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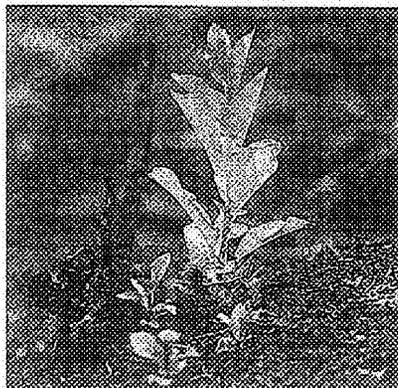
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Effects of Fire in Alaska and Adjacent Canada: A Literature Review

Leslie A. Viereck and Linda A. Schandelmeier



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INTRODUCTION

Land management agencies in Alaska are moving from past practices of fire control toward management of fire as a tool to meet resource management objectives. Information on the natural role of fire and the effects of fire in the northern environment is badly needed as a basis for formulating fire management plans.

For this report, we attempted to review and interpret all available literature on fire effects in Alaska and adjacent Canada, both in forested (taiga) and tundra regions. For the review we compiled an abstracted, computerized bibliography of fire effects in Alaska and adjacent Canada, containing about 750 references. The bibliography is stored on tape at the University of Alaska Computer Center, Fairbanks. Hard copies of the bibliography are available for review in the Institute of Northern Forestry Library, Fairbanks; the USDI Alaska Resources Library, Anchorage; Bureau of Land Management (BLM) offices in Anchorage or Fairbanks; or from the authors.

For the reader's convenience, we have selected the most important and most recent papers and listed them at the end of each section of this report. In addition, all references cited are listed at the end of the report.

FIRE EFFECTS INFORMATION SOURCES

Area and Subjects Covered

In the bibliography of fire effects for the tundra and taiga of Alaska and adjacent Canada, used as a source for this report, we have tried to include all published references and as many unpublished reports as we could find without an exhaustive search of agency files and libraries. For adjacent Canada (Yukon Territory, northern British Columbia, and western Northwest Territories), we attempted to include all published material covering fire effects on vegetation types similar to those found in Alaska.

We included references from outside Alaska and adjacent Canada if we felt they were pertinent to the Alaska situation or included some information not covered in the Alaska references. An example is references to fire effects in tundra ecosystems; several important studies in northern Canada are cited and few from Alaska. In like manner we have included references to fire and caribou and reindeer from across Canada,

and from Scandinavia and the Soviet Union, because our discussion would be incomplete without them.

We have included many references to studies in northern Minnesota (especially those of Heinselman and Ahlgren) because of the similarity of vegetation types in that area to those in Alaska and because several studies have direct application to the Alaskan situation.

In this report we have tried to cover all major topics of fire effects on biological systems. Fauna, flora, and ecosystem components such as soil processes, productivity, nutrient cycles, and plant-animal interactions are discussed. Where possible, we have included summaries of the effects of fire on individual species. More of these are in the wildlife section than in the vegetation section.

Systematic Reviews

We used two review papers as the starting point for most of our discussions and for our bibliography. The first of these is a review by Viereck (1973b), which covers much of the existing information on fire effects in the Alaska taiga. The second review paper, by Kelsall et al. (1977), has been especially important for reviewing the fire effects literature in Canada. Other reviews of significance to boreal areas are those by Lutz (1955) for Alaska and Kayll (1968) and Rowe and Scotter (1973) for Canada. For general reviews of fire effects not related specifically to the north, the book *Fire and Ecosystems*, edited by Kozlowski and Ahlgren (1974) is of particular value. We also used a series of review articles titled "A State-of-Knowledge Review," from the National Fire Effects Workshop held in Denver, Colorado, in April 1978.

We have not made a systematic review of all journals that might have published papers on fire effects. Several individuals and groups have done this in recent years, and we assume that those reviews were thorough.

Bibliographies and Computerized Searches

We searched some computerized bibliographies for pertinent key words. Other bibliographies, we searched manually. Among these is the fire ecology bibliography developed by M. J. Behan of the University of Montana for the International Biological Program (IBP), Coniferous Forest Biome, and the bibliography prepared in conjunction with the April 1978 National Fire Effects Workshop. We searched the following data bases:

1. FIREBASE--A bibliography of all aspects of wildfire and prescribed fire. Developed by the USDA Forest Service's Northern Forest Fire Laboratory in Missoula, Montana.
2. NTIS--National Technical Information Service.
3. AGRICOLA--Agricultural Sciences.
4. BIOSIS--Biological Abstracts Index Service.
5. ENVIROLINE--Environmental Information Center Inc.
6. SCISEARCH--Science Citation Index.

Two other bibliographies we reviewed are *Annotated Bibliography of Permafrost - Vegetation - Wildlife - Landforms Relationships* (Roberts-Pichette 1972) and *Fire in the Northern Regions - a Bibliography* (Larson 1969). While the Roberts-Pichette bibliography deals with the Canadian North, its main emphasis is permafrost. Therefore, it lacks some inclusions and discussions of fire effects. The Larson bibliography (1969) is not annotated, a large percentage of the citations relate to fire suppression, and much of the northern fire effects literature has appeared since the bibliography was published. A recent annotated bibliography prepared by LGL Limited for the Canadian Northern Economic & Development Branch of the Department of Indian and Northern Affairs (1975?) has been especially useful because it covers north-western Canada.

We used the *Arctic Bibliography* published by the Arctic Institute of North America, and the new computerized version called ASTIS (Arctic Science and Technology Information System). We also reviewed other bibliographies on specific subjects that are not directly related to northern areas. These are *Fire Impacts on Wildlife and Habitat* (Stanton 1975) and *A Selected and Annotated Bibliography for Wilderness Fire Managers* (Baker 1975).

Symposia and Workshops

An increased interest in fire effects in recent years has resulted in a number of symposia and workshops in both the United States and Canada, and additional meetings are planned. Proceedings of some of these workshops and symposia have been published, some are being published, and others will have no formal publication. Published and unpublished papers from these meetings (through June 1979) have been systematically reviewed. A chronological list of these meetings follows:

1970--The Role of Fire in the Intermountain West, a symposium, sponsored by the Intermountain Fire Research Council, was held in Missoula, Montana. The published proceedings contain several papers that relate directly to boreal forests.

1971--Fire in the Northern Environment, a symposium, sponsored by the Alaska Forest Fire Council and the Alaska Section of the Society of American Foresters, was held in Fairbanks, Alaska. The proceedings, edited by C. W. Slaughter, R. J. Barney, and G. M. Hansen, contain a good summary of the knowledge of fire effects in the North American taiga, and especially Alaska, at that time.

1972--Fire in the Environment, a symposium, sponsored by the North American Forestry Commission, FAO, was held in Denver, Colorado. The proceedings include a number of papers that relate to northern forests, as well as many general papers on fire effects and succession following fire.

1972--The Ecological Role of Fire in Natural Conifer Forests of Western and Northern North America, a symposium, sponsored by the Ecological Society of America and the American Institute of Biological Sciences, was held in Minneapolis, Minnesota. Proceedings, edited by A. L. Washburn and J. S. Creager, were published as a special issue of *Quaternary Research*, Vol. 3(3) (1973). The publication contains review papers on fire effects in Alaska (Viereck), Canada (Rowe and Scotter), and Minnesota (Heinselman, Swain, and Frissell), as well as papers on areas in mountains farther south. Also in this publication is an excellent summary on the role of fire in conifer ecosystems by Wright and Heinselman.

1975--Canadian Alaskan Seminar on Research Needs in Fire Ecology and Fire Management in the North. This meeting was sponsored by the North American Forestry Commission with the objectives of reviewing fire effects research in Alaska and northern Canada and identifying opportunities for developing joint United States-Canadian programs of research in fire ecology. It was held in Anchorage, Alaska, with a field trip to Fairbanks, Alaska. The proceedings present summaries of fire management practices, research, and policies in both Alaska and some northern areas of Canada.

1976--Fire Management in the Northern Environment, a symposium, sponsored by the Bureau of Land Management (BLM), was held in Anchorage, Alaska. BLM published partial proceedings in 1979.

1977--North American Forest Lands at Latitudes North of 60 Degrees, a symposium, held in Fairbanks, Alaska, dealt with the broad area of management of northern forests. It was sponsored by the University of Alaska, School of Agriculture and Land Resources Management, Agricultural Experiment Station, Cooperative Extension Service; the

Alaska Humanities Forum; the USDA Forest Service; and the USDI Bureau of Land Management in cooperation with the Alaska Federation of Natives; the Joint Federal-State Land Use Planning Commission for Alaska; the Society of American Foresters; and the State of Alaska, Forestry Section of the Department of Natural Resources. The proceedings, edited by University of Alaska staff, contain several papers that discuss the importance of fire in the boreal forest environment and the need for management systems that include fire as an element in management plans.

1977--Symposium on the Environmental Consequences of Fire and Fuel Management in Mediterranean Ecosystems, Mooney and Conrad, technical coordinators, was held in Palo Alto, California. While not directly related to fire effects in northern areas, the proceedings include general papers that relate to all forest types, including some on modeling of succession. Proceedings were published by the USDA Forest Service as General Technical Report WO-3.

1978--The Role of Past and Present Fire Frequency and Intensity on Ecosystem Development and Management, a symposium, sponsored by the International Scientific Committee for Problems of the Environment (SCOPE), was held in Honolulu, Hawaii. H. Mooney, J. M. Bonnicksen, N. L. Christensen, J. E. Lotan, and W. A. Reiners are editors of the proceedings, to be published by the USDA Forest Service.

1978--National Fire Effects Workshop, an interagency workshop, sponsored by the USDA Forest Service, was held in Denver, Colorado, to review the state of knowledge of fire effects. The results of this workshop are being published as six separate General Technical Reports from the Washington Office of the Forest Service. The reports cover the effects of fire on the following subjects: fauna, soils, fuels, water, air, and flora. To date (May 1980) five of the six have been published: *Effects of Fire on Fauna* (Lyon et al. 1978); *Effects of Fire on Soil* (Wells et al. 1979); *Effects of Fire on Fuels* (Martin et al. 1979); *Effects of Fire on Water* (Tiedemann et al. 1979); and *Effects of Fire on Air* (Sandberg et al. 1979).

1979--Fire in the Northern Circumpolar Ecosystems, a symposium, sponsored by SCOPE, International Man and the Biosphere (MAB), and the Fire Science Centre of the University of New Brunswick, was held in Fredericton, New Brunswick, in October 1979. The proceedings of the symposium, now in press, were edited by R. W. Wein. They include review papers on aspects of fire effects in Alaska, Canada, Scandinavia, and the Soviet Union.

* * *

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FIRE HISTORY and FIRE REGIMES

Fire History in Alaska

In Alaska fire records have been kept only since 1940. Lutz (1955) recorded some of the largest fires before 1940, and others have attempted to trace the fire history of individual areas, for example, Mount McKinley National Park (Buskirk 1976) and the Kenai National Moose Range (Johnson, A. 1975). Statistics for the period from 1940 to the present have been compiled by Barney (1969, 1971) and the Bureau of Land Management (BLM) (USDI 1978).

Barney and Stocks (1979) identified some of the difficulties of determining fire history in northern areas. They note the lack of long-time records. In addition, increased efficiency of detection systems in recent times has led to problems in data interpretation. These authors point out that climate, especially lightning frequency, has not changed in the last 100 to 150 years. The influx of miners and their activities around the turn of the century may have increased fire frequency but in general, the natural fire frequency should have been about the same for this period.

Barney (1971) estimated that before 1940, the average area burned each year in Alaska was 600,000 to 1,000,000 hectares. Although the numbers of occurrences of man-caused and lightning-caused fires in Alaska have increased in each of the decades since 1940, the average annual area burned by lightning fires has decreased about 10 percent per

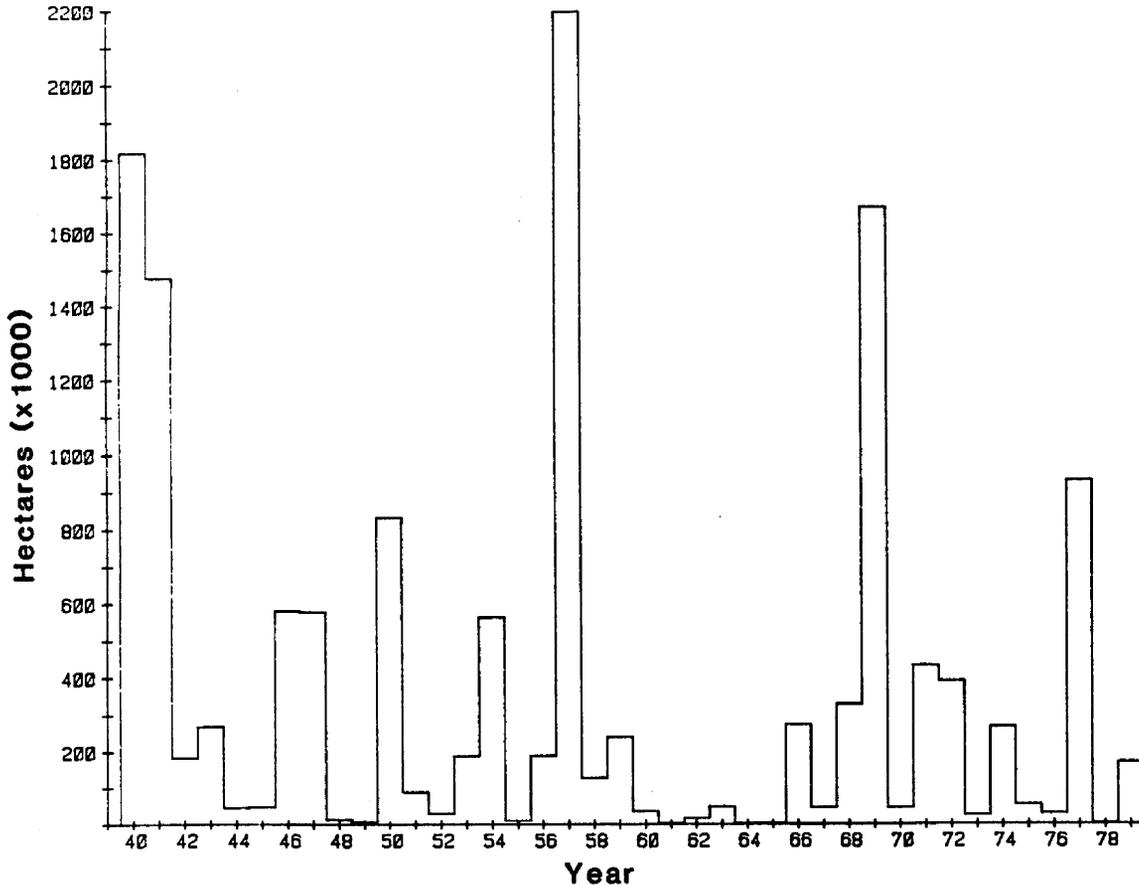


Fig. 1. Area burned in Alaska between 1940 and 1979.

decade, and the average annual area burned by man-caused fires in the 1970s is about one-tenth the annual average in the previous decade. Barney concluded that the apparent increased occurrences of fire are due to improved detection and reporting.

Statistical data for the Yukon Territory and Northwest Territories parallel Alaska data in many respects. Individual fires in the taiga tend to be large, often 50,000 hectares or larger during exceptional fire years, and may reach sizes of more than 200,000 hectares. Exceptional fire years are characteristic of the spruce ecosystem. Rowe et al. (1974) point out that in the southern area of the Mackenzie Valley, Canada, 42 percent of the fires studied occurred in 5 exceptional years and in the northern area 4 years accounted for 60 percent of the fires. The same trend occurs in Alaska. From 1940 to 1978, 6 years (1940, 1941, 1950, 1957, 1969, and 1977) accounted for 63 percent of the total area burned. (See Fig. 1.)

Fire years sometimes are synchronized over wide geographic areas. Although Rowe et al. (1974) found only 2 years where the fire years were

similar for the northern and southern areas of Mackenzie Valley (1865 and 1881), the earlier year has also been reported as a big fire year in Jasper Park (Tande 1977), in Montana (Arno 1976), and in Minnesota (Frissell 1973 and Heinselman 1973). A comparison of data on major fire years in Alaska and the Mackenzie Valley (Lutz 1955) with the data provided by Rowe et al. (1974) shows a correlation in 1893, 1915, 1937, 1941, 1950, and 1969. The large Alaska fire years of 1940 and 1957 had no counterpart in the Mackenzie area.

Periodicity in the occurrence of exceptional fire years has been suggested by many investigators. Fox (1978) proposed that fire years occur in 11-year cycles, following sun spots. Rowe et al. (1974) for the Mackenzie Valley and Heinselman (1973) for northern Minnesota suggested that in 1 year out of every 4, significant fire activity is probable. Wilton and Evans (1974) showed that the area burned in Newfoundland between 1910 and 1970 followed a periodic but not a cyclic pattern. They pointed out that the extreme fire years occur as pairs, with the first year less severe than the second. Data from Alaska and Canada on area burned show a rough correlation of annual area burned to a 9- to 11-year time interval. The question of periodic or cyclic patterns in the occurrence of large fire years remains unresolved.

Definition of Terms

The natural fire regime of an area has been defined by Heinselman (1978) as the total pattern of fires characteristic of a natural region or ecosystem. The pattern includes variations in ignition, fire intensity and behavior, average area of ecologically significant fires, recurrence intervals, and the general ecological effects on the ecosystem. Before discussing the fire regime of the taiga, we must define some additional terms.

Two types of fire periodicity can be determined for any unit of area or for a given vegetation type. These are "fire frequency" and "fire cycle."

1. "Fire frequency" or "return interval" refer to the time interval between successive burning of the same piece of land (Heinselman 1978) or the same stand of vegetation. It is usually determined by fire scars on fire-resistant trees or by historical records.

2. "Fire cycle" (Van Wagner 1978) or "natural fire rotation" (Heinselman 1973) is defined as the time period required to burn an area equivalent to the area being investigated. It is usually determined from fire records, but recently a method has been developed which uses the distribution of stand ages (Rowe et al. 1975, Van Wagner 1978, Yarie 1979). In this review paper, we use the term "fire cycle" to avoid the

confusion of the usual use of the word "rotation" in forestry to mean the time required to establish and grow tree stands to a specified condition of maturity.

Two other terms used frequently in fire regime descriptions are "fire intensity" and "fire severity." Albini (1976) states: "Perhaps no descriptor of wildfire behavior is as poorly defined or as poorly communicated as are measures of fire intensity."

As used by fire behavior scientists, the term "fire intensity" implies some measure of a rate of energy transmission at the fire front. It is usually expressed as a unit of heat energy/length/time, such as Btu/foot/second or kilocalories/meter/second (Albini 1976). The term has been used in a much broader sense, however, especially by fire ecologists, to mean the heat created by fire and its overall effect on vegetation and soils.

The problem lies with the fact that a low-intensity fire may burn slowly and deeply in the organic layer, thus having a greater effect on soils and revegetation than a high-intensity fire that leaves the surface organic layers intact but destroys the overstory. Because of this, the term "fire severity" has been used to indicate the overall effects of the fire on the ecosystem. In some cases the term has been restricted to meaning the effects of fire on the forest floor only. We feel that this is too restrictive.

Wells et al. (1979) state that fire intensity can be classified subjectively by using fire severity classes but this cannot always be done. Fire severity, especially as it relates to the forest floor, depends more on the moisture content of the organic layers than it does on the intensity of the fire. It is possible for a very intense crown fire to have little effect on the forest floor, especially if the organic layers are frozen, as is often the case early in the fire season in Alaska. Similarly, it is possible for a low-intensity surface fire to burn deeply into the organic layer, especially in late summer when the organic layer is thawed and may contain little moisture. Thus, the fire could severely affect the ecosystem, especially revegetation.

To use the term "fire intensity" only when the kilocalories/meter/second have been determined seems to us to be too restrictive. "Fire intensity" should be used in a more general way in discussing hot crown fires that consume much of the aboveground vegetation, rather than low-intensity fires that may leave large amounts of vegetation either live or dead. If fire behaviorists wish to restrict the meaning of "fire intensity" to definite measured physical characteristics, they should also restrict terms such as "reaction intensity" or "Byram's fireline intensity" as defined by Albini (1976).

In most papers that we reviewed, the terms "fire intensity" and "fire severity" are used in a general way, often interchangeably. We

see no advantage in narrow, restrictive use of either term, but suggest that the two terms be distinguished from each other and used as follows:

Fire intensity should be used in either a quantitative or qualitative way to indicate the type or amount of heat created by the fire.

Fire severity should be used to indicate the effect of the fire on the ecosystem, whether it affects the forest floor, tree canopy, or some other part of the ecosystem. To indicate the specific effect of the fire on the forest floor, we (Viereck et al. 1979) have developed forest floor severity classes. These are discussed in the soils section, page 19.

Fire Regime in the Taiga

The natural fire regime of the Alaska taiga may be characterized as having relatively high-intensity crown fires or severe surface fires that kill and regenerate entire stands (Heinselman 1978). The return interval is short to medium (50 to 200 years), and the ecologically significant fires are large, generally 25,000 to 50,000 hectares or larger.

Although little information is available on the taiga's natural fire cycle because of the taiga's remoteness and lack of fire records, Rowe et al. (1974) have shown that in the Mackenzie Valley, fire cycles are between 80 and 90 years for the black spruce type, 30 to 70 years for the jack pine type, and 300 years for the alluvial white spruce stands, many of which are islands and thus protected from fire. Smith and Henderson (1970) show an approximately 100-year cycle for the spruce types in northern British Columbia.

For the Alaska taiga, a fire cycle of about 200 years is estimated. Heinselman (1978) has modified the estimate to 130 years for open spruce-lichen forest and 100 years for closed black spruce.

Trigg's (1971) fire climatic zones correlate with established cycles for Alaska. The shortest cycles occur in interior Alaska and the Yukon Basin and longer fire cycles are typical of western and southwestern Alaska. In corroboration, Yarie (1979) estimated the natural fire cycle to be 49 years, basing his estimate on ages of 375 randomly located stands in the 3.6 million hectare Porcupine River area. He also determined the fire cycle for the following cover types: white spruce, 59.1 years.; black spruce, 58.9 years.; and deciduous tree stands, 28.6 years.

Because precipitation increases from western to eastern Canada, the length of the natural fire cycle should increase from west to east. No estimate of the fire cycle is available from the northern forested areas

of Canada, but in New Brunswick (Wein and Moore 1977), fire cycles of 230 years have been calculated for the red spruce-hemlock-pine type and more than 1,000 years for the high-elevation conifer types.

Wilton and Evans (1974) found that in Newfoundland over the past 60 years, 15 percent of the commercial forest and 12.5 percent of the total land area have burned. This gives a fire cycle of approximately 400 years for the forested areas and 480 years for the total land area. They emphasize that this is not a natural fire regime but one established under much development and many man-caused fires. These figures from eastern Canada indicate that the natural fire cycle is much greater in the wetter regions of the boreal forest than it is in the dryer western areas of western Canada and central Alaska.

Two elements must be considered in discussions of fire resistance in relation to spruce types and fire. One is the resistance of tree species to fire; the other is the susceptibility of a given forest type to fire. Balbyshev's (1964) study of the relative fire resistance of various taiga tree species in the Soviet Union showed that conifer trees are less resistant to fire than are deciduous trees, and among conifer trees, spruce is the least resistant. This means that when a fire burns through spruce stands, the trees are generally killed. In contrast, repeated ground fires in the larch and pine stands may leave fire scars but seldom kill the trees. Balbyshev concluded that repeated fires in the Soviet Union have acted to spread and make more dominant the fire-resistant trees, whereas the spruce have become more limited and confined to areas of lower fire frequency. In Alaska all of the tree species are relatively thin-barked and equally susceptible to fire. Distribution and abundance, therefore, seem to be related primarily to trees' ability to regenerate after fire.

In their discussion of susceptibility (or ease of ignition) of forest types in the boreal forest of Canada, Rowe and Scotter (1973) found that surface fires are initiated with greater difficulty in spruce than in pine forests, but that crown fires spread about equally in spruce and pine under the same conditions.

In the spruce type most fires are either crown fires or ground fires intense enough to kill the overstory trees.

The tendency of fires to crown is related to the distribution of fuels within the stands. In most black spruce stands, there is an open, flammable ericaceous shrub layer that can carry flame at .5 to 1 m above the surface. From that point, ignition into the crown can occur because dead, lichen-covered lower branches will carry flame directly into the crown. Layering of the lower branches also provides nearly continuous fuel from forest floor to tree crowns.

Fire Regime in the Tundra

The natural fire regime of the tundra is not well understood. In many tundra areas, fire may never occur or play a significant role but in other areas, it may have ecological significance even if the occurrence is rare. In general, the tundra areas can be characterized as having low- to moderate-intensity surface fires that may kill all aboveground parts but seldom destroy underground parts. The return interval may be as short as 100 years in some areas, such as the Seward Peninsula, but it is usually much longer. In some tundra areas, fire may never have occurred under current climatic conditions. In general, tundra fires are smaller than those in the adjacent taiga but under extreme conditions may cover 100,000 or more hectares.

Before 1970, fire was not recognized as an important part of the tundra environment. This was partly because evidence of fire cannot be distinguished easily a few years after the fire, partly because the tundra is so remote, and perhaps also because tundra fires may not have been common before the 1970s. There is some evidence that in Alaska, fires may occur much less frequently on tundra than they do in the taiga. Barney and Comiskey (1973) reported that only 1,600 hectares burned on the north slopes of the Brooks Range between 1969 and 1971, and they found little evidence of earlier fires.

Wein (1976) reported a number of fires for tundra areas from Alaska and adjacent Canada. The largest of 10 fires in western Canadian tundra was reported as only 1 km², whereas the fires in Alaskan tundra were generally much larger, with three fires on the Seward Peninsula burning 1,600 km².

The fire history of the Seward Peninsula illustrates some of the problems of fire documentation in remote tundra areas. Both Melchior (1974) and Racine (1979) reviewed the fire history of the Peninsula. The earliest records of fire come from geologists who in 1900 recorded that fires and smoke hindered their surveying efforts. Survey parties reported fires in 1903 and 1906. In 1926, Palmer reported that fires were often set by prospectors to clear vegetation and expose underlying rocks. According to Wein (1976), D. M. Hopkins of the U.S. Geological Survey mentioned seeing tundra fires on the Seward Peninsula in 1947, but did not recall seeing burned areas again until 1971.

Although BLM has kept records of Seward Peninsula fire locations since 1956, Melchior and Racine did not use BLM records to reconstruct the fire history of the Seward Peninsula because the records were difficult to access from their storage place in Denver, Colorado.

According to Salvatore De Leonardis, BLM, Alaska State Office (personal communication), known early fires on the Seward Peninsula in-

clude a large fire northeast of Teller in about 1947, two fires near Candle in about 1956 to 1958, and a 100,000-hectare fire south of Selawik in 1957.

Melchior (1974), reviewing fire records for 1969 to 1975, found that during that period, 21 reported fires, all lightning caused, burned 122 km² on the Seward Peninsula. The peak year was 1971. Fires apparently were uncommon on the Seward Peninsula during the period from 1973 to 1976, but the year 1977 brought attention to the fact that extensive fires could occur in tundra areas in Alaska. During 1977, approximately 3,600 km², almost all of which would be classified as tundra, burned on the Seward Peninsula. In addition, large fires burned in several other tundra areas, including the Arctic Slope.

The history of fire on the Seward Peninsula shows the difficulty of determining fire frequency in tundra areas. Because of the lack of trees for dating stand ages and because the vegetation recovers so quickly, it is nearly impossible to recognize and age burned areas that are more than a few years old. We know that there were extensive fires during the gold exploration and mining era, up through the 1920s, but we have no indication of numbers of fires or area burned until the BLM began to keep records in 1940. Complete records are available only from 1969 to the present, and they indicate extensive burning of the Seward Peninsula tundra in 1971 and 1977. The unusual circumstances of the 1977 fire season in western Alaska are documented in the BLM report, *The 1977 Fire Season* (USDI, Bureau of Land Management 1977).

Investigations of the Kokolik River fire of 1977 on the Arctic Slope showed that little is known of the fire history in that part of Alaska. Barney and Comiskey (1973) state that the lightning fires during the 1969-71 period were unique to the area and they could find no one who knew of earlier fires on the Arctic Slope. The Study Report 4 of the National Petroleum Reserve in Alaska (NPR-A) Task Force (1978), however, points out that five fires occurred east of NPR-A in 1969-71 and three known fires were inside an area adjacent to NPR-A in 1974-77. These fires, especially the 44 km² Kokolik River fire of 1977, raise a question about the frequency of tundra fires in all areas of the Arctic Slope. Other questions are whether this apparent increase in fires is due to increased reporting or whether fires actually have increased on the Arctic Slope, perhaps because oil exploration and production have increased there.

As has often been pointed out in ecological literature, the extreme fire years may have far more influence on the ecological condition than the normal or average years. We have no information on the frequency of hot dry summers in tundra areas or the potential for numerous or extensive fires during dry periods. The Seward Peninsula example shows that dry years such as 1977 need occur only once or twice a century to have an important influence on the tundra ecosystem.

One usually thinks of the cloud-covered Aleutian Islands as having excesses of moisture and no wildfires. The authors of two separate

papers on the vegetation of Amchitka Island, however, report fires in the tundra on the Island. Shacklette et al. (1969) reported that during the 1940s a 1 km² fire occurred in the crowberry heath type, which still showed conspicuous differences compared with the surrounding vegetation. Amundsen (1977) reported that on two occasions fire spread across crowberry meadow community types, but that the fire had no lasting effect on the vegetation and no discernible effect on the substrate or subsequent plant community composition.

Two authors attempted to summarize the history of tundra fires in Canada. Wein (1976) recorded all known tundra fires west of Hudson Bay. He found that only records of recent fires were available and that the number of fires reported was closely related to the accessibility of the areas. He concluded that fire frequency is much less in Canadian tundra areas than in forested regions and fires are small, usually less than 1 km².

Shilts (1975) reported on a number of tundra fires in Keewatin, just east of Hudson Bay, in 1973, which may have been an exceptional fire year. He concluded that if the 1973 season were repeated randomly once every 10 years, the entire study area of 143,000 km² would have been burned in 4,000 years. Such a fire frequency is low, but fire still may be an important influence on periglacial and soil-forming processes in the tundra.

This review of fire history in tundra areas shows the need for good fire records. Well-mapped fire boundaries, good characterization of vegetation types burned, and readily accessible records would aid greatly in determining the fire frequencies in different vegetation types and different areas in Alaska.

The importance of fire in the tundra types is difficult to determine because of the broad use of the term "tundra" in many fire reports and summaries. Bogs, grasslands, and even some forested areas have been grouped with tundra in many reports. For example, Adams (1974) reported that half of the area within the Alaska taiga in interior Alaska is considered "tundra." The moss mat in black spruce stands often is incorrectly referred to as "tundra" in some fire suppression reports.

The importance of LANDSAT imagery for fire records should be noted. Shilts (1975) and Rowe et al. (1975) in Canada, and Anderson and Belon (1973), Nodler et al. (1978), LaPerriere (1976a, b), and Hall et al. (1978) in Alaska have pointed out the value of using LANDSAT for mapping recent tundra fire boundaries. Rowe et al. (1975) state that burned areas can be mapped from LANDSAT images for up to 5 years after a fire. The LANDSAT images can thus be used for developing information on fire size and frequency in tundra areas, where fire records are usually not complete and evidence of fires disappears within a few years.

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EFFECTS of FIRE on SOILS

There are many different kinds of soils in Alaska because of the large area, climatic diversity, various bedrocks, and wide diversity of parent material related to recent glaciation or the lack of it. According to Rieger et al. (1979) five of the ten orders in soil taxonomy are represented within the State. Poorly drained soils with permafrost occupy one-third of interior, western, and arctic Alaska. Large areas are covered by organic soils, which are frozen in most of interior Alaska but unfrozen in coastal and southcentral Alaska. Most of the best forested sites are underlain by permafrost-free, well-drained soils--Cryochrepts in the Interior and Cryothods in southcentral Alaska.

Although considerable information has been collected from many regions on the effects of fire on soils, little information is available from Alaska. Lutz (1955) and Viereck (1973b) summarized the available information. Kelsall et al. (1977) reviewed information from northern Canada and Alaska and Viro (1969) reviewed information from prescribed burn studies in Scandinavia. Most recently, a state-of-the-art review of the effects of fire on soil was prepared for all of North America (Wells et al. 1979). Results varied so much from area to area that few general conclusions could be drawn.

Forest Floor Characteristics

Most taiga soils have a thick organic layer. In black spruce stands on permafrost sites, the organic layer may be 50 cm or more thick. The amount of organic layer removed by fire affects postfire succession, soil temperatures, permafrost depths, and amounts of nutrients available.

Forest floor fire severity is important because it determines the amount of organic material removed by the fire. This determines to a large degree the amount of warming and the changes in the active layer that may occur. Forest floor fires also affect the amount of nutrients released and may change the nutrient regime of the soil. In addition, forest floor fires have a direct effect on revegetation because they may

leave some plant parts for vegetative reproduction and destroy others. The amount of organic material remaining after fire also is important to the revegetation by buried seed, and it may determine which seed and spores that arrive after the fire establish successfully.

General observations on amount of organic layer removed by fires in Alaska is available from the Wickersham Dome fire in the Interior. This fire occurred early in the summer, before the organic layers had dried. Viereck and Dyrness (1979) found that 6 cm of organic layer was removed from lightly burned plots and 10 cm was removed from heavily burned plots. This was approximately 20 and 30 percent, respectively, of the organic layer. In other areas with thinner organic layers, the fire removed much less forest floor.

In an experimental burn at Washington Creek, we found that in July, a fire that followed a heavy rainfall removed only 5 cm or 14 percent of the forest floor, while in late August, a fire that followed a dry period removed as much as 15 cm or 62 percent of the organic layer (Viereck et al. 1979).

Wildfire in the spruce type in Alaska removes forest floor unevenly, leaving a patchy mosaic. The condition of the forest floor, as well as the amount of organic material removed, is used as an indicator of the severity of a fire's effect on the forest floor. Five forest floor severity classes were used to indicate degree of burning in the Washington Creek experimental fires (Viereck et al. 1979). These five classes, which include one unburned class, are as follows:

1. Heavily burned: Deep ash layer present, organic material in the soil consumed or nearly so to mineral soil, no discernible plant parts remaining.
2. Moderately burned: Organic layer partially consumed, shallow ash layer present, parts of woody twigs remaining.
3. Lightly burned: Plants charred but original form of mosses and twigs visible.
4. Scorched: Moss and other plants brown or yellow but species usually identifiable.
5. Unburned: Plant parts green and unchanged.

In subsequent work, Classes 3 and 4 were combined so that the forest floor might be characterized as lightly, moderately, or heavily burned.

Wells et al. (1979) pointed out that this system works well for characterizing a given place but that additional criteria are needed for characterizing the mosaic of burn patterns usually found in a larger

area. They suggested the following criteria, which may be useful to consider for standardization in Alaska:

1. Severely burned: More than 10 percent of the area has spots that are heavily burned, more than 80 percent moderately burned, and the rest lightly burned.
2. Moderately burned: Less than 10 percent heavily burned, but more than 15 percent moderately burned.
3. Lightly burned: Less than 2 percent heavily burned, less than 15 percent moderately burned, and the rest lightly burned or not burned.

Soil Temperature

In the organic soils of Alaska most of a surface fire's heat is lost into the air. If the organic layers are moist, little soil heating occurs (Agee 1973, Viereck et al. 1979). If most or all of the organic layer burns, however, some heat may transfer to the soil, perhaps even to mineral soil.

Van Wagner (1970) recorded heat gradients of $10^{\circ}\text{C}/\text{mm}$ in mineral soil and $28^{\circ}\text{C}/\text{mm}$ in organic soils in Ontario experimental fires in the jack pine type. He noted that surface temperatures of 450°C would have little effect below 5 cm in most northern forest soils. For the Inuvik area in Northwest Territories, Mackay (1977) calculated that even if a fire maintained a temperature at the surface of 500°C for nearly 30 minutes, the temperature rise at 30 cm (in this case the depth of the active layer) would be negligible.

No measurements have been published on the heat transfer during fire in northern soils. Measurements taken to several depths before and after the 1976 experimental fires at Washington Creek showed little or no fire-related change in soil temperatures. Analysis of extensive soil temperature measurements taken during the 1978 Washington Creek experimental fires should increase our understanding of heat transfer in the organic layers in the black spruce type for a wide range of burning conditions.

Long-term effects of fire on soil temperatures result from removal of the insulating organic layer, change in surface albedo, i.e., its ability to absorb or reflect heat, and the removal of the vegetation overstory. These long-term changes are discussed in the section on permafrost (page 24).

Soil Moisture

The effects of fire on soil moisture content seem to depend on the severity of the fire, the type of soil involved, the presence and absence of permafrost, and probably other factors. Lutz (1955) cites early work by Bühler (1918) and others to indicate that ". . . where the ground water is close to the surface, destruction of forest vegetation is known to result in a rise of the water table, producing swamp conditions."

The same phenomenon has been reported from Siberia by Kryuchkov, who indicated that following fire on permafrost soil, there was a surplus of moisture near treeline. He felt that the increased moisture caused a rich growth of vegetation that eventually caused the active layer to become shallower. Kane et al. (1975) found that following the Wickersham Dome fire, soil moisture increased compared with soil moisture in the unburned stand. They thought the increase was caused by reduced evapotranspiration.

On dryer sites with little organic material or where most or all of the organic layer is removed, however, soil moisture levels may be reduced or may fluctuate following fire. Kershaw and Rouse (1971) found that soil moisture was lower and fluctuated more on lichen woodland sites that had burned than on those that had not burned. In unburned lichen woodlands, the lichen layer tends to retain moisture and prevent evaporation, whereas the moisture evaporates quickly from the mineral soil exposed after fire.

In Alaska, it has been observed but not reported in the literature (personal communication, R. Norum 1977) that immediately after a fire, surface water is visible from the air. This may be partly because surface water is more visible after vegetation is burned away, but it is also thought that the water may come from melting permafrost layers. In addition, plant evapotranspiration ceases when fire kills the plants.

Soil Wettability

Following intense fires in many areas, especially in the southwestern United States, a water-repellent soil layer has been observed (DeBano et al. 1967). This has also been observed in the Pacific Northwest (Dyrness 1976). The only report of water-repellent soils in northern areas is given in Kelsall et al. (1977), who quote an unpublished report by Johnson and Rowe (1973) that water-repellent soils are widespread west of Great Slave Lake and are usually associated with fire-prone vegetation. No reports of water-repellent soils following fires have been recorded from Alaska.

Soil Nutrients

The effects of fire on soil nutrients vary. As with other soil properties, they depend mostly on fire intensity and severity, site condition, and original soil properties. In general, however, fire in the North is reported to make soil nutrients more available to plants. This accounts somewhat for increased site productivity after fire, especially in vegetation types on deep forest floors that have built up because of a slow decomposition rate. In these cases, burning releases plant nutrients that were tied up in the organic layers and not available to plants before a fire.

While pH usually tends to be acidic in northern organic soils, the acidity is dramatically increased by fire (Lutz 1955, Scotter 1971a, Armson 1969, Braathe 1974, Uggle 1958, Wells et al. 1979). Usually, exchangeable phosphorus, potassium, calcium, and magnesium also increase after the fire, but amounts vary considerably and some losses have been reported.

In some studies, immediate nutrient increases were reported to be followed by leaching losses. As a result, smaller amounts of nutrients could be available a few years following the fire than were available before the fire. Viro (1969) reported his study after prescribed burning in Scandinavia. He observed that there may be some phosphorus leaching, but loss of other mineral nutrients is negligible. Weber (1975) found an increase in phosphorus level the first season after burning, with a phosphorus decrease in subsequent years in small experimentally burned plots in the Northwest Territories, Canada. In postfire soil tests in northern Saskatchewan, Scotter (1963) found an increase in phosphorus and calcium, a decrease in pH, and no difference in potassium, magnesium, and sodium.

Changes in available nitrogen following fire in northern areas seem to vary and be subject to different interpretations. This is largely because nitrogen exists in several forms. Considerable amounts of nitrogen are lost as gas through volatilization when the forest floor and vegetation burn (Debell and Ralston 1970, Lutz 1955, Wells et al. 1979). Van Cleve (1971) estimates that as much as 2,000 kg/ha of nitrogen could be lost through the burning of the top 5 cm of the forest floor. Some of the nitrogen in the lower layers, however, may be converted to usable ammonia and nitrogen as a result of the fire. These become available to plants (Viro 1969). Heilman (1966, 1968) points out that much of the soil nitrogen tied up in the lower organic layers and in the permafrost may become available to the plants over several years following the fire, when the soils are warmer and the active layer thicker. Wells et al. (1979) point out that in many areas after fire, nitrogen fixation, both symbiotic and nonsymbiotic, is more active and may restore the nitrogen lost. This has not been reported for northern soils, however.

Information is lacking on the long-term effects of fire on soil nutrients. Weber (1974) found that nutrient increases seen the first season following fire were not followed by decreases in subsequent years. In an oft-quoted study from Norway, Skoklefeldt (1973) found that seedlings of Norway spruce and Scotch pine grew better on burned sites for 12 years, but after that, growth was better on the unburned sites.

Data on soil nutrient changes following fire in Alaska are extremely few. Lutz (1955) drew his conclusions primarily from other northern literature, mainly from Hesselman in Sweden, with the aid of data from 10 soil profiles in older white spruce stands on the Kenai Peninsula. Studying soil nutrients one year after a fire in black spruce in eastern Alaska, he found no significant differences but found a slight decrease in total cation exchange and an increase in potassium.

The soils analyses for nutrient changes following the Wickersham Dome fire were inconclusive because of high variability and because 15 cm cones of soil were taken for samples. This method masked any changes in the upper few centimeters of soil, where most changes would take place (Dyrness, in Viereck and Dyrness 1979).

Soil samples taken before and after the 1976 experimental fires in Washington Creek were analyzed for phosphorus only. In that study the available phosphorus increased by up to 50 times after the fire.

Dyrness carried out intensive soil sampling before and after the seven 1978 experimental fires. His samples are being analyzed and should provide useful information on the effects of various severities of fire on soil nutrients in the black spruce type.

Permafrost

Permafrost, a convenient short term for "permanently frozen ground," is defined as any part of the earth's crust, bedrock or soil mantle, that remains below 32⁰ F (0⁰ C) continuously for a number of years (Brown 1970). In Alaska permafrost is continuous in the northern and western areas, discontinuous in much of interior Alaska, and sporadic in southcentral Alaska (Ferrians 1965). "Continuous permafrost" means that permafrost underlies all or nearly all of the landscape, including small ponds and streams. In the zone of discontinuous permafrost, most north-facing and low-lying areas are underlain by permafrost, but south-facing slopes and areas surrounding bodies of water may be permafrost free. In the zone of sporadic permafrost, permanently frozen ground is limited to small patches and is usually confined to peat deposits.

The frozen material may be as thick as 300 meters in northern areas but only one to a few meters near the southern limit of permafrost.

Temperatures of the frozen material may be just below 0 °C in southern areas to as low as -15 °C in northern areas. Permafrost soils may be nearly ice free in coarse parent material or contain as much as 50 percent ice in fine-textured soil material. Ice-rich soils are important in relation to fire effects and fireline construction because the melting of the ice within permafrost causes subsidence and erosion.

FIRE EFFECTS and the ACTIVE LAYER

The thickness of the underlying permafrost is not as important in consideration of fire effects as the depth of seasonal thaw. This soil layer that overlies permafrost thaws each year and is termed the "active layer." In northern soils with thick moss cover, the active layer may not be more than 40 cm thick; in mineral soil it may be 2 to 3 m (Brown 1970). The thickness of the active layer is increased by fire and other disturbance.

The effects of fire on permafrost have been reviewed by Viereck (1973a), Kelsall et al. (1977), Brown and Grave (1979), and Brown (1979). Different reported fire effects on permafrost and soil temperature are largely due to differences in fire severity. In unburned areas the thick moss layer of northern spruce forests acts as an efficient insulator during the warm summer months, often limiting the seasonal thaw depth (the active layer) to less than 1 m. Typically in black spruce and tundra types, thaw depths range only from 30 to 75 cm. In burned areas, however, although the heat of the fire seems to have little effect on the active layer depth (Viereck et al. 1979), the removal of some of the insulating moss, the change in surface albedo, and removal of overstory vegetation result in warmer soil temperatures. Summer soil temperatures following fires were 3 to 5.5 °C warmer than before a fire in the lichen woodland, Northwest Territories (Rouse 1976) and about 6 °C warmer (at 10 and 20 cm) in a black spruce feathermoss layer following the Wickersham Dome fire in interior Alaska (Viereck and Dyrness 1979).

The long-term studies of Mackay (1977) and Viereck and Dyrness (1979) have yielded the best information on increased thawing following fire in northern taiga areas. Mackay followed the thaw depth after the 1968 fire at Inuvik. His data show a rapidly increasing depth of thaw each year for the first 4 years and then continued thawing at a reduced rate during the next 4 years. After 8 years the active layer increased from 38 to 92 cm in depressions and from 60 to 114 cm on ridges.

In Alaska, changes in the active layer thickness at the 1971 Wickersham Dome fire site have been monitored for 8 years. Active layer thickness has increased at a relatively constant rate and shows no sign of leveling. The thaw depth has increased from approximately 45 cm in 1971 to 183 cm in 1979. A comparison of thaw rates after the Inuvik and

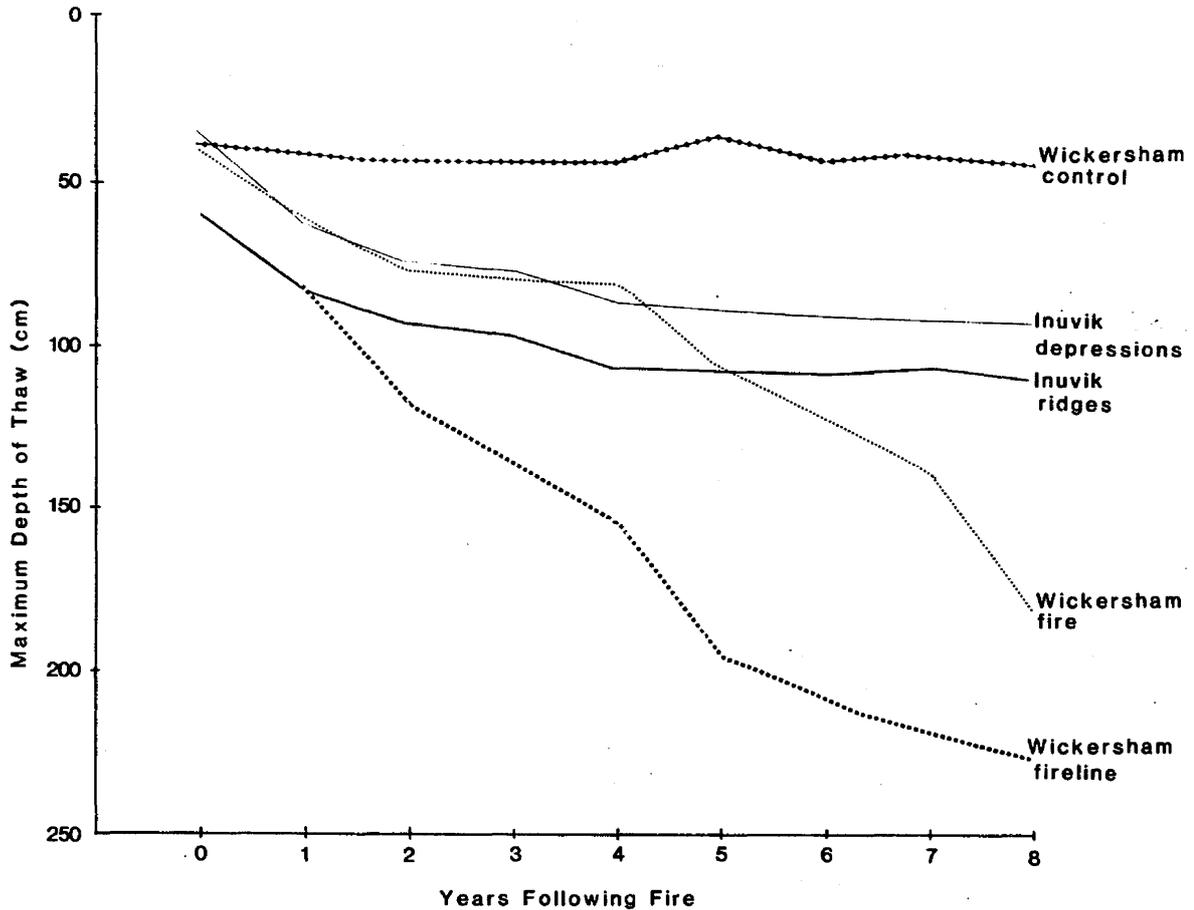


Fig. 2. Thaw depths for 8 years following the 1971 Wickersham Dome fire in Alaska and the 1968 Inuvik fire in Northwest Territories, Canada.

Wickersham Dome fires (Fig. 2) shows that the thaw depths continue to increase although the vegetation cover has been reestablished (Vioreck, in Vioreck and Dyrness 1979, and unpublished data).

The length of time required for the active layer to stabilize and return to its original thickness is not known. It will depend, to some degree, on the depth of the organic layer removed and the rate of revegetation. At the Wickersham Dome site the reestablished vegetation does not seem to be as good an insulator as are the feathermosses found in the mature spruce stands. The active layer probably will not reach its original thickness until the spruce stand with its feathermoss layer is well established. By comparing the active layer thickness in a number of known-aged burns, Vioreck (1973b) predicted that the active layer returns to its original thickness in interior Alaska approximately 50 years after fire. This agrees with Foote (1976), who reports that in the black spruce type, the canopy is reestablished 50 to 70 years

following fire. In northern Northwest Territories, Canada, in an area with a mean annual temperature of -10°C , the active layer thickness may be as little as 29 cm only 29 years following a fire (Black and Bliss 1978).

Increased soil temperatures and a thicker active layer can have beneficial and detrimental effects on the ecosystem. Warmer soil temperature and greater active layer thickness increase nutrient turnover and availability of nutrients to developing vegetation. Warmer soil improves growing conditions and accounts for increased productivity of sites after fire.

Detrimental effects of increased thawing of the permafrost layer are twofold. On steep slopes, release of the water in the previously frozen substrate, together with the removal of some or all of the overlying vegetation mat, may cause slope instability. This has resulted in mud- and landslides after fires in northern Canada (Heginbottom 1973, Rowe et al. 1974, Strang 1973a). Slides have also been observed on the 1966 Chicken fire and the 1971 Wickersham Dome fire sites in interior Alaska (Viereck, unpublished data; Lotspeich et al. 1970). In general, these slides occur on few burned areas in Alaska, primarily because the fires are seldom severe enough to completely remove the organic layer.

A second result of deeper thawing is the formation of thermokarst. This mounded and gullied topography results from the differential thawing of bodies of pure ice, usually in a polygonal pattern, lying at various depths in the organic and mineral substrate. In most cases, this thawing and subsidence is gradual over several years and seldom results in serious erosion and siltation. Occasionally, however, when thawing occurs where there is running water, active gullies may form. The length of time thermokarst topography may last after fire is not well documented, but at some sites in interior Alaska it remains 60-75 years following a fire (Viereck 1973a).

FROST ACTION after FIRE

The role of fire in initiating or increasing frost action may be of special importance to understanding the revegetation process in some tundra types.

One effect of fire on tundra soils is that it increases the thickness of the active layer. Fire, however, may have more significance in changing the active layer in forested than in tundra soils because overstory removal has less effect in tundra vegetation than in taiga. No long-term measurements have been made of active layer thickness changes in tundra areas. The 6-year record by Mackay (1977) from Inuvik is in an area that was originally forest rather than tundra.

First- and second-year measurements following fire in tundra areas are abundant, however. Wein and Bliss (1973) studied four areas: 1. the Elliott Highway--tussock tundra; 2. the Mosquito Fork on the Taylor Highway--tussocks with scattered black spruce; 3. Inuvik, NWT--tussocks with scattered trees; and 4. the Caribou Hills, NWT--tussock tundra. They found that the active layer depth increased by 35 to 59 percent in June and by about 25 percent in late autumn 1 year following fires. Variation in thaw depth was related to the surface conditions following fire, especially to the amount of organic material remaining.

Racine (1979) found little difference in thaw depth one year following the Seward Peninsula fires, but he found that the thaw went relatively deeper, reaching more frequently to mineral soil because of the removal of 5 to 15 cm of the original peat surface. One month following the Kokolik fire, the active layer was 35.4 cm thick compared with the 26.6 cm thickness in adjacent unburned tundra (Hall et al. 1978).

In the Soviet Union, Kryuchkov (1968) reported that after fire, the active layer thickness may be less than before because of the vigorous growth of the overlying sedges. Studies in Alaska and northern Canada have not indicated this, perhaps because of the lack of long-term measurements following fire in tundra areas.

Some investigators have reported that frost features, especially frost boils, become much more conspicuous following fire in some types of tundra (Racine 1979, Viereck and Johnson, pers. comm. 1979). This needs more investigation. Burning away of the organic material may make frost features more conspicuous, or the frost scars may actually be churned more actively. Racine's observations are from the Seward Peninsula and Viereck and Johnson observed frost features in some areas of the Kokolik River fire.

FIRELINES on PERMAFROST

A special problem occurs in areas underlain by ice-rich permafrost when vegetation and organic layers are removed by large equipment for fireline construction. The complete removal of the organic layer results in a deeper thaw than occurs under the burn itself. On ice-rich permafrost terrain, the effects can be disastrous. Some observers have stated that the effects of fire suppression activities are greater and last longer than the effects of the fire.

A fireline at the 1971 Wickersham Dome fire has thawed to 227 cm in 8 years, although an adjacent burned area has thawed to only 183 cm (Fig. 2). Subsidence of 1 meter and more is reported from the thawing under firelines at Inuvik (Mackay 1977). Because firelines are often located straight down slopes and in valley bottoms, water concentrates in the thaw areas and active water erosion is added to thermal subsi-

dence. Continued subsidence makes the surface unstable, and gullies are prevented from stabilizing. This erosion, siltation, subsidence, and gullying may continue for 10 years or more after fireline construction. Consequently, the lines may remain conspicuous features of the landscape long after fire effects can be discerned.

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EFFECTS of FIRE on WATERSHEDS

Available Information

The degree of impact fire has on basic hydrological processes is related to size and severity of the fire as well as site characteristics, rainfall, and firefighting methods employed. Large intense fires, however, appear to have the greatest potential for watershed and wildlife habitat damage (Rouse and Mills 1976, Tiedemann et al. 1979). Unfortunately, most Alaska hydrological data come from short-term studies. Long-range investigations would increase our understanding of fire's effect on hydrological processes in the North.

An increase in runoff after fire has been observed by many investigators. Following a wildfire in northcentral Washington, Helvey (1972) observed a 50-percent increase in runoff the first year. Rates of discharge are influenced by incoming precipitation (snowmelt, rain) and the capacity of soil to retain water. In turn, water-retention capabilities of soil are influenced by many factors, including slope, amount and duration of precipitation, soil characteristics, presence of permafrost, and amount and type of the vegetation present.

The taiga of Alaska seems to be fairly stable with regard to runoff and erosion. Viereck (1973b) credits this stability to the high water-holding capacity of the soil organic layers, rapid revegetation of partially burned organic soils, long periods when the soil is frozen, and low summer rainfall.

Serious erosion has resulted in the past from firelines constructed on permafrost terrain (Bolstad 1971, De Leonardis 1971). Fireline construction has been thought to have caused more erosion in some places than the effects of fire. To prevent erosion, every effort should be made to locate firelines away from low-lying permafrost sites and poorly drained areas. Studies by Neiland (1978), Bolstad (1971), and others have shown that serious erosion on firelines can be curbed by use of waterbars and other diversions and consideration of the terrain.

In Alaska and other northern regions, erosion can increase after severe fires that remove the insulating vegetation layer. Warmer soil temperatures lead to thawing of the permafrost layer. Water buildup in the previously frozen soil can lead to slumping and mud- and landslides, particularly on steep slopes. These phenomena have been observed following fires in northern Canada (Brown 1970, Heginbottom 1973, Rowe et al. 1974) and in Alaska on the 1966 Chicken fire and the 1971 Wickersham Dome fire site (Lotspeich et al. 1970; Viereck, unpublished data).

Thaw rates monitored after the Wickersham Dome and Inuvik fires show that the thaw depth continued to increase in spite of the fact that vegetation cover was reestablished (Viereck, in Viereck and Dyrness 1979; Viereck, unpublished data; Mackay 1977). The active layer should eventually stabilize and return to its original thickness. (See section on permafrost, page 24.)

Buckley (1958) reported decreases in water levels following extensive fires in 1950 in the Yukon Delta area of Alaska. He observed no conclusive evidence linking fire to the drop in the water level, however.

Losses of nitrogen and other nutrients increase after severe wildfires in some northern areas (Bradbury et al. 1975, Tiedemann et al. 1978). In interior Alaska after the Washington Creek fire, potassium concentrations were higher in streams draining burned areas than in streams draining unburned areas. Sediment load also increased in Washington Creek as a result of the thermal erosion of firelines (Lotspeich 1972). According to Tiedemann et al. (1979), "...nutrient losses via sediment and solution ...in general do not appear to represent a significant proportion of total site nutrient capitals."

Lotspeich (1972) investigated the effects of dropping 227 thousand liters of fire retardant in a small watershed during the 1971 Wickersham Dome fire. The retardant did not appear to cause high phosphate or nitrogen concentrations in Washington Creek. Even so, Lotspeich recom-

mended that retardants not be dropped near running water, to prevent adding loads of these chemicals to streams.

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EFFECTS of FIRE on VEGETATION

The Taiga

The extension of the boreal forest zone into Canada and Alaska is often referred to by the Russian word "taiga" to differentiate it from the closed, fast-growing forests of the more southerly region of the zone. In Alaska the taiga extends from the south slope of the Brooks Range, southward to its border with the coastal forests, eastward into Canada, and westward to a maritime treeline at the Bering and Chukchi Seas (Fig. 3). Approximately 32 percent of the Alaska taiga is forested, but only about 7 percent is classified as commercial forest. The unforested land consists of extensive bogs, brush thickets, grasslands, sedge meadows, and some alpine tundra.

In adjacent Canada the taiga extends from 69°N at the Mackenzie River Delta southward through Yukon Territory into northern British Columbia.

Taiga vegetation patterns consist of a mosaic of frequently occurring vegetation types, with a small number of individual species. The vegetation mosaic is the result of topography, climate, river meandering and flooding, parent material, presence or absence of permafrost, fire frequency and intensity, reproductive biology and autecology of individual species, and combinations of these factors.

In the uplands and on older river terraces, the dominant vegetation on most sites is stands of open and closed black spruce, especially the *Picea mariana*/feathermoss and *Picea mariana*/*Sphagnum* types. These open and closed black spruce types are especially widespread on poorly drained sites, including those underlain by permafrost, and on north-facing slopes. On the wettest sites, tamarack (*Larix laricina*) is associated with the black spruce. Toward the most northern areas and near altitudinal treeline, open stands of mixed black and white spruce occur, primarily as woodlands with an understory rich in lichen species (Viereck 1979). On many of these cold sites, black spruce stands are replaced directly by other black spruce after fire, but occasionally birch and rarely aspen intervene before the mature black spruce stands are reestablished.

On the warmer, well-drained sites, the mature forests consist of tall, fast-growing, closed or open white spruce stands, primarily the *Picea glauca*/feathermoss community type. Successional to the spruce on these sites are open and closed deciduous stands of birch, aspen, or birch and aspen mixed.

Bottomland spruce and balsam poplar forests are common along all of the major taiga rivers in Alaska and adjacent Canada. These and the

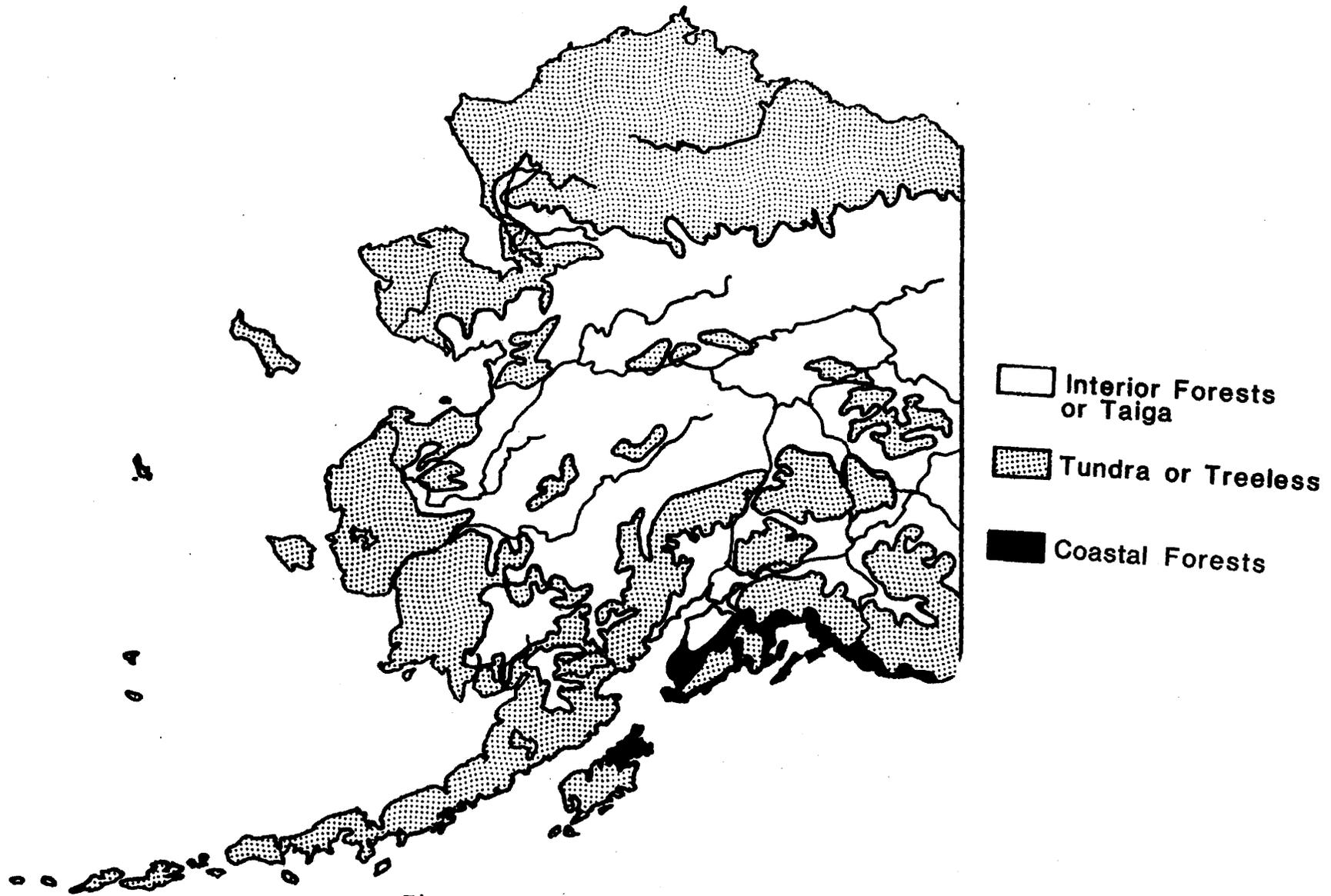


Fig. 3. Boundaries of the taiga, tundra, and coastal forests in Alaska.

successional stands of shrubs and balsam poplar that lead to them are some of the most productive in the taiga.

Although lodgepole pine (*Pinus contorta*) does not occur in Alaska, it is prevalent on dry sandy soils in the southern portion of the Yukon Territory and diminishes in importance to the west and north. In many areas lodgepole pine forms dense stands following fire.

Shrublands are common along most small watercourses and frequently form broad bands near treeline. These shrublands are composed primarily of alder (*Alnus crispa* and *A. tenuifolia*), willows (*Salix* spp.), and resin birch (*Betula glandulosa*).

Other treeless types occurring commonly in the taiga are grasslands on south-facing bluffs, and bogs, marshes, and aquatic types in low-lying wet areas. Alpine tundra occurs on the hills and mountains. (See section on tundra vegetation types, page 61.)

AUTECOLOGICAL RELATIONSHIPS in the TAIGA

The revegetation sequence following fire in the taiga can be understood by examining common species in the forests and their adaptations to frequent fires. Zasada (1971) and Zasada et al. (1979) in Alaska, Uggla (1958) in Scandinavia, and others have studied the autecology of a number of species after fire.

Black Spruce

Black spruce is not fire resistant and is usually killed by fire. It is adapted to fire, however, primarily through its semiserotinous cones. Cone and seed production in black spruce has been studied in the southern parts of the boreal forest and in northern areas of Canada (Black and Bliss 1978, Wein 1975b) and Alaska (Zasada 1971). These investigations indicate that black spruce may begin to produce cones as early as 10 to 15 years following fire, but usually does not attain optimum seed production until after 50 to 150 years. Seed matures in late summer, and some seed is dispersed throughout the year. Fifty percent or more of the viable seed remains in the cones 1 year after ripening, and about 15 percent remains after 5 years (Wilton 1963).

Wein found that after fire in northern Canada, the black spruce seed germination varied from 0 to 19 percent 6 years after a fire and from only 0 to 1 percent 20 years after a fire.

Seed dispersal patterns following fire in black spruce are not well known. Seedfall continued for at least 2 and 3/4 years following a fire in a 70-year-old black spruce stand in Alaska, but the quantity of seed was not significantly different from that which had fallen in

unburned stands for the same period (Zasada et al. 1979). In Newfoundland after a relatively hot fire, about half the black spruce seed fell during the first 60 days (Wilton 1963). Seed viability also dropped quickly, from about 60 percent immediately following the fire to about 20 percent in the spring of the following year. In Alaska Zasada et al. (1979) measured a real germination of 90 percent for an unburned black spruce stand, 65 percent for the year following a fire, and 32 percent for second-year seeds.

Establishment of seedlings usually occurs the first year after fire and continues for several years. In Canada, Wein (1978) found that 6 years after the Inuvik fire 22 percent of the established black spruce seedlings were 4 years of age, and 35 percent were 5 years of age. This indicates that the second and third summers following the fire were the greatest for seedling establishment.

In Alaska we found a general increase in seedling number through the first three summers following the 1971 Wickersham Dome fire (Viereck and Dyrness 1979). But during the first 3 years of seedling establishment where the fire had burned about one-third of the organic layer but did not expose mineral soil, only 0.2 to 1.8 percent of the seeds had produced seedlings (Zasada et al. 1979). The study illustrates the importance of a suitable seedbed for germination, in addition to an adequate seed source.

Black spruce also reproduces abundantly by layering of the lower branches. This adaptation may be important for persistence of clones of black spruce north of the present treeline and in increasing the density of spruce stands following fire. It does not seem to be important, however, as an adaptation to recovery following fire. The layered branches are usually buried in moss and are easily destroyed by fires. The layering habit may be important in the susceptibility of black spruce stands to crown fires, since layered branches form a continuous fuel source from the ground to the crowns of the trees, especially in more open stands. The layering habit, shallow roots, thin bark, and abundant lichens on the lower branches make the black spruce particularly susceptible to death from fire. Usually, only at the very edges of fires or where fires crept slowly through the moss mat have black spruce survived to leave a fire scar record. The persistence and abundance of black spruce in areas of high fire frequency are due primarily to its early production of abundant seed in semiserotinous cones.

White Spruce

Unlike black spruce, white spruce seems to have little adaptation to frequent fires. White spruce grows where fire frequencies may be lower, however. In flood plains, white spruce is usually found on islands or terraces close to the river where chance of burning is

slight, although some flood-plain white spruce stands have burned in Alaska.

In the uplands, white spruce tend to be in isolated clumps surrounded by hardwoods, which are also less subject to fire than are the more continuous stands of black spruce. Quirk and Sykes (1971) observed that in uplands white spruce stringers remained unburned while adjacent black spruce stands burned several times. They concluded that organic layer moisture was higher in the white spruce stands, making them less susceptible to fire.

Because white spruce seed matures and falls in one year, no old seed reserve is left in the trees, as it is in black spruce. In addition, the interval between good white spruce seed crops may be 10 to 12 years. Areas burned during a period of low seed production, therefore, would have difficulty regenerating to white spruce. In the taiga, most fires occur in June, before the white spruce seed is ripe. Even in good seed years, the main seed source would have to be outside the burned area or from surviving trees within the burned area. Seed dispersal distance for white spruce is about 2 tree heights at 45 to 60 m, so dispersal within a burn is limited.

Another autecological factor to be considered is that there may be a correlation between heavy fire years and increased white spruce seed crop the following year. The initiation of flower buds in white spruce can be correlated with a warm dry period in June and the first half of July (Zasada and Gregory 1969). These same conditions create high fire potential. Since 1957 in interior Alaska, 1958 and 1970 were the best seed years, whereas 1957 and 1969 were years of extensive fires which burned large areas.

Deciduous Trees

Birch and aspen are well adapted to fire and come back quickly after fire from vegetative reproduction and seed germination. Birch is a prolific seed producer and produces regularly as many as 728 million seeds per hectare (Zasada and Gregory 1972). The seeds are winged and can travel moderate distances in windy weather.

Aspen is well adapted to invade burns by seed, because it produces large quantities of light, tufted seed, which the wind can transport long distances. Because the seed is viable for only a short time, however, both seedbed and weather conditions must be ideal for stands to establish from seed following fire. Aspen stands reproduce mostly by vegetative means (Gregory and Haack 1965) and individual clumps of aspen tend to extend after fire. Following the Wickersham Dome fire, aspen produced nearly 200,000 root suckers per hectare.

Although birch reproduces by stump sprouts, and stands with several

stems originating from old stumps are common, many birch stands appear to be of seed origin.

Balsam poplar reproduces prolifically by root and branch suckers and stump shoots following logging (Zasada et al., in preparation). The effect of fire on balsam poplar is not described in the literature, however, even though balsam poplar is an occasional species in the uplands in the Alaskan taiga.

Shrubs

We have combined shrub species into general categories based on their fire-adaptive characteristics. All of the common shrubs in the black spruce type are capable of vegetative reproduction by underground rhizomes, stems, or roots. They can also reproduce from stump sprouts unless the organic layer has been destroyed. Since some of the underground parts remain after fire, revegetation can occur from these.

Available information on the relative depth of these underground parts indicates that some shrubs survive fires of different intensities better than others. Calmes and Zasada (1979) found that *Ledum groenlandicum* underground stems were at depths of 15 to 30 cm and that *Rosa acicularis* rhizomes were deeper, 20 to 30 cm. Flinn and Wein (1977) found that *Ledum groenlandicum* stems were 40 to 50 cm deep in the bogs of New Brunswick. *Vaccinium vitis-idaea* has abundant branched underground stems embedded at about 2 to 3 cm in the humus. Thus, they are able to survive light fires but are usually killed by moderate to heavy fires (Ugglå 1958). In *Vaccinium uliginosum*, *V. vitis-idaea*, and *Ledum groenlandicum*, initial sprouting following fire may be from the fire-pruned aerial stems. Sprouts from burned stems and rhizomes become evident later, usually the year following the fire.

The ability of different species to form sprouts from stumps after fire is varied. Tree birch seems to lose some of its sprouting ability with age, but old decadent willows produce sprouts prolifically immediately after fire. Alder is more susceptible to complete killing by fire than is willow, and its resprouting is less vigorous and prolific. No information is available on the stump sprouting ability of the shrub birch, *Betula glandulosa*.

When most of the organic material of the forest floor is destroyed by fire, shrubs must regenerate by seed. Shrubs may be divided into three groups according to the types of seed they produce. The small, extremely light-seeded species capable of reseeding over long distances are primarily *Salix*. Their seeds are usually viable only for short periods of time. Dispersal time varies with species, although generally there are spring- and fall-seeding willows (Zasada and Viereck 1975, Zasada and Densmore 1977). The degree to which these species invade after a fire depends on the time of year of the fire, weather, and

presence of a mineral seedbed. A wet period after seed dispersal allows for germination, but a dry period can cause enough seed viability loss to prevent germination. The chance of light-seeded species establishing years after fire lessens as the available mineral soil seedbed sites are occupied by the faster growing herbaceous species or mosses.

The second category of shrubs has thin-walled light seeds that are not well adapted for long-distance dispersal or resistance to heat and that do not maintain viability long. This group of seeds usually shows a nondeep or conditional dormancy, meaning the seeds germinate better following cold stratification (Calmes and Zasada 1979, Densmore and Zasada 1977). This mechanism insures the seed will not germinate during the fall.

Shrubs in this group include *Alnus* spp., *Vaccinium uliginosum*, and *V. vitis-idaea*. Their seeds are usually destroyed by fire and must be transported into the burned area. The most common sequence is for these species to reproduce by vegetative means in lightly burned areas and to produce large numbers of flowers and seeds later.

The third category of shrub species is those with thick-coated hard seeds that not only are fire resistant but may be stimulated by fire (Cushwa et al. 1968). Some of the shrub species in this category are *Viburnum edule*, *Rosa acicularis*, and *Rubus idaeus*. Their seeds usually show a dormancy pattern that requires a warm period followed by a cold period before germination takes place (Densmore and Zasada 1977, Densmore 1979).

Herbs

Herb species have many of the same fire-adaptive reproduction mechanisms as shrubs. In the black spruce type in northern areas, the two most common herb species following fire are fireweed (*Epilobium angustifolium*) and bluejoint (*Calamagrostis canadensis*).

Fireweed has light seeds and can easily invade heavily burned areas. It may persist into later stages of succession and revegetate lightly burned areas through the spread of rhizomes. Moss (1936) studied the vegetative reproduction of the species and thought that rhizomes are usually only 2 to 4 cm deep in the soil (Uggla 1958). Therefore, they are destroyed by fires of moderate to heavy intensity. Observations in Alaska indicate that fireweed seedling invasion of burned areas is far more important than vegetative reproduction by rhizomes. Foote (1976) has shown that fireweed usually does not persist into the mature black spruce stands. This also accounts for the lack of vegetative reproduction following fire. Fireweed spreads rapidly, however, through the growth of underground rhizomes from mineral soil into areas where the organic layer prohibits seedling establishment.

Bluejoint, on the other hand, usually occurs in mature black spruce stages and produces many rhizomes after light to moderate burning. It is also a prolific seed producer, although the spread by rhizomes appears most important except in areas burned to mineral soil.

Horsetails (*Equisetum sylvaticum* and *E. arvense*) are widespread herb species in the black spruce type. Their underground rhizomes are deep, usually in mineral soil, allowing them to reinvade burned areas. They may become the most abundant herbaceous species after fire. Because horsetail is found throughout the successional sequence to mature black spruce stands, it is available for revegetation following fire in any stage of succession (Foote 1976).

Only two herbaceous species seem to have long-lived seeds that are stimulated to germinate by fire: *Geranium bicknellii* and *Corydalis sempivirens*. *Corydalis* has been observed as an early invader of burned areas throughout much of the boreal forest (Rowe and Scotter 1973, Heinselman 1973, Ahlgren 1966a, Scotter 1964, Viereck and Dyrness 1979), but germination characteristics and requirements of its seed have not been tested.

Mosses and Lichens

Mosses and lichens are important in the successional sequences following fire in the taiga. Several studies (Scotter 1964, Black and Bliss 1978, Maikawa and Kershaw 1976) show that cryptogams follow a more typical succession pattern than do vascular plants. They seem to have an orderly sequence of species after fire.

The pioneer mosses and liverworts may be divided into two types; those that persist through the fire and those that reinvade by spores. Species of *Polytrichum* have deep rhizoids that are usually in mineral soil. They, like *Equisetum*, are able to survive all but the most severe fires and are able to come back by vegetative means after fire. The other group of species, primarily *Marchantia polymorpha*, *Ceratodon purpureus*, and *Pohlia nutans*, reinvade mineral soil surfaces from spores.

The feathermosses, primarily *Hylocomium splendens* and *Pleurozium schreberi*, are extremely important in the black spruce succession following fire. Although small patches may survive fire, it is not until a spruce canopy is established that the feathermosses spread and become the dominant mosses. Tamm (1964) has shown the importance of shade and tree canopy for the development of *Hylocomium* in the Swedish forest. Black spruce also seems to need shade for its revegetation sequence. On mesic sites, these two feathermoss species may make up as much as 75 to 80 percent of the forest floor cover in mature black spruce stands. In dryer and more open sites, moss cover is less and lichen cover greater.

The mats and clumps of sphagnum mosses within the black spruce stands usually do not completely burn, even under extremely dry conditions because of the mosses' high moisture content. Although sphagnum is usually killed by fire, moist clumps of dead moss remain for several years and are good sites for shrub establishment.

The invasion and succession of lichens in the dry open lichen woodlands in central and northern Canada is well documented (Kershaw et al. 1975, Maikawa and Kershaw 1976, Scotter 1964). Much less is known of the ecology of the lichen species invading burned areas on mesic black spruce sites.

The first lichen to become established may be the short-lived *Icmadophila ericetorum*¹, which grows on dead sphagnum clumps. Foliose lichens in the genus *Peltigera* often become established on the moss mat within 5 years. As early as 10 to 15 years after fire, the cup lichens or horn lichens and *Cetraria* spp. and *Cladonia* spp. may invade (Black and Bliss 1978, Scotter 1964, Ahti 1959). As conditions in the stand change with canopy establishment and closure and the development of a moss mat, the lichen species change. Mature stands become dominated by the reindeer lichens, *Cladina alpestris*, *C. rangiferina*, and *C. arbuscula*.

The autecology of individual lichen species and the actual mechanisms of establishment and growth have not been adequately studied. It is assumed that the lichens reinvade by fragments that are blown into the burned areas, but this has not been documented.

EFFECTS of SEVERITY of FIRE on TAIGA VEGETATION

In Alaska one important factor that may determine successional sequence after fire is the amount of organic material in the forest floor removed by fire. In order to quantify this effect, we have used five forest floor fire severity classes (Vioreck et al. 1979).

Severity of a wildfire is difficult to determine after a few years. Consequently, severity isn't taken into account when revegetation sequence after fire is discussed. Depth of burn obviously is important, especially in an ecosystem where much revegetation is from buried plant parts. A heavy burn that removes most of the organic layer usually

¹ Lichen names in this report follow Hale and Culberson (1970), *A Fourth Checklist of the Lichens of the Continental United States and Canada*. These authors separate the commonly called "reindeer lichens" into the genus *Cladina*. They also use *Cladina arbuscula* for the formerly named *Cladonia sylvatica*.

kills the underground parts of most if not all of the shrubs. Because *Equisetum* rhizomes and *Polytrichum* rhizoids go into the mineral soil, they may be the only species to survive on these sites. The mineral soil is an ideal seedbed, however, for most species that come into the burn by seed. Mineral soil areas may become quickly covered with *Marchantia*, *Ceratodon*, and *Epilobium*. Mineral soil sites also are best for black spruce seed germination.

On the other hand, a light burn that kills only the aboveground plant parts and chars and kills the moss layer leaves the underground plant parts of the shrubs and many herbs intact. Revegetation is rapid from rhizomes and root and stump sprouts. This type of burn encourages the proliferation of shrubs that reproduce from underground rhizomes, such as the *Vaccinium* and *Ledum* species.

Buried seeds that persist in the organic layers or mineral soil of unburned stands are regeneration sources. Amounts of seed vary considerably among vegetation types (Moore and Wein 1977) and locations. Although E. A. Johnson (1975) found no viable seeds in mature black spruce sites at Great Slave Lake, Northwest Territories, near the northern treeline, Moore and Wein (1977) reported 370 seeds per m² in black spruce stands in New Brunswick and Archibold (1979) reported 426 seedlings per m² in a white spruce-birch-aspen stand in northern Saskatchewan. Johnson (1975) showed that buried seed populations generally decrease in a northward direction under unburned forests.

Depth of burn is important in determining the numbers of seeds that may germinate. Moore and Wein (1977) found that 81 percent of the viable seeds in the spruce type were in the upper cm of the organic layer and 95 percent were found in the upper 4 cm of the organic layer. Thus, although a severe burn on the forest floor may produce a good seedbed, it also may destroy some or all of the seed stored in the forest floor.

The longevity of buried hard-coated seeds is not known, but many seem to persist in the soil and organic layers for decades. As mentioned previously, many of these seeds also are known to be fire resistant and the seed of some species is stimulated by fire.

The importance of buried seeds to revegetation following fire in Alaska vegetation types has not been investigated.

REVEGETATION after FIRE

In the TAIGA

The successional sequence after fire in the taiga is complex. (See Fig. 4.) It is related to a number of variables, which include the

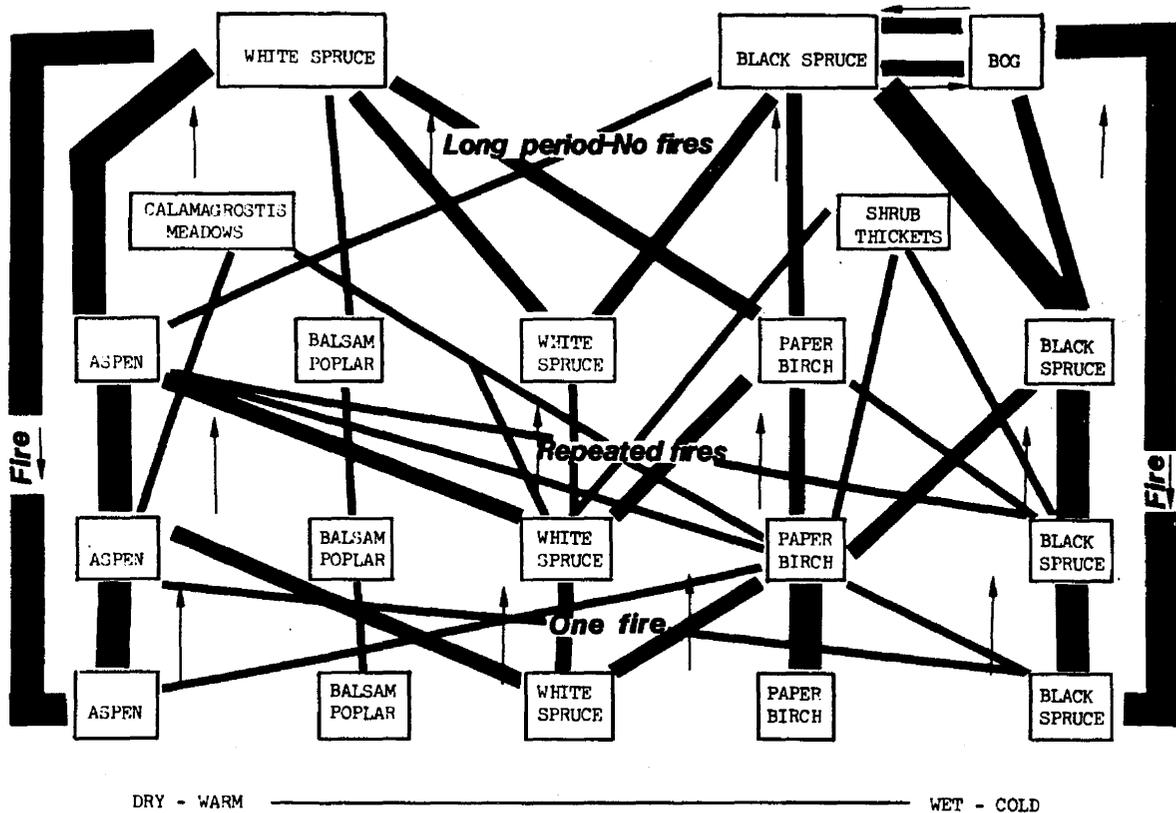


Fig. 4. Patterns of forest succession following fire in Alaska.

preburn vegetation type and age, climate, fire severity, time of burn, parent material, presence and absence of permafrost, and the weather. No single general sequence of vegetation follows fire in the spruce type throughout Canada and Alaska. Large differences occur among revegetation sequences in revegetation rates and the species involved.

Figure 4 shows some of the many paths of revegetation that have been observed following fire in interior Alaska. The original preburn forest type is shown on the bottom row of boxes. The thickness of the line is related to how commonly each of the revegetation sequences occurs. Thus, black spruce is usually replaced directly by other stands of black spruce but occasionally is replaced by aspen or birch. Aspen stands, usually on warm dry sites, are most often replaced by other aspen stands but occasionally are revegetated by birch or a grass meadow after fire. Eventually, with a long period without fire, the aspen stands are invaded by white spruce or occasionally black spruce. The climax vegetation on well-drained sites is white spruce and on cold wet sites black spruce, often with an alternating bog cycle.

In spite of this variability, three patterns of succession following fire have been described from Alaska and northern Canada. The first

occurs on the productive, mesic sites, dominated by mature white spruce stands. The second successional sequence occurs on wet, poorly drained, permafrost sites, dominated by black spruce. The third successional sequence, on open lichen woodlands, has been described extensively from areas in Canada but not from Alaska, even though the mature vegetation type occurs in Alaska. This type is found on some peatlands, but is most common on well-drained glacial deposits and near treeline in northern Canada. It is usually dominated by black spruce, but also occasionally by white spruce.

White Spruce/Feathermoss Type

On dry upland sites, primarily south-facing slopes, the mature forest vegetation is white spruce, paper birch, aspen, or some combination of these species. The deciduous tree species represent successional stages of revegetation developing after fire (Fig. 5). Occasionally, if a seed source is available and seedbed conditions are ideal, white spruce invades within a year or two after the fire, and even-aged stands develop without the intervening hardwoods.

Foote (1979) recognized these seven distinct stages in revegetation after fire:

1. Newly burned
This stage lasts a few weeks to a year.
2. Herb-tree seedling stage
One to 5 years after the fire, fast-growing mosses and herbs and tree seedlings are established.
3. Shrub (willow) and tree sapling stage
In this stage, 6 to 25 years after fire, the willow shrubs and tree saplings dominate the stands and form a nearly continuous canopy, which begins to shade out the herbaceous and moss layer.
4. Dense hardwood stage
Birch and aspen form a dense canopy that tends to shade out much of the understory that has developed since the fire.
5. Mature hardwood stage
Aspen stands mature at about 80 years. Birch stands then gradually open through natural thinning.
6. Mature birch and white spruce
At 100 years and more, the successional sequence reaches a stage in which mature white spruce stands, often with a component of old birch trees, are dominant.

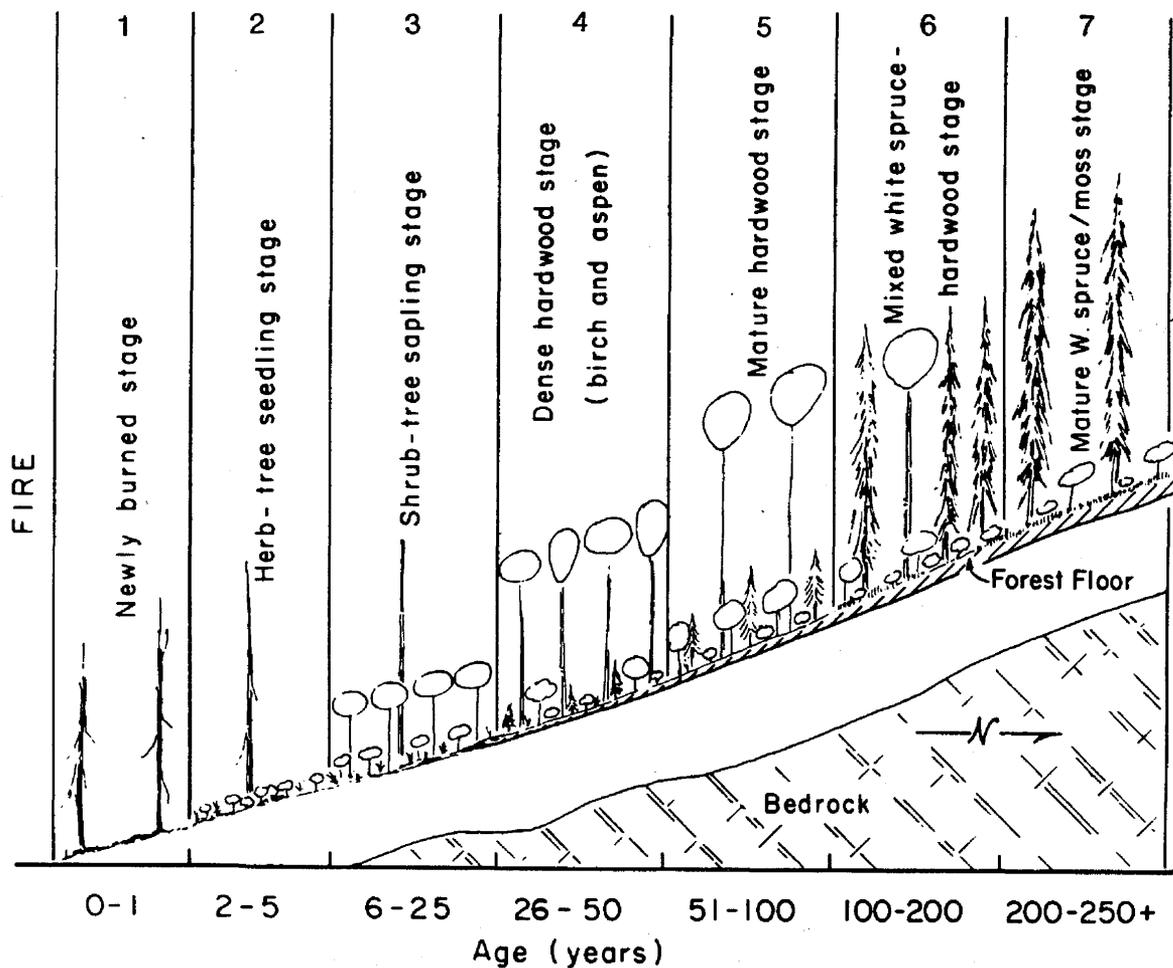


Fig. 5. Stages in succession following fire on upland white spruce sites in interior Alaska.

7. White spruce/moss
The mature stands are composed of white spruce with thick moss mats on the forest floor.

Lutz (1955) and Foote (1976) consider the white spruce stands to be the climax vegetation of these sites, the end point in the succession following fire on well-drained upland sites. It has been suggested, however, that some old upland white spruce stands may be replaced by black spruce and bog or a treeless moss/lichen association (Wilde and Krause 1960, Strang 1973b).

On the flood plains of Alaska, evidence is substantial that older white spruce stands are replaced by black spruce as permafrost develops under the accumulating moss and organic layers (Drury 1956, Viereck 1970).

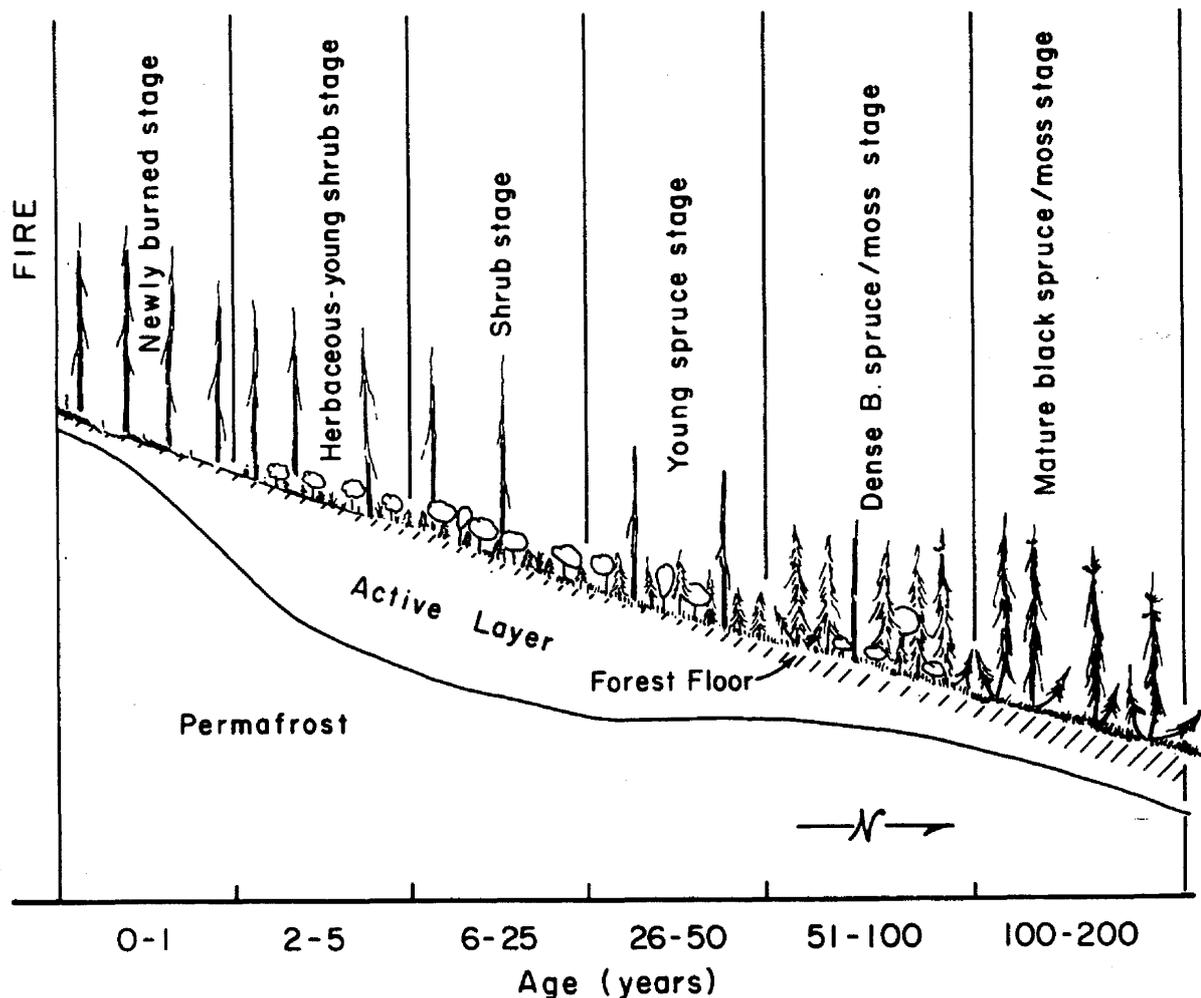


Fig. 6. Stages in succession following fire on permafrost black spruce sites in interior Alaska.

Black Spruce/Feathermoss Type

In Alaska and adjacent Canada, black spruce stands are widespread on wet, poorly drained sites and in uplands and lowlands underlain by permafrost. The black spruce type is widespread over most of the area. It is also the type with the highest fire frequency. Therefore, it has received the most attention in fire effects and revegetation studies.

In Alaska we followed revegetation after the 1971 Wickersham Dome fire (Vioreck and Dyrness 1979). We compared revegetation on a number of known-age burns in interior Alaska (Foote 1976) and on some permanent vegetation plots established after the 1950 Porcupine River fire (Foote 1974). A series of experimental, controlled fires, where prefire

vegetation was recorded and fire intensity was monitored during the burning, has also been utilized to determine revegetation sequences (Vioreck et al. 1979).

Foote (1979) has described, as follows, six stages in the revegetation sequence for black spruce in interior Alaska on mesic sites that support mature closed to open black spruce/feathermoss communities. The stages are illustrated in Fig. 6.

1. Newly burned
Lasts from a few weeks to a year. At this stage the forest floor is dominated by charred mosses and mineral ash. If the burn is light to moderate, sucker shoots of shrubs, *Calamagrostis*, and *Polytrichum* may appear.
2. Herbaceous-young shrub stage
Lasts from 1 to 4 years and is the time of species establishment. Bare mineral soil areas are covered with *Marchantia*, *Ceratodon purpureus*, *Polytrichum commune*, *Epilobium angustifolium*, tree seedlings, etc. Sprouting species, primarily *Calamagrostis canadensis*, *Rubus chamaemorus*, and *Equisetum silvaticum*, become abundant.
3. Shrub stage
The shrubs dominate the vegetation. Toward the end of this stage, the shrub canopy closes, leaf litter becomes abundant, herb and moss cover increases, and the first lichens, usually the foliose lichens *Peltigera canina* and *P. apthosa*, become established. This stage usually occurs from 6 to 25 years after fire.
4. Young black spruce
This stage occurs 26 to 50 years after fire. Stands are usually dense. Toward the end of this stage, the spruce canopy becomes closed and the shrubs reduced in cover.
5. Dense black spruce - *Pleurozium* stage
The stage occurs 51 to 100 years after the fire. Black spruce, low shrubs, and *Pleurozium schreberi* dominate.
6. Mature black spruce/feathermoss stage
This is the final stage in the sequence of postfire succession. Black spruce trees, saplings, and seedlings dominate the stand.

The last three stages are dominated by trees. The tall shrub layer of willows and alders begins to thin out, but the low shrub layer continues to expand and increase in cover. The invasion and rapid development of feathermosses occurs, and a thick organic layer develops. This layer ties up the available nutrients, creates colder soil temperatures, and results in the return of a shallow active layer on many

sites. Another significant invasion is that of the fruticose lichens, the *Cladonia* and *Cladina* species, and additional foliose lichens such as *Nephroma acticum*, which together may make up at least 20 percent cover.

Once the tree canopy is well established, the changes in the vegetation sequence are slower and more subtle. During the older stages, the tree canopy is mostly closed, although the stem density is smaller, averaging 2,200 stems per hectare. The moss layer remains about the same as in the younger tree stage, except that *Hylocomium splendens* increases and both fruticose and foliose lichen decline in cover. Because of the high fire frequency in interior Alaska and the well-developed fuels in these black spruce stands, a fire is most likely to occur during this stage of vegetation sequence.

If fire does not occur, the development of the black spruce type into a mature stand follows without any major changes. Tree densities stay about the same, 1,700/hectare for black spruce. A few paper birch may persist into the mature stage. The spruce tend to grow in clumps produced by layered branches, and there are more openings in the canopy than in earlier stages. Because of this, the shrub layers, especially the low shrub layer, are better developed than they are during the 60- to 90-year period when the canopy is more closed. The moss cover in the mature stands is dense and covers nearly 75 percent of the forest floor, but the lichen cover continues to decline on these mesic sites so that total lichen cover of both foliose and fruticose lichens averages only 2 percent.

It is difficult to speculate on what would happen in this sequence if fire did not occur for 200 years or more. Drury (1956) and Viereck (1970) have described a situation in wet lowland sites where the black spruce are replaced by bog and a cycle of bog and forest. In the mesic upland sites, there seems to be only a minor thinning of spruce with age and ample layerings are ready to replace dying trees. In the sequence described by Foote (1976), sphagnum mosses do not show a definite trend, although they increase from 2 percent cover in the 69- to 90-year stage to 5 percent cover in the mature stands.

Paludification, the creation of wet boggy conditions through the development and spread of sphagnum mosses, could result in more open stands and bogs on the colder and wetter sites. Foote's work gives no evidence that white spruce will replace black spruce, even on mesic upland sites, as suggested by Lutz (1955) who states, "In these situations [well-drained uplands] it [black spruce] must be regarded as a temporary fire type which will, in the course of time, give way to white spruce." Lutz felt that on wet sites, black spruce represents a physiographic climax, "...an essentially stable, self-perpetuating community, reproducing itself by both seedling growth and layering." (Lutz 1955).

Black and Bliss (1978) describe a similar sequence for black spruce near treeline in the uplands adjacent to the Mackenzie River in Northwest Territories. Although most of the species involved are similar to those found in Alaska, there are some conspicuous differences related to the more northern latitude and the adjacent tundra. The somewhat longer fire rotation allowed these authors to report on stands 300 years old. They described four stages in the revegetation sequence:

Stage 1, which occurs from 1 to 20 years following the fire, is similar to Stages 1 to 3 of Foote (1979) for Alaska. The second stage is similar to the last three stages described from Alaska. The oldest stage in the succession contains stands that were 200 to 300 years old. These were found only in isolated pockets that escaped fire. The general increase in lichens with age continues, with *Cladina* species still dominant. The density of black spruce increases in these older stands, due to reproduction by layering. Density reaches as much as 8,000 stems per hectare in 275-year-old stands. There is no evidence that the sequence would eventually change into more open or treeless stands.

In contrast, Strang (1973b) found lower tree densities in the older stands, with many dead and dying trees and little reproduction. Strang's sites were in the same general areas as those of Black and Bliss but in all of the stands he studied, *Picea glauca* either was an important component or was the only tree species in the stand. It is possible that Strang was observing a successional sequence similar to those Drury (1956) described for the Kuskokwim River in Alaska, where spruce stands became more open with time.

A number of other studies have been made of the open black spruce stands in the vicinity of the Mackenzie River in the Northwest Territories. The 1968 Inuvik fire and adjacent burned and unburned stands have received considerable attention, especially by Wein. Wein (1975b) followed revegetation of the Inuvik fire in some detail for the first 6 years after the fire. He compared it with an adjacent shrub-dominated 20-year-old fire site. Although he reported only generally on revegetation, he noted that in the early years after the fire, the black spruce stands seem to follow the general pattern described by Black and Bliss (1978).

Black Spruce/Lichen Woodland

The open black spruce lichen type has been studied throughout the northern areas of Canada, where it is widespread. Little attention has been given to it in Alaska, however, where it is less widely distributed. This type is important as winter range for caribou. Thus, several of the succession studies in the black spruce-lichen woodland were part of larger studies of caribou range and populations (Scotter 1964; Bergerud 1971, 1974; Hustich 1951; Ahti and Hepburn 1967). Johnson and Rowe

(1975) and Maikawa and Kershaw (1976) have studied this type in the central part of the Canadian Shield, in the region southeast of Great Slave Lake, and in the Caribou Hills in central Northwest Territories.

The first stage of revegetation, which lasts from 1 to 20 years is dominated by the pioneer mosses, such as *Ceratodon purpureus*, *Polytrichum juniperinum* Hedw., *P. piliferum* Hedw., and *Marchantia polymorpha*. Crustose lichens, primarily *Lecidea* spp., may cover as much as 20 percent of the ground in this stage. In some areas a number of vascular plants, especially *Epilobium angustifolium*, *Calamagrostis canadensis*, and several other grasses and sedges, also are important.

The second stage, which occurs commonly from 10 to 60 years following a fire, is characterized by the invasion and dominance of fruticose lichens. Of these, several *Cladonia* species are the most prominent. Ahti (1959) and Bergerud (1971) both describe this stage as the "horn lichen stage" because of the dominance of *Cladonia crispata* (Ach.) Flat and other closely related species. On some sites, feather-mosses may become established and spread during this period. There is also a development of low ericaceous shrubs, especially *Vaccinium vitis-idaea* and *Ledum groenlandicum*. An open tree canopy is established during this stage.

Older lichen stands, ranging around 100 years of age, generally shift to species that are dominated by *Cladonia alpestris* (L.) Harm. and *C. rangiferina* (L.) Harm. In the Drumlin area of the Northwest Territories, Maikawa and Kershaw (1976) report an exception to this pattern, in which stands 60 to 130 years of age are dominated by *Stereocaulon paschale* (L.) Hoffm. In some sites during this stage, tree cover density increases, resulting also in an increase in the cover of the feathermosses *Hylocomium splendens* and *Pleurozium schreberi*. On other sites the lichen mat persists under an open spruce canopy.

Relationship of Black Spruce and other Vegetation Types

We have discussed the most common situation--the direct replacement of a black spruce stand by another stand with similar species. There are many examples, however, where other tree species are involved in the black spruce succession. Viereck (1973b) diagrammed these relationships for Alaska and Canada. (See Fig. 4, page 48.)

The invasion of black spruce burns by birch and aspen is more common in the southern parts of the boreal forest than it is in the northern. This is due primarily to the decrease in abundance of birch and aspen in the more northern areas. From northern Saskatchewan, Scotter (1964) reported that dense stands of *Betula papyrifera* may come

in after fires in the black spruce type but eventually are replaced by black spruce. Reports from farther north in the Mackenzie area, Black and Bliss (1978) for example, mention *Betula papyrifera* only as an occasional component of the black spruce types.

Little is known about the conditions required for the conversion of forest type from black spruce to hardwood after fire. Lutz (1955) and Viereck (1973b) suggest that such a conversion may result from either intense fires, which destroy the black spruce cones in the treetops and at the same time provide a good mineral soil surface for germination of the hardwood species, or it may result because fire in the black spruce type reoccurs before the spruce has been able to produce a cone crop.

Of special interest in Alaska are stands of aspen with understories of black spruce. Aspen usually occurs on dry warm slopes in interior Alaska and is replaced in time with white spruce. On old river terraces, usually underlain by coarse river alluvium, however, aspen stands sometimes are found with understories of black spruce. We speculate that in these cases, a severe fire removed the organic layer completely and allowed aspen to seed in at the same time as the black spruce. The coarse river alluvium and the lack of an organic layer provide a temporary, warm, well-drained site for the aspen. Aspen, being relatively short lived, is eventually replaced by the spruce and the associated moss and organic layer, and the site reverts to a cold wet condition.

The relationship between *Picea glauca* and *Picea mariana* also is interesting. Drury (1956) and Viereck (1970) have described a situation in Alaska where alluvial white spruce stands are replaced by black spruce on the older river terraces because of the formation and rise of the permafrost table associated with the buildup of the insulating organic layer. On the other hand, Lutz (1955) and Scotter (1964) have suggested that on some mesic upland sites, white spruce should be considered the climax species that, without fire, would replace black spruce. Viereck (1970) has suggested that even in the upland sites, the black spruce may replace white spruce on sites that are underlain by permafrost. It is possible that on some sites, white spruce may replace black spruce, while on wetter and colder sites, the opposite may occur. The difficulty in resolving this uncertainty relates to the high fire frequency in most northern areas and the scarcity of examples of the later stages of succession.

EFFECTS of FIRE

On TAIGA ECOSYSTEM COMPONENTS and PROCESSES

We need to think of fire as an ecosystem process rather than as an effect on particular organisms or plant and animal communities. Wright and Heinzelman (1973) suggest that there are a number of general prin-

principles that relate to fire effects in the conifer ecosystems. Vitousek and Reiners (1975) and Odum (1969) have discussed the changes in ecosystem components and processes that occur during succession.

Some scientists have attempted to look at ecosystem processes relating to the black spruce ecosystem. The subject is discussed in the studies of the 1968 Inuvik fire by Wein and others, the studies of the 1971 Wickersham Dome fire by scientists at the Institute of Northern Forestry (Viereck and Dyrness 1979), the detailed studies of the lichen-dominated ecosystem by Kershaw and Rouse (1976) and their colleagues (Kershaw et al. 1975), and by Rencz and Auclair (1978) in eastern Canada.

Figure 7 shows some hypothesized changes in five critical variables in a black spruce ecosystem following fire. This figure was developed as part of a study of the black spruce ecosystem in Alaska (Zasada et al. 1977). The five variables are as follows:

1. Overstory/biomass and living forest floor.
2. Dead and decaying forest floor biomass.
3. Available nutrient pool of nitrogen and phosphorus.
4. Soil temperature.
5. Soil moisture.

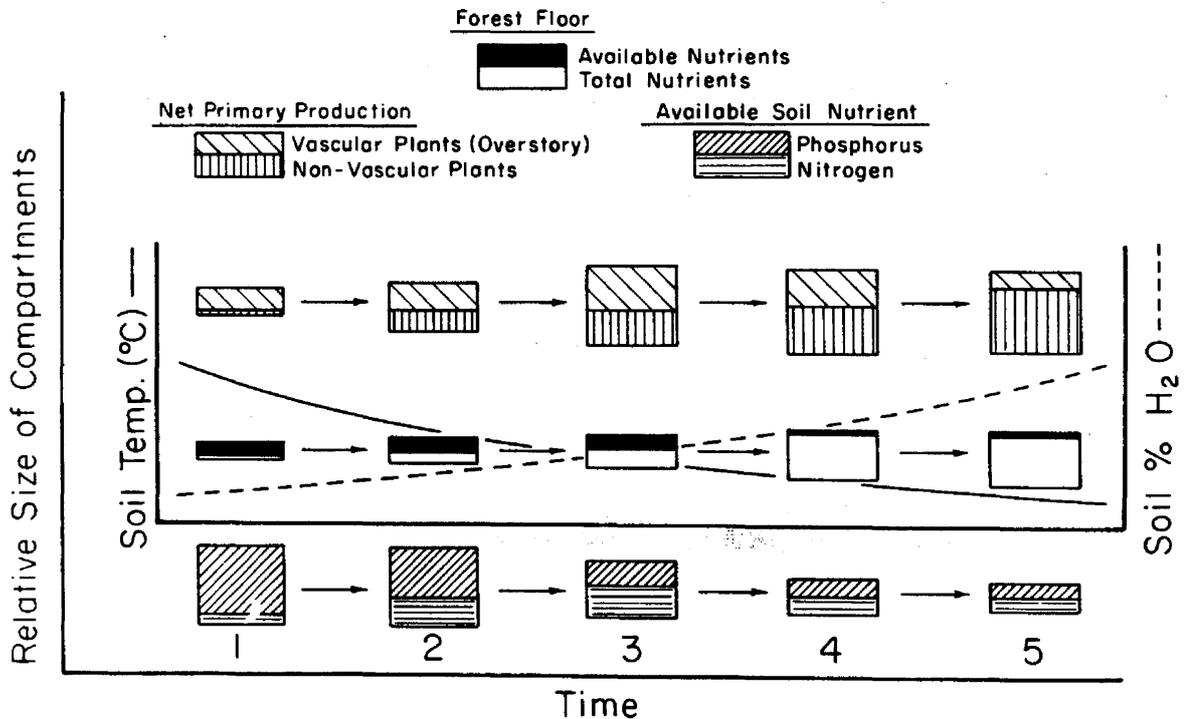


Fig. 7. Hypothetical successional changes in a burned black spruce stand being revegetated by more black spruce (from Zasada et al. 1977).

The time axis of Fig. 7 represents the stages of succession through the mature black spruce/feathermoss forest to a more open black spruce/sphagnum type, a span of about 300 years.

Just prior to a fire in the black spruce type, which would most usually occur during the third or fourth stage shown in Fig. 7, the overstory and forest floor biomasses are high, but the available nutrient pool is relatively low because most of the available nutrients are tied up in the surface organic layers and overstory. Decomposition is slow--about 2 percent of the organic matter in the forest decays each year (Van Cleve et al. 1979). Soil temperatures during the growing season are low, about 3 to 6 °C at 10 cm (Viereck and Dyrness 1979). Permafrost is as close as 30 cm below the surface and the active layer of annual thawing is entirely within the organic layer. Because of the impervious permafrost, the continued slow melt of ice in the active layer during the summer, and the high water-holding capacity of the mosses and organic layer, the amount of moisture is high throughout the summer at depths of 10 cm and deeper. In the organic layer, the amount of moisture by weight remains well above 100 percent.

Following fire, all of these components are changed drastically. The overstory biomass is greatly reduced by the fire, although standing dead may persist for up to 60 years. The biggest effect is in the forest floor, which is partially or completely removed by fire. Burning of forest floor material immediately releases large quantities of available nutrients (Grier 1975, Stark 1977). For example, the quantities of available phosphorus are greatly increased. As much as 50 times the mass of phosphorus before the fire was available following an experimental burn in a 70-year-old black spruce stand in Alaska (Viereck et al. 1979). Nitrogen, on the other hand, may be volatilized by fire, and quantities of available nitrogen may be reduced from those before the fire.

Soil temperatures become warmer and the permafrost layer recedes after fire because of several factors. These include removal of the overstory, change in albedo, thinning of the organic layer, and death of the moss layer. Viereck and Dyrness (1979) showed that summer soil temperatures were, in general, 5 to 6 °C warmer in the soil at depths of from 10 to 50 cm the summer following the 1971 Wickersham Dome fire than they were in an unburned 70-year-old black spruce control plot. Kershaw and Rouse (1976) have shown a similar increase in soil temperature following fire in the black spruce/lichen woodland in central Canada. They found that the increase in surface soil temperatures could still be shown 25 years following the fire.

One of the most significant changes brought about by the increase in soil temperature after fire is a thickening of the active layer. The depth of thaw may be two to three times greater following fire than it was before the burn. Seven years following a fire in the black spruce type in Alaska, the depth of thaw had increased from 40 cm in the

unburned stand to 140 cm in the burned area (Viereck and Dyrness 1979). Similar thaw has been shown for the Inuvik fire in Canada (Mackay 1977). This increased thawing trend lasts for 10 to 15 years. It is followed by a gradual return to the preburn depth after about 50 years, when the insulating effect of the feathermoss mat has been completely reestablished (Viereck 1973b).

For the first few years following fire, the nutrient turnover is rapid and productivity is high. With more nutrients available, herbs and shrubs grow rapidly (Ahlgren 1960, Stark and Steele 1977). The pioneering bryophytes, especially *Marchantia*, and the herbs, *Epilobium angustifolium* and *Calamagrostis canadensis*, take up the available nutrients immediately following the fire and recycle them quickly through their dead and decaying plant parts. Productivity is high because of the warmer soil and the increased nutrients. These species, which have high relative nutrient requirements and rapid growth rates, have an advantage over other species in the early stages of succession but compete less successfully in the nutrient-poor later successional stages. Decomposition rates also are relatively high during this period.

Few data are available to compare the productivity of burned and unburned black spruce stands in Alaska and northern Canada. Wolff and Zasada (1979) found that 3 to 7 years after a fire, the amount of willow browse available to moose increased from 6.5 to 44.1 kg/ha, while in adjacent unburned stands, the available browse was less than 10 kg/ha. This study took into account only *Salix* spp. available to moose but gave an indication of the increased productivity of the shrub layer following fire.

Total biomass accumulations for the first 4 years following the Wickersham Dome fire in Alaska were approximately 160 g/m², giving an average annual accumulation of 40 g/m². Wein (1975b) showed biomass accumulations 5 years following the Inuvik fire, of approximately 200 g/m², for an average annual accumulation of 40 g/m². No comparable figures are available for a mature black spruce ecosystem. But from biomass measurements in a 130-year-old black spruce stand, the annual foliage production has been estimated to be 24 g/m², while the total annual aboveground tree production was 168 g/m² and the productivity of the moss layer in the same stand has been shown to be 125 g/m² or about five times that of the tree foliage production (Van Cleve et al. 1979). In young recently burned stands, most of the productivity is in the herb and shrub species; in mature stands, most of the productivity is in the tree and moss layers.

As time passes following fire, the biomass and productivity of the mosses and lichens increase faster than those of the vascular plants. This is especially true once the feathermosses become widespread. As mentioned above, on a unit area basis the productivity in the moss layer may be nearly as great as that of the tree layer.

Forest floor biomass increases greatly once the tree canopy is established and the feathermosses are abundant. Equilibrium may be reached between decomposition and accumulation in the forest floor in some sites; but on most of the cooler, moister sites, the forest floor continues to thicken and accumulate material. The criterion for a climax ecosystem--that net increment of biomass should equal zero--is not attained (Vitousek and Reiners 1975). As the forest floor thickens, it accumulates nutrients that are no longer available in the ecosystem nutrient pool. The mature black spruce ecosystem is considered to be a nutrient-poor system that holds tightly to its nutrients. One indication of this is that black spruce may retain their needles for up to 25 years (Van Cleve et al. 1979).

In addition to acting as a nutrient sink, the thickening forest floor acts as an increasingly efficient insulating layer. Soil temperatures become lower as the moss layer thickens and shade from the tree and shrub canopy increases. Soil moisture also increases as the permafrost rises and the water-retaining organic layer develops. These conditions all contribute to developing the typical less productive, nutrient poor, black spruce ecosystem that has a thick organic layer closely underlain by permafrost. At this point, or earlier in the successional sequence, the forest usually burns, returning nutrients to the available form and once again increasing the site productivity. Thus, fire in this type of ecosystem returns the site to a more productive condition and partially substitutes for the reduced decomposition rate.

In long absence of fire, it is hypothesized (Fig. 7) that the forest floor would continue to thicken, further tying up nutrients. Moss and lichen productivity would continue to increase compared with that of the tree overstory, and the overstory would become more open and less productive. Soil temperatures would continue to decrease and soil moisture increase, creating conditions that encourage the development of the sphagnum mosses over the feathermosses. This condition could eventually result in paludification of the site and the development of treeless bogs. Fire is thus an essential ecosystem process that maintains the permafrost-dominated black spruce/feathermoss ecosystem. The black spruce ecosystem supports the concept of Vitousek and Reiners (1975) that most forest ecosystems change in patches of various sizes. This change is controlled by intrinsic factors of the ecosystem or by extrinsic factors of the environment. In the black spruce ecosystem, fire serves to recycle the vegetation before it reaches the steady-state climax condition.

* * *

The Tundra

The tundra vegetation types occur in Alaska westward and northward of treeline and altitudinally above the treeline. By definition they occur beyond the limit of tree growth. In Alaska tundra occupies 740,000 square kilometers or approximately 50 percent of the area of the State. (See Fig. 3, page 39.)

The many variations in tundra vegetation patterns are related in part to differences in topography, slope, aspect, and substrate.

In Alaska until recently, three main subdivisions of tundra had been recognized and mapped (JF-SLUPC 1973, Viereck and Little 1972). These are: wet tundra, 9 percent; moist tundra, 17 percent; and alpine tundra, 23 percent. But in this report we follow the preliminary classification of Viereck and Dyrness (1980), which breaks the tundra into five main classes: 1. sedge and grass tundra (mostly the wet tundra); 2. tussock tundra (the moist tundra); 3. mat or cushion tundra (primarily mat and cushion tundra); 4. herbaceous tundra; and 5. shrub tundra.

REVEGETATION after FIRE in the TUNDRA

Interest in fire effects in tundra vegetation has developed relatively recently. As a consequence, little information is available from Alaska and much of it is short term, from studies of the 1977 fires. In Alaska information on fire effects comes primarily from a man-caused fire in a study site in alpine tussock tundra on the Elliott Highway and from recent studies of the Seward Peninsula fires and the Kokolik fire of 1977.

In Canada information on the effects of fire on tundra has come from the Inuvik fire of 1968, which burned in a treeline area where tundra was interspersed with forested areas. It is often difficult to separate data obtained in tundra sites from data from forested sites.

In general, it can be said that tundra fires are extremely variable, that tundra vegetation is seldom completely destroyed by fire, and that recovery is usually rapid and by vegetative means. The most important effects seem to be an increase in the active layer and increased flowering of many of the species, especially the sedge tussocks. In most cases, all signs of the fire have disappeared by 6 to 8 years. In areas with abundant lichen cover, however, recovery may take much longer. Shacklette et al. (1969) found an area on Amchitka Island, Alaska, that had burned 20 years earlier. It still contrasted conspicuously with adjacent unburned areas because of the lack of *Cladonia* lichens and the slow recovery of *Empetrum* in the burned area.

Most of the studies of tundra revegetation following fire include only one or two years of data and contain little information about the severity of the fire. Wein and Bliss (1973) discussed revegetation 1 and 2 years following fires on four sites, two of which are cottongrass tussock and two, black spruce woodland with tussocks. Rapid resprouting occurred, so that productivity in the burned stands was nearly equal to that of the unburned stands after only 2 years. Most revegetation occurred by vegetative means by species that were previously on the site. Wein and Bliss report, however, invasion by one moss (*Polytrichum juniperinum*), a liverwort (*Marchantia polymorpha*), and abundant seedlings of the sedge tussock *Eriophorum vaginatum*. The only other seedlings reported were very low densities of bluejoint (*Calamagrostis canadensis*). The flowering of the sedge increased significantly compared with that on unburned areas. Some of the mosses and lichens and the crowberry (*Empetrum nigrum*) showed no recovery. Labrador tea (*Ledum groenlandicum*) recovered fastest of all the shrubs.

Johnson (Hall et al. 1978) visited the Kokolik area just one month after the fire and found that all the aboveground shrub parts had been killed and none had resprouted at the end of August. By contrast, most of the sedge tussocks in the burned area showed some regrowth from shoots, and sedges showed considerable regrowth in the lightly burned, wetter, low-lying areas. Shrubs sprouted from underground roots and stems the following year.

Racine (1979) found great variation in the recovery of vegetation one year after the Seward Peninsula fires of 1977. The vegetation on the sedge-tussock tundra showed the fastest recovery rate, with 20 to 25 percent cover, which contrasted with only 4 to 7 percent cover on both the dryer and wetter sites. He found that the developing vegetation resulted from sprouting of sedges and dwarf shrubs, seed germination of grasses and sedges, and colonization of liverworts and mosses. Sedge tussocks and cloudberry (*Rubus chamaemorus*) were the most prolific resprouters, whereas the sedge tussock and bluejoint produced the most seedlings. Where the organic mat was burned to mineral soil, a number of forb seedlings were found, including fireweed (*Epilobium angustifolium*), Jacob's ladder (*Polemonium boreale*), and other "weedy" species.

BIOMASS and PRODUCTIVITY

Biomass accumulation and productivity data following tundra fires are available from two studies. Wein and Bliss (1973) found that productivity in the burned tussock site on the Elliott Highway was 45.0 g/m²/yr the first year following fire. For a similar site and vegetation type in the Caribou Hills, Canada, Wein and Bliss (1973) found 33.0 g/m²/yr productivity 2 years following a fire. In comparison, unburned tundra in the same areas produced 88.3 and 36.5 g/m²/yr respectively. Wein (1975b) reported on the biomass accumulation in

tundra and forest types 5 years after the Inuvik fire. He presented no data, but his graph indicates accumulations in 5 years of about 200 g/m². His interesting conclusion was that biomass accumulation was "remarkably uniform" from the 10 forest, shrub, and tundra communities sampled.

The TREELINE and FIRE

A special term that should be mentioned is "pyrogenic tundra." Kryuchkov (1968) first reported that fires at the northern limits of trees in Siberia may result in the permanent displacement of treeline to the south. He termed the tundra that results from these fires "pyrogenic tundra." He felt that the cause of the treeline displacement was that a heavy vegetation cover following the fires actually reduced the depth of annual thaw, resulting in colder soils and increased soil moisture to the level that trees could no longer grow on the sites.

The same type of phenomenon has been observed in Canada (Black and Bliss 1978, Larsen 1965, and Ritchie and Hare 1971). The retreat of treeline in Canada is generally thought to be the result of climatic deterioration, but fire also has been important.

Nichols (1976) found that periods of extensive fires destroyed trees over large areas at treeline and that trees were unable to reinvade the tundralike vegetation that formed after the fires. Bryson et al. (1965) showed that the forests in Keewatin, Canada, failed to regenerate after fires 3,500 and 900 years ago. The treeline retreated as much as 280 kilometers.

In some areas of northern Canada, black spruce clones, reproducing by layering of the lower branches, are able to maintain themselves vegetatively for hundreds of years far north of the present continuous treeline.

In western Alaska and on the south slopes of the Brooks Range, fire occurs frequently in treeline areas. No studies have been conducted in Alaska, however, that indicate whether or not fires have been important in determining the location of treeline. Whereas fire might be instrumental in restricting treeline by killing trees at their limits, tundra fires near the treeline might provide a favorable seedbed for tree seeds and aid in the expansion of treeline during favorable climatic periods (Viereck 1979).

* * *

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EFFECTS of FIRE on ANIMAL LIFE

Caribou and Reindeer

AN UNRESOLVED PROBLEM

No subject related to fire effects is more controversial than that of the effects of fire on caribou range and caribou populations. The problem was thoroughly reviewed recently for Canada and Alaska by Kelsall et al. (1977) and by Davis et al. (1978). The latter paper is most thorough in its review of the Alaska situation, and especially for the Fortymile caribou herd in eastern Alaska.

In this review we have attempted to summarize the above two reviews and to point out gaps in knowledge on fire-caribou interactions. As with any review of a controversial subject, this review will not produce any new information nor will it resolve the controversies. This can only be done with additional research in each of the geographic areas being considered. As pointed out by Kelsall et al. (1977) there has been a comprehensive and continuous research program on caribou since 1947, and yet many questions remain unresolved. We know the following facts:

1. Caribou numbers have declined drastically in Canada and in Alaska.
2. Fire destroys lichens in the forest floor and those growing on trees.
3. Recovery of lichens is slow following fire.
4. Caribou select out and feed on lichens during critical winter months.

5. Fire frequency is high and is thought to have increased in the 1900s in the northern parts of the taiga where caribou spend the winter months.

Most early observers concluded that the increased fire, caused by man's movement into northern forests and development there, was the prime reason for the caribou declines. This was a widely held and published opinion of many scientists up through the 1960s. One can find the idea repeated in many publications dating even into the 1970s (Loughery and Kelsall 1970, Scotter 1971b, Pruitt 1978).

In a series of papers since the late 1960s, the point of view has been presented that fire has not been responsible for the decline of caribou herds in most areas of Alaska and Canada and that in fact, a certain level of fire frequency may be necessary for optimum development of the lichen-rich winter ranges of the caribou (Bergerud 1971, 1974; Davis et al. 1978; Johnson and Rowe 1975; Maikawa and Kershaw 1976; Miller 1976a and b). In addition, some scientists have questioned the degree to which caribou are dependent on lichens for survival (Skoog 1968, Davis et al. 1978). In Canada investigators disagree as to whether or not there has actually been an increase in fire frequency on caribou winter range that could have resulted in the decline of the caribou herds (Scotter 1964, Johnson and Rowe 1975).

FIRE and LICHENS

An important aspect of the general problem of the effect of fire on caribou populations is that of the interrelationship of fire and lichens. Several studies, in particular those of Palmer (1941), Palmer and Rouse (1945), and Scotter (1964), have shown that the fruticose lichens, especially those of the genus *Cladina*¹ (or subgenus *Cladina* of the genus *Cladonia*), are very susceptible to fire and that their recovery is extremely slow. These *Cladina* species, especially *C. rangiferina*, *C. arbuscula*, and *C. alpestris*, have been found to be the lichens caribou prefer (Ahti and Hepburn 1967).

The time required for lichens to recover from fire appears to vary widely. Davis et al. (1978) illustrated this in a table showing the lichen type, type of habitat, regeneration time, and source. Interestingly, those who reported that fire is important in limiting caribou populations (Scotter 1964, 1971b; Lutz 1955; Palmer and Rouse 1945) also

¹ Lichen names in this report follow Hale and Culberson (1970), *A Fourth Checklist of the Lichens of the Continental United States and Canada*. These authors separate the commonly called "reindeer lichens" into the genus *Cladina*. They also use *Cladina arbuscula* for the formerly named *Cladonia sylvatica*.

report the longest time for lichen recovery, 50 to more than 100 years; whereas those who conclude that fire is not the causal factor in caribou decline (Miller 1976b; Bergerud 1971, 1974) report shorter times for lichen recovery--15 to 40 years. One must realize that the recovery rate may be related to climate, severity of fire, and original vegetation type, and thus all reported figures may be accurate. As an example, Skuncke (1969) reported no recovery of *Cladina alpestris* 140 years following a severe wildfire in Sweden, but good lichen recovery only 20 years after a light, controlled burn. The slow recovery rates reported by Palmer were from the Seward Peninsula of Alaska, while the rapid rates reported by Bergerud (1971, 1974) were from the open lichen woodlands of Newfoundland, where the climate is warmer than in Alaska.

In relatively recent times, Pegau (1968, 1970, 1972, 1973) studied lichen recovery rates following fire and disturbance in Alaska. In some cases he used old enclosures and plots established by Palmer. In the Nelchina area, he found that *Cladina arbuscula* and *C. rangiferina* usually recovered within 30 to 40 years.

Fire does not appear to destroy lichen ranges under all conditions. Some studies have indicated that fire may increase lichen cover, especi-

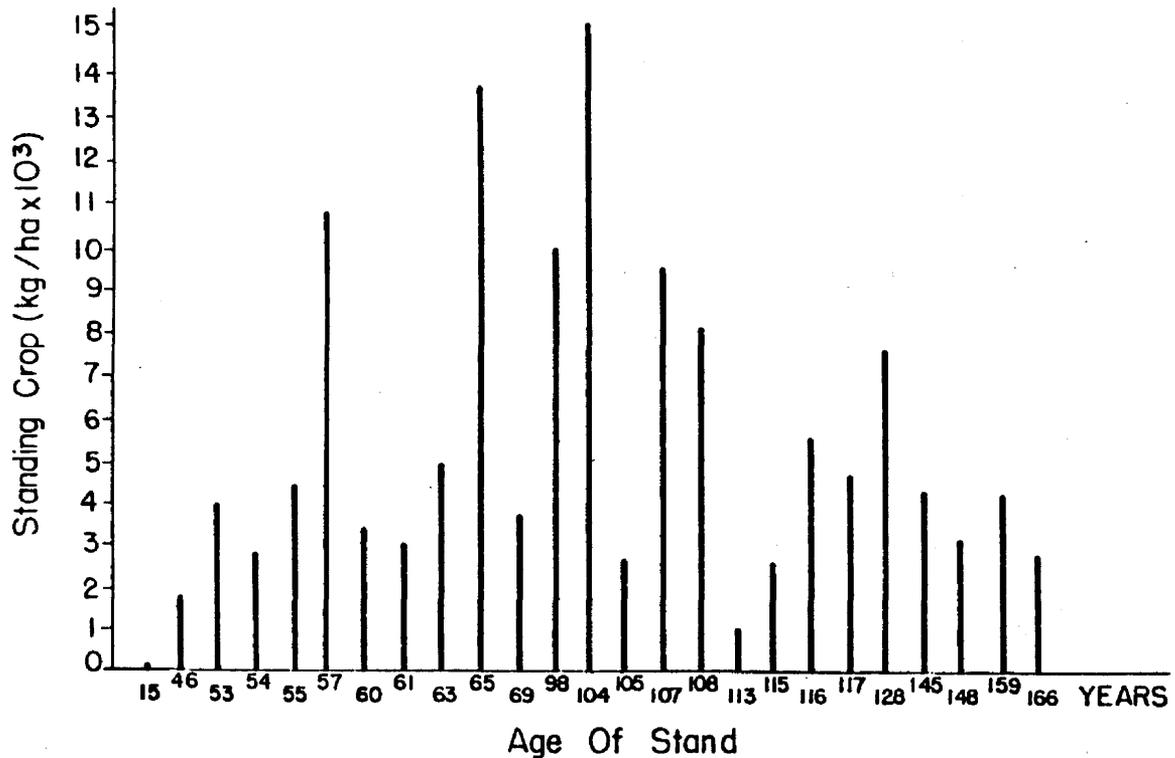


Fig. 8. Comparison of stand age with standing crop of lichens in sites used by caribou in Manitoba and Saskatchewan during 1972 and 1973 (from Miller 1976b).

ally where thick carpets of mosses have developed. Miller (1976b) and Kershaw et al. (1975) pointed out that in many middle-aged spruce stands in Canada, lichen quantities reach a maximum in from 60 to 120 years and decrease in older stands (Fig. 8). Miller showed that lichen biomass reached a maximum of 10,000 to 15,000 kg/ha in spruce stands of from 50 to 120 years old and decreased in older stands to 3,000 to 5,000 kg/ha. Bergerud (1971) concluded that forest fires in Newfoundland increased the extent of caribou winter range by altering closed canopy forests to open lichen woodlands or shrub barrens. These studies indicate that at least infrequent fire is necessary to maintain optimum lichen cover.

Some authors (Ahti and Hepburn 1967) recommended that prescribed burning be used to increase lichen cover and improve caribou range, especially in sphagnum peatlands, treeless bogs, and wooded muskegs in Newfoundland. Light burning has been suggested as a method to improve reindeer range in Scandinavia (Skuncke 1969). Miller (1976b) concluded that fire improved caribou range by increasing heterogeneity, which favored the growth of some lichen species that grow in early successional stages.

CARIBOU and LICHENS

Another question related to the fire-caribou problem is, How dependent are caribou on lichens for winter range? Biologists disagree as to whether lichens are essential in the diet of the caribou or whether caribou select lichens because they are available in winter. Kryuchkov (1978) and Klein (1974) have described a population of reindeer living where there was little lichen cover (1 to 3 percent). In experiments, the reindeer seemed to thrive on a diet with low lichen content. Kryuchkov believes that this population has developed the capability to live on lichen-low diets as the lichen cover was gradually reduced through overgrazing. Both Skoog (1968) for Alaska and Bergerud (1971, 1974) for Newfoundland conclude that caribou do not require lichens for survival during the winter, although both authors show that caribou utilize lichens heavily when they are available.

OTHER CONSIDERATIONS

Fires may affect caribou in ways other than reducing the lichen cover of winter range. Banfield (1954) suggested that caribou avoid recent burns because of the difficulty of moving through downed trees. Pruitt (1959) suggested that snow is compacted in burns and caribou avoid the burns for this reason. On the other hand, vegetation greens up earlier in burned areas and for a few years following fire may be richer in nutrients. Reindeer on the Seward Peninsula utilize recently burned areas in the fall and early spring. Bergerud (1974) has suggested that large burns allow "buffer species" of prey to increase. This

in turn encourages predator increase that ultimately affects the caribou populations.

Scientists seem generally to agree that fire has always been a part of the taiga environment, and therefore, that caribou have been able to maintain their populations despite widespread fires. There also seems to be general agreement that the caribou populations in both Alaska and Canada have declined since the early 1900s. Skoog (1968), however, pointed out that the decline has not been steady and that in Alaska there is evidence that population highs occurred in the 1860s and 1920s and lows in the 1890s and 1940s. These low population periods do not seem to coincide with periods of reported increase in fire frequency in Alaska. In addition, as pointed out by Davis et al. (1978), in the Nelchina caribou herd range, major fires that occurred in the 1940s were followed by an expanded caribou population through the 1960s.

Bergerud (1974) examined the decline of the North American caribou populations in the 1900s and presented four possible hypotheses:

1. Caribou numbers decreased because of a lichen shortage, caused by increased fire and logging.
2. The numbers decreased because of increased hunting by human beings, augmented by increased wolf predation.
3. The decline was due to a combination of 1 and 2.
4. The decline was due to movement of caribou to marginal areas.

Bergerud concluded that the main cause of the decline of the herds was as stated in hypothesis number 2, the increased hunting by human beings. He could find no evidence of inadequate winter range for the existing caribou herds in Canada.

CARIBOU and FIRE in ALASKA

For Alaska, Davis et al. (1978), using results of their own studies and those of a thorough earlier study by Skoog (1968), reviewed the population history of each of the major caribou herds in Alaska and the fire history of each herd's range. They point out the difficulty of obtaining a historical perspective because fire records were inadequate before the 1940s and few estimates of caribou numbers were documented. On a statewide basis, they found, data were insufficient to support more than the generalization that the population fluctuations do not seem to correlate with the periods of suspected higher fire frequency during the gold mining and early development era.

Davis et al. (1978) attempted to summarize the effects of fires on

each of six regions that contain one or more caribou herds. Most of their information is from Skoog (1968), with recent information on the caribou populations from their own studies. We have summarized their conclusions as follows:

Region I. Southwest Alaska and the Alaska Peninsula

The Alaska Peninsula herd has not been affected by fire because of the low fire frequency in the area. The population may have been isolated from the other caribou herds by large fires that occurred in 1935 in the Kvichak River and Lake Iliamna areas.

Region II. Western Alaska with the McKinley, Mulchatna, Beaver, and Kuskokwim Mountains herds

Skoog (1968) pointed out that fires have been widespread in the winter range of these areas. He felt that the potential utilization of the area had been severely restricted because of fire damage to winter ranges. He felt, however, that the lichen and sedge stands along the Alaska Range were more than adequate to support the existing caribou populations. Davis et al. (1978) concluded that there is no obvious correlation between recent reduced numbers of caribou in the area and the incidence of fires. The 1977 Bear Creek fire, which covered more than 154,000 hectares on the north side of the Alaska Range, occurred where caribou had wintered in the past.

Region III. Northwest Alaska - Western Arctic herd

Skoog (1968) stated that fire had not been important in the area except in the southeastern quadrant. Davis et al. (1978) stated that although the caribou herd in the area "...declined dramatically between 1970 and 1976... to date it does not appear that wildfires played a significant role in that decline."

Region IV. Northeast Alaska - Porcupine herd

This area has had the highest fire frequency of any of the regions. Davis et al. (1978) state, "Concurrent with extensive burning in the late 1930s and early 1940s, large emigrations occurred either east into Northwest Territories or west into the Western Arctic (Region III). The correlation is apparent, but a causal relationship can probably never be established." [The area continues to have a high fire frequency, with a natural fire cycle for the forested area of 49 years (Yarie 1979).]

Region V. Eastcentral Alaska - the Fortymile herd

Davis et al. (1978) conducted a detailed analysis of the effects of fire on the Fortymile herd. They examined the potential herd-carrying

capacity of the various vegetation types within the area and looked in detail at the fire history and the population estimates over the past years. They used the most conservative estimates in their considerations of range potential and caribou numbers. Biomass figures from Pegau's (1972) work in the Nelchina area were used to calculate that the carrying capacity of the Fortymile range exceeded 500,000 caribou in 1956.

Their conclusions are that although fires have been extensive in the area and that nearly 1.5 million acres of lichen habitat were destroyed between 1956 and 1976, the fires were not extensive enough to cause the great decline that has occurred within the herd. During that 20-year period, the caribou numbers never approached the maximum in carrying capacity of the range. The authors calculated that the carrying capacity of the area and the magnitude of the population here decline (from 30,000 to 15,000 head between 1967 and 1970) exceeded the total calculated carrying capacity decreases from 1955 to 1976. They conclude that, "...the population decline of the Fortymile herd has not been the result of habitat destruction, and that the limiting factor at present is not range."

Ahti and Hepburn (1967) had concluded that present lichen ranges in northern Ontario could support six times as many caribou as were presently occupying the range.

Region VI. Southcentral Alaska - Nelchina, Mentasta, and Kenai herds

The Nelchina area has been subject to widespread fires since before the white man arrived (Skoog 1968). Skoog felt, however, that there was adequate winter range for the existing herd, especially in the alpine areas not subject to extensive fires. Pegau (1972), however, disagreed with Skoog, and felt that the range was badly deteriorated by too many animals. Davis et al. (1978) point out that there is no obvious correlation between fires and caribou abundance in the Nelchina area. They state, "...most major fires occurred during the 1940s,...yet during the late 1940s through 1960s the population expanded considerably."

Davis et al. (1978) reviewed the history of fire and caribou herds on the Kenai Peninsula in detail because it has been used by many authors as an example of where widespread fires resulted in the complete annihilation of a caribou herd. Skoog (1968) and Davis et al. (1978), however, point out that the Kenai Peninsula is marginal as caribou range and that it was an "overflow" area during times of high caribou populations in other areas. They state that the caribou disappearance from the Kenai in the early 1900s may have been only partially or not at all related to the widespread fires of the 1880s and 1890s. Davis et al. (1978) conclude that, "It is likely that factors other than wildfire were responsible for the decline of Kenai caribou during the early twentieth century."

From exhaustive review of the fire-caribou situation in Alaska, Davis et al. (1978) conclude the following:

The evidence from caribou populations in Alaska and Canada suggests that fire has not been the major limiting factor to most caribou populations including the Fortymile herd, and that the proper evaluation of its role in caribou declines must be analyzed on a case-by-case basis. The textbook ecology conclusion that fire has been the cause of widespread North American caribou declines in the twentieth century does not seem tenable. It can be argued that fires can temporarily reduce the absolute abundance of forage available, but in most instances it does not appear that the amount of forage available at any given time is low enough to be considered the limiting factor for most caribou herds.

Our own conclusions are that the evidence is not conclusive as to the degree of effect, if any, that widespread wildfires in Alaska and adjacent Canada have had on the caribou populations. The caribou is a difficult animal to study because of its wide ranging, migratory habits, its reliance on different areas and vegetation types at different times of the year, and its relative isolation. There seems to be no disagreement that fire has burned over large areas of winter range in the past 80 years. Most investigators would agree that this process has been continuing for centuries without serious detriment to the caribou herds. An increase in fire frequency has occurred in many areas with modern development and at the same time, caribou numbers have decreased. But that fire is the cause has not been proved. Other aspects of increased development, such as increased hunting, disruption of migration routes by roads and pipelines, control and lack of control of predators, may be as important or more important than the effects of fire.

Lastly, it should be pointed out that to generalize and extrapolate from one area to another or from one herd to another is unwise. Kelsall et al. (1977) have noted that two of the studies that showed no correlation between fire and caribou populations (Bergerud 1971, 1974; Miller 1976b) were carried out in areas of low fire frequency, whereas those of Scotter (1963, 1964, 1967, 1971b) and Kelsall (1968), which concluded that fire was responsible for reducing caribou numbers, were carried out in areas of higher fire frequencies. The studies in Alaska by Skoog (1968) and Davis et al. (1978) also have shown that different factors may be affecting different caribou herds. Some herds are found in areas with high fire frequencies, and others in areas with low fire frequencies. Some herds have increased despite extensive fires, while others have declined during periods of extensive fires.

* * *

REINDEER and FIRE

Most of the information on caribou and fire applies also to reindeer, with one significant difference. Caribou are able to change migration patterns or move into unburned areas following extensive wildfires and return to a burned area whenever the vegetation has recovered. Reindeer, however, are usually restricted to certain areas by herd ownership patterns and range allotments. Summer range that has burned recovers rapidly and may, in fact, provide more biomass and nutritious forage and for a longer time in the summer than before the area was burned. However, if extensive winter range within any one herd allotment is burned, reindeer could have difficulty obtaining enough food to maintain themselves through the winter.

As with the caribou, the problems revolve around recovery rates of lichens and whether or not lichens are essential to the animal's diet. As mentioned in the caribou discussion, Klein (1974) cites the case of the Hargrin reindeer in Siberia, which thrive where few lichens are available. Under controlled conditions, these reindeer did better and used less lichen range than did the control reindeer group.

In 1977 extensive fires in western Alaska burned large amounts of reindeer range on the Seward Peninsula. These burned areas are an ideal site for study of the effects of fire on reindeer summer and winter range. They should also offer opportunities to study herding problems related to fires within given range allotment areas.

GAPS in KNOWLEDGE

On FIRE-CARIBOU INTERACTIONS

Although considerable research has been done on caribou in Alaska, we have relatively little detailed information on range conditions and effects of fire on caribou and reindeer range.

Klein and White (1978) state that the extensive 1977 fire sites in western and northwestern Alaska should be used for general studies on long- and short-term effects of fires on summer range for reindeer and caribou. They also discuss the need for detailed studies of the effects of fire in the spruce/lichen wintering areas of the caribou in all parts of Alaska.

Nothing is known of optimum fire frequencies for various types of caribou and reindeer range. Nor can one determine from available information whether an area has been burned too much in the past or whether fire may be needed to improve range conditions.

Fire history maps and vegetation maps are needed for critical habitat in Alaska. LANDSAT and aerial photographs have been used to

demark both recent fire areas (LaPerriere 1976a,b; Shilts 1975; Hall et al. 1978) and caribou ranges (Nodler et al. 1978, LaPerriere 1976a). These types of studies should be continuing so that at any time, we can determine the percentage of any given area that has been burned, over any given time span.

Information is needed for each of the major caribou ranges in Alaska on the recovery rate time of lichens following fire and the age of stands with maximum biomass and growth of lichens.

Some of the information determined for one area will be useful in other areas of caribou range, but as noted previously, each range unit may have peculiar conditions or different fire frequencies and recovery rates. Verification studies will be needed from region to region, even within Alaska.

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Moose

MOOSE POPULATION CHANGES and FIRE

Moose occur throughout the taiga and adjacent tundra areas of Alaska and have long been residents of interior and southcentral Alaska (Lutz 1960). It is generally recognized that moose browse is more abundant in successional stands than in mature forest types, and that moose populations have increased in many areas of Alaska and northern Canada following wildfire. There are, however, some examples where extensive wildfires have not been followed by moose population expansion.

A number of studies have linked moose population increases to fires in Alaska. Probably the best known is that of the population increases following the 116,000 hectare Kenai fire in 1947 (Spencer and Chatelain 1953, Peterson 1955). The estimated number of moose in the burned area increased from 0.24 moose per km² in 1950 to 1.0 moose per km² in 1953 (calculated from number reported for the total area). Twenty-four years after the fire the moose population had increased to 10.6 moose per km² (Bailey 1978).

Moose population increases following fire have been reported from other areas of Alaska. Buckley (1958) reported a general increase in moose in Alaska following an increase in wildfire during the first half of the twentieth century. He stated that it was highly unlikely that moose had ever been more abundant in Alaska than they were during the 1950s. Chatelain (1954) related moose abundance in the Kenai, Susitna, and upper Copper River areas to previous extensive fires there. Coady (1973) reported an increase in moose browse and moose following a 1957 fire on the Tanana Flats, south of Fairbanks, Alaska. Increases of moose populations following fire have also been documented for northern Canada (Scotter 1964, 1971a) and Minnesota (Peek 1974).

LeResche et al. (1974) considered one additional variable to be important; the period of time the browse remains abundant in the height range between snow level and within reach of moose.

The importance of browse during the critical winter period has been shown in a study by Sigman (1979), who found that in winter, moose moved into a part of the 1947 Kenai burn that was being crushed. The moose fed on the bark of the felled aspen and used snow packed by crushing equipment to travel on.

More available moose browse is produced after wildfire than was present in the original stand before it burned. Although some investigators have described postburn browse quantities and the length of time browse is available, no one has compared this information with data on preburn conditions or related it to fire severity.

These two factors have much to do with the quality and quantity of browse produced (Fig. 9).

Some general information is available on the length of time that browse is available to moose following fire. Scotter (1964, 1971a), using moose pellet group counts, found that moose utilized burned areas from 1 to 50 years following a fire. In the Kenai area, Spencer and Hakala (1964) found that optimum browse occurred between 5 and 20 years, but that occasionally browse was available for 60 to 70 years. Observations of exclosures in some areas of high moose population on the Kenai Peninsula indicate that moose may be able to prolong the browse period by keeping the willows and aspen from growing above their reach. An example is the 1959 Kenai Lake burn, where LeResche et al. (1974) reported that succession has been retarded by moose browsing the shrubs and hardwoods to the snow level annually. They stated that generally, however, moose are unable to alter the rate of postburn succession. The quantity and quality of browse may be reduced if the moose overutilize it and destroy some favored forage species. Overutilization also may eventually deplete plant and soil reserves and result in a decline in productivity (Wolff 1978, Menke 1973).

Wolff and Zasada (1979) examined moose browse following fires in the Fairbanks area. They found that aspen regenerate maximum browse quality in burned stands faster than do other species. Aspen suckers become available the first year following the fire and produce large quantities of browse for up to 10 years. After that, most of the browse is tall and out of reach of the moose. These investigators found that no browse was available to moose in aspen stands that were 35 and 70 years of age.

Willow and birch develop from sprouts following fire. Their growth is somewhat slower than that of aspen, and they reach maximum browse production at 11 to 16 years following fire, declining markedly after 20 years. If the fire is intense enough to prevent regeneration from root and stump sprouts, regeneration must be from seed. Browse availability may be delayed by about 5 years due to the slower development of seedlings (Fig. 9).

In general wildfires are followed by increased available moose browse that usually lasts from 20 to 25 years. Some fires, however, do not produce significant increases in moose browse. The increases are undoubtedly related to the prefire vegetation and the severity of the fire. A fire that is severe enough to remove the entire organic layer may kill the underground parts of browse species but may provide good conditions for regeneration by seed. A less severe fire, on the other hand, may result in increased sprouting if the original browse species are not totally destroyed. A light to moderate fire in a stand that does not have a complement of browse species may result in little to no increase in browse.

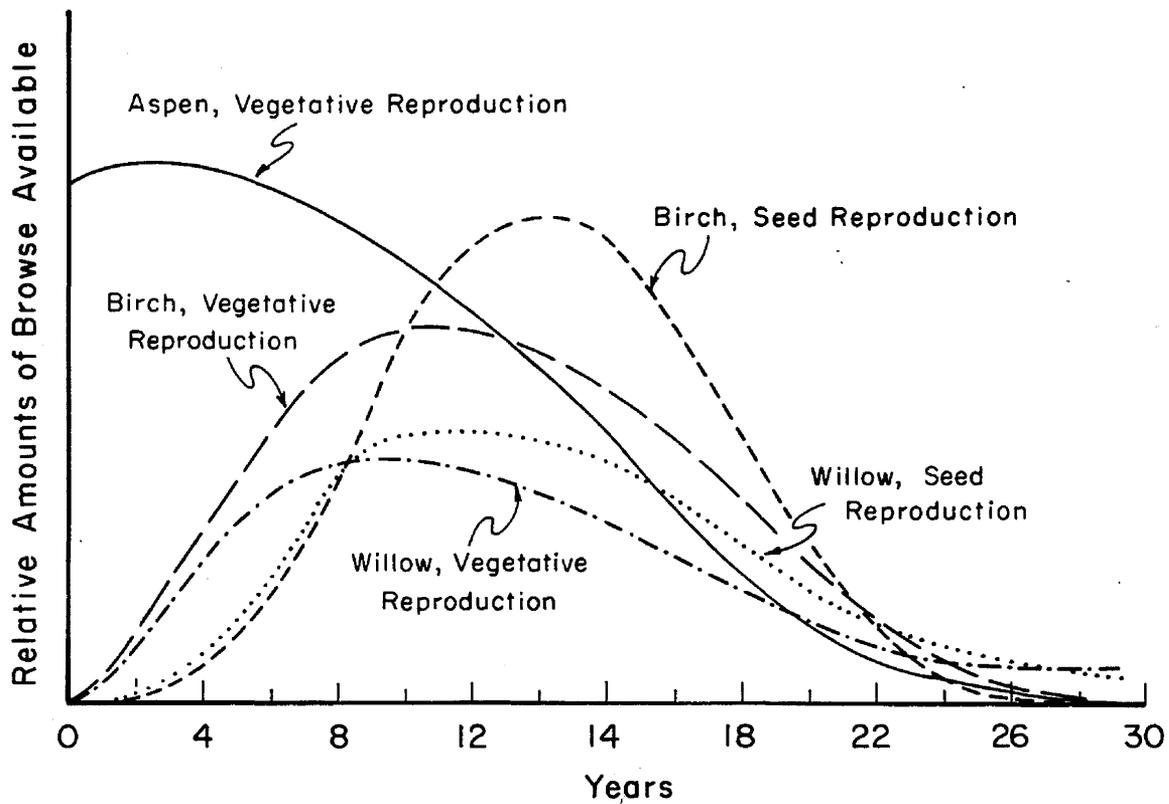


Fig. 9. Relative amounts of moose browse available compared with the time since fire or other disturbance in interior Alaska (from Wolff and Zasada 1979).

In addition to the amount of browse produced, cover, traditional use of the area, and availability of moose in adjacent areas, other factors undoubtedly are important in determining moose utilization of burned areas.

GAPS In KNOWLEDGE

On FIRE-MOOSE INTERACTIONS

Intensive research on moose has been conducted in Alaska over the past 25 years because of the animal's importance as a big game species. Studies of moose food habits and browse in the 1947 and 1969 Kenai Peninsula burns have been conducted in moose pens on the Kenai National Moose Range and in other parts of the Kenai Peninsula. In addition, investigations of browse improvement through experimental burning and crushing have been made. The only results published are by Sigman (1979), who reported on use of felled and crushed trees by moose at the time of crushing. Some moose range research has also been carried on in

the Interior, on the Tanana River. There is a lack of information on a number of problems related to fire and moose. Information gaps in the following subjects became apparent during this review:

1. The quantity and quality of browse following fire, including identification of the original vegetation type, interval between fires, and differences in fire severity. The prescribed fire and experimental fire programs on the Chugach National Forest, the Kenai National Moose Range, and the Washington Creek fire ecology site should be utilized heavily for obtaining this information.

2. The whole problem of "traditional use of areas," the dynamics of burn invasion by moose, the optimum size of burns, and the optimum number of unburned islands left within burns.

3. The effects of moose on the developing vegetation. Is there an optimum browse utilization? This implies that a moose population can use the browse and prolong the time that browse is available.

4. The possible competition between moose and snowshoe hares, and how hare cycles interact with fire frequencies and moose populations.

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Furbearers

It has been suggested that wildfire destroys the habitat of furbearers, causing a decline in their numbers in Alaska (Robinson 1952, Sumner 1951). More recently Kelleyhouse (1978) and others have pointed out that fires have positive effects on some species, such as muskrat, beaver, snowshoe hare, and weasel, but may have at least short-term adverse effects on marten. No information is available in the northern literature for other important furbearers, such as fox, lynx, and wolf.

SNOWSHOE HARE

The effects of fire on snowshoe hares have been studied by numerous investigators (Grange 1965; Wolff 1977, 1978; Fox 1978; Keith and Surrendi 1971).

According to Wolff's studies in interior Alaska (1977, 1978), during population lows, snowshoe hares prefer stands of dense black spruce and willow-alder thickets. During population highs, they use recently burned areas, but lack of cover makes the burns less desirable than the unburned forest. In summer the hares' food consists mainly of herbaceous plants and low shrubs, which are most abundant in open areas. Recently burned sites with inclusions of unburned spruce should be preferred habitat because of availability of food and cover. Wolff (1977) stated that, "a patchy environment which provides refuges in winter and more open summer range allows hares to shift seasonally in response to a change in diet and generally take advantage of changing environmental conditions."

In northcentral Alberta, Keith and Surrendi (1971) reported no direct mortality of snowshoe hares due to fire, although pregnancy rates and numbers of juveniles were reduced immediately after fire. In their

study, the authors found that hares abandoned severely burned areas, but reoccupied them the second summer following the fire.

Although evidence suggests that available food supply sets upper limits to hare populations, Grange (1965) and Fox (1978) have proposed that the cyclic nature of hare populations also at least partially is due to the relationship of fire to plant succession, which at some stages potentially leads to an increase in snowshoe hares. Grange felt that the chance for "population explosions," which characterize the snowshoe hare cycle, was limited to very early stages in forest revegetation soon after a fire.

Fox (1978) showed that there is a "...reasonable coincidence between the Canadian lynx cycle and the occurrence of forest and brush fires." He suggested that the vegetation sequence following fire leads to an increase in snowshoe hares, resulting in the observed snowshoe hare cycle in northern areas. He concluded that the snowshoe hare-lynx cycle is a forced oscillation brought about by the cyclic nature of forest fire frequencies, "rather than a predator-prey, parasite-host, or herbivore-vegetation" cycle. Although this is an interesting hypothesis, there are few if any biological data to support it.

MARTEN

Lensink (1953) found that in interior Alaska the distribution of marten was coincident with that of spruce, the critical element in marten habitat. He pointed out that factors that control the extent and distribution of spruce, such as physiography and fire, must be considered in a study of marten.

In the early 1950s, it was suggested (Lensink 1953, de Vos 1951) that management of marten habitat required control of fires, because burned areas and mixed or pure stands of trembling aspen and paper birch were usually poor marten habitat. Koehler and Hornocker (1977), however, reported that in Idaho, at least, periodic and incomplete burning created a mosaic of discontinuous fuel types and openings that provided the necessary food items for marten during the summer. In Alaska, British Columbia, and Idaho, marten utilized voles more than any other food item.

According to Koehler and Hornocker (1977), marten use open meadows and burned areas in the summer and fall if they provide adequate cover and food. They found that voles were abundant in mesic sites within meadows and burned areas and that the marten did not require cover of dense stands during the summer.

Although these studies show that marten require spruce forest, they also suggest that fire may not be as destructive of marten habitat as was once thought. Fire may create habitats that provide a food source, at least during the summer. It appears that the immediate effects of

fire are detrimental to marten populations because of the destruction of the spruce forest, but over a long time, fire may be beneficial and even necessary for producing a mosaic of vegetation patterns optimum for marten habitat. In Alaska, Lensink's findings should be reevaluated, and additional investigations made of the relationship of fire to marten habitat. Some of the recent large fires in previously good marten habitat, such as the 1977 Bear Creek fire, should provide good opportunities for study.

LYNX

While no information is available on the direct interaction of fire and lynx, the well-established snowshoe hare-lynx cycle (Keith 1963, Bulmer 1974, Brand et al. 1976) indicates that what is good for the snowshoe hare is good for the lynx. Thus, the evidence reported in the snowshoe hare section of this report indicates that fire should have a positive effect on lynx populations by increasing the supply of their main food source, snowshoe hares.

While this is implied by Grange (1965) and Fox (1978), no biological data are available to substantiate the hypothesis that fires are beneficial to lynx populations. Information needs to be gathered on the relationship of lynx populations to ages of the numerous large fire areas in interior and southcentral Alaska.

MUSKRAT

No information is available on the effects of fire on muskrat in Alaska. From farther south, however, it has been reported that muskrat hunters burn marshes to encourage vegetation that produces most food for muskrats (Errington 1963, Davis 1959, Kayll 1968). In many areas marshes may be maintained by periodic fires (Errington 1963). Klein (1971) observed that productivity of some marshes in Alaska seems to be maintained by periodic flooding and fires, but he also points out the need for data to back up this general observation.

In relation to both muskrat and waterfowl, we need to know far more about the frequency of fires in marsh areas, the effects of burning on productivity, and the maintenance of marshes by fire.

BEAVER

Fire is beneficial to beaver because it produces favorable environmental conditions for them. Beaver are adapted to early stages of forest succession and therefore, are especially abundant in areas recently burned or logged (Hakala 1952, Patric and Webb 1953, Lawrence 1954, Neff 1955).

According to Lawrence (1954), "in Michigan beaver follow the aspen,

becoming abundant following disturbances and [then] persist until their cutting activities and the course of plant succession again produce unfavorable conditions." The same is true in some parts of Colorado (Neff 1955).

Patric and Webb (1953) listed postfire types which include aspen and willow as important for beaver. Hakala's (1952) description of beaver habitat in the Goldstream Creek and Chatanika River area of Alaska mentioned abundant poplar and birch after fire in a spruce forest. Murray (1961) stated that after fire in spruce stands in the upper Tanana River area, Alaska, the increase of aspen and cottonwood created favorable habitat for beaver.

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Small Mammals

Few studies have been made of effects of fire on small mammals in Alaska. Long-term effects are particularly difficult to predict without further study because of individual site and fire differences and changes in the vegetation composition with time.

Hakala et al. (1971) discussed immediate effects of a fire that occurred in 1969 on the Kenai National Moose Range in southcentral Alaska. They noted that although fire probably took its toll of small animals, including red squirrels, shrews, and voles, it probably didn't cause much direct loss of life.

MICROTINES

Ellison, working in the same area (Kenai National Moose Range) immediately after the 1969 fire, found dead voles in the smoldering ashes. A year after the fire, however, he found that the number of

voles seemed to be nearly equal inside and outside the burn, although the number of shrews may have been fewer in parts of the burn (Hakala et al. 1971). West's studies (West 1979b, 1977) suggest that red-backed voles (*Clethrionomys rutilus*) used the Wickersham Dome fire area the first postfire growing season, but that they did not overwinter on the burned area until the fourth year after the fire. Tundra voles (*Microtus oeconomus*) were not found in recently burned areas, but West predicted they can be expected to reach peak density 6 to 14 years after fire, depending on plant succession.

In another study on the Kenai Peninsula, Quinlan (1978b) found that habitat changes caused by fire apparently reduced the suitability of the site for small mammals. Buech et al. (1977) reached similar conclusions in northeastern Minnesota. In five study sites, each in different successional stages of white spruce forest, Quinlan found fewer mammals of all species in burned areas than in mature forest. In the Kenai Peninsula study, red-backed voles (*Clethrionomys rutilus*) and dusky shrews (*Sorex obscurus*) reinvaded burned areas and reached densities similar to or greater than those found in mature forest 20 years after fire. This is contrary to West's findings in interior Alaska. Quinlan reported tundra voles were found only in the 40- to 50- and the 150- to 200-year-old stands.

Research in other parts of the United States shows higher numbers of small mammals on burned areas than in virgin forest, often as early as the first year after the fire (Sims and Buckner 1973, Krefting and Ahlgren 1974, Ahlgren 1966b). In these areas, fire-created habitat and food conditions are favorable to the increase of seed-eating mice species such as the deer mouse (*Peromyscus maniculatus*).

GROUND SQUIRRELS

The possibility of a relationship between forest fires and ground squirrel color in Alaska was explored by Guthrie (1967). He suggested that the arctic ground squirrel found in the Yukon Flats area has darker fur or melanism because the darker individual is favored over the lighter individual when the squirrels invade burned-over areas. Guthrie feels that it is more than a coincidence that the Yukon Flats area, which is particularly susceptible to fire, has the highest density in Alaska of melanistic squirrels.

Citellus undulatus osgoodi, a large ground squirrel inhabiting the Yukon Flats basin, relies on several plants for food. Guthrie thinks that fire encourages growth of plants that ground squirrels eat, but that nonmelanistic squirrels are more susceptible to predation. Thereby, melanistic squirrel survival is favored in burned areas. He concludes that melanism in ground squirrels of the Yukon Flats appears to be a polymorphic adaptation that permits the squirrel to take advantage of a favorable environmental situation. Guthrie's paper is the only refer-

ence suggesting that changes in mammal pelage might be associated with burned forest, and that this adaptation might be significant in survival of a species whose food is increased when vegetation succession is altered by burning.

RED SQUIRRELS

Surprisingly, no information is available on the effects of fire on red squirrel populations in Alaska and adjacent Canada. Because squirrels are dependent on spruce cones for much of their food (Brink and Dean 1966, Smith 1968), it is assumed that burned areas do not provide good squirrel habitat until the spruce become reestablished and begin to produce cones. General observations suggest this would be 30 or 40 years following a fire in the black spruce type and considerably longer in the white spruce types. In typical fire patterns, however, small stands of spruce frequently remain unburned. If these are large enough, they may support small squirrel populations until the burned areas begin to produce adequate cones.

Since red squirrels are included in the diet of marten, the effects of fire on squirrel populations in Alaska are important. If squirrel densities in known-aged burns are established, we can determine the amount of time needed to reestablish red squirrel populations.

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Birds

Little information is available on the effects of fire on bird populations in the North. In Alaska, Kelleyhouse (1978) reviewed the effects of fire on wildlife, including birds.

Two studies from the Kenai Peninsula (Quinlan 1978a, Ellison 1975) followed changes in bird communities after fire. Quinlan's research (1978) focused on bird communities in white spruce forests of the Chugach National Forest, and Ellison (1975) studied densities of Alaskan spruce grouse before and after fire. In addition, some of the southeastern Alaskan research conducted in logged areas may be applicable (Kessler and Harrington 1979). Otherwise, we are dependent on scattered reports for information. In Kozlowski and Ahlgren (1974), Bendell

pointed out that the wide variation in bird response that occurs after fires makes it difficult to generalize about fire ecology. Since the environment is changed in many ways after fire, it is difficult to pinpoint cause and effect relationships between the action of fire and the response of birds to it. Many experts feel each fire should be considered as a separate case, because sufficient data are not available to generalize about the fire effects on individual species (Bendell 1974).

Certain immediate responses to fire are predictable. Fires change bird habitat, disrupt nestings, and kill unfledged young birds. Most studies show fluctuations in the density and abundance of birds immediately following fire. Reactions of individual birds, however, depends on their attachment to their individual home range, mobility, and ability to find cover.

The major long-term effect of fires on birds involves changes in the vegetation. Plant succession may be different after each fire, because fires occur in different age stands and under different site conditions in the same area. And it is because of these site differences that a wide variety of bird life can be found in fire areas.

GAME BIRDS

Many investigators have commented on the effects of fire on gallinaceous birds and waterfowl.

Spruce Grouse

Following the severe 1969 Swanson River fire on the Kenai Peninsula, Ellison (1975) found that the subsequent spring breeding population of spruce grouse in the area was reduced by 60 percent. The population decline varied with the extent, severity, and patchiness of the fire.

Fires are not wholly detrimental to spruce grouse habitat, however. The absence of fire might cause white spruce, the preferred habitat of spruce grouse, to be replaced by open black spruce. Since fire retards permafrost development by setting back vegetation succession, fire may be necessary to maintain grouse habitats.

Ruffed Grouse

Ruffed grouse prefer aspen forest. Many investigators (Weeden 1965; Sharp 1963, 1971; Rusch and Keith 1971) have found that ruffed grouse flourish when their habitats are subject to periodic fires.

Light fires remove undesirable plant wastes, rejuvenate key food plants, and help control plant disease. A severe fire may have an

immediate detrimental effect on ruffed grouse habitat. A population of ruffed grouse in Alberta (Doerr et al. 1971) was reduced by half the first and second springs following a fire, but returned to near normal after 2 years.

Sharptailed Grouse

Sharptailed grouse thrive in recently burned areas. According to Weeden (1965), in interior Alaska sharptailed grouse are likely to be the first species of upland game birds to occupy a recent burn. They remain as long as an "open" vegetation type persists.

Ptarmigan

According to Weeden (1965), fires that result in replacement of mature, dense forest by shrubby growth probably benefit willow ptarmigan. Those resulting in permanent grasslands or reseeding directly to conifers may be of no advantage.

Godfrey (1972) reported that willow ptarmigan and rock ptarmigan regularly migrate into the boreal forest in winter and feed upon willow and birch buds. They confine their activities to forest edges and to the young shrubby plants that succeed following fire. In interior Alaska willow ptarmigan have been frequently observed feeding on the winter buds of willows that came back abundantly after the 1971 Wickersham Dome fire.

Waterfowl

In some regions waterfowl are dependent on periodic fires to maintain their habitat. In many areas, prescribed burning has been used to keep habitat open for them. In Alaska, however, Komarek's comments (1971) still are true: "No investigations of any serious nature have been made on the effect of fires upon habitats of the waterfowl that frequent interior Alaska."

Lensink (1953), working in the Yukon Flats area of Alaska, said that numerous fires had reduced "vast areas to a seral stage consisting primarily of willow. This stage is perhaps more beneficial to waterfowl than the climax." Klein (1971) stated that productivity of several major waterfowl areas in interior Alaska seems to be maintained by periodic floodings and fire. No studies have been conducted, however, to determine if productivity in breeding areas actually is increased by fire.

Buckley (1958) considered that fire might have both positive and negative effects on waterfowl habitat in Alaska. He postulated that the water table might be lowered following fire and that this would reduce waterfowl habitat. He suggested that on the other hand, removal of

Table 1. Summary of the species benefitting from and adversely affected by habitat changes caused by wildfire. Alternative habitat listings indicate other habitats in which the species are known. Assignments were made on the basis of the investigator's observations in the Kenai Lake area and information given in Gabrielson and Lincoln (1958), Williamson and Peyton (1962), Isleib and Kessel (1963), Spindler (1975), and Noble (1977). Alternative habitats are as follows: 1) Any early successional stage caused by avalanches, powerlines, logging, wildfire, earthquakes, other; 2) marsh or lake margins; 3) flood plains; 4) stream margins; 5) subalpine meadows and alder patches; 6) seral birch or aspen stands; 7) mature black spruce forest; 8) mature Sitka spruce forest; 9) mature forest in parklike stand.*

Species benefitting from wildfire		Alternative Habitats	Species adversely affected by wildfire		Alternative Habitats
Breed only in burned areas	Common Flicker	3,9	Breed only in mature forest	Gray Jay	6,7,8,9
	Alder Flycatcher	1,2,4,5,6,		Black-capped Chickadee	6,8,9
	Tree Swallow	3,4,		Boreal Chickadee	6,7,8,9
	Savannah Sparrow	1,2,3,5,		Varied Thrush	6,8,9
	White-crowned Sparrow	1,5,7,9,		Ruby-crowned Kinglet	6,7,8,9
	Golden-crowned Sparrow	1,5,7,9	Golden-crowned Kinglet	8	
Breed at highest densities in burned areas	Orange-crowned Warbler	1,2,4,6,9,	Yellow-rumped Warbler	6,7,8,9	
	Dark-eyed Junco	1,2,3,6,7	Townsend's Warbler	7,8,9	
Edge species	Hairy Woodpecker	3,9	Breed at highest densities in mature forest	Pine Siskin	7,8,9
	Olive-sided Flycatcher	2,4,6,7,9		White-winged Crossbill	8
	Western Wood Peewee	2,4,6,9		Spruce Grouse	6,8
	Bohemian Waxwing	7,8,9		Brown Creeper	8
			Swainson's Thrush	6,8,9	

*From Quinlan, S. E. 1978a. Bird communities and white spruce succession on the Kenai Peninsula. Pages 1-34 in USDA For. Serv., Chugach Natl. For., Seward, Alaska. Fire related wildlife studies on the Kenai Peninsula. Unpublished rept.

woody vegetation by fire would increase the attractiveness of the area to waterfowl species. He attributed an increase in the waterfowl population from 8.1 to 12.8 birds/km² in a 1957 Selawick burn to new plant growth that, because of the fire, started 2 weeks earlier than usual. He felt that the additional 2-weeks nesting time might have increased survival significantly.

OTHER BIRDS

Studies by Bock and Lynch (1970) and the Alaska Cooperative Wildlife Research Unit (1963) suggest that a few years after a fire, the avifauna often is more diverse on the burned plots than in the neighboring unburned areas. This is probably because small unburned pockets left in the burned areas create diverse habitats for birds.

In studies of successional stages of white spruce forest following fire on the Kenai Peninsula, Quinlan (1978a) found that number and diversity of birds increased with succession from the 9-year-old forest to the 100-year-old forest. In the forest older than 100 years, that diversity began to decrease.

Major changes in bird succession are associated with plant succession in white spruce forests of the Kenai. Since each bird species requires a unique set of habitat features, each reacts differently to habitat changes.

On the basis of the information Quinlan collected, some generalization can be made about the effects of wildfire on the populations of breeding bird species in the area. In Table 1, from Quinlan's report, the species which benefit or are adversely affected by fires are categorized.

SUMMARY

Fires have various effects on bird populations, but little is known about these effects. Some species seek out burned areas for food or breeding purposes. Others, such as birds of the climax forests, may be adversely affected for awhile but may require infrequent fires for the continuation or renewal of their habitat. Few studies in northern areas directly show changes in bird populations following fire. Most conclusions are derived from speculation on how bird populations might be affected by vegetation changes.

An important question that has received little attention in Alaska is how wildfire in the extensive waterfowl breeding areas such as the Yukon Flats may affect the productivity of aquatic plants, and how this, in turn, might affect the breeding and rearing success of waterfowl.

Little is known about bird diversity in burned areas compared with

that in unburned forests. We need more information on all aspects of the effects of wildfire on bird populations in both forested and tundra areas.

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Aquatic Life

AVAILABLE INFORMATION

Although considerable hydrological information is available, we have little information on the effects of fire on aquatic life. Tiedemann et al. (1979), however, recently reviewed North American literature on this subject.

The only two Alaskan studies, Hakala et al. (1971) and Lotspeich et al. (1970), are not very detailed. Lotspeich et al. (1970) investigated water quality after a fire in the Fortymile area of interior

Alaska and concluded that changes in the chemical makeup of the water due to fire were too small to affect the benthic macroinvertebrates studied. They concluded that the effects of fire were less damaging than the effects of firefighting activities. Erosion and siltation from fireline construction and use of firefighting equipment can adversely affect organisms. Lotspeich et al. (1979) suggested in their report that erosion from heavy equipment use increased stream turbidity. The turbidity may have had minor effects on some organisms, but the sampling scheme and methods used could not measure these effects if they were present.

Phosphate-base fire retardants can contribute to fish die-off or eutrophication of small lakes (Kelsall et al. 1977, Lotspeich and Mueller 1971). Hakala et al. (1971) discussed the possible effect of Phoschek fire retardant on fish kill in the Swanson River on the Kenai Peninsula, Alaska, during the 1969 Swanson-Russian Rivers fires. Salmon mortality was high along the lower 8 or 10 miles of the Swanson River about the time the fire retardant was dropped, but salmon arriving 4 days later were not affected. Although water sample analysis gave no positive clues to what caused the fish kill, high carbonate levels were present in the water.

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Terrestrial Invertebrates

AVAILABLE INFORMATION

Terrestrial invertebrate populations have not been investigated as extensively as larger plant and animal populations because they have not been considered as important economically. In Alaska, information on how fire affects invertebrates is limited. Therefore, generalizations based on available data are necessarily tentative.

The effects of a fire on invertebrate populations depend on many factors, including intensity and duration of the fire, site characteristics, and the nature of the organism in question. We know that adults and eggs of many invertebrate species are killed by fire and that habitat and food supplies of many others are destroyed. The influence of fire on the spread and destruction of some insect pests and diseases, particularly those that attack economically important tree species, can be seen. It has been shown that for about 10 years following large insect epidemics, such as that of the spruce budworm, there is a high probability of large intense fires. This natural cycle is being changed, however, by logging and fire suppression (Flieger 1971).

Although no conclusive Alaskan studies have been done on terrestrial invertebrates, Beckwith and Werner (1979) sampled arthropod populations on burned and unburned control plots of the Wickersham Dome fire area in interior Alaska. They found a decrease in most arthropod populations in burned areas along with an increase in spider populations. This decrease was attributed to predation by spiders. Higher spider predation in burned areas was linked to lack of protective ground vegetation for prey species.

Empidid smoke flies, insects that are attracted to fires, have been reported from Alaska (Evans 1972). These flies are important agents in the wood breakdown process.

Ahlgren (1974) summarized the effects of fire on soil organisms. He concluded that fire was more influential in forest than in grassland, and with the exception of mesofauna species and spiders, the population reductions after fire did not seem to be directly caused by heat. Soil organisms were affected more by postfire changes in the environment.

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Other Wildlife

In reviewing fire effects literature, we were unable to find much information on the effects of fire on some of the larger taiga and tundra wildlife species.

The black bear is wide ranging in the taiga of Alaska and adjacent Canada, feeding on both plant and animal material. Hatler (1972) studied the food habits of the black bear in interior Alaska and found that in a good year, blubberies (*Vaccinium uliginosum*) made up nearly 50 percent of the bears' diet. He noted that recently burned areas usually had good berry crops and that bears were often found feeding in these areas in the fall. He felt that a mosaic of burned and unburned forests was most suitable as bear habitat.

We found no reference to the relationship between grizzly bears and fire in Alaska. These larger bears tend to roam more in tundra areas than in forested areas. They too utilize berries in their feeding, however, and it is possible that fire in tundra and adjacent forest areas might enhance their fall food supply.

Dall sheep inhabit alpine tundra areas but they occasionally range into open grassland areas at treeline, especially during periods of heavy winter snows or severe storms. Geist (1971) observed that sheep usually are not affected by fire but that some of the open grassland areas in which they occasionally feed may be created and maintained by fire.

We found no information on fire effects on wolves in Alaska. Kelsall et al. (1977) and Kelleyhouse (1978) suggested, however, that fires that create higher populations of moose would favor wolves, whereas fires that reduce caribou range might cause local reductions in wolf populations or cause wolves to shift from a caribou to a moose diet, since the younger successional states are utilized more by moose than by caribou (Scotter 1971b).

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