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Fire Cycles and Community Dynamics in Lodgepole Pine Forests

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ABSTRACT

The influences of fire on succession, community diversity and stability, expression of serotiny, stand establishment, development of stand structure, and fuel accumulation are discussed for lodgepole pine forests. Fire, fuel accumulation, and stand development interact in a complex biological network. Mortality factors, such as mountain pine beetle, suppression mortality, and fire cause fuels to build up on the ground, creating varied fire intensity potentials. Fires initiate a chain of biological events that affects the development of lodgepole pine stands; in turn, the characteristics of stands affect their susceptibility to mortality, fuel accumulation, and fire potential.

Fire, more than any other single factor, is responsible for the establishment and structure of most of the lodgepole pine *(Pinus contorta)* forests we know today. The literature abounds with evidence that lodgepole pine owes its prominence to repeated fires, particularly in the Rocky Mountains from Colorado through Alberta and British Columbia (Clements 1910, Mason 1915, Smithers 1961, Wellner 1970, Habeck 1972). Lodgepole pine has existed in fire-dependent ecosystems for as long as man can determine. Analysis of pollen taken from bogs in Idaho and throughout the Pacific Northwest has shown that lodgepole pine was the predominant postglacial tree invader (Hansen 1943). Throughout postglacial periods, recurrent fires that sometimes covered extensive areas probably hindered development of climax forests and favored lodgepole pine.

The purpose of this paper is to examine the relationships and interdependence between fire and lodgepole pine. Succession, community diversity and stability, serotiny, stand establishment, fuel buildup, and fire intensity/stand structure relationships are discussed.

FIRE AND COMMUNITY DYNAMICS

Fire's repeated presence is not surprising considering its important biological role. Fire periodically redistributes biomass and recycles carbon and plant nutrients. It is part of the producer-decomposer cycle in certain ecological systems. In northern climates where decay is slow, minerals required for plant growth are stored in increasing quantities in trees and the forest floor. Fire aids the decomposition phase by periodically converting accumulated organic matter to more basic elements. However, the exact importance of fire's role to lodgepole pine in releasing stored minerals is poorly understood.

Perhaps of much more significance to the ecosystem than actual quantities of released minerals is the timing of release and the chain of events triggered by fire. Following fire, soil chemistry changes, soil temperature increases, soil biotic activity usually increases, and frequently new species and life forms appear, as succession begins from a new position on a cyclic pathway (Ahlgren and Ahlgren 1960).

FIRE AND SUCCESSION

Lodgepole pine is an aggressive pioneer species that readily establishes itself on burned-over areas. Over time, lodgepole pine tends to be replaced by more tolerant species. Probably the most common successional cycle is replacement of lodgepole pine by the spruce-fir climax type. Other species also succeed lodgepole pine in different habitats (Larson 1929, Daubenmire and Daubenmire 1968). In western Montana alone, lodgepole pine is found in 18 habitat types (Pfister et al. 1972). Fire may interrupt succession at any point in the history of the stand. The result is a variety of vegetative cycles that tend to maintain lodgepole pine.

In pure lodgepole pine stands fire usually results in a return to lodgepole pine. In stands that include lodgepole pine and other species, fire usually favors an increase of lodgepole pine in the new stand because of its closed cone habit and related seeding advantage. In young mixed stands, especially, fire favors an increase in lodgepole pine because lodgepole produces seed at a younger age than other species (Whitford 1905). Occasionally, other species have the advantage for establishment; for example, western larch *(Larix occidentalis)* on sites favorable to its moisture requirements. Larch, having highly fire-resistant bark, may also outcompete lodgepole pine when fires frequently recur (Hansen 1943).

Fire frequency affects rate of succession, longevity, initial stocking of lodgepole pine, and presence of climax species. Throughout the range of lodgepole pine, the interval between fires probably ranges from a maximum of 500 years (Hendrickson 1970) to less than 100 years. The interval between any two fires in one area can be only a few years. Fire frequency varies regionally, depending upon summertime dryness and incidence of lightning; and it varies locally depending upon factors such as slope, aspect, elevation, and natural fire barriers.

Large fires seem to recur at intervals unrelated to longevity of lodgepole pine. This is contrary to the notion that the interval between fires depends on longevity because ground fuels build up rapidly in overmature stands. Longevity in the Rocky Mountains of the United States and Alberta is often more then 250 years (Mason 1915, Horton 1956). One stand in southwest Montana was 450 years old. Fire, as we know, has occurred frequently in the Rocky Mountains during these periods. In parts of Alberta, the interval between fires has averaged 67 years (Day 1972). In northeastern Oregon, northeastern Washington, and adjacent northern Idaho, lodgepole pine stands break up with heavy mortality by 100 years of age (Trappe and Harris 1958, Tackle 1961). Here the period between fire cycles may approximate stand longevity, or it may be much greater. Longevity tends to be inversely related to rate of succession; both probably depend on site moisture.

The kind of fire that burns over an area can influence stand density and indirectly, rate of succession. Open stands permit faster rates of succession than more dense stands (Cormack 1953). In open stands of lodgepole pine in Alberta, spruce will seed in irregularly until the canopy is closed, which often takes 40 years. In well-stocked lodgepole pine stands, spruce may be able to seed in for only 10 to 15 years (Horton 1956). Subalpine fir *(Abies lasiocarpa)* becomes established similarly to spruce, but being more tolerant it increases in abundance throughout the life of the stand.

In eastern Alberta, fire often favors aspen *(Populus tremuloides)* over lodgepole pine where the two grow in mixed stands. Except after intense burns that kill its roots and prevent suckering (Smithers 1961), aspen is better adapted to fire than lodgepole pine. For about the first 50 years after fire, aspen tends to dominate, but thereafter lodgepole pine begins to overtop the aspen. The pattern of long-term succession in this region is in question because few stands reach more than 100 years of age before a fire disturbance is repeated. A trend to white spruce *(Picea glauca)* as climax species is indicated (Moss 1953).

Fire is not always necessary for maintenance of lodgepole pine as a species. It may actually be a true climax species in some locales (Mason 1915). In Colorado, for example, Moir (1969) found evidence of a narrow lodgepole pine climax zone between the Douglas-fir *(Pseudotsuga menziesii)* and spruce/subalpine fir zone.

Extensive areas of pure lodgepole pine, as found in southeastern Idaho and western Wyoming, may exist because of isolation from seed supplies of species having the potential to replace lodgepole pine. Originating after fire (Tackle 1961), these stands will probably continue to cycle from young to old lodgepole pine because fire inevitably recurs. However, lodgepole pine regenerates well in the absence of fire if soil and light are favorable (Tackle 1954, Beetle 1961). Stands may perpetuate themselves in an uneven-aged condition.

There is some concern that effective fire control will lead to a reduction of lodgepole pine unless it is regenerated on cutover areas (Bloomberg 1950). Theoretically, complete fire control could drastically reduce lodgepole pine by permitting climax types to prevail. In a summary of the acreages covered by conifers in the northern Rocky Mountains (Wellner 1970), climax types accounted for 13 percent of the total; lodgepole pine, 25 percent. Apparently, fire suppression and land practices have not greatly affected the acreage of climax forest in the northern Rocky Mountains. However, by reducing the number of acres burned during the past 25 years, fire control has no doubt permitted increased establishment and growth of climax species in the understories of lodgepole pine, as it has in Glacier National Park (Habeck 1970). Long-term effects of fire control are unknown.

In the future, reduction in acreage, if any, of lodgepole pine will depend on effectiveness of fire control, policies regarding containment of fires, and regeneration practices on cutover lands. Ecologically, it seems unwise to change the land coverage of lodgepole pine to any great extent. To maintain a proper balance of lodgepole pine with other species, man must manage fire competently with full awareness of its biological effects.

COMMUNITY DIVERSITY AND STABILITY

Fire is a key element in the ecological diversity and stability of lodgepole pine. Properly considered, diversity includes not just lodgepole pine alone but the entire forest community of which it is a part. Species, age classes, life forms, and community mosaic are important aspects of diversity.

Fire contributes to diversity of plant and animal communities by recycling vegetative communities. During early developmental stages of a forest community, postfire vegetation is largely composed of invading annuals, resprouting perennials, and brush species, many of which diminish and die off after a tree canopy forms. The young postfire community supports a variety of animal life and many species are unique to this stage. Annual productivity is concentrated in the herbaceous and brush species that provide forage for a buildup of large herbivores. Big game, small mammals, birds, insects, and other smaller forms of animal life tend to cycle both in species and in numbers along with the succession of vegetation. The varied age distribution of forest stands created by different stages of growth and succession leaves a patchwork pattern upon the landscape that contributes to diversity.

In the lodgepole pine subclimax in Yellowstone National Park, Taylor (1969) found that younger seral stages had more birds and small mammal species, more individuals per acre, and more efficient energy utilization than the older seral stages. When feeding, large herbivores preferred the younger stands of lodgepole pine to the older stands. Following crown closure, the number of wildlife species was reduced, although certain birds and small mammals found the closed forest habitat more suitable.

Not long after crown closure, certain shrubs and herbs disappear and along with them many bird and mammal species. The time a lodgepole pine forest remains open and conducive to high species diversity depends largely upon initial stocking after fire and the rate of reestablishment. Fire intensity influences initial stocking in several ways, which will be described later.

In the literature, ecologists tend to concur that community stability, species diversity, and annual productivity are positively related (Loucks 1970). The dependence of one upon the other is not altogether clear; however, Loucks states that to achieve high levels of species diversity and high productivity man should restore the mechanisms that triggered the recycling and rejuvenation of biotic systems. Fire in lodgepole pine ecosystems must certainly be regarded in this light because it is a rejuvenating mechanism.

Community stability, so often defined in terms of species diversity, is more accurately reflected in the ability of a plant community to resist change (Vogl 1970). So defined, lodgepole pine communities perpetuated by fire are very stable, especially where lodgepole is a subclimax species. In contrast, fire in climax types normally results in extreme change—replacement of climax forest by pioneer species.

Perpetuation of lodgepole pine through repeated fire cycles markedly demonstrates a dependence on fire. Mutch (1970) hypothesized that fire-dependent plant communities burn more readily than nonfire-dependent communities because natural selection has favored development of characteristics that make them more flammable. Lodgepole pine seems to fit the hypothesis in several ways. Its foliage, like most conifers, is highly flammable and susceptible to crown fires. Perhaps unique to lodgepole pine as a conifer is the creation of large quantities of small- to medium-sized ground fuels by recurrent fire, bark beetle infestations, and suppression mortality. Fire itself creates fuel characteristics in the ecosystem that often enhance the growth potential of future fires.

FIRE AND SEROTINY

The role of fire in opening serotinous cones is well known. Serotinous cones do not open at maturity but open after exposure to temperatures of 45 degrees to 50 degrees C. (Clements 1910), which breaks resin bonds and permits cone scales to flex so that the seed can be released. Serotinous cones ensure an abundant supply of seed to regenerate a new stand after fire. Less well understood is the role of fire in evolutionary selection of the serotinous cone habit. Does fire select for serotiny and if so, has serotiny been developed or maintained by fire over time? Fire-controlled genetic selection for cone serotiny is logical because stands originating from fire are probably established primarily from serotinous cones (Lotan 1967).

After studying geographic variation of lodgepole pine, Critchfield (1957) suggested that fire was the selective agent primarily responsible for the evolutionary divergence of the Rocky Mountain and Sierra Nevada subspecies groups in the cone characteristics associated with the closed-cone habit. Rocky Mountain lodgepole pine is commonly a closed-cone population and has evolved in the presence of repeated fires of high intensity. Sierra Nevada lodgepole pine are open-cone populations and seem to have evolved primarily in the presence of light surface fires. Closed cones offer a distinct advantage for regeneration after intense fires; whereas, they would handicap regeneration after light fires that supplied insufficient heat for breaking the resin bonds.

Fires develop all degrees of intensity but are usually grouped into high- and low-intensity classes, partly to facilitate discussion and partly because quantitative values of intensity are seldom known. Ground fires are often low-intensity fires that typically creep and smolder through the forest floor and surface fuels and sporadically burn out the crowns of individual trees. Crown fires are characteristically high-intensity fires that burn continuously through crown canopies and are usually accompanied by hot ground fires.

The degree of cone serotiny also varies locally within the Rocky Mountains (Lotan 1967, 1968) and the Pacific Coast region (Critchfield 1957). Correlating the influence of fire with these local variations is difficult because specific fire records are lacking for long periods. However, a hypothetical model of fire selection in lodgepole pine[1] indicates that fire frequency can be responsible for varying degrees of serotiny, even if more than one independently segregating gene is operative in determining serotiny.

A higher degree of cone serotiny would be expected on areas where frequently repeated, high-intensity fires occurred than on

[1]David A. Perry and James E. Lotan. "A Model of Fire Selection for Serotiny in Lodgepole Pine" (in process for Can. J. For. Res.).

areas with less fire history. Where fires are infrequent, open-cone trees would have more opportunity for regeneration. Within the Rocky Mountains, local factors, such as slope, aspect, elevation, natural landform barriers, and fuels, influence fire frequency and fire size. On a larger geographic basis, variation in lightning incidence (Fuquay 1962) and fire season severity also influence the frequency and size of fires. Probability of ignition and fire size are greater in old burns where the fire-killed trees remain as fuel (Lyman 1945, Barrows 1951). Once fire-killed, a mature lodgepole pine stand will likely experience a high-intensity fire within 40 to 60 years; and this tends to increase the proportion of closed-cone lodgepole pine.

Not all fires in the Rocky Mountains are of high intensity. Low-intensity ground fires also occur (Leiberg 1904, Horton 1956). Low-intensity fires and other natural stand disturbances would theoretically tend to increase the proportion of open-cone trees in a stand. Thus, the degree of cone serotiny could oscillate considerably: repeated crown fires increasing the proportion of closed-cone trees and low-intensity fires or lack of fires decreasing the proportion of closed-cone fires.

If fire history can be correlated to degree of cone serotiny on a local geographic basis, then cone serotiny is related to many biological factors in the lodgepole pine forest. For example, mortality in lodgepole pine (such as bark beetle epidemics, mistletoe, and suppression mortality) provides for a buildup of ground fuels that increases the probability of large, high-intensity fires; thus, mortality factors would relate to selection for cone serotiny.

LODGEPOLE PINE–FIRE CYCLE INTERACTIONS

Many interrelated factors influence the lodgepole pine fire cycle. Some of the more notable ones are shown in Figure 1. Seedling establishment and subsequent development of stand density, age structure, and composition depend, in part, on the type of fire

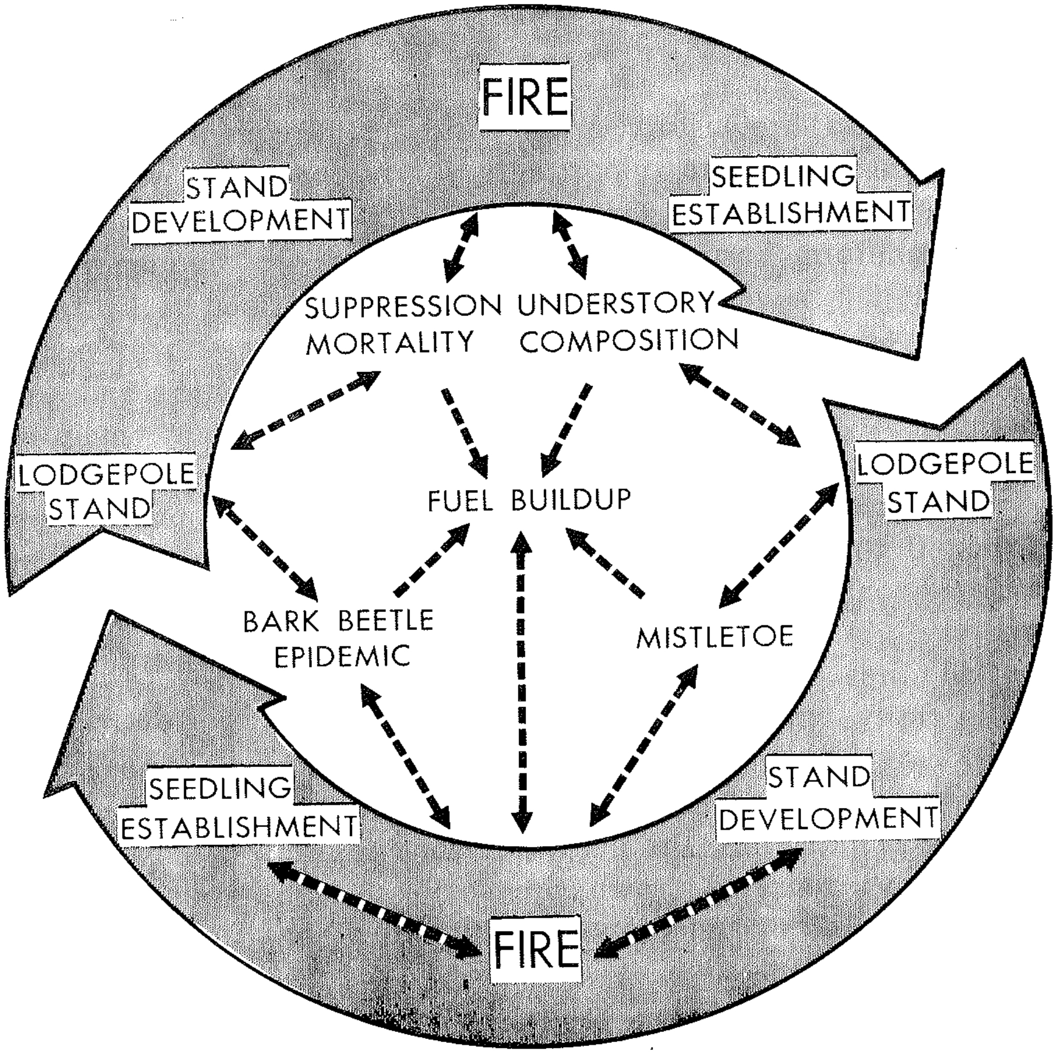

Figure 1. Lodgepole pine fire cycle showing interrelationships among influences.

that last occurred. A wide range in these stand conditions is introduced by fire in lodgepole pine forests (Whitford and Craig 1918). In turn, the developing stand characteristics influence the type of fire that will next occur and perhaps when it will occur. During growth and development of a stand, the fuel and related fire potential undergo change, depending largely upon the pattern of natural mortality and stage of succession. Weather also is a critical influence on the intensity and pattern of fires, as well as development of stand and fuel characteristics.

The pattern of growth and development of lodgepole pine stands, as influenced by fire, has significant economic ramifications for timber production. Stand density with its effect on diameter growth and the likelihood of reaching rotation age are probably the major fire-influenced concerns of economic consequence.

STAND ESTABLISHMENT

The physical development of a new lodgepole pine stand, following fire, begins as a function of the amount of seed stored per acre and the probability of a seedling becoming established (Lotan and Jensen 1970). The amount of seed stored per acre varies widely in lodgepole pine. For a given stand, the timing of fire occurrence could make considerable difference in the amount of seed available after fire. For example, a fire in a young, dense stand that contained few cones would tend to leave a low seed supply. However, because a large seed supply probably exists in many stands of serotinous lodgepole pine, stand establishment depends more on existence of a good seedbed and little competition than on seed supply. Condition of seedbed and competition affect the probability of a seed becoming a seedling. This probability relates basically to satisfying moisture, light, temperature, and nutrient requirements of germinating seeds. Fire influences the probability of seedling establishment in various ways:

1. It removes the organic forest floor and exposes different amounts of mineral soil.
2. It changes soil-nutrient levels, usually with a short-term increase in available ions essential for plant growth.
3. It increases light by eliminating shade cover.
4. It usually reduces, to varying degrees, the amount and vigor of vegetation that competes with seedlings for moisture and light.
5. It increases the daily range in soil temperatures, which enhances germination of lodgepole pine seed (Bates 1924).
6. It impairs soil moisture-holding capacity, most likely by very intense fires on xeric sites (Horton 1953).
7. Without soil cover, the surface may erode, resulting in displacement of seeds and washout of very young seedlings—affecting pattern of regeneration.
8. It opens cones when heat is sufficient.
9. Seed viability may be lost where fire is very intense.

Fire influences stand establishment and subsequent development largely due to variations in intensity. High-intensity fires, often large in size, have accounted for the major fire patterns in Rocky Mountain lodgepole pine (Leiberg 1904, Smithers 1961, Wellner 1970). Nonetheless, low-intensity fires have occurred on a significant acreage as evidenced by the existence of uneven-aged lodgepole pine stands (Leiberg 1904, Smithers 1961, Gabriel 1970) and observation of fires in progress. Much of the area burned by low-intensity fires occurs during less severe burning periods of a large fire. Ground fires of low intensity frequently occur within the perimeter of a large fire and along the back (upwind side) and flanks of the large fire. Variations in local winds, topography, fuels, and fires themselves result in unburned and lightly burned islands within the boundaries of large fires. Duration of fire at a given point and frequency of occurrence also affect stand establishment.

EFFECTS OF HIGH-INTENSITY FIRES

High-intensity fires on mesic and wet sites create good seedbed conditions, and when seed is abundant, dense stands are established. On dry sites where litter accumulations are low, high-intensity fires can cause low stocking because of impoverishing the soil and reducing water-holding capacity (Horton 1953).

Crown fires may cause maximum release of viable seed or may actually destroy large quantities of stored seed. Muraro (1971) explains this with two examples. A hot ground fire with considerable crowning kills all trees and exposes much mineral soil. Serotinous cones open, and with good seedbed conditions and abundant seed, a dense stand results. However, as intensity continues to mount to "blowup" conditions, a severe crown fire develops. Branches up to 1/2-inch diameter are consumed. Temperatures become lethal to seed. Viable seed is limited and a low-density stand results.

The extent to which high-intensity fires reduce quantities of viable seed is speculative. Temperatures and heat durations lethal to seed in serotinous cones (Beaufait 1960) can certainly exist in very high-intensity fires. The turbulent pulsating nature of high-intensity fires also could cause wide variation in the amount of viable seed released over short distances.

It is difficult to separate the effects of fire from other factors that influence seedling establishment. However, when other influences are favorable, seed supply abundant, and fire treatment ideal for seed release and exposure of mineral soil, stocking can be extremely high. Some stagnated stands have contained 300,000 seedlings per acre at 1 year of age and 101,000 stems per acre at 70 years of age (Mason 1915).

High-intensity fires in lodgepole pine are apt to remove most of the duff (F + H layers) and expose the mineral soil. Not only must the fire be intense, moisture must also be low for duff to burn off. Moisture content of duff is apt to be low during the period of summer when most high-intensity fires occur. Duff is often nearly completely removed because in lodgepole pine it is usually shallow and relatively easy to burn off. I have never seen it average more than 5 centimeters in depth for many stands sampled in the Intermountain Region, and stands frequently average about 2 to 3 centimeters in depth. Muraro (1971) reports some depth values greater than 5 centimeters in Alberta.

Competition from herbs and brush for moisture, light, and perhaps nutrients influences regeneration density even after high-intensity fires. One stand in Yellowstone National Park, as an example, reestablished with 156 trees per acre. The low density was attributed to severe competition from herbaceous plants (Taylor 1969). The original stand may have burned when the duff moisture content was high. The moderate heat flux to the soil resulted in optimum conditions for vigorous resprouting of resident vegetation.

EFFECTS OF LOW-INTENSITY FIRES

Moisture content of duff is a critical factor in preparation of good seedbeds by low-intensity fires. When duff is very dry (less than about 10 percent moisture content), a smoldering, creeping fire will expose mineral soil. At duff moisture contents above about 20 percent, low-intensity fires become ineffective at exposing substantial amounts of mineral soil (Gisborne 1928). For some low-intensity fires, moisture content may vary enough so that a mosaic of good and poor seedbeds is produced. Stocking would tend to vary accordingly. Horton's (1953) experience with wildfires in Alberta is that low-intensity fires on moist sites are unable to reduce the duff layer, which results in a poor seedbed and low stocking. On dry sites, low-intensity fires may provide an excellent seedbed with the potential for high stocking.

Mortality after low-intensity fires is sporadic; thus, thinned stands often result. In time, two-aged stands often become established. Three-aged stands from two light ground fires are sometimes encountered (Horton 1953, Tackle 1954). Regeneration proceeds until canopies are closed over in a period of 5 to 40 years.

Some low-intensity fires in lodgepole pine cause very little mortality even when up to 80 percent of a tree's foliage is removed.[2]

Ample seed for regeneration is normally available even if a light fire leaves serotinous cones unopened. Seed from nonserotinous cones regularly provides an annual seedfall (Mason 1915, Lotan 1970). The abundance of regeneration in a partially opened stand probably depends primarily upon degree of understory competition and openness of the canopy.

[2]B. D. Lawson. *Fire Spread in Lodgepole Pine Stands.* Can. For. Serv., Pacific For. Res. Centre Internal Rep. BC-36, 119 p. 1972.

In stands of mixed species, including lodgepole pine, the varying degrees of natural resistance to fire among species favors survival of some over others. Habeck (1970) found in Glacier National Park, for example, that ponderosa pine *(Pinus ponderosa),* western larch, and Douglas-fir, all species with relatively thick protective bark on their lower boles, survive ground fires that lodgepole pine does not. These species often occur above a dense layer of lodgepole pine and larch regeneration.

Lodgepole pine has a medium resistance to mortality by surface fires (Starker 1934). Except for climax Douglas-fir, lodgepole pine has a greater fire resistance than other climax species it associates with. Spruce and subalpine fir, for example, have dense branching habits and shallow root systems, making them quite susceptible to mortality from surface fires. Lodgepole pine has the same or less fire resistance than other commonly associated seral species.

The survival success of lodgepole pine in a mixed stand depends not only on its fire resistance relative to other species but also on the seed potential of the associated species. Considerable latitude exists for the development of species composition, age structure, and density of mixed stands after low-intensity fires.

DEVELOPMENT OF FUEL AND FIRE POTENTIAL

Fuel is fundamentally organic matter that plays an intricate part in functioning of the ecosystem. In fuel resides the potential for initiating many biological activities in the forest community. Fuel is not just biomass; however, it is the only portion of the biomass that will burn and release heat in a fire.

Fuel conditions are ever changing in forest ecosystems and especially in lodgepole pine forests. Some fuel properties, particularly moisture and chemical ones, change daily and seasonally. Quantities of ground fuels, which often control the size and intensity of fires, change by building up and then dropping over the years. Fuel quantities have their own cycles that are not necessarily correlated with stand chronology. Ground fuel quantities that are conducive to high-intensity fires develop largely from various natural causes of mortality. Growth of young understory climax species and annual litterfall also contribute to ground fuel quantities. The numerous natural causes of mortality are closely interwoven in the pattern of stand development and fire, as exemplified in Figure 1.

Two similar terms, fire potential and fire hazard, that denote fire behavior are used in the remainder of this paper. Fire potential has a broad meaning. It refers to fire growth and heat release potentials of fuel. Usually, rate of spread and intensity are the fire characteristics implied, but occasionally duration of heat and smoldering tendency are meant. Fire hazard is a term referring to the difficulty of controlling fire, which is primarily a function of rate of spread and intensity.

MORTALITY-CAUSED FUEL BUILDUP

Fire. Historically, fire may have created more ground fuels than any other single cause of mortality, including annual litterfall. Certainly, fire can create more fuel in a short time than other mortality factors. Different types of fires affect the fuel quantities and the representation of particle sizes differently. Hence, flammability of fire-created fuels can vary considerably.

Muraro (1971) describes some of the fire/fuel interactions related to three levels of fire intensity in lodgepole pine. After a low-intensity fire, weakened trees die, become snags, then fall. Ground fuel quantities build up moderately. After a moderate-intensity fire that has crowned, ground fuel will become abundant for an extended period. Deep burning quickly brings the first blowdowns; other fire-killed trees fall as roots rot away; more and more trees with branches become ground fuels.

After a high-intensity fire, deep burning over most of the area assures complete downfall in a short time. Ground fuel quantities are high after the fire, but because intense burning eliminates the small branches, most of the fuel is of large size and lies close to the ground where it is less flammable and more rapidly decomposed.

After a fire of moderate intensity, the burned area would likely support dense regeneration; and with the heavy ground fuels it would later be prone to high-intensity fire. If the fire occurred in a young stand, the limited seed would probably be destroyed and a very open stand, or no stand, would result. Muraro suggests that a natural process of fuel modification by fire intensity may discourage second fires of high intensity on severely burned areas and encourage high-intensity fires on areas that have been moderately burned.

Suppression mortality. Natural thinning, which begins soon after dense stands are established, can contribute materially to ground fuels. In stands where crown competition is not severe, suppression mortality contributes little to ground fuels. Leiberg (1904) in an early survey of fire history in southwest Montana was impressed that 98 percent of the fires restocked with overly crowded lodgepole pine. After reaching 80 to 100 years of age, these stands have become by natural thinning a tinderbox of dead, slender trees. Leiberg believed that the large, high-intensity fires were due to the large quantities of dead material accumulated partly from past fires and partly from suppression mortality.

Insects. Insects create ground fuels by killing trees and influence flammability by opening up stands for increased drying. One insect, the mountain pine beetle (*Dendroctonus ponderosae* Hopk.), overshadows all others as a cause of fuel buildup in lodgepole pine. Using yield table volumes and dbh–mortality relationships determined by Evenden and Gibson (1940)–I calculated 60 to 90 tons per acre of beetle-killed boles and crowns possible on medium sites. The actual buildup on the ground of beetle-killed trees begins about 5 years after fire (Flint 1924) and proceeds for about 10 years.[3]

The mountain pine beetle (Roe and Amman 1970), like fire, apparently has been active as long as lodgepole pine has existed. The large increase in ground fuel and associated increase in the probability of large, high-intensity fires due to beetle epidemics suggests that the relationship among beetles, fire, and lodgepole pine tends to perpetuate lodgepole pine. The mountain pine beetles' strong preference for large trees gears heavy fuel buildup to a time when stands are mature or overmature. In some areas, this is when climax species are developing prominence in the understory and together with the ground fuels present a high chance of crown fire. This situation operates against succession to climax stages.

Disease. Fungal diseases in lodgepole pine contribute to ground fuel accumulation, but generally are minor influences compared to other sources of mortality (Mason 1915). Locally, however, canker rots and root rots can cause significant ground fuel buildups (Nordin 1954).

Dwarf mistletoe (*Arceuthobium americanum* Nutt.) commonly adds to ground fuel quantities and is probably most important in mature or older stands where it has had time to spread and weaken trees. It, like the mountain pine beetle, may also prefer larger sized trees (Hawksworth and Hinds 1964). Dwarf mistletoe enhances vertical fuel continuity and the likelihood that ground fires will burn out individual tree crowns. The witches'-brooms from dwarf mistletoe create clumps of closely spaced small branches that trap fallen needles. The result is a scattering of vertically oriented fine fuel arrays at a compactness conducive to optimum flammability.

[3] Archie L. Gibson. "Status and Effect of a Mountain Pine Beetle Infestation on Lodgepole Pine Stands." USDA For. Insect Lab., Coeur d'Alene, Idaho. 1943. Unpubl. Off. Rep., 34 p.

Annual litterfall. Annual litterfall slowly builds up the forest floor until it is reduced by fire or reaches equilibrium with decay, which can take several hundred years (Olson 1963). The quantity of forest floor has little influence on development of high-intensity fires. However, along with moisture content, the forest floor greatly influences fire's effects on the soil and plant and animal life. The greater the depth of the forest floor, the longer it takes to reduce moisture to the point where it will readily burn; thus, forest floor quantities can moderate fire effects depending upon the moisture content when fires occur.

Others. This discussion has touched upon most of the major sources of mortality that contribute to buildup of ground fuel. Others, such as breakage from wind and snow, are also important. Climax species advancing beneath lodgepole pine crowns deserve mention as flammable ground fuels. The foliage of climax species such as spruce and fir is much more flammable than other living understory vegetation; it provides vertical continuity of fuel and a high rate of potential heat release that encourages crown fires. Although development of an understory of climax species is not a typical mortality-caused fuel buildup, it usually progresses rapidly after mortality opens up the lodgepole pine canopy.

CROWN FUELS

Fuel characteristics of tree crowns change as stands grow and develop. Stand density and stand growth determine fuel characteristics and related fire potential in the crown. The likelihood of a ground fire becoming a crown fire depends, in part, on how high the crown canopy is above the heat source. Potential intensity and fire size depend, in part, on the spacing of trees and the quantity of crowns per unit area. Fire potential of crown fuels depends upon stand conditions which, in turn, are frequently affected by the nature of the preceding fire. In this way, fire and lodgepole pine are mutually related.

THE FUEL ACCUMULATION CONCEPT

General usage of the term "fuel accumulation" erroneously implies a steady buildup of fuels and fire hazard from the time a stand is established until man or fire interrupts the process. It is true that biomass increases in regular increments throughout the life of a stand, but not necessarily fuel quantities and fire potential. In fact, fire potential often decreases while biomass increases.

Two consistencies seem to stand out in the concept of fuel accumulation applied to lodgepole pine (Fig. 2). (1) Fuel quantities and fire potential become predictably high as stands become overmature. (2) Fuel quantities and fire potential cannot be predicted from age in young and immature stands. Curve A, Figure 2, corresponds to what Muraro (1971) describes as typical fire hazard in lodgepole pine where young stands, especially dense ones, are most hazardous. Least hazardous are moderately dense to open advanced immature and mature stands. Hazard increases as stands become overmature and ground fuels build up from downfall and establishment of shade-tolerant species. Curve C of Figure 2 depicts conditions not uncommonly found. Ground fuel quantities and fire potential remain relatively low throughout the life of a stand until it undergoes decadence. Individual stands can vary anywhere between curves A and C during younger growth periods, and develop higher fire potential at later periods of growth (curve B).

The decline in fire potentials, Figure 2, is not due solely to net losses of organic matter but to changes in fuel compactness, arrangement, particle sizes, and moisture. Over time, a concentration of ground fuels undergoes physical deterioration and settling. Fuels compact as supporting branches decay. Branches touching the soil resist drying. Finer particles incorporate in the forest floor. The sum effect is reduced flammability. In the opinion of experienced fire control officers, the fire hazard in lodgepole pine peaks 25 years after a burn

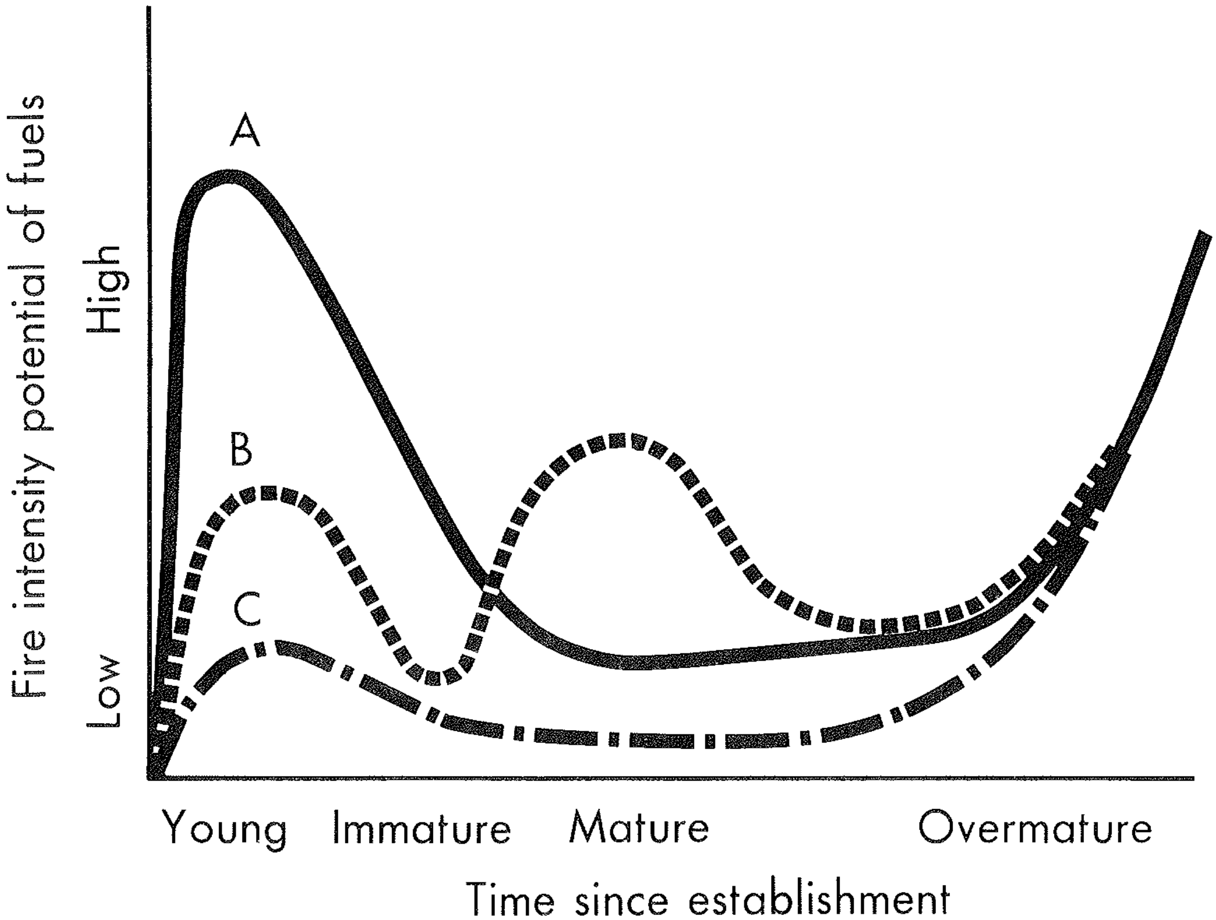

Figure 2. Fuel cycles and fire intensity potential in lodgepole pine.

(Lyman 1945). Thirty-five years after its peak, the hazard has declined 50 percent; in 60 years it has been reduced to a moderate level. Mason (1915) suggested fire-killed timber took 60-120 years to decay. (I believe he meant decayed to a point where it no longer contributed measurably to rate of fire spread and intensity.)

The variation in fuels and fire potential shown in Figure 2 illustrates the danger of one generalized fuel accumulation concept when dealing with individual stands and specified land areas. The principle that fuels build and fall in cycles is essential to understanding and managing forest ecosystems; however, managing actual land units requires specific predictions of existing fire potentials. For this purpose, the concept that fuels accumulate with time is insufficient because it has a high chance of a large error.

Predicting fuels and fire potential using combinations of stand density, average dbh, and age is also risky. In an extensive study of lodgepole pine fuels in British Columbia, Muraro (1971) concluded that, except for aerial fuels, predictive equations based on stand characteristics were inadequate (nonsignificant correlation coefficients) for modern land management. The missing information needed for providing useful correlations is stand history, particularly the variable influence of fire on fuel quantities during the early years of a stand. In the absence of good correlations, observation and fuel sampling must be used to furnish predictions of fire potential on specific sites.

Little fuel sampling in lodgepole pine has been done except for forest floor quantities. Some dead ground fuel quantities encountered in lodgepole pine are shown in Table 1.

Table 1. Range of Loadings for Dead Ground Fuels Determined in British Columbia and the United States' Northern Rocky Mountains

Location[1]	Diameter of Woody Material[2] 0-1.3 cm	1.3-10 cm	Over 10 cm	Forest Floor (L+F+H Layers)	No. of Stands
	(Kg/m^2)				
British Columbia	0.02-0.16	0.25-1.90	0.25-3.88	0.88-9.38	10
Northern Idaho, Montana, and Wyoming	.05-.26	.26-1.86	.78-7.05	1.19-6.51	9

[1]British Columbia by Muraro (1971); Idaho, Montana, and Wyoming by author.

[2]The diameter limit was 1.3 cm for British Columbia data, but actually 1.6 cm for the United States.

FIRE GROWTH CHARACTERISTICS

How do fire growth characteristics in lodgepole pine compare with other forest types? Rate of fire spread and fire intensity in lodgepole pine are not as great as in other types, such as western larch, Douglas-fir, western white pine *(Pinus monticola),* and cedar/hemlock *(Thuja plicata)/(Tsuga heterophylla),* according to the judgment of many experienced fire control officers (Lyman 1945). However, the fire potential in lodgepole pine is greater than in spruce, fir, and aspen, largely because the duff of lodgepole pine is faster drying (Smithers 1961).

Statistics gathered for all wildfires fought by the USDA Forest Service during 1931-44 in northern Idaho and Montana provide some comparative fire data (Barrows 1951):

1. Ignition potential—the number of fires per million acres—for lodgepole pine is lower than that of other forest types:

Lodgepole	=	50
Fir/larch	=	40, the lowest
Douglas-fir	=	70
Grand fir	=	410, by far the highest.

2. Rate of spread from origin of fire to time of attack by suppression forces averaged 2 chains (132 feet) of perimeter per hour in lodgepole pine stands. This is about average for all forest types. It is greater than for spruce/fir and less than for Douglas-fir and ponderosa pine.
3. Of the fires in lodgepole pine, 76 percent were less than one-fourth acre; 95 percent, less than 10 acres; and 99 percent, less than 300 acres. Only ponderosa pine exceeded lodgepole pine in percent of fires greater than 10 acres.
4. Percent of ignitions in lodgepole pine by material first ignited:

Duff	=	36
Green treetops	=	5
Snags	=	30
Grass	=	10
Wood on ground	=	14
Miscellaneous	=	5

SUMMARY

Fire, more than any other single factor, is responsible for the establishment and structure of most of the lodgepole pine forests we know today. Fire, fuel accumulation, and stand development in lodgepole pine comprise an intricate network of biological interactions. Mortality from agents such as mountain pine beetle, suppression mortality, and fire itself causes fuels to build up on the ground and create varied fire intensity potentials. Fires initiate a chain of biological events in the ecosystem that influence the development of lodgepole pine stands. The structure of the developing stands in turn affects the susceptibility to mortality, fuel buildup, and fire potential.

The accumulation of ground fuels and related fire intensity potential seems to follow two consistencies: (1) fuel quantities and fire potential become predictably high as stands reach overmaturity; and (2) fuel quantities and fire potential in young and immature stands cannot be predicted from age alone.

Seedling establishment and subsequent development of stand density, age structure, and composition of lodgepole pine forests depend largely on intensity and frequency of fires. Fires in lodgepole pine vary from ground fires of low intensity to crown fires of high intensity. For given localities, they occur at average intervals of about 60 to 500 years. High-intensity fires probably accounted for the major fire pattern in lodgepole pine, although low-intensity fires have been responsible for the development of many uneven-aged lodgepole pine stands.

Lodgepole pine over much of its range exists in fire-dependent ecosystems where succession to climax species is frequently interrupted by fire. Here, fires provide diversity by creating a mosaic of age classes, life forms, and species. Lodgepole pine has been perpetuated through postglacial time by repeated fires. If fire is removed, we must face the critical question—can productive and viable lodgepole pine ecosystems be maintained? Proper management of lodgepole pine requires that we manage fire competently with full awareness of its biological effects.

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