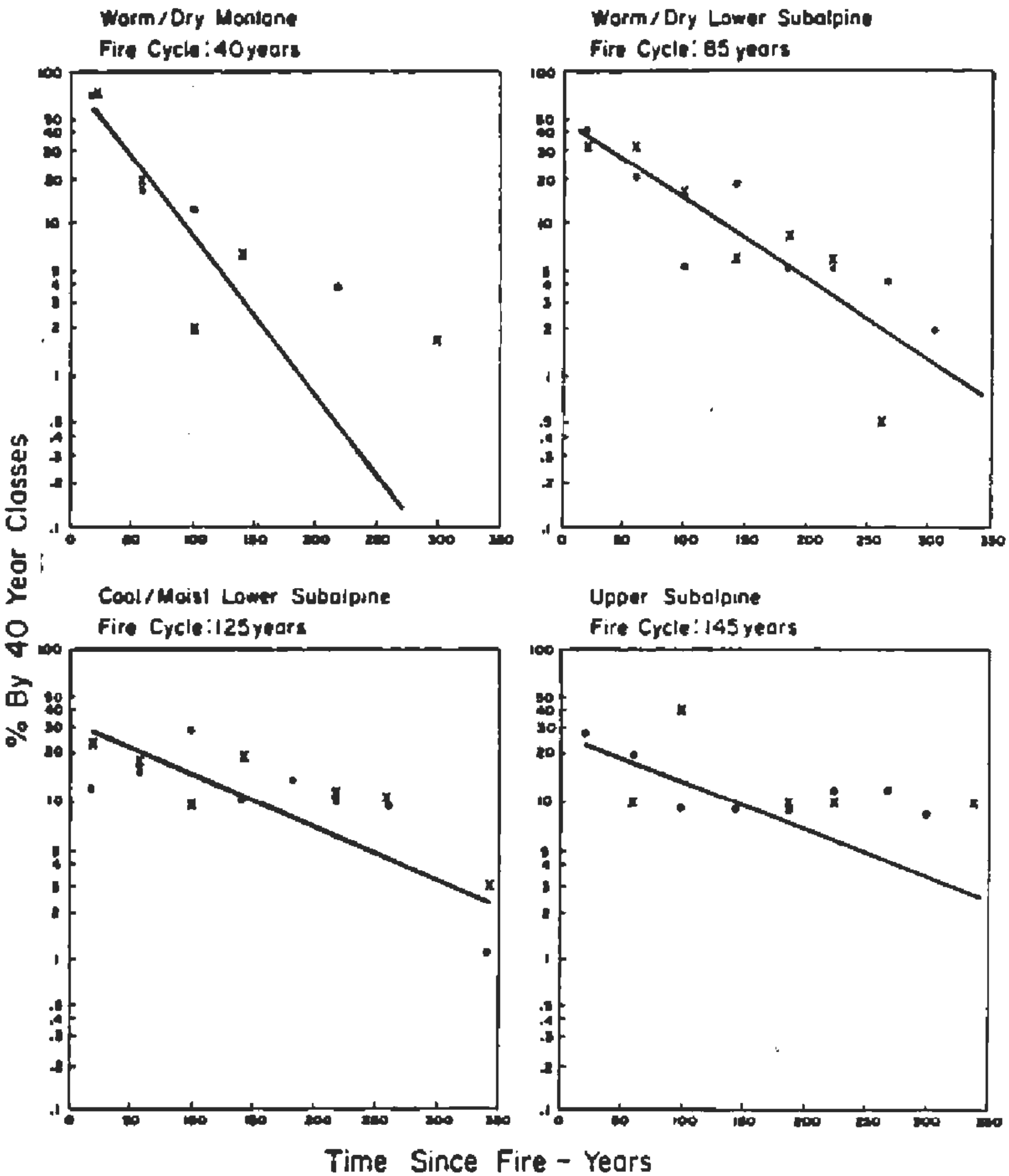

Figure 23: Time since fire as of 1880 (·) and fire interval (x) distributions for Banff National Park fire group sample plots with line estimates for theoretical fire cycles. Blank frequency classes are not plotted to avoid zeroes on semi-log graphs.

1978). Given constant flammability with stand age, the annual probability of burning (p) is 1/C, and the single year frequency of fire intervals or time since fire is given by:

$$f(x) = p \exp(-px) \quad (6)$$

where x is age (years). This equation was used to derive theoretical fire cycle lines in Figure 23 assuming a fire cycle of 40 years in warm/dry montane, 85 years in warm/dry lower subalpine, 125 years in cool/moist lower subalpine, and 145 years in the upper subalpine forests. The similarity of fire interval and 1880 time since fire distributions, and the fit to the theoretical fire cycle line of some groups suggest that historically many BNP areas burned randomly. The probability of burning remained relatively constant with stand age. Van Wagner's (1978) analysis of age-class distributions in Alberta foothill forests shows a similar pattern of fire occurrence. In contrast, other researchers of northern Rocky Mountain forests conclude that the probability of burning is not constant with stand age, but increases as stands become older and biomass accumulates (Habeck and Mutch 1973, Romme 1980). More fire history information is required to better evaluate the relationship of stand age to probability of burning in BNP.

Biomass of Fire Groups

Biomass estimates for BNP forests are within the range of other studies of similar forests types reviewed in Chapter 2. Major biomass components are the ground layer (litter, moss and duff), downed wood and crown bolewood, foliage and branchwood. Figure 24 illustrates a breakdown of these components for BNP fire groups.

Crown Layer

As in other forests that have been studied (reviewed by Art and Marks 1971, Parde 1980, Cooper 1983), crown layer foliage, branchwood and bolewood constitute a major portion of biomass in BNP forests--42% to 71% of total biomass in fire groups. Heaviest crown layer weights occur where time since fire is long and/or forest productivity is high. The effect of long times since fire is best shown by Fire Group 6 (lower subalpine spruce-fir), a type usually successional from lodgepole pine forests (Groups 2 and 5) in Alberta's mountains (Day 1972, Holland and Coen 1982). The relatively heavy crowns of Engelmann spruce and subalpine fir (Brown 1978) and increased number and size of stems create a maximum crown biomass in these stands between 150 and 300 years after fire (Figure 15). However, crown layer biomass tends to decrease with further time. Bloomberg (1949) and Day (1972) observe a similar reduction in crown layer biomass in old spruce/fir forests. Day (1972) states that timber volumes might fall to one-third of maximum due to low nutrient cycling in the heavy humus layer and stagnant tree growth.

The effect of forest productivity on crown layer weight is shown by the comparison of warm/dry lower (Group 3) and cool/moist (Group 5) lower subalpine lodgepole pine forests. Cool/moist forest types tend to

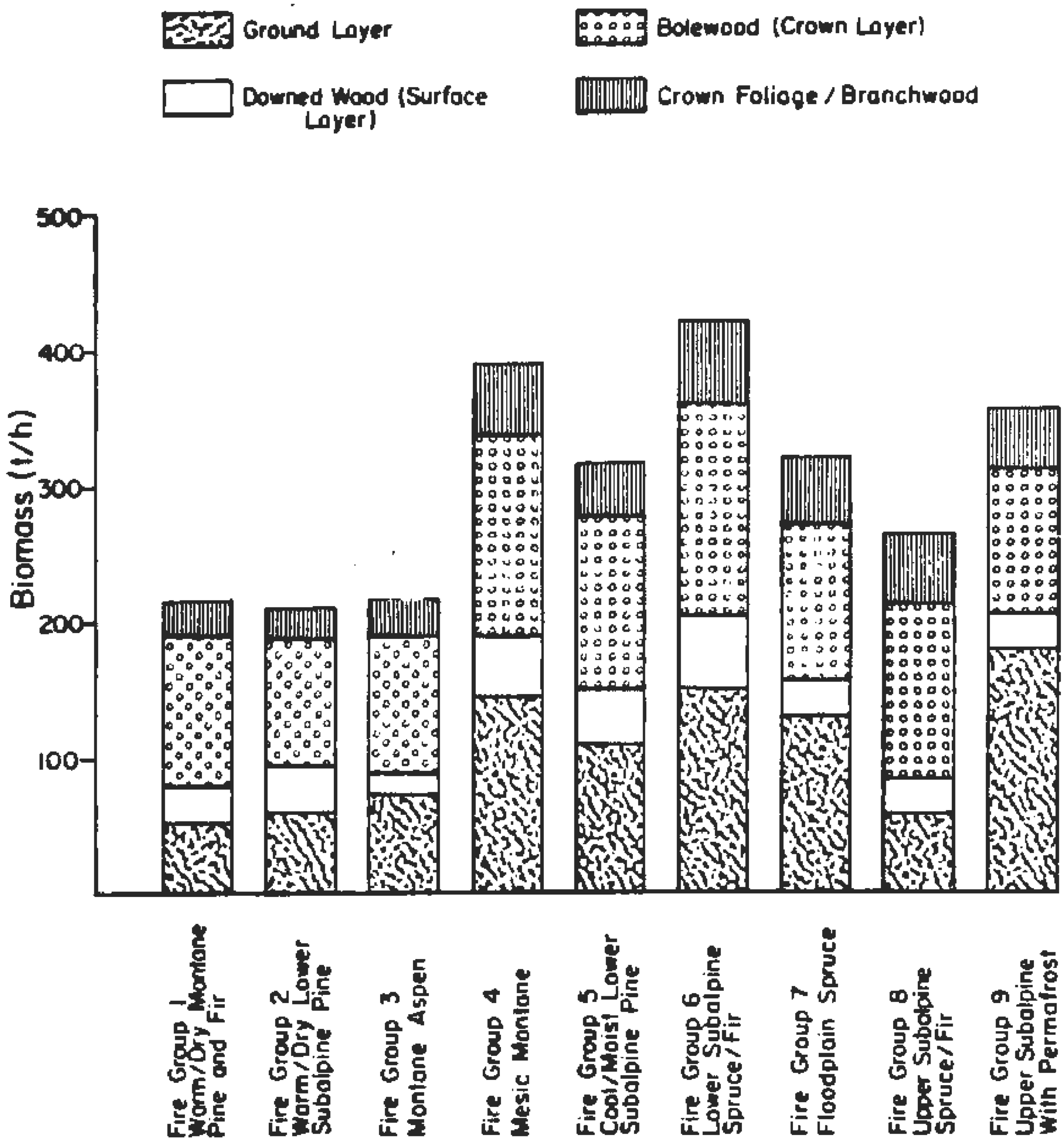

Figure 24: Biomass of the ground layer, downed wood, bolewood and crown foliage/branchwood components for Banff National Park fire groups.

be more productive in the Rocky Mountains (Pfister and Arno 1977), and in BNP have greater crown layer biomass (Table 17) and bolewood accumulation rates (Figure 15).

Crown biomass development in BNP forests appears contrary to some patterns reviewed in Chapter 3. For example, in many BNP forests, foliage and branchwood biomass does not become constant at an early stand age--but increases steadily for up to 200 years after fire. This difference reflects the process of succession in natural stands that may be unlike the managed plantations upon which Madgwick (1976) bases his observations. As noted above, succession in BNP stands leads to fewer light-crowned lodgepole pine and increases in the number and size of heavy-crowned Engelmann spruce and subalpine fir.

Surface Layer

Downed wood is the dominant biomass component in the surface layer of BNP forests, constituting 4 to 13% of total stand biomass for fire groups. This fraction compares to 11% estimated for Colorado lodgepole pine forests (Alexander 1979) and 2% for a Washington subalpine forest (Turner and Singer 1976).

Spatial variation of downed wood between fire groups can be partially explained by crown layer productivity and fire history. Highest downed wood biomass (averaging approximately 50 t/ha) is found in lower subalpine forests of Engelmann spruce and subalpine fir which have high productivity during early stand ages and have escaped burning for over 200 years. Most of the downed wood in these forests results from the mortality of lodgepole pine as stand development occurs (Day 1972). Similarly, Oberheu and Mutch (1975), Brown (1975), Hawkes (1979), Jeske and Bevins (1979), Romme (1980) and Brown and See (1981) all report a general pattern of increased downed wood quantities in stands of over 200 years in age.

The length of the fire interval preceding the last fire is a notable factor influencing downed wood biomass in warm/dry montane and lower subalpine forests. As Fahey (1983) observes in a Wyoming study, the mass of deadfall inherited from the previous stand can be substantial in lodgepole pine forests. In BNP, each fire-free year in the preceding stand's bolewood development can add significant quantities of coarse downed wood to the current stand with all other variables controlled (Table 21). This carry-over effect is enhanced by the relatively slow decomposition rates of wood in northern forests (McFee and Stone 1966, Harvey _et al_. 1981, Fahey 1983). In spite of the slow rates of decomposition, many BNP forests have a surface layer relatively free of deadfall, particularly warm/dry montane and warm/dry lower subalpine lodgepole pine stands. This characteristic probably results from frequent historic fires that consumed dead wood and killed trees in earlier forests before large quantities of bolewood accumulated.

Shrub biomass is only a minor component in BNP forests, providing less than 1% of fire group biomass except in Fire Group 9 (upper subalpine forests with permafrost). Shrub layer weight estimations compare well to studies in forest types reviewed in Chapter 3 (Habeck 1976, Jeske and Bevins 1976, Hawkes 1979). Spatial variation between most fire groups is not significant; a low but relatively consistent shrub cover exists in almost all BNP closed forest types (Holland and Coen 1982). The exceptionally high shrub biomass in Fire Group 9 results from shrub-like subalpine fir that has high cover in these stands (Holland and Coen 1982).

Although time since fire is not a statistically significant variable in explaining shrub biomass in most BNP forests (Table 21), plots of shrub biomass as a function of time since fire and fire intensity/severity (Figure 27) show that intense and severe fires may result in high shrub biomass in young stands (<50 years), similar to results reported by Jeske and Bevins (1976) for Glacier National Park, Montana forests. Also of interest is the apparent importance of the length of the last fire interval in regulating shrub biomass in Fire Group 1 (Table 21). The shorter the last fire interval the lower the shrub biomass in the current stand. No explanation for this observation was found in the literature.

Herbaceous plants and dwarf shrubs in BNP forests' surface layer are also not heavy biomass components, although the light loadings are again comparable to several Rocky Mountain forest studies referenced in Chapter 3 (Habeck 1976, Jeske and Bevins 1976, Alexander 1979, Hawkes 1979). Spatial and temporal variation of herb/dwarf shrub biomass appears to be related to canopy characteristics, fire history and topographic (aspect and elevation) factors. Warm/dry montane, warm/dry lower subalpine lodgepole pine and montane aspen forests (Groups 1, 2 and 3) have high herb/dwarf shrub biomass, low crown foliage/branchwood biomass and foliage bulk density, frequent historic fires, and low elevation warm/dry conditions (Table 17). With increased time since fire, herb/dwarf shrub biomass decreases in these forests (Figure 16), probably due to increased crown layer biomass and density (discussed above) which reduces the throughfall precipitation and solar radiation necessary for herb/dwarf shrub production (Anderson *et al*. 1969, Pyke and Zamora 1982). Similarly, moister and cooler forests in BNP's montane and lower subalpine ecoregions (Groups 4, 5, 6 and 7) have low herb/dwarf shrub biomass, probably the result of relatively heavy and dense crown layers (Table 17).

Ground Layer

Litter, moss and duff in the ground layer of BNP forests are significant biomass components, constituting from 22% to 49% of total stand biomass for fire groups. These fractions of total stand biomass compare favorably to estimates for an Alberta aspen forest (Lousier and Parkinson 1976), a Washington subalpine forest (Turner and Singer 1976) and Minnesota aspen, pine and spruce stands (Alban *et al*. 1978).

Differences in ground layer components between fire groups are due to the interaction of factors such as forest floor micro-climate, forest production rates, decomposition rates, and time since fire. Since this study did not evaluate all of these factors, only general explanations are possible.

Warm/dry montane, warm/dry lower subalpine lodgepole pine and montane aspen forests (Groups 1, 2 and 3) have relatively low ground layer biomass (<75 t/ha) with high litter cover (Table 17). Decomposition rates can be comparatively slow in warm, open forests (Fogel and Cormack 1977, Fahey 1983). However, ground biomass probably does not accumulate because frequent fires (Figure 9) remove organic matter and prevent the growth of large quantities of crown bolewood that would eventually fall and partially decompose.

In cooler and moister BNP forests with longer fire intervals (Groups 4, 5, 6, 7 and 9) a heavy ground layer occurs (>100 t/ha). The successional development of warm/dry lower subalpine lodgepole pine (Group 2) to spruce-fir (Group 6) also results in higher ground biomass (Figure 17). Thus, even if decomposition rates do not vary substantially between warm/dry and cool/moist forests, the long fire intervals in the cool/moist stands allow ground biomass to accumulate. In addition, net primary production in the crown layer is probably higher in cool/moist forests than warm/dry forests (Pfister _et al_. 1977). This could result in more organic material being deposited in the ground layer (Brown and See 1981).

Moss and litter biomass and cover follows expected patterns in all fire groups. A moss layer usually develops early in cool/moist lower subalpine forests (Figure 17) where the micro-climate is most favorable. In contrast, the moss layer develops slowly in warm/dry montane and warm/dry lower subalpine forests, possibly requiring the cooler and moister conditions created by increasing crown bulk density with stand age (Figure 15). Once a moss layer forms, litter cover and biomass decrease substantially, probably because mosses enhance litter decomposition (Bernier and Roberge 1962).

Upper subalpine spruce-fir (Group 8) has low ground layer biomass (Table 17) in spite of long times since fire in many stands (Appendix B). No information on decomposition rates is available for these forests, but rates may be slow due to the climate at high elevations. Therefore, light ground biomass probably results from low productivity in the upper subalpine forest (Pfister _et al_. 1977) which provides less material for inclusion into the ground layer.

Fire Behavior Potential in Fire Groups

Rate of Spread

Fahnestock's (1970) key for evaluating surface fire rate of spread gives highest ratings to fire groups with high herb/dwarf shrub cover and biomass such as the warm/dry montane forests (Group 1), montane aspen (Group 3) and warm/dry lower subalpine lodgepole pine (Group 2). As reviewed in Chapter 3, similar patterns are observed for forests in Idaho and Montana (Barrows 1951), British Columbia (B.C. Ministry of Forests 1979), and Waterton Lakes National Park (Grigel et al. 1977). Young forests with high herb/dwarf shrub cover (Figure 16) also appear to have potential for rapid rates of spread (Figure 19) based on Fahnestock's (1970) key.

Predicting rates of spread based on the quantity of fine fuels in the surface layer gave ratings for BNP forests differing from Hawkes' (1979) estimates for nearby Kananaskis Provincial Park. For example, Hawkes found relatively low fine fuel loadings in lodgepole pine forests whereas in BNP these stands appear to have comparatively high fine fuel biomass (Table 17) which could result in fast rates of spread. Kananaskis lodgepole pine forests are possibly cooler and moister than BNP stands with less herb/dwarf shrub biomass to contribute to fine fuel loadings.

Van Wagner (1977, 1983) suggests that on the basis of fine fuel availability, rates of spread in northern forests may be highest in young stands, low in well-stocked mature stands, and increase again as forests become overmature and begin to break-up. The evaluation of fine fuels as a function of time since fire shows this pattern in BNP's cool/ moist lower subalpine forests (Figure 19).

Surface Fire Intensity

Assuming a constant rate of spread, surface fire intensity depends on the availability and quantity of surface layer fuel (Byram 1959). In BNP, montane and lower subalpine forests dominated by spruce and subalpine fir (Groups 4 and 7) have the highest quantities of surface fuel (Table 17). The British Columbia Ministry of Forests (1979) and Hawkes (1979) also give high fire intensity ratings to similar forest types.

Due to increased biomass, potential surface fire intensities become high in old-aged BNP forests (Figure 19). However, lower subalpine forests have a period of low fire intensity potential in mid-aged stands. Brown (1975) and Van Wagner (1983) also describe a period of low fire intensity potential in mid-aged lodgepole pine and boreal forests respectively.

Crown Fire Potential and Mortality

Predicting the potential of BNP forests to support high intensity crown fires is essential to safely managing fires in BNP. The degree of crown layer mortality that occurs due to intense or severe (deep burning) fires is a key factor in dictating post-fire succession in Rocky Mountain forests (Habeck and Mutch 1973, Brown 1975, Fisher and Clayton 1983).

Warm/dry montane stands of lodgepole pine and Douglas-fir (Group 1) and montane aspen forests (Group 3) have historically had the most frequent understory fires (Figure 10), and currently have relatively low crown fire potential as indicated by Fahnestock's (1970) key and the rate of spread required to initiate crowning calculated with Van Wagner's (1977) equation. Horton (1956), Brown (1975), Tande (1979), Arno (1980), and Fisher and Clayton (1983) also describe the occurrence of fires that leave many crown layer trees surviving in low elevation Rocky Mountain forests. Probable explanations include the high, open crowns of montane trees (Table 17) which are not conducive to the initiation and propogation of crown fire (Van Wagner 1977). Ground and surface layer biomass is relatively low and thus surface fire intensities and severities may not be high enough either to kill cambium and roots or scorch crowns. In addition, fires in the montane zone of BNP often occur under relatively moderate weather conditions which are not conducive to explosive crown fires (White 1984).

BNP forests dominated by spruce and fir (Groups 4, 6, 7, 8, 9) have the highest crown fire potential (Table 17). These fire groups also exhibit a history of fires which totally killed the overstory (Figure

10). Forests of spruce and subalpine fir favor intense crown fires due to low heights to live crown, high foliage bulk densities, abundant ladder fuels, and often heavy fuel loading in the surface and ground layers. The B.C. Ministry of Forests (1977) corroborate this finding for British Columbia spruce-fir forests.

In warm/dry (and possibly cool/moist) lower subalpine BNP forests, crown fire potential (estimated by the rate of spread to initiate crowning) is high in young (<50 years since fire), low in mature forests (50-150 years) then increases again in forests remaining free of fire for more than 150 years. Van Wagner (1983) outlines the same pattern for crown fire potential in northern boreal forests. Crown fires may start easily in young BNP forests where live tree foliage is near the ground. However, total crown mortality rarely occurs (Figure 20), possibly because the low foliage bulk density in young stands (Figure 15) will not sustain a continuous crown fire (Fahnestock 1970, Van Wagner 1977). In addition, the low ground biomass in young forests (Figure 17) may be insufficient to sustain a severe fire that would totally kill tree cambium and roots. In mid-aged mature forests, potential for the initiation of crown fire decreases due to pruning of lower branches on lodgepole pine which increases the height to flammable live foliage. However, fires in this stage historically often killed most of the overstory (Figure 20), possibly due to severities which killed roots and cambium. With further time since fire, a spruce/fir understory develops with live foliage near the ground. Crown fire potential increases at this time, and historically, most fires ending intervals longer than 200 years totally killed the overstory (Figure 20). This concurs with the findings of Tande (1979), Hawkes (1979), Arno (1980), and Fisher and Clayton (1983) for other Rocky Mountain forests.

Resistance to Control

Potential handline construction rates (Murphy and Quintilio 1977) indicate that spruce and subalpine fir forests with deep ground layers and heavy downed wood biomass (Groups 4, 6, 7, 9) will give the greatest control problems among all BNP fire groups (Table 17). For example, in fire groups with resistance to control ratings of 22, handline construction rates would be limited to 7 meters per person per 45 minute hour (from Table 9). Thus, in spruce and subalpine fir forests, effective line construction will in most cases require larger equipment such as bulldozers. Hawkes (1979) and British Columbia Ministry of Forests (1979) also report high resistance to control in these forest types. As discussed above, ground layer depth accumulates with time since fire in all BNP forests; this factor increases the resistance to handline construction as stands become older.

Biomass and Fire: A Preliminary Model

The analysis of fire history, biomass, and fire behavior information for BNP forests supports the central hypothesis of this study that the fire regime (frequency, intensity and severity) is a prime regulator of biomass in BNP forests. Biomass characteristics in turn are major determinants of intensity and severity. As described by Olson (1981) and MacLean et al. (1983), fire regulates biomass through : 1) oxidation of organic material to ash, gas and mineral elements; and 2) redistribution of biomass components. Biomass influences fire behavior through the quantity and distribution of fuels. In general, the longer BNP forests remain fire-free, the more will biomass accumulate and the greater the probability that fires will be intense and severe, sharply reducing biomass. This observation concurs with Olson's (1981) theory that in many ecosystems the product of fire frequency multiplied by biomass release may be relatively constant over the long term, despite wide variations in fire frequency and the biomass released.

The results of this study show that fire regime and biomass characteristics vary both in spatial and temporal dimensions. Site variables (elevation, aspect, slope, hygrotope) largely control this variability through their influence on both biomass accumulation patterns, and the fire regime. To illustrate these effects, I have developed a preliminary model of fire and biomass interaction in BNP closed forests. Initially, we will consider a hypothetical BNP forest stand that is an intergrade between the warm/dry montane and warm/dry lower subalpine fire groups as an example. A constant climate since 1500 A.D., and a fire cycle of 60 years with equal probability of burning with stand age are assumed. Biomass in the example forest stand can be plotted as a function of a possible fire regime for the period 1500 A.D. to 1980 A.D. (Figure 25). The estimates for biomass of various components are derived from Figure 21, extrapolated back to zero years since fire. Hypothetical fires occur in the years 1500, 1525, 1575, 1825, 1850, and 1900. With a 60 year fire cycle (C) and uniform probability of burning with age, the fire interval distribution will be approximated by a negative exponential curve (Rowe _et al_. 1975, Van Wagner 1977, Johnson 1979). The probability of a stand remaining fire-free for at least a given period (x) can be calculated with the equation:

$$f(x) = e^{(-1/C)x} \tag{7}$$

Included on Figure 25 are probability values calculated for each fire interval.

Assuming that the hypothetical stand experienced a low intensity/severity fire in 1500, substantial crown bolewood, branchwood and foliage remain. The probability of remaining fire-free for at least 25 years to the year 1525 is relatively high ($p = .66$) when another low intensity/severity fire is shown which reduces the ground biomass. A 50 year fire interval ($p = .43$) is ended by an intense and severe fire in 1575. This fire totally kills the crown layer, removes most of the ground layer, and converts about 150 t/ha of bolewood into the dead wood biomass component.

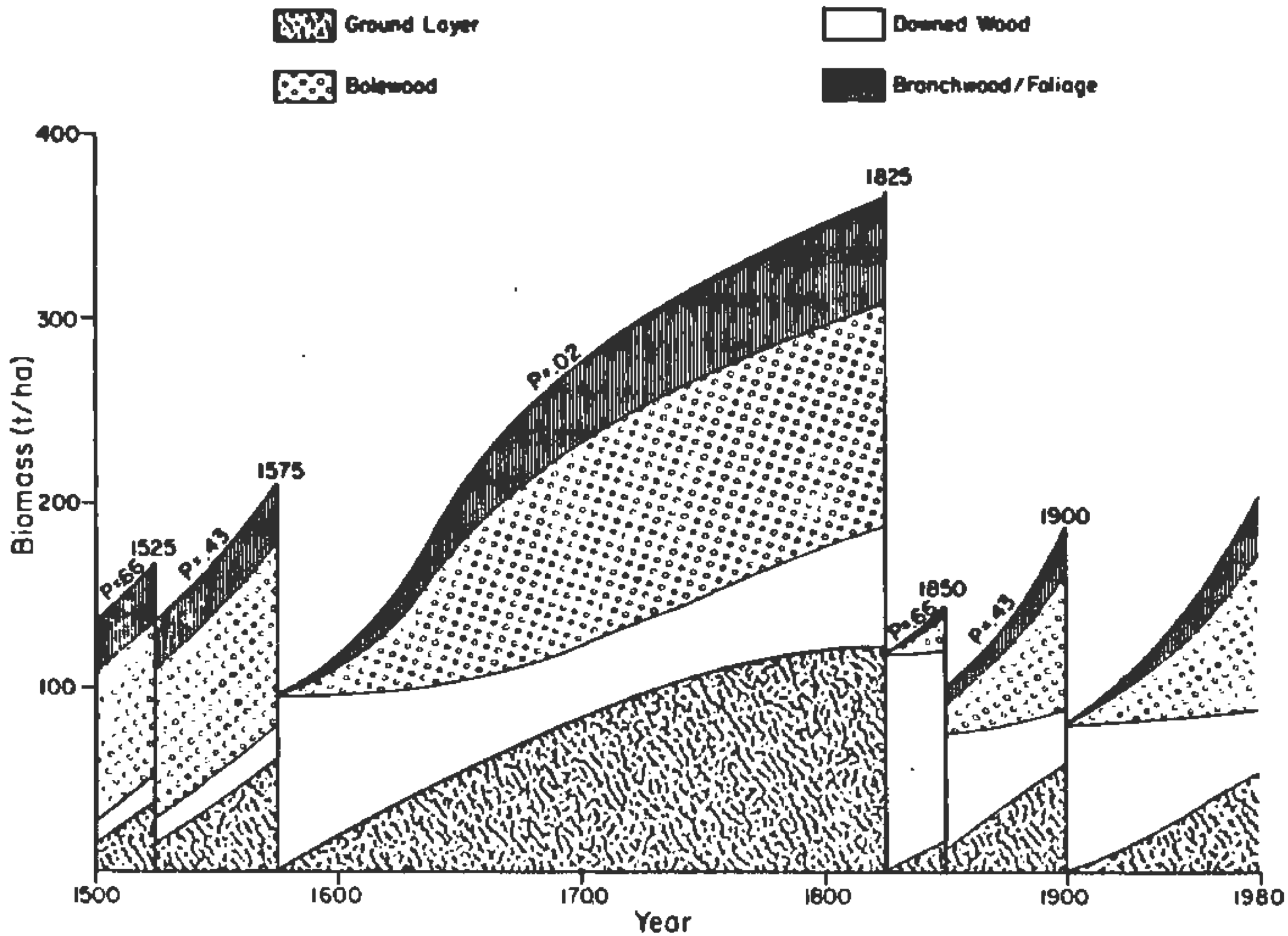

Figure 25: Biomass in a hypothetical warm/dry montane -- warm/dry lower subalpine forest plotted as a function of a possible fire regime for the period 1500 - 1980. The P values indicate the probability of fire intervals being at least as long as shown.

The long interval (250 years) between fires in 1575 and 1825 has only a low probability of being at least this long ($p = .02$), but by chance could occur. Total stand biomass builds up through the period to in excess of 350 t/ha. Because of high foliage bulk density, low rates of spread required to initiate crowning, and heavy ground and surface layer biomass accumulations, the 1825 fire is almost certain to be a crown fire of high intensity and severity. The fire removes most of the ground layer and creates over 150 t/ha of dead bolewood and branchwood. Subsequent fires in 1850 and 1900 further oxidize and redistribute biomass components.

The period after 1900 reflects a time of increasingly effective fire suppression in BNP (White 1984). The probability of fire decreases substantially in the hypothetical forest stand, and thus by 1980 the time since fire is 80 years, similar to large areas of warm/dry montane and lower subalpine forests in BNP. Total biomass is less than 200 t/ha but still accumulating. Like current conditions in most BNP forests, dead wood biomass is relatively low (<30 t/ha)--the result of fires in the 1800's which restricted bolewood accumulation and consumed downed logs.

The method of illustration presented above is extended to warm/dry montane, warm/dry lower subalpine, cool/moist lower subalpine, and upper subalpine fire groups in Figure 26. Again, an equal probability of burning with stand age and constant climate is assumed. The graphs

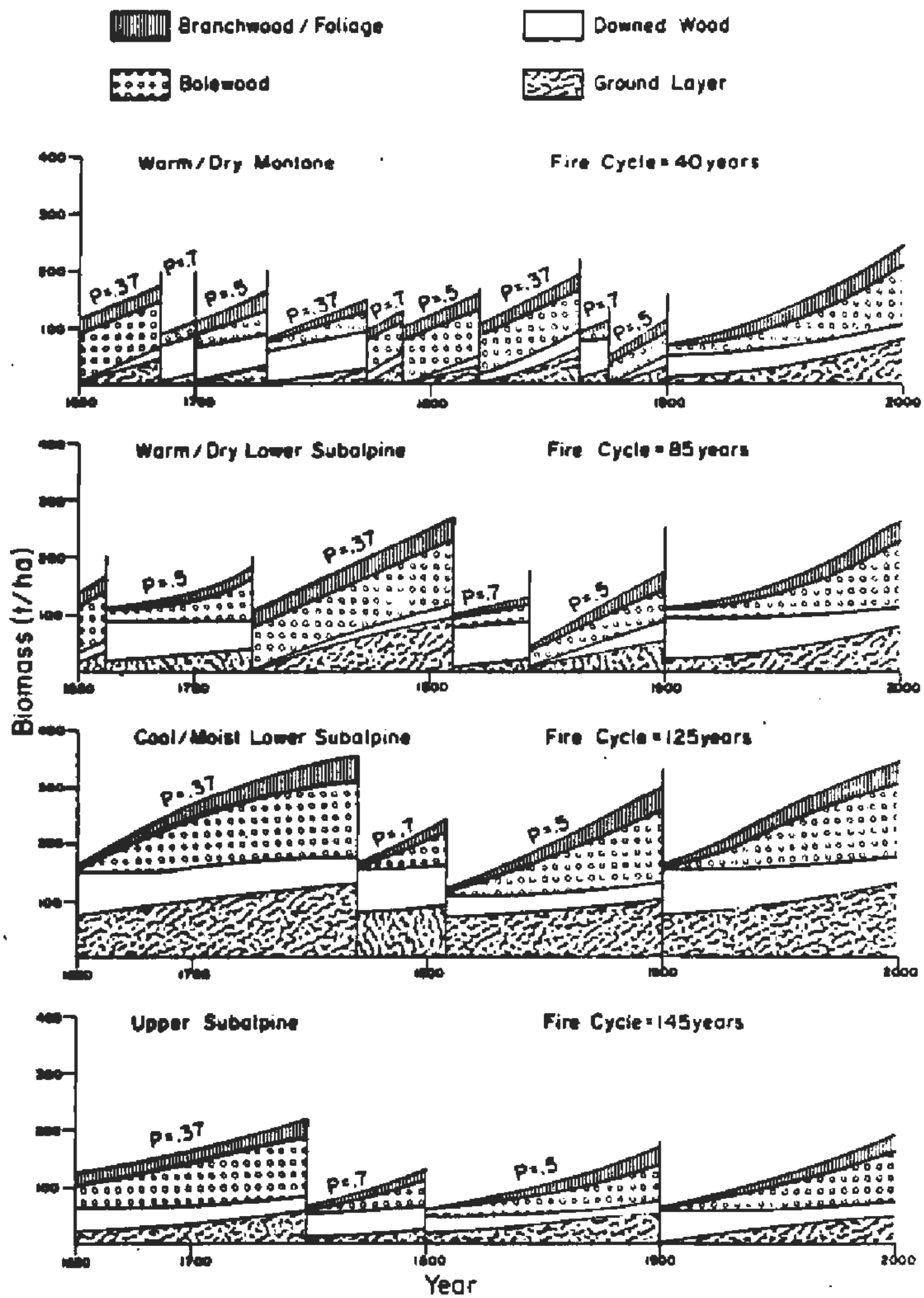

Figure 26: Biomass in Banff National Park fire groups as a function of a possible fire regime for the period 1650-2000. The p values indicate the probability of fire intervals being at least as long as shown.

reconstruct biomass accumulation sequences back into the past from 1900 with probabilities of .5, .7 and .37 that fire-free intervals will be at least as long as shown. Interval lengths for probabilities are calculated assuming a 40 year fire cycle in warm/dry montane, 85 years in warm/dry lower subalpine, 125 years in cool/moist lower subalpine and 145 years in upper subalpine fire groups. The p = .37 intervals represent mean fire intervals for the group. In other words, only 37% of stands should escape fire for longer than the mean interval if the probability of burning is equal with stand age (Van Wagner 1978). Estimates for biomass components as a function of time since fire are derived from Figures 18 and 21. Both low intensity/severity and high intensity/severity fires are illustrated in warm /dry montane and warm/dry lower subalpine forests. No fires occur after 1900 to illustrate the results of fire suppression since that time.

The effects of biomass accumulation rates and the probability of fire in BNP fire groups are synthesized by Figure 26. In warm/dry montane forests, biomass remains relatively low throughout the period prior to 1900. Even with rapid accumulation of biomass, the high probability of short fire intervals rarely permits biomass levels to exceed 200 t/ha. Biomass is also usually less than 200 t/ha in upper subalpine forests, primarily due to low accumulation rates in this long fire interval type. High biomass accumulation rates and a high probabilty of long fire intervals combine to create heavy (>300 t/ha) biomass conditions in cool/moist lower subalpine forests.

The probability of fire in all BNP forests prior to 1900 appears to have been great enough that only infrequently would BNP forests reach maximum or steady state biomass conditions (Odum 1969). In this respect, Olson (1981) proposes four hypotheses for the influence of fire in regulating biomass:

1) Low or zero intensity and/or frequency of fires allow live and dead biomass to increase until accumulation equals decomposition, export and consumption (e.g. steady state biomass situation);
2) Infrequent high intensity fires may allow the ecosystem to reach steady-state biomass conditions but then remove or redistribute a large portion of biomass, starting major new successional sequences;
3) High intensity and relatively frequent fires prevent the ecosystem from reaching biomass conditions that would be perpetuated in the absence of fire; or
4) High intensity and/or frequent fires alter ecosystem development, possibly diminishing primary production through depletion of site nutrient reserves, and thus decreasing intensities of subsequent fires.

In BNP forests, Olson's (1981) third hypothesis appears to have been the primary historical influence of fire on biomass. Infrequently, the steady-state conditions proposed under the first hypothesis may have been maintained by low intensity fires in warm/dry montane forests. Maximum biomass conditions proposed by the second hypothesis may have been occasionally attained in cool/moist lower subalpine or upper subalpine stands. Evidence for Olson's (1981) fourth hypothesis--frequent fires diminishing primary productivity and thus subsequent fire intensities--is not directly quantified in this study of BNP forests. However, some subalpine areas in BNP are only slowly regenerating to forest cover after a series of relatively frequent fires (e.g. the Palliser Range along the Cascade River, and the Goat Range along the Spray River). The slow regeneration of forests has resulted in low biomass conditions and thus may provide some evidence for frequent fires diminishing productivity. Another explanation could be that the short fire intervals reduce the seed bank required for tree regeneration (Kessell 1979). Whatever the reason, the occasional long fire interval that can occur randomly in all BNP fire groups should allow a recovery of tree cover and maintenance of long term productivity.

The effects of fire suppression since 1900 on the biomass-fire inter-relationship are well illustrated by Figure 26. The results of reducing the probability of fire are most evident in warm/dry montane forests where biomass has accumulated to levels which had only a small probability of occurring in the pre-1900 fire regime. The heavy biomass will result in fires characterized by intensities and severities greater than historical levels. Mortality in the crown layer will be high, perhaps reaching 100% in many cases. High crown mortality will in turn dramatically effect biomass components and successional development in future forests. For example, full crown mortality will result in a preponderance of even-aged forests instead of the multi-aged forests currently found in the montane ecoregions (Tande 1977). In addition, the high intensity fires will create a pulse of abnormally high downed wood biomass that will alter nutrient storage patterns (Fahey 1983) and possibly the behavior of future fires. Thus, the disruption of the pre-1900 fire regime may result in a long term chain- reaction of events significantly departing from the "natural" conditions Banff National Park is established to preserve.

Recommendations for Further Study

This study provides only a preliminary view of the dynamic interaction between fire and biomass in Banff National Park forests. Several topics require further research:

1) Standing dead wood (snag) biomass was not estimated in this study. This component is extremely important in recently burned forests (<30 years) and could exceed 100 t/ha. In Colorado lodgepole pine stands ranging from 57 to 282 years in age, Alexander (1979) found the density of dead trees numbered up to 5,681 stems/ha.

2) Biomass in forests less than 10 years after fire was sampled by four plots in this study but requires detailed analysis. Biomass changes can be extremely rapid in northern forests for several years after fire due to high rates of decomposition, production and post-fire leaching and erosion (Vitousek and Reiners 1975, Viereck and Schandelmeier 1980, MacLean *et al*. 1983). The effects of these processes on biomass components in recently burned BNP forests require assessment.

3) Biomass should be monitored in individual stands through time. The approach utilized in this study required stratifying spatially different forests into fire groups, and evaluating temporal sequences within each group. The temporal analysis assumed that environmental variables within each group are relatively homogenous, and that all changes observed were due to stand history (Mueller-Dumbois and Ellenberg 1974, Laven 1982). The ability to only partially explain biomass components as a function of stand history variables with regression analysis indicates that the fire groups may not be homogenous, and that other site or stand history variables may be significantly important. Useful information on fire and biomass could thus be gained by following individual stands for some length of time and evaluating biomass change and pathways. This evaluation could be combined with study topics 1 and 2 (above) by evaluating biomass prior to prescribed burning and for some years after on several individual sites treated with various intensities and severities of fire. The information gathered would provide a basis for dynamic simulation models that could more accurately predict biomass change with time (Muraro 1971).

4) Further progress must be made in predicting fire behavior potential in BNP forests. The work described here provides only relative estimates of fire rate of spread and intensity between fire groups. However, the ultimate success of BNP's fire management program is dependent on accurately predicting fire behavior under variable topographic, fuel and weather conditions. Continued progress in the Canadian Forest Fire Danger Rating System (Alexander 1982) and the

possible application of the Rothermel (1972, 1983) fire model to Banff fire groups could improve fire behavior predictability.

5) Finally, more research is required to evaluate the relationship of stand age to probability of burning. Preliminary analysis in this study and by Van Wagner (1978) indicates that the probability of burning does not vary with stand age in Alberta Rocky Mountain and foothill forests. However, this finding contradicts Habeck and Mutch (1973) and Romme (1980) who state that the probability of burning increases with stand age in forests of the northern Rocky Mountains of the United States. Continued fire history and fire behavior potential research may clarify this discrepancy.

CHAPTER 8

CONCLUSIONS

The fire regime is an important determinant of biomass in closed forests of Banff National Park. Biomass in turn influences fire characteristics such as intensity and depth of burn.

The relationship between fire, biomass and the ecological land classification of Banff National Park (Holland and Coen 1982) is significantly important to park managers. The relationship allowed the delineation of nine fire groups combining closed forest vegetation types with similar fire history, biomass and potential fire behavior characteristics. Although fire groups are not sharply defined, they can be viewed as intervals along a continuum of fire and biomass conditions in BNP. The applicability of the fire group concept to the ecological land classification maps of the park can facilitate ecologically sound fire management on a park-wide basis. For example, knowledge of fire group characteristics can be combined with ecosite maps to determine how much land should be burned to maintain vegetation management objectives.

The historic regime (frequency, intensity, and severity) of fires in BNP forests appears similar to other areas studied in the northern

Rocky Mountains (Arno 1980). Both fire interval and time since fire distributions show that, prior to 1880, mean fire intervals ranged from 40 years or less in low elevation montane forests to over 140 years in the upper subalpine ecoregion. Primary factors in the differences in fire frequency are probably climate and human use patterns. In concurrence with Van Wagner's (1978) hypothesis for Alberta foothill forests, many BNP forest appear to have burned randomly with a probability of burning that was independent of stand age. However, the character (intensity and severity) of historic fires was not random. Fires ending long intervals tend to be intense and severe, causing complete mortality in the forest crown layer.

An understanding of the fire regime and biomass accumulation characteristics allows interpretations of biomass patterns in BNP fire groups. Historically, frequent fires maintained low biomass levels in warm/dry montane forests despite relatively high accumulation rates. Cool/moist lower subalpine forests with high productivity and relatively infrequent fires reach highest mean biomass levels. Upper subalpine forests have the lowest fire frequency, but accumulate organic matter slowly, and thus have moderately low biomass.

Of the various roles proposed by Olson (1981) for fire's function in regulating biomass, the most applicable to pre-1880 BNP forests was that high intensity and relatively frequent fires prevented the ecosystem from reaching biomass conditions that would self-perpetuate in the absence of fire (e.g. "climax" conditions). In other words, the historic fire regime in most BNP forests stimulated a continuous response of change; at the individual stand level, steady state or climax biomass conditions rarely occurred. However, at the ecosystem level the continual presence of fire maintained a relatively stable diversity of biomass conditions. Van Wagner and Methven (1981) provide a similar example in their analysis of fire regime effects in boreal forests. Detailed fire history work in the Canadian Rockies (Tande 1979, Hawkes 1980) show that this fire-biomass interaction could have been relatively unchanged prior to 1880 back to at least 1650 A.D.

Parks Canada policy (1979a) states that national parks will be "managed with minimal interference to natural processes to ensure the perpetuation of naturally evolving land and water environments and their associated species." The program of suppressing the important natural process of fire has caused widespread changes in the distribution of biomass in BNP forests. The effect is particularly evident in warm/dry montane forests. Fire suppression in these stands has resulted in 1980 biomass conditions reaching levels that were only infrequently attained in the past. The lower fire frequency will be compensated for by fires of higher intensity and severity in most BNP forests. These shifts in the fire regime may result in long term effects in biomass and ecosystem characteristics.

Options for managing fire in BNP forests are limited--even with ecological implications identified. Fire management initiatives must continually recognize the possibility of high intensity fires. Unchecked random ignition fires or poorly conducted planned ignition (prescribed) fires present unacceptable risks to public safety, park facilities, and neighboring lands. However, temporal patterns of biomass accumulation and fire behavior potential clearly show that continued fire suppression only increases the probability that future fires will have high intensities.

The relative changes due to fire suppression are greatest in warm/dry montane forests, which also have the greatest frequency of low intensity fires. These forests should receive fire management priority because of the relative magnitude of biomass change and the high probability of easily controlled fires. The BNP Warden Service is cautiously conducting planned ignition fires in the warm/dry montane forests of the Bow Valley. If these burns prove successful, the program should be expanded to warm/dry and cool/moist lower subalpine forests where the probability of extreme fire behavior is higher. The knowledge obtained from the planned ignition program can guide decisions on when and where to let random ignition fires burn.

The close proximity of forests with potential for extreme fire behavior and the world-famous tourist attractions of Banff National

Park will challenge the ideals of national park management. Parks Canada must recognize that the long-evolved fire and biomass interrelationship makes progressive management of fire a difficult, but essential, component of natural resource preservation.

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APPENDIX A

BANFF NATIONAL PARK ECOLOGICAL LAND CLASSIFICATION ECOSITE TYPES

(from Holland and Coen, 1982)

ECO-SITE	ECO-REGION	LANDFORM, GENETIC MATERIAL	CALCAR-EOUS-NESS	TEX-TURAL GROUP	SOILS	VEGETATION
AL1	L. Subalp.	fluvial	calc	[illegible]	Brunisol	pine/buffaloberry,
[illegible]	L. Subalp.	fluvial	calc	[illegible]	Brunisol	spruce-fir
AT1	Montane	glacio-fluvial	calc	cro	Brunisol	subxeric pine, pine/buffaloberry
AT2	Montane	glacio-fluvial	calc	cro	Brunisol	grassland > subxeric pine
AE1	U. Subalp.	strat drift	non	cro	dry: Brunisol wet: Gleysol > Organic	open spruce-fir wet shrub thicket, wet herb meadow
[illegible]	L. Subalp.	morainal	calc	med	dry: Brunisol > Luvisol wet: Gleysol, Organic	pine/buffaloberry, open spruce, wet shrubby meadow, birch fen
[illegible]	L. Subalp.	strat drift	calc	var	dry: Brunisol > Luvisol wet: Gleysol, Organic	pine/buffaloberry open spruce, wet shrubby meadow, birch fen
[illegible]	L. Subalp.	strat drift	calc	var	dry: Brunisol wet: Gleysol, Organic	spruce-fir open spruce, wet shrubby meadow, birch fen
[illegible]	U. Subalp.	landslide	var	var	Brunisol, Regosol	open mixed coniferous, open spruce-fir
[illegible]	U. Subalp.	landslide	var	var	Brunisol	spruce-fir, open spruce-fir, larch
[illegible]	Alpine	colluvial	calc	med	Brunisol, Regosol	[illegible] tundra
[illegible]	L. Subalp.	glacio-fluvial	calc	cro	Brunisol	subxeric pine, pine/buffaloberry
[illegible]	L. Subalp.	glacio-fluvial	calc	cro	Brunisol	mesic pine
[illegible]	L. Subalp.	glacio-fluvial	calc	cro	Brunisol	spruce-fir
[illegible]	L. Subalp.	morainal	calc	med	Brunisol > Podzol	spruce-fir
[illegible]	L. Subalp.	morainal	calc	med	Brunisol	spruce-fir
[illegible]	L. Subalp.	strat drift	calc	var	Brunisol	spruce-fir
[illegible]	L. Subalp.	residual	var	med	Brunisol (lithic)	spruce-fir
[illegible]	L. Subalp.	residual	var	med	Brunisol (lithic)	pine/buffaloberry, mesic pine
CA1	L. Subalp.	morainal	non	med	dry: Brunisol wet: Gleysol, Podzol, Organic	spruce-fir open spruce, open spruce-fir, wet shrubby meadow, birch fen
CA3	L. Subalp.	morainal	non	med	Brunisol	spruce-fir
CA4	L. Subalp.	morainal	non	med	Brunisol	pine/buffaloberry, mesic pine
[illegible]	U. Subalp.	fluvial	var	[illegible]	Regosol	dry shrub thicket, moist shrub thicket
CP1	U. Subalp.	residual	[illegible]	med	Brunisol (lithic)	spruce-fir, open spruce-fir, larch
[illegible]	L. Subalp.	morainal > fen	var	var	wet: Gleysol, Podzol, Organic dry: Brunisol	open spruce, open spruce-fir > wet shrubby meadow, birch fen mesic pine, spruce-fir
[illegible]	Montane	eolian	calc	var	Regosol	shrubby grassland
[illegible]	Montane	eolian	calc	var	Regosol	white spruce
[illegible]	Alpine	morainal	non	cro	Brunisol, Podzol	heath tundra
[illegible]	U. Subalp.	morainal	non	med	Brunisol	spruce-fir, open spruce-fir
[illegible]	U. Subalp.	morainal	non	med	Brunisol > Podzol	larch
[illegible]	U. Subalp.	morainal	non	med	dry: Brunisol wet: Gleysol, Podzol, Brunisol	spruce-fir, open spruce-fir, larch open spruce-fir, moist herb meadow
[illegible]	U. Subalp.	morainal	non	med	Brunisol > Podzol	heath tundra > open spruce-fir
[illegible]	U. Subalp.	colluvial	non	cro	Brunisol	spruce-fir, open spruce-fir
[illegible]	U. Subalp.	colluvial	non	cro	Brunisol > Regosol	avalanche complex > open mixed coniferous, open spruce-fir
[illegible]	U. Subalp.	colluvial > rock	calc	cro	Brunisol > Regosol	open mixed coniferous > open spruce-fir
[illegible]	Montane	fluvial	calc	[illegible]	Brunisol	pine/buffaloberry
[illegible]	L. Subalp.	colluvial	non	var	Brunisol > Regosol	avalanche complex > spruce-fir
[illegible]	L. Subalp.	colluvial	non	var	Brunisol	spruce-fir
[illegible]	Montane	landslide	calc	med	Brunisol, Regosol	subxeric pine, pine/buffaloberry
[illegible]	L. Subalp.	morainal	calc	med	Brunisol > Regosol	subxeric pine, open mixed coniferous, open white spruce
[illegible]	L. Subalp.	morainal	calc	med	northerly: Brunisol southerly: Brunisol, Regosol	pine/buffaloberry grassland, low shrub-herb meadow
[illegible]	L. Subalp.	fluvial > fen	var	[illegible]	Gleysol > Regosol, Organic	Engelmann spruce, open spruce > wet shrubby meadow, birch fen
[illegible]	L. Subalp.	fluvial	calc	[illegible]	Gleysol	sedge fen
[illegible]	L. Subalp.	fluvial > fen	var	[illegible]	Gleysol > Regosol, Organic	wet shrubby meadow, birch fen, wet shrub thicket

ECO-SITE	ECO-REGION	LANDFORM, GENETIC MATERIAL	CALCAR-EOUS-NESS	TEX-TURAL GROUP	SOILS	VEGETATION
HD1	Montane	fluvial	calc	strat	Regosol	aspen
HD2	Montane	fluvial	calc	strat	Regosol	open white spruce
HD3	Montane	fluvial	calc	strat	Regosol	white spruce, spruce-Douglas fir
HD4	Montane	fluvial	calc	strat	Regosol	grassland > subxeric pine
HE1	Alpine	residual	var	med	Brunisol (lithic), Regosol (lithic)	avens tundra
HE2	Alpine	rock > regolith	calc	med	nonsoil > Brunisol (lithic), Regosol (lithic)	unvegetated > avens tundra
HS1	L. Subalp.	landslide	var	var	Brunisol	pine/buffaloberry, mesic pine
HS2	L. Subalp.	landslide	var	var	Regosol, Brunisol	open mixed coniferous, open white spruce,
HS3	L. Subalp.	landslide	var	var	Brunisol	spruce-fir
JM1	Alpine	morainal	non	med	Brunisol > Podzol	heath tundra, avens tundra
KA1	Alpine	fluvial	var	strat	Regosol, Gleysol	dwarf shrub-herb meadow, avens tundra
LV1	U. Subalp.	morainal	non	crs	Brunisol > Podzol	larch
LV2	U. Subalp.	morainal	non	crs	Brunisol > Podzol	heath tundra > open spruce-fir
LV3	U. Subalp.	morainal	non	crs	Brunisol > Podzol	spruce-fir, open spruce-fir
MC1	L. Subalp.	lacust	calc	fine	wet: Gleysol, Brunisol dry: Luvisol, Brunisol	open spruce, birch fen mesic pine, spruce-fir
ML1	L. Subalp.	morainal	non	crs	Brunisol > Podzol	spruce-fir
ML2	L. Subalp.	morainal	non	crs	Brunisol	pine/buffaloberry, mesic pine
ML3	L. Subalp.	morainal	non	crs	Brunisol	spruce-[illegible] pine
MP1	Alpine	morainal	calc	med	Brunisol, Regosol	avens tundra, heath tundra
MO1	U. Subalp.	fluvial	var	strat	Brunisol, Regosol	spruce-fir, open spruce-fir
M?1	U. Subalp.	[illegible]- fluvial	calc	crs	Brunisol	spruce-fir, open spruce-fir
MR1	Montane	lacust	calc	fine	wet: Gleysol dry: Luvisol > Brunisol	open spruce pine/buffaloberry, mesic pine
MT2	U. Subalp.	fluvial	var	strat	Gleysol	wet shrub thicket, moist shrub thicket
MT3	U. Subalp.	fluvial, fen	var	strat	Gleysol, Organic	wet herb meadow, cottongrass fen, sedge fen
NY1	Montane	morainal	calc	med	Brunisol > Regosol	Douglas fir, pine/buffaloberry
NY3	Montane	strat drift	calc	var	northerly: Brunisol southerly: Regosol	spruce-Douglas fir, pine/buffaloberry open Douglas fir, low shrub-herb meadow, Douglas fir
PL1	U. Subalp.	morainal	calc	med	Brunisol	spruce-fir, open spruce-fir
PL2	U. Subalp.	morainal	calc	med	Brunisol > Podzol	larch
PL4	U. Subalp.	morainal	calc	med	Brunisol > Podzol	heath tundra > open spruce-fir
PL5	U. Subalp.	morainal	calc	med	dry: Brunisol wet: Gleysol, Podzol, Brunisol	spruce-fir, open spruce-fir, larch wet shrub thicket
PP1	L. Subalp.	fluvial	calc	strat	Regosol	pine/buffaloberry, subxeric pine
PP2	L. Subalp.	fluvial	calc	strat	Regosol	balsam poplar, aspen
PP3	L. Subalp.	fluvial	calc	strat	Regosol	spruce-fir
PP4	L. Subalp.	glacio- fluvial	calc	crs	Regosol	herb mat
PP6	L. Subalp.	fluvial	calc	strat	Regosol	open spruce-fir, open white spruce
PP7	L. Subalp.	fluvial	calc	strat	Regosol	moist shrubby meadow, dry shrub thicket
PR1	L. Subalp.	morainal	calc	med	Brunisol > Luvisol	mesic pine
PR2	L. Subalp.	morainal	calc	med	Brunisol > Luvisol	pine/buffaloberry
PR3	L. Subalp.	morainal	calc	med	Brunisol > Luvisol, (gleyed)	pine/buffaloberry
PR4	L. Subalp.	strat drift	calc	var	northerly: Brunisol southerly: Brunisol > Luvisol, Regosol	spruce-fir subxeric pine, pine/buffaloberry
PR5	L. Subalp.	strat drift	calc	var	Brunisol > Luvisol	pine/buffaloberry, mesic pine
PT1	Montane	morainal	calc	med	Brunisol, Luvisol	pine/buffaloberry
PT2	Montane	morainal > rock	calc	med	Brunisol (lithic) > Luvisol (lithic)	subxeric pine, pine/buffaloberry
PT5	Montane	morainal	calc	med	Brunisol, Luvisol	aspen
PT6	Montane	morainal > fen	calc	med	dry Brunisol, Luvisol wet: Gleysol, Organic	mesic pine, pine/buffaloberry black spruce-pine, open spruce
RD1	Alpine	colluvial	non	med	Brunisol, Regosol	avens tundra, heath tundra
RE1	Montane	lacust	calc	fine	Luvisol > Brunisol	pine/buffaloberry, mesic pine
SB1	L. Subalp.	colluvial	calc	med	Brunisol, Regosol	avalanche complex > spruce-fir
SB2	L. Subalp.	colluvial	calc	med	Brunisol, Regosol	spruce-fir
SB3	L. Subalp.	colluvial	calc	med	Brunisol, Regosol	subxeric pine, pine/buffaloberry
SB4	L. Subalp.	colluvial > rock	calc	med	Brunisol, Regosol	open mixed coniferous, open white spruce subxeric pine, low shrub-herb meadow
SB5	L. Subalp.	colluvial	calc	med	Brunisol, Regosol	grassland

ECO-SITE	ECO-REGION	LANDFORM, GENETIC MATERIAL	CALCAR-EOUS-NESS	TEX-TURAL GROUP	SOILS	VEGETATION
[illegible]	U. Subalp.	morainal	var	med	Cryosol > Brunisol	spruce-fir
[illegible]	L. Subalp.	[illegible]	calc	fine	Luvisol, Brunisol	pine/buffaloberry, mossy pine
[illegible]	U. Subalp.	morainal > fluvial	non	med	Gleysol, Podzol (gleyed) Brunisol (gleyed)	small herb meadow, dwarf shrub herb meadow, > heath tundra, wet shrub thicket
[illegible]	U. Subalp.	morainal > fluvial	var	med	Gleysol, Podzol (gleyed) Brunisol (gleyed)	open spruce-fir
[illegible]	U. Subalp.	morainal > fluvial	var	med	Gleysol, Podzol (gleyed) Brunisol (gleyed)	small shrub thicket, wet shrub thicket
TA[illegible]	Montane	eolian veneer	calc	med	Regosol	grassland, low shrub-herb meadow
TA[illegible]	Montane	eolian veneer	calc	med	Regosol > Brunisol	white spruce
TK1	Alpine	colluvial	non	crs	Brunisol, Regosol	heath tundra, avens tundra
TR1	U. Subalp.	morainal	var	med	Brunisol	dry shrub thicket, moist shrub thicket, open spruce-fir
TR2	U. Subalp.	morainal	var	med	Brunisol	grassy tundra, grassland
[illegible]	L. Subalp.	strat drift	non	crs	Brunisol	subalpine pine, pine/buffaloberry
[illegible]	L. Subalp.	strat drift	non	crs	dry: Brunisol wet: Gleysol > Organic	subalpine pine, pine/buffaloberry open spruce, wet shrubby meadow, birch fen
[illegible]	L. Subalp.	fluvial	non	[illegible]	Brunisol	spruce-fir
[illegible]	L. Subalp.	fluvial	non	[illegible]	Brunisol	pine/buffaloberry, mossy pine
VL1	[illegible]	fluvial, fen	calc	fine	Gleysol, Organic	sedge fen > wet shrubby meadow, wet shrub thicket
[illegible]	Montane	fluvial	calc	[illegible]	Gleysol	white spruce > wet shrubby meadow, wet shrub thicket
VL4	Montane	fluvial	calc	strat	Gleysol	white spruce
VL5	Montane	fluvial	calc	strat	Gleysol > Regosol	wet shrub thicket
[illegible]	U. Subalp.	colluvial	calc	med	Brunisol, Regosol	spruce-fir, open spruce-fir
[illegible]	U. Subalp.	colluvial	calc	med	Brunisol, Regosol	avalanche complex > spruce-fir, open spruce-fir
[illegible]	U. Subalp.	colluvial > rock	calc	med	Brunisol, Regosol	open mixed coniferous > open spruce-fir
[illegible]	U. Subalp.	colluvial	calc	med	Brunisol, Regosol	Engelmann spruce
[illegible]	U. Subalp.	colluvial	var	med	Brunisol, Regosol	grassland > dry shrub thicket, grassy tundra
[illegible]	U. Subalp.	colluvial	non	med	Brunisol	larch
[illegible]	U. Subalp.	colluvial	non	med	Brunisol	spruce-fir, open spruce-fir
[illegible]	U. Subalp.	colluvial	non	med	Brunisol > Regosol	avalanche complex > spruce-fir, open spruce-fir
[illegible]	U. Subalp.	colluvial > rock	non	med	Brunisol > Regosol	open mixed coniferous > open spruce-fir
[illegible]	L. Subalp.	morainal	calc	med	Regosol	herb mat

Ecoregion Column

The landscape is subdivided into Ecoregions which reflect macroclimate. The three Ecoregions, Montane, Subalpine, and Alpine, with the subdivision of Subalpine into Upper Subalpine (U. Subalp.) and Lower Subalpine (L. Subalp.) provide four distinct categories.

Landform, Genetic Material Column

Landforms and genetic materials are defined according to the Canadian System of Soil Classification.

- kame drift = ice contact stratified drift.
- landslide = rock and soil avalanche.
- lacustr. = glaciolacustrine.
- morainal > fan = the landscape characterized by a pattern of morainal landforms interspersed with lesser amounts of fan landforms.
- residual = unconsolidated bedrock.
- regolith = a mosaic of morainal, eolian, fluvial, colluvial etc. materials.

Calcareousness Column

This column indicates the calcareousness of the parent materials associated with each Ecosite.

- calc. = calcareous.
- non. = noncalcareous.
- var. = a given mapped area can be either calcareous or noncalcareous or both.

Textural Group Column

This column indicates the textural group into which the geologic material (and frequently portions of the solum) falls.

Soils Column

This column indicates the dominant soil orders.

- Brunisol > Regosol — the landscape has a pattern dominated by Brunisolic soils with a lesser percentage of Regosolic soils.
- Brunisol, Luvisol — either Brunisolic or Luvisolic soils or both occur in any given map area.
- dry: Brunisol, Luvisol / wet: Gleysol, Organic — jointly, this symbolism indicates an inseparable landscape pattern dominated by well drained soils and a lesser percentage of poorly drained soils.
- northerly: Brunisol, Luvisol / southerly: Regosol — jointly, this symbolism indicates contrasting but inseparable components on northerly aspects (Brunisols, Luvisols) and southerly aspects (Regosols).

Vegetation Column

This column indicates the common vegetation associated with each Ecosite. Mixtures of species within a layer are indicated by a hyphen and a virgule separates layers.

- pine/buffaloberry, mesic pine: indicates that in a given map area either or both of the two vegetation types occur.
- grassland > subxeric pine: the landscape is characterized by a pattern dominated by grassland with a lesser percentage of subxeric pine.

APPENDIX B

Fire and Biomass Descriptive Statistics for Banff National Park Fire Groups

Descriptor	Fire Group	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Elevation (meters)	1	29	1504.2069	129.9853	1280.0000	1920.0000
	2	62	1689.8548	164.2735	1433.0000	2040.0000
	3	5	1399.6000	57.5743	1341.0000	1463.0000
	4	14	1558.1538	173.1237	1372.0000	1920.0000
	5	39	1716.8421	172.6542	1432.0000	2073.0000
	6	37	1747.8919	154.4923	1417.0000	1981.0000
	7	8	1597.6250	247.8617	1381.0000	2073.0000
	8	20	2032.8000	169.9736	1554.000	2240.0000
	9	6	1978.6667	100.9944	1798.0000	2057.0000
	All	220	1701.2294	216.5437	1280.0000	2240.0000
Slope (degrees)	1	29	11.2759	10.3368	0.0000	35.0000
	2	62	13.2097	9.8299	0.0000	35.0000
	3	5	3.0000	3.4641	0.0000	8.0000
	4	14	7.8462	6.5682	0.0000	20.0000
	5	39	10.2368	9.1339	0.0000	40.0000
	6	37	10.3243	7.1804	2.0000	33.0000
	7	8	0.3750	1.0607	0.0000	3.0000
	8	20	15.1500	7.8020	3.0000	31.0000
	9	6	17.8333	8.0850	8.0000	32.0000
	All	220	11.2248	9.1571	0.0000	40.0000
Cosine of Aspect	1	29	-0.3763	0.5768	-0.9994	0.9994
	2	62	-0.3134	0.7115	-1.0000	1.0000
	3	5	-0.6063	0.5830	-0.9660	0.4225
	4	14	0.3492	0.6421	0.9847	1.0000
	5	39	0.2079	0.8217	-0.9926	1.0000
	6	37	0.0093	0.7792	-0.9946	0.9962
	7	8	0.0327	0.7919	-0.9962	0.9659
	8	20	0.1380	0.7556	-1.0000	1.0000
	9	6	0.5603	0.4253	-0.0866	0.9962
	All	220	-0.0652	0.7623	-1.0000	1.0000

Descriptor	Fire Group	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Hygrotope	1	29	2.5517	0.5061	2.0000	3.0000
	2	62	2.6935	0.4648	2.0000	3.0000
	3	5	3.0000	0.0000	3.0000	3.0000
	4	14	3.0769	0.2774	3.0000	4.0000
	5	39	3.4737	0.8617	2.0000	6.0000
	6	37	3.3243	0.5299	3.0000	5.0000
	7	8	5.5000	0.5345	5.0000	6.0000
	8	20	2.9500	0.6048	2.0000	5.0000
	9	6	4.5000	0.5477	4.0000	5.0000
	All	220	3.1239	0.8415	2.0000	6.0000
Fire Intervals (years)	1	59	41.0847	45.1447	7.0000	290.0000
	2	110	69.8455	66.8154	2.0000	468.0000
	3	12	19.7500	8.8536	6.0000	34.0000
	4	12	89.0000	52.3763	20.0000	200.0000
	5	58	110.2931	85.3180	8.0000	423.0000
	6	27	129.6667	87.8705	18.0000	340.0000
	7	8	69.3750	55.5953	16.0000	175.0000
	8	8	172.6250	108.6093	47.0000	370.0000
	9	1	119.0000			
	All	295	79.2034	75.8545	2.0000	468.0000
Time Since Fire as of 1980 (years)	1	29	60.5862	28.1939	24.0000	129.0000
	2	62	87.7097	49.2433	13.0000	257.0000
	3	5	62.6000	38.4942	34.0000	130.0000
	4	14	166.3846	92.0159	41.0000	331.0000
	5	39	102.7692	44.8808	13.0000	199.0000
	6	37	250.4595	111.7245	86.0000	451.0000
	7	8	157.6250	89.7058	41.0000	290.0000
	8	20	200.5789	108.8053	60.0000	400.0000
	9	6	317.0000	140.3923	130.0000	500.0000
	All	220	137.2477	103.5554	13.0000	500.0000

Descriptor	Fire Group	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Time Since Fire as of 1930 (years)	1	29	39.9310	49.8017	6.0000	280.0000
	2	62	62.1935	68.9304	1.0000	430.0000
	3	5	25.6000	30.5254	5.0000	79.0000
	4	14	125.1538	83.9860	20.0000	280.0000
	5	39	57.9744	36.5574	2.0000	148.0000
	6	37	199.4595	111.7245	35.0000	400.0000
	7	8	108.6250	86.8676	6.0000	239.0000
	8	20	149.5789	108.8053	9.0000	349.0000
	9	6	266.0000	140.3923	79.0000	449.0000
	All	220	99.4862	100.5150	1.0000	449.0000
Time Since Fire as of 1880 (years)	1	21	40.0000	49.4667	0.0000	230.0000
	2	62	53.7258	66.2098	0.0000	380.0000
	3	3	12.4000	11.1490	0.0000	29.0000
	4	14	93.3846	71.3238	4.0000	230.0000
	5	39	60.3077	50.7285	0.0000	210.0000
	6	37	168.6216	98.4921	1.0000	350.0000
	7	8	82.5000	66.2032	17.0000	189.0000
	8	20	121.0000	99.7809	6.0000	299.0000
	9	6	216.0000	140.3923	29.0000	399.0000
	All	210	84.6101	89.1785	0.0000	399.0000
Fire Intensity/ Severity Index	1	70	2.6429	1.2043	1.0000	4.0000
	2	37	2.0876	1.0946	1.0000	4.0000
	3	13	3.7692	0.4385	3.0000	4.0000
	4	19	2.0000	1.1547	1.0000	4.0000
	5	81	1.7654	1.0401	1.0000	4.0000
	6	60	2.0167	1.1423	1.0000	4.0000
	7	13	2.1538	1.2142	1.0000	4.0000
	8	22	2.1364	1.1253	1.0000	4.0000
	9	7	2.5714	1.1339	1.0000	4.0000
	All	422	2.1682	1.1647	1.0000	4.0000

Descriptor	Fire Group	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Stand Age (years)	1	29	91.8966	38.2262	40.0000	230.0000
	2	62	109.5484	60.4306	12.0000	270.0000
	3	5	100.6000	22.4455	80.0000	130.0000
	4	14	233.1538	82.0344	105.0000	350.0000
	5	39	124.9211	63.2970	13.0000	386.0000
	6	37	281.4054	100.8325	87.0000	450.0000
	7	8	161.7500	62.7643	87.0000	290.0000
	8	20	223.2105	119.0059	60.0000	430.0000
	9	6	336.6667	123.2342	130.0000	500.0000
	All	220	164.5392	106.4911	12.0000	500.0000
Mean Fire-Free Interval (years)	1	29	52.7195	33.8731	18.6000	165.5000
	2	62	85.6702	48.8138	28.8000	257.0000
	3	5	46.4100	46.8463	21.0000	130.0000
	4	14	143.4615	94.4505	72.0000	331.0000
	5	39	118.0439	55.2244	39.2500	265.5000
	6	37	251.9865	104.0205	95.5000	451.0000
	7	8	149.9479	95.7651	33.7500	290.0000
	8	20	214.7193	101.0363	73.6667	400.0000
	9	6	312.5833	146.1644	130.0000	500.0000
	All	220	137.7944	104.6417	18.6000	500.0000
Tree Density (stems/ha)	1	29	1895.0345	1522.7710	360.0000	7194.0000
	2	62	1764.2258	1238.2277	0.0000	5747.0000
	3	5	680.2000	335.5469	326.0000	1107.0000
	4	14	1184.8462	768.0631	545.0000	3496.0000
	5	39	2104.8421	2250.8602	0.0000	14084.0000
	6	37	1755.5405	925.5423	704.0000	4830.0000
	7	8	1338.1250	807.0984	526.0000	2699.0000
	8	20	1266.4000	635.6513	348.0000	2659.0000
	9	6	1406.0000	642.7780	481.0000	2386.0000
	All	220	1708.9450	1391.6132	0.0000	14084.0000

Descriptor	Fire Group	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Stand Basal Area	1	29	34.9069	18.5993	8.1000	92.3000
(m^2/ha)	2	62	31.1419	15.0665	0.0000	68.8000
	3	5	26.6200	8.4960	17.5000	37.2000
	4	14	43.4462	18.1727	16.5000	80.4000
	5	39	41.2605	18.9822	0.0000	93.0000
	6	37	49.6459	21.6797	10.3000	110.8000
	7	8	37.0125	13.5135	16.5000	51.9000
	8	20	39.6250	27.4979	5.6000	133.8000
	9	6	34.9667	17.4684	17.7000	53.5000
	All	220	38.2761	19.7864	0.0000	133.8000
Foliage Biomass	1	29	9.0462	4.1613	1.7900	16.8100
(t/ha)	2	62	8.9603	4.4811	0.0000	23.0700
	3	5	4.6420	0.7712	3.7100	5.8000
	4	14	20.4831	8.9907	7.7800	39.6800
	5	39	15.7974	8.4008	0.0000	37.4100
	6	37	25.1411	9.9682	5.8800	49.2000
	7	8	19.3500	8.2918	6.2700	27.6700
	8	20	18.1355	7.4305	4.5900	29.9200
	9	6	18.7350	8.3369	8.5600	30.4500
	All	220	14.9900	9.4128	0.0000	49.2000
Foliage and Branch-	1	29	25.9041	12.6544	3.9600	50.2600
wood Biomass	2	62	25.6187	13.7101	0.0000	73.0600
(t/ha)	3	5	29.2020	10.6435	15.7000	44.0000
	4	14	51.8377	20.5553	19.5700	94.1800
	5	39	38.1468	18.5409	0.0000	99.6800
	6	37	63.9186	27.1662	13.0800	137.4500
	7	8	46.3700	18.3641	15.4600	65.3800
	8	20	50.4910	30.5941	9.4200	153.3700
	9	6	45.7267	20.7179	22.9100	67.5300
	All	220	39.5834	24.2893	0.0000	153.3700

Descriptor	Fire Group	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Bolewood Biomass (t/ha)	1	29	107.3882	63.9798	14.1011	280.6510
	2	62	92.7598	48.6065	0.0000	218.2664
	3	5	98.6813	29.1726	61.7471	132.9807
	4	14	136.4158	58.0591	45.1395	227.8590
	5	39	127.3846	63.6518	0.0000	287.0759
	6	37	150.2136	75.4782	17.1421	367.3180
	7	8	110.5840	43.0188	45.8459	170.5528
	8	20	124.3571	108.3237	12.2726	524.2271
	9	6	101.9374	55.2867	42.4716	169.2887
	All	220	117.0373	67.9572	0.0000	524.2271
Height to Live Crown (m)	1	29	7.3414	4.1827	0.0000	15.0000
	2	62	6.1387	3.7162	0.0000	14.0000
	3	5	7.6200	3.0947	4.8000	12.5000
	4	14	6.2923	3.3569	2.0000	12.8000
	5	39	6.4211	2.9920	0.0000	14.0000
	6	37	5.2378	2.0574	1.9000	10.3000
	7	8	5.9375	2.7292	2.2000	9.8000
	8	20	2.6750	1.3439	0.5000	5.5000
	9	6	2.3000	1.0863	0.8000	3.9000
	All	220	5.8073	3.3757	0.0000	15.0000
Height to Dead Crown (m)	1	29	2.0667	2.4798	0.0000	11.2000
	2	62	1.9132	2.2711	0.0000	8.7000
	3	5	3.7800	0.6723	2.8000	4.6000
	4	14	1.5692	1.8436	0.0000	5.9000
	5	39	1.7152	1.5750	0.0000	7.4000
	6	37	1.3686	1.3594	0.0000	6.1000
	7	8	1.2750	0.9083	0.3000	2.9000
	8	20	0.5105	0.4306	0.0000	1.2000
	9	6	0.4667	0.2944	0.0000	0.8000
	All	220	1.6199	1.8558	0.0000	11.2000

Descriptor	Fire Group	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Foliage Bulk Density (kg/m^3)	1	29	0.1355	0.0762	0.0200	0.3500
	2	62	0.1410	0.0714	0.0000	0.3900
	3	5	0.0840	0.0673	0.0100	0.1600
	4	14	0.2385	0.1824	0.0900	0.6800
	5	39	0.2378	0.1472	0.0000	0.7900
	6	37	0.3111	0.1945	0.0900	1.0200
	7	8	0.2450	0.1396	0.0900	0.4700
	8	20	0.2220	0.1007	0.0700	0.4200
	9	6	0.3117	0.1379	0.1000	0.4800
	All	220	0.2063	0.1441	0.0000	1.0200
Herb/Dwarf Shrub Biomass (t/ha)	1	29	0.6721	0.5037	0.0600	2.0400
	2	62	0.5061	0.5218	0.0500	3.0700
	3	5	0.8120	0.1906	0.5800	1.0000
	4	14	0.3746	0.3647	0.0100	1.0700
	5	39	0.3313	0.4189	0.0100	1.9600
	6	37	0.1832	0.1836	0.0000	1.0000
	7	8	0.2300	0.2042	0.0400	0.6400
	8	20	0.6620	0.7317	0.0100	2.5600
	9	6	0.2183	0.2177	0.0300	0.5600
	All	220	0.4383	0.4846	0.0000	3.0700
Herb/Dwarf Shrub Cover (%)	1	29	70.6897	18.9324	15.000	105.0000
	2	62	57.8226	17.8248	25.0000	120.0000
	3	5	90.0000	11.7260	70.0000	100.0000
	4	14	39.0000	22.7046	10.0000	80.0000
	5	39	43.2105	23.2625	7.0000	85.0000
	6	37	31.7297	18.5961	5.0000	80.0000
	7	8	36.8750	14.6232	20.0000	60.0000
	8	20	52.7500	19.9654	15.0000	80.0000
	9	6	27.8333	10.8704	15.0000	40.0000
	All	220	50.1147	23.7735	5.0000	120.0000

Descriptor	Fire Group	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Shrub Biomass (t/ha)	1	29	1.5141	2.3839	0.0800	10.2700
	2	62	1.2721	1.3702	0.0000	6.1700
	3	5	0.4620	0.3924	0.1100	1.0900
	4	14	1.3646	1.6048	0.0000	4.8300
	5	39	2.2408	2.4053	0.0000	8.3900
	6	37	2.7443	3.5205	0.0000	14.9200
	7	8	1.3363	1.5370	0.0600	4.8800
	8	20	2.8050	3.9771	0.0000	16.8400
	9	6	6.8033	4.1824	0.8000	11.2700
	All	220	2.0052	2.7190	0.0000	16.8400
Shrub Cover (%)	1	29	32.0690	16.8776	5.0000	75.0000
	2	62	33.3871	14.7319	5.0000	65.0000
	3	5	30.0000	22.0794	5.0000	65.0000
	4	14	32.5385	23.7789	5.0000	80.0000
	5	39	39.0263	22.6864	5.0000	90.0000
	6	37	36.4865	22.9802	3.0000	85.0000
	7	8	20.8750	9.3570	10.0000	35.0000
	8	20	35.1500	20.4277	5.0000	75.0000
	9	6	49.1667	12.8128	30.0000	65.0000
	All	220	34.7294	19.3754	3.0000	90.0000
Downed Wood (<.5 cm) Biomass (t/ha)	1	29	0.3438	0.3609	0.0400	1.5100
	2	62	0.2376	0.1528	0.0300	0.5800
	3	5	0.1760	0.0802	0.0600	0.2800
	4	14	0.4538	0.2335	0.0900	1.0300
	5	39	0.2592	0.1571	0.0600	0.9500
	6	37	0.4205	0.2496	0.0800	1.2200
	7	8	0.5713	0.6405	0.0800	2.1100
	8	20	0.3915	0.3363	0.0800	1.0600
	9	6	0.3833	0.1440	0.2000	0.5600
	All	220	0.3281	0.2706	0.0300	2.1100

Descriptor	Fire Group	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Downed Wood (.5-1.0 cm) Biomass (t/ha)	1	29	0.3103	0.2648	0.0400	1.2200
	2	62	0.3868	0.2721	0.0300	1.1000
	3	5	0.1300	0.0596	0.0500	0.2100
	4	14	0.4815	0.1961	0.1300	0.8000
	5	39	0.3359	0.1546	0.1000	0.8500
	6	37	0.4697	0.2699	0.0400	1.1300
	7	8	0.6175	0.5755	0.1700	1.9700
	8	20	0.5320	0.2724	0.1700	1.1200
	9	6	0.4400	0.1490	0.2800	0.7000
	All	220	0.4045	0.2717	0.0300	1.9700
Downed Wood (1.0-3.0 cm) Biomass (t/ha)	1	29	1.0662	0.8255	0.1100	4.0500
	2	62	1.3592	1.2207	0.0400	7.2300
	3	5	0.4980	0.4668	0.2300	1.3300
	4	14	1.7977	1.0863	0.4600	3.8400
	5	39	1.0821	0.7651	0.1900	3.1400
	6	37	1.3951	0.9073	0.0500	3.7600
	7	8	1.8700	1.6128	0.6100	5.6700
	8	20	1.4520	1.0127	0.1100	3.8900
	9	6	1.5250	1.0766	1.1500	2.8000
	All	220	1.3152	1.0363	0.0400	7.2300
Downed Wood (3.0-5.0 cm) Biomass (t/ha)	1	29	1.3493	1.2561	0.0000	5.2300
	2	62	1.6202	1.9267	0.0000	11.0500
	3	5	1.5760	1.6485	0.4700	4.4200
	4	14	1.3708	0.9981	0.2900	3.3600
	5	39	1.1977	1.2043	0.0000	6.5700
	6	37	1.0770	0.8427	0.0000	4.6100
	7	8	1.0750	0.8271	0.0000	2.4500
	8	20	0.7040	0.5902	0.0000	2.0200
	9	6	0.8233	0.5964	0.0000	1.7500
	All	220	1.2761	1.3633	0.0000	11.0500

Descriptor	Fire Group	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Downed Wood (3.0-5.0 cm) Biomass (t/ha)	1	29	1.3493	1.2561	0.0000	5.2300
	2	62	1.6202	1.9267	0.0000	11.0500
	3	5	1.5760	1.6485	0.4700	4.4200
	4	14	1.3708	0.9981	0.2900	3.3600
	5	39	1.1977	1.2043	0.0000	6.5700
	6	37	1.0770	0.8427	0.0000	4.6100
	7	8	1.0750	0.8271	0.0000	2.4500
	8	20	0.7040	0.5902	0.0000	2.0200
	9	6	0.8233	0.5964	0.0000	1.7500
	All	220	1.2761	1.3633	0.0000	11.0500
Downed Wood (5.0-7.0 cm) Biomass (t/ha)	1	29	2.5107	2.8103	0.0000	13.1800
	2	62	2.8866	4.1738	0.0000	25.3700
	3	5	1.9000	1.7705	0.0000	4.2700
	4	14	2.0500	1.7204	0.2800	5.9200
	5	39	1.5859	1.8699	0.0000	10.5900
	6	37	1.8149	1.3472	0.2400	5.2100
	7	8	1.2713	0.7724	0.4600	2.5300
	8	20	0.8165	0.6151	0.0000	2.0900
	9	6	1.0083	0.4544	0.2500	1.5300
	All	220	2.0524	2.7464	0.0000	25.3700
Sound Downed Wood (>7.0 cm) Biomass (t/ha)	1	29	8.8069	10.8617	0.0000	42.3800
	2	62	9.9832	16.3692	0.0000	94.0600
	3	5	4.9540	5.6392	0.0000	12.8600
	4	14	21.5115	17.5958	1.1100	50.4000
	5	39	7.0592	7.5921	0.0000	29.9400
	6	37	18.4427	23.4982	0.0000	109.3200
	7	8	12.0838	10.0877	4.5400	32.4900
	8	20	5.1165	9.7888	0.0000	42.2500
	9	6	7.3867	6.8641	0.0000	16.9000
	All	220	10.7713	15.6921	0.0000	109.3200

Descriptor	Fire Group	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Rotten Downed Wood	1	29	14.8369	21.6721	0.0000	73.1900
(>7.0 cm)	2	62	20.1218	26.8016	0.0000	100.1000
Biomass	3	5	3.7680	7.4454	0.0000	17.0700
(t/ha)	4	14	21.4246	26.8817	0.4700	84.8100
	5	39	28.2395	33.1724	0.3100	134.8600
	6	37	28.5168	24.4938	0.0000	102.5700
	7	8	9.0400	21.1466	0.3800	61.3000
	8	20	18.7745	22.5030	0.0000	90.1600
	9	6	16.1500	13.2027	3.8400	37.8100
	All	220	21.3532	26.3208	0.0000	134.8600
Total Downed Wood	1	29	28.5362	31.1836	1.4200	117.2200
Biomass	2	62	36.4705	35.2460	1.2400	131.9500
(t/ha)	3	5	13.0020	9.1561	2.7000	23.5400
	4	14	49.1138	39.9481	6.3100	143.7500
	5	39	39.7649	34.6304	3.6100	140.9300
	6	37	52.1381	37.0667	3.5500	129.4300
	7	8	26.5513	33.5616	8.2000	107.8300
	8	20	27.7540	28.5614	1.0000	112.2100
	9	6	27.7150	12.2863	5.7300	41.1900
	All	220	37.4700	34.5599	1.0000	143.7500
Fine Downed Wood	1	29	1.7203	1.3424	0.3600	6.5300
(<3.0 cm)	2	62	1.9835	1.4552	0.2100	7.8500
Biomass	3	5	0.8040	0.5829	0.3400	1.8200
(t/ha)	4	14	2.7331	1.3363	1.3000	5.5800
	5	39	1.6772	0.8999	0.5200	3.7500
	6	37	2.2854	1.2384	0.5600	4.7800
	7	8	3.0588	2.8045	1.0700	9.7500
	8	20	2.3755	1.4957	0.6900	5.7500
	9	6	2.3483	1.2439	0.9200	3.8400
	All	220	2.0478	1.4032	0.2100	9.7500

Descriptor	Fire Group	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Coarse Downed Wood	1	29	26.7838	30.8819	0.7900	116.1200
(>3.0 cm)	2	62	34.6118	34.7730	0.5800	128.1500
Biomass	3	5	12.1980	8.8987	2.0800	21.7200
(t/ha)	4	14	46.3569	38.8116	4.0700	138.1700
	5	39	38.0823	34.5475	2.8200	139.8700
	6	37	49.8514	36.3834	2.4600	125.4600
	7	8	23.4700	30.8060	7.0100	98.0800
	8	20	25.4115	27.8854	0.0000	107.6300
	9	6	25.3683	1.8075	4.8200	39.9400
	All	220	35.4530	34.0108	0.0000	139.8700
Moss Cover	1	29	29.3103	25.2390	0.0000	90.0000
(%)	2	62	35.7258	25.3475	0.0000	80.0000
	3	5	4.0000	5.4772	0.0000	10.0000
	4	14	69.2308	19.1318	30.0000	90.0000
	5	39	66.7949	23.0984	10.0000	100.0000
	6	37	75.8108	14.7438	30.0000	90.0000
	7	8	63.1250	15.3384	40.0000	80.0000
	8	20	48.0000	20.2874	20.0000	80.0000
	9	6	70.8333	26.3470	20.0000	95.0000
	All	220	51.5297	28.9709	0.0000	100.0000
Moss Biomass	1	29	1.9114	2.3428	0.0000	8.0288
(t/ha)	2	62	2.0246	2.0184	0.0000	7.8744
	3	5	0.2162	0.4026	0.0000	0.9264
	4	14	6.3423	4.0989	1.3896	14.3592
	5	39	5.6019	4.0178	0.1544	14.8224
	6	37	6.9021	3.5921	0.6176	17.1384
	7	8	4.4583	1.8388	1.2352	7.1024
	8	20	2.1770	1.6045	0.0000	6.4848
	9	6	5.8415	3.2261	1.5440	10.6536
	All	220	3.8931	3.5941	0.0000	17.1384

Descriptor	Fire Group	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Litter Cover (%)	1	29	64.7586	24.3760	10.0000	90.0000
	2	62	57.9839	25.4542	10.0000	95.0000
	3	5	92.0000	8.3666	80.0000	100.0000
	4	14	23.8462	20.7318	0.0000	70.0000
	5	39	27.8205	23.1072	0.0000	80.0000
	6	37	15.5405	16.7408	0.0000	70.0000
	7	8	30.0000	10.3510	20.0000	50.0000
	8	20	43.2500	21.5989	10.0000	75.0000
	9	6	17.5000	22.0794	0.0000	60.0000
	All	220	41.6119	29.5354	0.0000	100.0000
Litter Biomass (t/ha)	1	29	4.1214	2.1134	0.2735	9.8460
	2	62	3.6746	2.2486	0.5470	11.2135
	3	5	10.1195	3.6694	7.1110	16.1365
	4	14	2.7350	2.0129	0.0000	6.0170
	5	39	2.0548	1.6587	0.0000	6.2905
	6	37	1.7297	1.8370	0.0000	7.3845
	7	8	2.0854	1.7781	0.2735	4.6495
	8	20	2.3794	2.1298	0.2735	9.0255
	9	6	1.2308	1.2563	0.0000	3.5555
	All	220	2.9648	2.4651	0.0000	16.1365
Duff Depth (cm)	1	29	4.0172	2.2026	0.7000	10.4000
	2	62	4.4339	3.2104	0.7000	16.3000
	3	5	5.4800	1.1009	3.8000	6.8000
	4	14	11.4923	6.1908	3.9000	23.8000
	5	39	8.8359	4.2307	1.8000	23.1000
	6	37	12.2946	5.1159	3.8000	28.4000
	7	8	10.6375	5.7493	3.0000	18.5000
	8	20	4.6150	1.7049	1.2000	7.6000
	9	6	14.7000	6.4122	8.000	25.1000
	All	220	7.4580	5.2384	0.7000	28.4000

Descriptor	Fire Group	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Duff Biomass (t/ha)	1	29	47.0017	25.7705	8.1900	121.6800
	2	62	51.8763	37.5614	8.1900	190.7100
	3	5	64.1160	12.8806	44.4600	79.5600
	4	14	134.4600	72.4321	45.6300	278.4600
	5	39	103.3800	49.4990	21.0600	270.2700
	6	37	143.8468	59.8564	44.4600	332.2800
	7	8	124.4588	67.2665	34.1000	216.4500
	8	20	53.9955	19.9471	14.0400	88.9200
	9	6	171.9900	75.0225	93.6000	293.6700
	All	220	87.2585	61.2893	8.1900	332.2800
Total Stand Biomass (t/ha)	1	29	217.0492	85.3830	62.0641	436.4314
	2	62	214.2027	76.5165	55.6778	412.6977
	3	5	216.6110	58.4119	136.7945	280.3307
	4	14	382.6438	131.9428	185.2361	635.1071
	5	39	316.0407	93.8414	132.3497	543.0499
	6	37	421.6765	121.1996	105.2017	720.8382
	7	8	316.0740	84.8994	226.0717	477.6995
	8	20	264.6211	146.8734	71.7227	772.3326
	9	6	361.4630	148.1403	185.3936	541.8975
	All	220	290.1819	128.2075	55.6778	772.3326
Resistance to Handline Construction	1	29	10.6552	3.7252	4.0000	20.0000
	2	62	11.6935	4.3892	4.0000	21.0000
	3	5	9.2000	1.7889	7.0000	11.0000
	4	14	22.1538	9.1364	8.0000	36.0000
	5	39	17.6410	6.2513	7.0000	39.0000
	6	37	22.8378	7.7550	9.0000	43.0000
	7	8	21.3750	9.2572	8.0000	22.0000
	8	20	11.8000	4.9054	4.0000	22.0000
	9	6	21.1667	6.9402	11.0000	29.0000
	All	220	15.6849	7.6582	4.0000	43.0000

Descriptor	Fire Group	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Rate of Spread Rating I	1	29	42.6552	21.2692	5.0000	95.0000
	2	62	34.9839	19.6022	6.0000	90.0000
	3	5	75.6000	12.1778	66.0000	95.0000
	4	14	28.3077	19.3149	3.0000	61.0000
	5	39	26.9737	17.0429	5.0000	65.0000
	6	37	24.2778	15.0345	8.0000	68.0000
	7	8	19.7500	17.3514	3.0000	57.0000
	8	20	31.7500	18.3098	6.0000	65.0000
	9	6	23.5000	20.4915	4.0000	62.0000
	All	220	32.1889	20.2612	3.0000	95.0000
Rate of Spread Rating II	1	29	6.4731	3.1830	2.5400	15.8700
	2	62	6.0603	2.4326	2.1900	12.6400
	3	5	8.5380	2.0483	6.6000	11.5800
	4	14	6.7554	5.5063	2.0400	22.4200
	5	39	5.5744	2.9087	1.2000	14.6500
	6	37	6.3473	4.2063	1.8200	20.9500
	7	8	5.9250	3.4922	1.4800	12.0600
	8	20	7.2835	4.5545	2.7200	21.7300
	9	6	10.4683	5.1835	3.0300	16.4200
	All	220	6.4023	3.5665	1.2000	22.4200
Surface Fire Intensity Rating	1	29	22.2186	13.5717	10.9100	59.3700
	2	62	24.5103	14.6446	9.5700	65.9700
	3	5	17.9560	4.3946	12.9400	22.5300
	4	14	29.4615	17.4160	10.7300	68.0600
	5	39	26.0854	14.5590	10.3000	67.8100
	6	37	31.3535	15.6062	11.6000	60.8600
	7	8	20.6238	14.0802	10.9400	54.6700
	8	20	22.2045	12.3884	9.9100	55.0700
	9	6	24.4417	6.9173	13.4100	29.5500
	All	220	25.4333	14.5069	9.5700	68.0600

Descriptor	Fire Group	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Crown Fire Potential Rating	1	29	3.4483	1.1522	2.0000	7.0000
	2	62	3.2258	1.3234	0.0000	7.0000
	3	5	0.2000	0.4472	0.0000	1.0000
	4	14	6.8846	0.5829	6.0000	8.0000
	5	39	4.8462	1.4607	0.0000	7.0000
	6	37	6.9189	0.9826	3.0000	9.0000
	7	8	7.2500	1.2817	5.0000	9.0000
	8	20	6.8000	1.3611	3.0000	9.0000
	9	6	6.8333	1.6021	5.0000	9.0000
	All	220	4.8881	2.1530	0.0000	9.0000
Rate of Spread Required to Initiate Crown Fire (m/min)	1	29	7.0903	6.6748	0.0000	27.7700
	2	62	5.9160	5.9521	0.0000	22.8600
	3	5	6.6900	3.5578	3.2100	10.6500
	4	14	5.2231	6.3742	0.3700	23.7200
	5	39	5.0795	4.1207	0.0000	18.5700
	6	37	3.0108	2.6015	0.2600	10.3500
	7	8	5.4825	4.5546	0.4200	15.2300
	8	20	1.5450	1.3118	0.0900	4.4100
	9	6	0.8733	0.7454	0.2900	2.3100
	All	220	4.8551	5.1111	0.0000	27.7700

APPENDIX C

REGRESSION ANALYSIS STATISTICS OF FIRE GROUP DESCRIPTORS ON FIRE HISTORY AND SITE VARIABLES

Table C1: Statistics from regression analysis of selected crown layer descriptors on fire history and site variables.

Descriptor	Independent Variable	warm/dry montane B	warm/dry montane Partial F	warm/dry lower subalpine B	warm/dry lower subalpine Partial F	cool/moist lower subalpine B	cool/moist lower subalpine Partial F	upper subalpine B	upper subalpine Partial F
Foliage biomass (t/ha)	Constant			- .86		-42.92		10.48	
	Time since fire			.06	18.26		1.25	.04	15.01
	Last fire interval	No		.02	6.95		1.87	N/A	
	Intensity/severity index	Significant		2.31	10.89		.16	N/A	
	Slope	Regressions			.04		.74		.06
	Cosine aspect				3.85		.33		.06
	Elevation				.95	.04	4.97		.10
				R^2 = .25		R^2 = .22		R^2 = .38	
Foliage and branchwood biomass (t/ha)	Constant	-4.12		1.64		13.91		30.61	
	Time since fire	.18	4.53	.14	15.93	.23	9.41	.09	4.39
	Last fire interval		.04	.05	4.77		1.88	N/A	
	Intensity/severity index	6.75	14.17	6.00	13.11		1.09	N/A	
	Slope		.51		.56		2.23		.09
	Cosine aspect		1.54		2.13		1.42		.22
	Elevation		.52		.83		.70		.02
		R^2 = .37		R^2 = .24		R^2 = .34		R^2 = .15	
Bolewood biomass (t/ha)	Constant	-45.05		49.46					
	Time since fire	1.41	12.72	.29	7.95				
	Last fire interval		.22		3.40	No		No	
	Intensity/severity index	22.60	7.65	12.00	7.30	Significant		Significant	
	Slope		.64		.83	Regressions		Regressions	
	Cosine aspect		.46		.03				
	Elevation		1.93		.07				
		R^2 = .37		R^2 = .14					

Table C2: Statistics from regression analysis of selected surface layer descriptors on fire history and site variables.

Descriptor	Independent Variable	warm/dry montane		warm/dry lower subalpine		cool/moist lower subalpine		upper subalpine	
		B	Partial F	B	Partial F	B	Partial F	B	Partial F
Herb/dwarf shrub cover	Constant	175.52		65.908				89.69	
	Time since fire		.56	-.139	13.13			-.08	8.12
	Last fire interval		.11		.02	No		N/A	
	Intensity/severity index		.10		1.94	Significant		N/A	
	Slope		.08		.00	Regressions		-1.48	11.20
	Cosine aspect		.02		2.37			-10.70	5.28
	Elevation	-.069	7.87		.03				.95
		R^2 = .25		R^2 = .12				R^2 = .48	
Herb/dwarf shrub biomass	Constant			.68					
	Time since fire			-.003	6.75				
	Last fire interval	No			.53	No		No	
	Intensity/severity index	Significant			.71	Significant		Significant	
	Slope	Regressions			.01	Regressions		Regressions	
	Cosine aspect				.54				
	Elevation				.03				
				R^2 = .07					
Shrub cover	Constant	25.861		58.605				213.08	.83
	Time since fire		.90		1.86				
	Last fire interval	.144	7.07		.05	No		N/A	
	Intensity/severity index		1.87	-3.115	7.12	Significant		N/A	
	Slope		.62	.487	8.99	Regressions			.18
	Cosine aspect		.03		1.93			14.45	8.05
	Elevation		2.14		3.52			-.09	14.61
		R^2 = .21		R^2 = .14				R^2 = .41	

Table C2: Cont'd

Descriptor	Independent Variable	warm/dry montane $\underline{B}$	warm/dry montane Partial F	warm/dry lower subalpine $\underline{B}$	warm/dry lower subalpine Partial F	cool/moist lower subalpine $\underline{B}$	cool/moist lower subalpine Partial F	upper subalpine $\underline{B}$	upper subalpine Partial F
Shrub biomass	Constant	-.13						-3.94	
	Time since fire		1.26					.02	9.15
	Last fire interval	.033	35.66	No		No		N/A	
	Intensity/severity index		.97	Significant		Significant		N/A	
	Slope	.067	4.97	Regressions		Regressions		.23	5.16
	Cosine aspect	1.35	6.56						.99
	Elevation		.18						.06
		R^2 = .65						R^2 = .32	
Coarse downed wood, biomass (≥3 cm)	Constant	39.631		25.11				1.28	
	Time since fire		.38		.01				.01
	Last fire interval	.273	9.60	.12	9.96	No		N/A	
	Intensity/severity index	-8.86	5.45		.63	Significant		N/A	
	Slope		1.73		2.20	Regressions		1.53	7.15
	Cosine aspect		.50		1.31				.69
	Elevation		.39		3.59				2.45
		R^2 = .51		R^2 = .10				R^2 = .23	
Fine downed wood, biomass (<3 cm)	Constant	-5.39		.738					
	Time since fire		3.68		.85				
	Last fire interval		.32	.005	13.12	No		No	
	Intensity/severity index		.35	.319	8.05	Significant		Significant	
	Slope		.41		1.53	Regressions		Regressions	
	Cosine aspect		.76		.77				
	Elevation	.004	5.50		.09				
		R^2 = .34		R^2 = .15					

Table C3: Statistics from regression analysis of selected ground layer descriptors on fire history and site variables.

Descriptor	Independent Variable	warm/dry montane B	warm/dry montane Partial F	warm/dry lower subalpine B	warm/dry lower subalpine Partial F	cool/moist lower subalpine B	cool/moist lower subalpine Partial F	upper subalpine B	upper subalpine Partial F
Moss cover (%)	Constant	142.90		100.20				31.85	
	Time since fire	.50	9.87	.23	24.70			.01	10.01
	Last fire interval		.75	.09	10.21	No			N/A
	Intensity/severity index		.22	6.96	10.67	Significant			N/A
	Slope		.62		2.31	Regressions			.01
	Cosine aspect		2.08	10.13	11.28				1.08
	Elevation	-.09	8.97	.06	15.76				.02
		R^2 = .37		R^2 = .39				R^2 = .30	
Moss biomass (t/ha)	Constant	12.67		7.74				.82	
	Time since fire	.04	6.29	.03	36.25			.01	7.04
	Last fire interval		.70	.01	8.53	No			N/A
	Intensity/severity index		1.21	.78	10.27	Significant			N/A
	Slope		.11		1.49	Regressions			.64
	Cosine aspect		1.59	1.36	15.44			1.33	4.95
	Elevation	-.01	7.98	-.06	12.28				4.19
		R^2 = .31		R^2 = .44				R^2 = .40	
Litter cover (%)	Constant	-43.07		.02		-38.81		61.84	
	Time since fire	-.40	6.08	-.21	21.80	-.08	3.92	-.11	13.99
	Last fire interval		.94	-.13	21.78		.17		N/A
	Intensity/severity index		.58	-7.70	13.49		.50		N/A
	Slope		.20		.65		.30		.12
	Cosine aspect		1.79	-10.50	13.61		.31		1.89
	Elevation	.09	7.28	.06	14.82	.04	4.30		.06
		R^2 = .30		R^2 = .43		R^2 = .28		R^2 = .37	

Table C3: Cont'd

Descriptor	Independent Variable	warm/dry montane		warm/dry lower subalpine		cool/moist lower subalpine		upper subalpine	
		B	Partial F	B	Partial F	B	Partial F	B	Partial F
Litter biomass (t/ha)	Constant	3.68		2.63				-.05	
	Time since fire		.02		2.96				.01
	Last fire interval		.43		1.22	No		N/A	
	Intensity/severity index		.75		2.77	Significant		N/A	
	Slope	.07	5.84	.05	3.96	Regressions		.14	9.62
	Cosine aspect	1.58	8.50	-.76	7.34				2.39
	Elevation		2.35						.11
		R^2 = .32		R^2 = .13				R^2 = .29	
Total ground biomass (t/ha)	Constant	-.03		96.31				26.13	
	Time since fire	.51	7.08	.28	9.23			.27	10.45
	Last fire interval		.33	.24	16.86	No		N/A	
	Intensity/severity index	10.36	6.99	14.01	10.49	Significant		N/A	
	Slope		.30		.49	Regressions			3.22
	Cosine aspect	19.94	6.35	16.54	7.30				2.64
	Elevation		.19		3.81				1.52
		R^2 = .35		R^2 = .28				R^2 = .30	