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SILVICULTURE OF SUBALPINE FORESTS IN THE CENTRAL AND SOUTHERN ROCKY MOUNTAINS: The Status of Our Knowledge

by Robert R. Alexander

ABSTRACT

The status of our knowledge about the silviculture of subalpine forests in Wyoming, Colorado, and New Mexico is described. The ecology and resource of the Rocky Mountain subalpine are briefly described, followed by in-depth reviews of the spruce-fir type and lodgepole pine type. The relevant literature is included, along with unpublished research, observations, and experience. Research needs are considered as well as what is already known.

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SILVICULTURE OF SUBALPINE FORESTS IN THE CENTRAL AND SOUTHERN ROCKY MOUNTAINS: The Status of Our Knowledge

Robert R. Alexander

Timber management research in the subalpine forests of the central and southern Rocky Mountains has provided a large body of knowledge on the silvics, silviculture, and management of forest tree species during the past 50 or more years. Research results and observations have been presented as individual articles in a variety of publications. Furthermore, a few summary writeups for individual species have been published for specific areas of research. Included are (1) silvical characteristics (Alexander 1958a, 1958b; Strothmann and Zasada 1957; Tackle 1961a; U.S. Department of Agriculture [USDA] 1965), (2) regeneration requirements (Roe et al. 1970), (3) planting procedures (Ronco 1972), (4) partial cutting practices (Alexander 1972, 1973), and (5) general bibliographies (Christensen and Hunt 1965, Ronco 1961a, Tackle and Crossley 1953). In Canada, summary publications on regeneration, silvics, silviculture, and management have been prepared by Armit (1966), Dobbs (1972), and Smithers (1961).

Much of the existing knowledge is still not being used by land managers, however, because it is either not readily available or not in a form and language that can be easily understood. It is the purpose of this document, therefore, to assemble in one place a comprehensive summary of available knowledge on timber management applicable to Rocky Mountain subalpine forests. Included are (1) past research done in the central and southern Rocky Mountains, (2) work done elsewhere, but corroborated by observations in the central and southern Rockies, and (3) research done elsewhere, where similar information is lacking for subalpine forests. From these facts, ideas, and observations, guidelines are developed to answer the question "to what extent are we now able to recommend timber management practices to meet a variety of uses." The report is intended specifically as a field guide for professional foresters and land managers who are responsible for prescribing and supervising the application of silvicultural treatments in the woods.

In the following sections, the report will cover (1) the ecology and resource of the subalpine, and (2) the silvics, silviculture, and management of (a) the Engelmann spruce (*Picea engelmannii* Parry)- subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) type, and (b) the lodgepole pine (*Pinus contorta* Dougl.) type. The spruce-fir and lodgepole pine types have been handled in detail separately. There is some repetition of information common to both types, but each type was handled separately to facilitate the use of available information and recommended practices by foresters and land managers. Major emphasis is placed on the silviculture and management of old-growth, and the establishment of new stands.

Rocky Mountain Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) and quaking aspen (*Populus tremuloides* Michx.) also occur in the subalpine, but their ecology, silviculture, and management are described in another report on the mixed conifers of the Southwest.

THE ROCKY MOUNTAIN SUBALPINE

ECOLOGY

The subalpine is here defined as the highest forested area in the States of Wyoming, Colorado, and northern New Mexico (fig. 1). It may occur as low as 7,000 ft elevation in northern Wyoming to as high as 12,000 ft in northern New Mexico. These subalpine forests occupy what most ecologists call the subalpine zone (9,000 ft to timberline) and the upper montane zone (7,500 to 9,000 ft).

Habitat Conditions

CLIMATE

The continental climate of the central and southern Rocky Mountains is influenced by three principal air masses: (1) Storms move into the Rocky Mountains from the Pacific Ocean during winter and early spring, carrying relatively large amounts of moisture which are released on the western slopes as the air masses rise over the mountains (Johnson and Cline

Figure 1.—Distribution of spruce-fir and lodgepole pine in the central and southern Rocky Mountains.

1965, Marr 1961, USDA 1941). Only small amounts of moisture fall on the east slopes. These same storm fronts from the west pass too far north during the summer to provide much moisture. (2) Snowfall also occurs when polar continental air moves south parallel to and east of the Front Range during the winter and interrupts the normal westerly flow (Marr 1961). (3) Normally, the warm, moist air from the Gulf of Mexico moving upslope provides moisture along the east slope of the Rockies during the spring and early summer, but at elevations below the subalpine zone (Marr 1961). However, when the storm track from the west moves south through northern New Mexico and combines with or causes a northward flow of the Gulf air, the higher southern and eastern Rocky Mountains receive moisture (Johnson and Cline 1965). In addition, convective thunderstorms release some moisture in the high mountains during the summers.

The diverse topography in the Rocky Mountains results in various microclimates in the subalpine that change significantly over short distances. In general, temperature decreases and precipitation increases with an increase in elevation (Daubenmire 1943). Climatic records for subalpine areas are mostly from valley stations, but a few representative records for forested areas are provided by Baker (1944), Bates (1924), Haeffner (1971), and Marr et al. (1968).

The climate of the subalpine can be classified as cool and humid, with long, cold winters and short, cool summers (Alexander 1958a, Marr 1961, Thornthwaite 1948, Wilm and Dunford

1948). Mean annual temperature is below 35° F, and frost can occur any month of the year. Precipitation is usually greater than 24 inches annually. Most precipitation is received as snowfall, although the San Juan Mountains of southwestern Colorado and the mountains of northern New Mexico receive considerable summer rainfall. Winds are predominantly from the west, and may be highly destructive (Alexander 1954, 1964; Alexander and Buell 1955; Daubenmire 1943).

GEOLOGY AND RELIEF

With the exceptions noted below, the Rocky Mountains are anticlinal structures with igneous and metamorphic cores (Eardley 1962, Thornbury 1965).

The Absaroka Mountain Range in northwestern Wyoming extends in a north-south direction about 80 miles with an average width of 50 miles. It is not a linear uplift, but a broad plateau of volcanic breccia and basalt that has been deeply eroded leaving isolated, rugged mountain peaks. Glacial erosion has strongly etched the steep walls surrounding the mountain peaks (Eardley 1962, Fenneman 1931).

The Bighorn Mountains of north central Wyoming are an isolated spur of the Rocky Mountains. They are characterized by a central core of Precambrian granites and schists partly covered on the north and south by arched formations of sedimentary conglomerates that form elevated plateaus. Steeply inclined sedimentary strata flank the core on the east and west (Bowman 1911, Fenneman 1931).

The Wind River Mountains of western Wyoming are characterized by a central core of Precambrian crystalline rock. The subsummit uplands consist of granites. Older sedimentary rocks flank the mountains on the northeast side as high as 9,000 to 10,000 ft. Further to the east are foothills of sedimentary rock (Eardley 1962, Fenneman 1931).

The Front Range of the Rocky Mountains extends in a north-south direction from the Arkansas River in Colorado through the Medicine Bow Mountains in southern Wyoming (Thornbury 1965). It is characterized by a central core of Precambrian granites, schists, gneisses, and dolomites that may be largely concealed in some areas by glacial drift (Curtis 1960, Mears 1953, Oosting and Reed 1952, Thornbury 1965). Sedimentary rocks are locally present, but are not very important (Retzer 1962).

The plateaus of western Colorado consist of sedimentary strata that have been pushed upward without folding over a central core of Precambrian granites. The granite rocks are exposed where rivers have dissected the sedimentary rock. Masses of igneous rock — basalt, andesite, and rhyolite — protrude through the sedimentary mantle in places to interrupt the plateau feature of this area (Bowman 1911, Eardley 1962, Fenneman 1931).

The San Juan Mountains of southwestern Colorado are distinct from other mountain ranges in Colorado because they are predominantly volcanic lavas and tuffs over sedimentary rock (Cross and Larson 1935, Larson and Cross 1956). These mountains were carved by both glacial and water erosion from the volcanic mantle whose original surface had little relief (Fenneman 1931, Mather 1957). Precambrian granites are locally abundant (Stevens and Ratte 1964). The Jemez Mountains of north central New Mexico are an extension of the San Juan Mountains.

The Sangre de Cristo Range in southern Colorado and northern New Mexico resembles the Front Range. These mountains consist of a steep north-south anticlinal uplift of intrusive Precambrian granites flanked by sedimentary shales, sandstones, limestones, and conglomerates to the east and west that occasionally overreach the crest (Eardley 1962, Fenneman 1931).

SOILS AND LANDFORMS

There is only limited knowledge of the soils and landforms of the subalpine. Soils are young, and both soils and landforms complex. General descriptions and typical soil profile characteristics are given by Johnson and Cline (1965) and Retzer (1956, 1962), but the basic information on soils and landforms needed to determine the capability and suitability of forest land for different management activities is not available.

In the lower subalpine below 9,500 ft elevation, and in the upper montane, soil parent materials are varied and mixed. Glacial deposits, alluvial fan sediments, stream alluvium, and materials weathered in place from country rock predominate. Minor deposits of aeolian sediments occur locally. Crystalline rocks such as granite, gneiss, schist, granodiorite, and rhyolite are the principal bedrocks. Of the great soils groups of major importance, Grey Wooded soils are the most extensive and occur on all aspects. Brunizems are most frequently found under mixed grasslands and open timber on south slopes. Chestnut soils occur largely on south slopes at lower elevations. Brown Forest soils are found under open timber, on stream terraces, or alluvial fans, on all except north slopes. Humic Gley soils occur extensively in poorly drained upper ends of stream valleys in association with Bog soils. Lithosols are found whenever bedrock occurs near the surface (Johnson and Cline 1965).

In the upper subalpine above 9,500 ft, soil parent materials also vary according to the character of the bedrock from which they originated. Crystalline granitic rocks predominate, but conglomerates, shales, sandstones, basalts, and andesites commonly occur throughout the region. Most valleys have been glaciated, and glacial deposits are common. Of the great soils groups, Brown Podzolic and Classic Podzol soils occur extensively on all aspects. Groundwater Podzols are found in the more poorly drained areas. Grey Wooded soils are found where timber stands are less dense and parent materials finer textured. Brown Forest soils occur mostly at the lower margins of the upper subalpine, along stream terraces, and valley sideslopes. Lithosols, Bog, and Humic Gley soils occur under the same conditions as in the lower subalpine (Johnson and Cline 1965).

Vegetation

The diversity of habitats in the central and southern Rocky Mountain subalpine forests has long been recognized by foresters and ecologists, but the basic biological and ecological information needed to understand the vegetation associations that make up these forests, their requirements, and responses to management practices is limited. The early work of Rydberg (1915, 1916) provides a general and historical background as well as some information on specific geographical areas, and Bates (1924) discussed the general relationships of forest types.

LIFE ZONES

Altitudinal-vegetation zones have been a common way of differentiating vegetation (Daubenmire 1943, 1946, 1969; Marr 1961). In addition, there is a geographical zonation of tree species in the Rocky Mountain subalpine.

In the mountains of northern Wyoming, subalpine forests grow at elevations between 7,000 and 10,500 ft. Lodgepole pine is the principal species, but there are extensive stands of Engelmann spruce and subalpine fir above 9,500 ft. Common associates are aspen at all elevations, and Rocky Mountain Douglas-fir below 8,000 ft. Minor species include limber pine (*Pinus flexilis* James) and whitebark pine (*Pinus albicaulis* Engelm.)

In the mountains of southern Wyoming and north and central Colorado, subalpine forests are found between 8,000 and 11,500 ft elevation. Engelmann spruce and subalpine fir are the principal species above 9,000 ft on north-facing slopes and above 10,000 ft on all other slopes (Dix et al.[2], Langenheim 1962, Marr 1961.) Lodgepole pine covers extensive areas between 8,000 and 10,500 ft, but reaches maximum development on south- and west-facing slopes between 9,000 and 10,000 ft elevation (Dix et al.[2]). At lower elevations, it occurs in the Douglas-fir type (Daubenmire 1943). The characteristic zonal pattern of lodgepole pine is attributed primarily to moisture at lower elevations and temperature at higher elevations (Tackle 1965). Aspen also occupies extensive areas between 7,500 to 10,500 ft (Langenheim 1962, Marr 1961). Aspen occurs in nearly pure stands on all aspects between 8,000 and 9,000 ft, and on south slopes to 10,500 ft (Dix et al.[2]). Above 9,000 ft on north slopes it usually occurs as islands of trees in grassland and shrubland (Langenheim 1962, Morgan 1969). Douglas-fir below 8,500 ft, and limber pine and bristlecone pine (*Pinus aristata* Engel.) at higher elevations are minor components of these subalpine forests.

On the higher plateaus of western Colorado, the altitudinal range of subalpine forests is restricted by topography to between 9,000 and 10,500 ft. Spruce and fir are the principal species, and aspen the most common associate below 10,000 ft. Douglas-fir is the most important "minor" species, but limited areas of lodgepole pine do occur.

In southwestern Colorado and northern New Mexico, subalpine forests grow from 8,500 to 12,000 ft elevation. Spruce, subalpine fir, and corkbark fir (*Abies lasiocarpa* var. *arizonica* (Merriam) Lemm.) are the characteristic species above 8,500 ft on north slopes and 10,000 ft on south slopes. Douglas-fir grows between 8,500 and 9,500 ft, but does not form pure stands. In the Douglas-fir type, aspen and white fir (*Abies concolor* (Gord. and Glend.) Lindl.) are common associates and blue spruce (*Picea pungens* Engel.) and southwestern white pine (*Pinus strobiformis* Engel.) minor associates.

Throughout the Rocky Mountain subalpine, the upper limits grade into alpine tundra through an ecotone of Krummholz (Daubenmire 1943, Marr 1961, Patten 1963). Engelmann spruce is the dominant Krummholz species (Wardle 1968).

[2]*Dix, Ralph L., Ordel A. Steen, and Steven Whipple. 1972. A progress report on approaches to a classification scheme of subalpine forests of the southern Rocky Mountains. (Unpublished report by the Colo. State Univ. Dep. Bot. and Plant Pathol.; copy on file with study FS-RM-1201.27, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*

SUCCESSIONAL STATUS

In classifying mountain vegetation into elevational zones, most ecologists have considered the Engelmann spruce-subalpine fir community the climax vegetation above 9,000 ft, and Douglas-fir climax in the upper montane. The monoclimax theory proposes that all other communities in the subalpine will eventually converge into these two climaxes, which are limited only by regional climate (Clements 1936). Vegetation, however, is a function of topographic, physiographic, edaphic, and biotic factors as well as climate. Not only spruce-fir and Douglas-fir, but lodgepole pine and aspen seem to form stable communities in various habitats in the subalpine (Daubenmire 1943, Langenheim 1962, Mason 1915a, Moir 1969).

Although climax forests are not easily displaced by other vegetation, fire, logging, and insects have played an important part in the successional status and composition of spruce-fir forests. Complete removal of a spruce-fir stand by fire or logging results in such drastic environmental changes that spruce and fir are usually replaced by lodgepole pine, aspen, or shrub and grass communities (Roe et al. 1970, Stahelin 1943). The kind of vegetation initially occupying the site usually determines the length of time it takes to return to a spruce-fir forest. It may vary from as few as 50 years if the site is initially occupied by lodgepole pine or aspen to as many as 300 years if grass is the replacement community (fig. 2). However, the factors that determine the kind of replacement community are not fully understood (Bates 1917b, Marr 1961, Stahelin 1943). On the other hand, attacks by spruce beetles (*Dendroctonus rufipennis* (Kirby)) have usually resulted in a change in the dominant element in the stand from spruce to fir. Because of its larger size and longer life, spruce eventually regains its dominant position in the stand, only to be removed again by spruce beetles.[3]

Most foresters and ecologists agree that lodgepole pine is an aggressive pioneer and invader, and its occurrence is largely due to fire (Clements 1910, Stahelin 1943). There is less agreement on its successional status. Foresters consider lodgepole pine to be seral in stands that are only a temporary occupant of the site. In those situations, stands have either a mixed overstory composition or contain appreciable amounts of advanced reproduction of other species such as spruce, fir, or Douglas-fir. If mountain pine beetles (*Dendroctonus ponderosae* Hopk.) attack those stands, the larger lodgepole pines are removed, thereby shortening the time required for climax species to occupy the site. On the other hand, many lodgepole pine stands are the result of catastrophic fires, and some areas have burned so often and so extensively that large acreages are nearly pure

[3] *Schmid, J. M., and T. E. Hinds. Regrowth of spruce-fir stands following spruce beetle outbreaks. (Manuscript in preparation at Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*

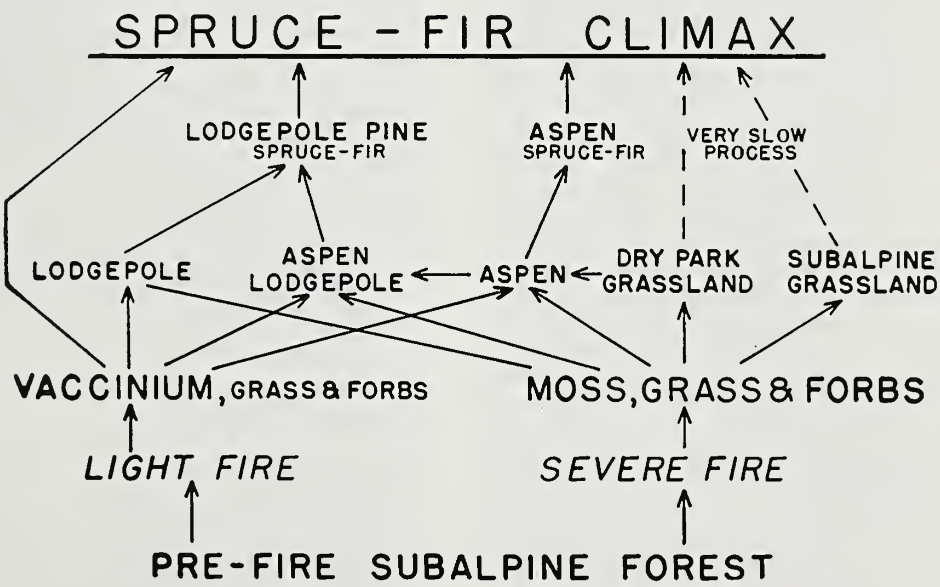

Figure 2.—Succession in subalpine forest after fire (Stahelin 1943).

pine. In those situations, lodgepole pine is maintained on the area as a subclimax because there is no seed for the normal climax species (Tackle 1961a, 1965). In other situations where lodgepole pine is held on an area by either natural or artificial means, it is also considered stable. One example of a naturally stable lodgepole community is along the east slopes of the Front Range at lower elevations. Douglas-fir, the climax species, does not reproduce itself in stands dominated by lodgepole pine because the sites are too dry (Moir 1969).

Aspen is also a pioneer species that becomes readily established by means of vigorous root suckers after disturbance (Baker 1925, Gifford 1966). It is generally considered a fire subclimax, successional to spruce and fir at higher elevations (Stahelin 1943) and Douglas-fir at lower elevations, although lodgepole pine may be an intermediate occupant of the site. However, Baker (1925) considered aspen a climax relative to management in its area of optimum development in western and southwestern Colorado. In other areas, aspen appears stable where there is either no conifer seed or the site is too dry for these species to become established.

Fire, insects, and logging have converted Douglas-fir stands to lodgepole pine, aspen, and grass and shrub communities in many places in the upper montane.

HABITAT TYPES

It is obvious that forest vegetation in the subalpine is not a simple mosaic that can be readily classified by vegetation zones. Rather it consists of a wide variety of integrated, disturbance-induced forest communities, many representing various stages of secondary succession that are difficult to treat except as developmental series related to either specific climaxes or stable plant communities. Daubenmire and Daubenmire (1968) define these relatively stable plant communities as habitat types, primarily on the basis of the relative reproductive success of trees because this indicates which species will become self-perpetuating dominants in the overstory. Habitat types are considered the basic ecological subdivisions of landscapes. Each has a distinctive potential as to successional stage, and is recognized by a distinctive overstory-understory combination (Daubenmire and Daubenmire 1968).

In northern Idaho and eastern Washington, Daubenmire and Daubenmire (1968) identified 21 habitat types, each with a distinct ecology. Subalpine fir occurs in 8 habitat types, usually as a major climax species, while spruce and lodgepole pine occur in 12, where they are considered to be successional to whatever species are climax in the particular habitat type. In western Montana, Pfister et al. (1972) using the same procedures, identified 30 habitat types. Subalpine fir occurs in 14, usually as a major climax species, while spruce and lodgepole pine occur mostly as seral species in 15 and 19 habitat types, respectively. Furthermore, management implications are keyed to each habitat type.

In the subalpine forests of Utah, Pfister (1972) identified four habitat types. Subalpine fir occurs in three as a major climax species. Spruce is a major climax species in the one habitat type where fir is missing, and a minor climax species in two others. Lodgepole pine occurs in two habitat types as a seral species. Regeneration systems are keyed to habitat types.

There have been few attempts to classify subalpine forest vegetation into habitat types in the central and southern Rocky Mountains; our knowledge of vegetation associations is fragmentary. Oosting and Reed (1952) recognized one habitat type, *Picea engelmannii-Vaccinium scoparium*, in the Medicine Bow Mountains of southern Wyoming, but their study was confined to a small area. Dye and Moir,[4] described the forest vegetation in spruce-fir forests near Sierra Blanca peak in southern New Mexico, but their observations were limited to a single habitat type, *Abies lasiocarpa-Ribes* spp./*Senecio sanguiosorboides*. Moir (1969, 1972) working in lodgepole pine forests that he considered to be climax along the east slope of the Front Range, identified two habitat types, *Pinus contorta-Vaccinium myrtillus* above 9,500 ft and *Pinus contorta-Geranium fremontii* on the drier slopes of the upper montane. Reed (1969) developed a classification using Daubenmire's procedures for the Wind River Mountains of northwestern Wyoming that recognized the following five habitat types:

1. *Pinus albicaulis-Potentilla diversifolia.* A topographic climax on upper elevation, exposed sites.
2. *Picea engelmannii-Vaccinium scoparium.* All upper slopes.
3. *Abies lasiocarpa-Pyrola secunda.* All slopes, mid-elevation.

[4]*Dye, A. J., and W. H. Moir. 1972. Spruce-fir forests at its southern distribution in the Rocky Mountains, New Mexico. (Unpublished report by the Colo. State Univ. Dep. Range Sci.; copy on file in project 1201, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*

4. *Pseudotsuga menziesii* (var. *glauca*) - *Symphoricarpos oreophilis.* Lower north- and east-facing slopes.
5. *Populus tremuloides-Symphoricarpos oreophilis.* Lower south- and west-facing slopes.

Almedia (1970) in a study of lodgepole pine understory vegetation in Wyoming, identified the following plant communities:

1. *Pinus-Vaccinium.*
2. *Pinus-Carex.*
3. *Pinus-Calamagrostis.*
4. *Pinus-Elymus.*

He described the floristic composition, changes in vegetation associated with grazing and succession, and the management implications in terms of forage yields and carrying capacity for each plant community.

Steen and Dix[5] worked on a phytosociological classification of subalpine forests in the Medicine Bow Mountains of Wyoming, along the Front Range, and in the San Juan Mountains of Colorado. They tentatively identified the following vegetation associations:

1. *Picea engelmannii-Vaccinium* spp. All slopes.
2. *Picea engelmannii-Polemonium delicatum.* Upper slopes.
3. *Picea engelmannii-Cardimine cordifolia/Mertensia ciliata.* Moist lower slopes.
4. *Pinus contorta-Pachistima myrsinites.* Dry mid to lower slopes.
5. *Abies lasiocarpa-Carex geyeri/Pachistima myrsinites.* Drier midslopes.
6. *Abies lasiocarpa-Moss* spp. Dry midslopes.
7. *Populus tremuloides-Symphoricarpos* spp. Dry lower slopes.
8. *Populus tremuloides-Thalictrum fendleri.* Mid south-facing slopes.
9. *Populus tremuloides-Festuca thurberi.* Drier upper south-facing slopes.

Wirsing,[6] working on a classification of the Medicine Bow Mountains of southern Wyoming and using Daubenmire's procedures, has tentatively identified the following habitat types:

[5]*Steen, Ordel A., and Ralph L. Dix. 1972. A preliminary classification of subalpine forests in the southern Rocky Mountains. (Unpublished report by the Colo. State Univ. Dep. Bot. and Plant Pathol.; copy on file with study FS-RM-1201.27, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*

[6]*Wirsing, John M. 1973. Forest vegetation in southwestern Wyoming. M.S. thesis, 170 p. Wash. State Univ., Pullman.*

1. *Populus tremuloides-Carex geyeri.* Lower to middle south slopes.
2. *Picea engelmannii/Abies lasiocarpa-Vaccinium scoparium.* Mid to upper slopes.
   a. *Sibbaldia/Bistorta* phase (weakly defined).
   b. *Pinus contorta-Vaccinium scoparium.* (community or seral type).
3. *Picea engelmannii/Abies lasiocarpa-Carex geyeri.* Midslopes.
   a. *Pinus contorta-Carex geyeri.* (community or seral type).
4. *Pinus flexilis-Hesperochloa kingii.* Topographic climax within *Picea/Abies* habitat type.
   a. *Koeleria cristata* phase. Upper southwest-facing slopes and ridgetops.
   b. *Pulsatilla ludoviciana* phase. Drier, upper southwest-facing slopes and ridgetops.
5. *Pinus ponderosa-Carex geyeri.* Lower slopes.
   a. *Sedum lanceolatum* phase. Drier lower slopes.
   b. *Lupinus argenteus* phase. Well-drained lower slopes.

Habitat conditions in the central and southern Rocky mountains are much more diverse. The wise management of this resource will require a common system of classifying all forest lands into units of like biological potential as a means of (1) recognizing plant associations, (2) determining what species grow together, how they reproduce, and grow, and (3) anticipating their response in terms of successional trends and stability when subjected to different management prescriptions. Furthermore, the vegetation classification should be integrated with soils and landforms to provide capability and suitability classes for a variety of uses.

THE RESOURCE

Area and Volume

The subalpine forests are the largest and most valuable timber resource in Colorado and Wyoming. They are less important in terms of total commercial forest land and sawtimber volume in New Mexico.

In Wyoming, lodgepole pine grows on about half of the commercial forest land in the subalpine (table 1). Engelmann spruce and subalpine fir are second in importance in land area, followed by Rocky Mountain Douglas-fir and aspen. However, spruce-fir forests contain the largest volume of sawtimber in Wyoming. Lodgepole pine is second, followed by Douglas-fir and aspen (Choate 1963).

In Colorado, spruce-fir forests occupy only about one-third of the commercial forest land, but contain nearly 70 percent of the sawtimber volume in the subalpine (table 1). Aspen accounts for more of the commercial forest land than either lodgepole pine or Douglas-fir, but less sawtimber volume (Miller and Choate 1964).

In New Mexico, Rocky Mountain Douglas-fir grows on about half of the commercial forest land in the subalpine, but it seldom grows in pure stands (table 1). Spruce and true firs occupy the second largest area of commercial subalpine forests, followed by aspen. About 10 percent of the sawtimber volume is in aspen; the remaining 90 percent is about equally divided between spruce and the true firs, and Douglas-fir (Choate 1966).

One of the features of the spruce-fir and Douglas-fir forests throughout the Rocky Mountain subalpine is the imbalance in age-class distribution (table 2). The largest proportion of area is in sawtimber-sized stands, and the smallest in seedling and sapling stands. The imbalance in age-class distribution is not as serious in lodgepole pine and aspen forests, but many of the pole-sized timber stands are either overmature or growing on sites that are not likely to produce a sawtimber-sized tree.

The acreage, volume, and stocking class data in tables 1 and 2 are only approximate. They are based on Forest Survey estimates made more than 10 years ago, and a recent study (Wikstrom and Hutchison 1971) indicates that too much area was included in the timber growing base because of inadequate information on land availability, growth capacity, and land capability. Furthermore, some of the area available and suitable for timber growing is either technologically or economically unusable at the present time (Wikstrom and Hutchison 1971).

Properties and Uses of Wood

Engelmann spruce is one of the lightest of the important commercial woods in the United States. The wood is generally straight grained, has moderately small shrinkage, can be readily air dried, and is a uniform color (McSwain et al. 1970). It is rated low in beam and post strength and in shock resistance (USDA 1955). The wood is soft and machines well for ordinary uses. It has good nail-holding properties, glues well, and is easy to work, but paint-holding properties are only average. If sufficient time is allowed, the lumber can be kiln dried without difficulty. The heartwood and sapwood are not durable when used under conditions favorable to decay. Spruce is considered somewhat resistant to preservative treatment; however, crossties have been successfully pressure treated for many years (Anderson 1956). Subalpine fir wood is light in weight, low in bending and compressive strength, moderately limber, soft, and low in resistance to shock. Shrinkage of wood is rated small to moderately large (USDA 1955).

The lumber of spruce is likely to contain many small knots. Consequently, it yields only minor amounts of select grades of lumber, but a relatively high proportion in the common grades (Mueller and Barger 1963). In the past, spruce was used principally for mine timbers, railroad ties, and poles. Today much of the lumber of both spruce and fir is used in home construction where high strength is not required, and for

Table 1.--Acreage and volume (International 1/4-inch log scale) of sawtimber on commercial forests in the central and southern Rocky Mountains, by species and States

Species	Colorado		Wyoming		New Mexico		Arizona		South Dakota	
	M acres	*MM bm*	*M acres*	*MM bm*	*M acres*	*MM bm*	*M acres*	*MM bm*	*M acres*	*MM bm*
Engelmann spruce and true firs	3,393	33,260	847	9,541	525	5,257	110	2,147	0	0
Ponderosa pine	2,347	3,783	992	2,072	4,334	16,188	3,658	22,883	1,330	3,268
Douglas-fir	1,451	5,411	701	3,566	1,000	5,025	130	1,476	0	0
Lodgepole pine	2,068	6,024	1,802	5,798	0	0	0	0	--	--
White pines	139	472	166	1,256	43	640	--	186	--	--
White spruce	0	0	--	13	0	0	0	0	23	201
Aspen	2,794	3,482	320	159	367	1,233	79	259	0	0
Total	12,275	52,731	4,853	22,632	6,269	28,343	3,977	26,951	1,534	3,716

Table 2.--Percentage of commercial forest land area in the central and southern Rocky Mountains, by species, stocking classes, and States

Species and stocking class	Colorado	Wyoming	New Mexico	Arizona	South Dakota
Engelmann spruce and true firs:					
Sawtimber	81	82	85	100	0
Poletimber	14	14	5	--	0
Seedlings and saplings	1	1.5	7.5	--	0
Nonstocked	4	2.5	2.5	--	0
Ponderosa pine:					
Sawtimber	64	73	90	95	53
Poletimber	23	20	3.5	2.5	41.5
Seedlings and saplings	1	3	2	1	4.5
Nonstocked	12	4	4.5	1.5	1
Douglas-fir:					
Sawtimber	72	72	90	100	0
Poletimber	27	22	8.5	--	0
Seedlings and saplings	0.5	3	--	--	0
Nonstocked	0.5	3	1.5	--	0
Lodgepole pine:					
Sawtimber	34	47	0	0	0
Poletimber	60	45	0	0	0
Seedlings and saplings	5	6.5	0	0	0
Nonstocked	1	1.5	0	0	0
White pines:					
Sawtimber	45	46	100	0	0
Poletimber	52	44	--	0	0
Seedlings and saplings	2	6	--	0	0
Nonstocked	1	4	--	0	0
White spruce:					
Sawtimber	--	100	0	0	100
Poletimber	--	--	0	0	--
Seedlings and saplings	--	--	0	0	--
Nonstocked	--	--	0	0	--
Aspen:					
Sawtimber	7	18	49	44.5	0
Poletimber	80	57	43.5	49.5	0
Seedlings and saplings	13	16	7.5	6	0
Nonstocked	--	--	--	--	0

prefabricated wood products. In recent years, rotary cut spruce veneer has been used in plywood manufacture. Other uses of spruce include specialty items such as violins and pianos and in aircraft construction (Anderson 1956, McSwain et al. 1970). Spruce and fir have not been used much for pulp and paper, but their pulping properties are excellent. Long fibers, light color, and absence of resins permit them to be pulped readily by the sulfite, sulfate, or groundwood processes (Anderson 1956, USDA 1955).

Lodgepole pine wood is generally straight, but uneven grained. The wood is moderately soft, moderately weak in bending and edgewise compression, moderately low in shock resistance, easy to work, easy to glue, and average in paint-holding ability. It holds nails or screws moderately well, shrinks moderately, but seasons easily. It is not durable under conditions that favor decay. Lodgepole pine yields mostly narrow boards and little select grades of lumber, but a high proportion of Grade 3 Common or better (Kotok 1971).

Lodgepole pine was once used primarily for railroad ties, mine timbers, and rough construction lumber. Today much of the lumber is used in light frame construction, particularly as 2- by 4-inch, 8-foot studs. It is especially valued for knotty pine paneling and cabinets because of its uniform color, small tight knots, and dimpled surface. Lodgepole pine is easily pressure treated and is used extensively for fenceposts, corral poles, and transmission and telephone poles. Its pulping properties are good and it can be readily pulped by the sulfate and groundwood processes (Kotok 1971).

THE SPRUCE-FIR TYPE

STAND CONDITIONS

Old-growth spruce-fir forests grow on a wide range of sites with a great diversity of stand conditions and characteristics. This diversity complicates the development of silvicultural systems needed to convert old-growth to managed stands for a variety of uses. For example, spruce-fir forests are the dominant elements in a number of near-climax vegetation associations throughout the central and southern Rocky Mountains, but they do not have the age-class structure of true climax forests. Some stands are clearly single-storied, indicating that desirable spruce forests can be grown under even-aged management. Others are two- or three-storied, and multi-storied stands are not uncommon (Alexander 1973, LeBarron and Jemison 1953, Miller 1970). These later stands may be the result of either past disturbances such as fire, insect epidemics, or cutting, or the gradual deterioration of old-growth stands associated with normal mortality from wind, insects, and diseases. The latter circumstance is especially evident in the formation of some multi-storied stands. On the other hand, some multi-storied stands appear to have originated as uneven-aged stands, and are successfully perpetuating this age-class structure.

The composition of spruce-fir forests varies considerably with elevation. At mid elevations (10,000 to 11,000 ft), these forests are frequently pure spruce in the overstory with fir predominating in the understory. For example, in the central Rocky Mountains spruce commonly makes up 70 percent or more of the overstory basal area, and fir from two-thirds to three-fourths of the understory and advanced reproduction (Alexander 1957a, 1963; Hodson and Foster 1910, Oosting and Reed 1952). This composition in relation to structure has developed under natural conditions because spruce is more exacting in its seedbed requirements and less able to compete with fir under low light intensities common to dense forests. Once established, however, spruce lives longer than fir and is less susceptible to disease (Alexander 1958a, 1958b). Exceptions are in stands attacked by spruce beetles, where fir is the dominant element in both the overstory and understory (see footnote 3).

At higher elevations, spruce may form essentially pure stands while at lower elevations where sites are usually drier, the density of spruce relative to fir may be low. In these latter situations, lodgepole pine is frequently more numerous in the overstory than spruce (see footnote 2).

Advanced spruce and fir reproduction is likely to be older than it appears because the early growth of both is slow. Spruce commonly takes from 20 to 40 years to reach a height of 4 to 5 ft, even under favorable conditions, whereas under a dense canopy, spruces 4 to 6 ft tall may be 75 or more years old (Oosting and Reed 1952). Spruce and fir reproduction suppressed for long periods of time will respond to release, however, and make acceptable growth (Alexander 1973).

PAST CUTTING HISTORY

Limited areas of the original spruce-fir forests were logged in the late 1800's to provide fuel, lumber, and timbers for early mining camps. Cutting on the National Forests dates back more than 50 years, but until the 1950's only relatively small quantities of timber were harvested. Cutting has accelerated rapidly since.

Most cuttings in spruce-fir forests before 1950 in the central and southern Rocky Mountains were of a type that could be collectively called "partial cuttings." They ranged from removal of a few individual trees to removal of all the larger, more valuable trees in the stand. Seedbed preparation was usually limited to the disturbance created by logging, and slash was untreated or lopped. Most skidding was done with horses.

In general, heavy partial cutting — usually considered necessary to make logging profitable — was not successful as a means of arresting stand deterioration or increasing net increment on residual trees. For example, residual stands of spruce-fir in Colorado suffered heavy mortality when 60 percent of the original volume was removed by individual-tree selection (Alexander 1956a, 1963) (fig. 3). Net increment was only about one-third of that in uncut stands. Similar results followed heavy partial cutting elsewhere in the central Rocky Mountains (USDA Forest Service [USDA-FS] 1933),

Figure 3.—Individual-tree selection cutting that removed 60 percent of the volume in spruce-fir. Blowdown losses were heavy because the original dense stand was opened up too much. Fraser Experimental Forest, Colorado.

and in the northern Rockies (Roe and DeJarnette 1965). Even when mortality was not a problem, heavy partial cutting left the older, decadent stands in a shabby condition, with little appearance of permanent forest cover.

Windfall, the principal cause of mortality, increased as the intensity of cutting increased. Low stumpage values and the generally scattered pattern of windfall usually prevented salvage of blowdown after partial cutting. Not only was the volume of windthrown trees lost, but the combination of down spruce and overstory shade provided breeding grounds for spruce beetles.

Partial cutting was successful — in the sense that the residual stand did not suffer heavy mortality — in some spruce-fir stands where large reserve volumes were left in protected locations. In one study in northern Idaho, windfall losses were light after a partial cutting that left a residual stand of 6,000 board ft (fbm) per acre in a sheltered location on deep, well-drained soil (Roe and DeJarnette 1965). On the Grand Mesa National Forest in Colorado, where spruce trees are relatively short and there are no serious wind problems associated with topography, few trees blew down when about 40 percent of the original volume was removed from two-storied stands. In single-storied stands, however, only about 30 percent of the original volume could be safely removed. On the other hand, heavier partial cutting that removed 50 percent or more of the original volumes per acre from spruce-fir forests in the dry "rain shadow" of the Continental Divide on the Rio Grande National Forest did not result in blowdown to the residual stand. However, these two-storied stands were growing on sites where productivity was very low. Individual trees were short, widely spaced, and therefore relatively windfirm before cutting.

There are also numerous examples of early cuttings — between 1910 and 1930 — on many National Forests in Colorado where very light partial cutting — removal of 10 to 15 percent of the stand — did not result in substantial windthrow of residual trees.

Although an overstory tends to favor fir reproduction over spruce, regeneration success of spruce has been acceptable under a wide variety of partial cutting treatments (Alexander 1963, Roe and DeJarnette 1965).

In the early 1950's harvesting shifted to clearcutting. The first clearcuttings were in narrow strips (200 to 400 ft wide) or small patches, with little seedbed preparation or slash disposal (fig. 4). Advanced regeneration was not completely destroyed. In general, windfall losses were less than after heavy partial cutting, and the cutovers were usually adequately re-

Figure 4.—Clearcutting that removed 50 percent of the volume in narrow, alternate strips in spruce-fir. Fraser Experimental Forest, Colorado.

stocked with a combination of surviving advanced and new reproduction (Alexander 1956a, 1957a, 1963, 1966d, 1968; Averill and Andrews 1964). By the late 1950's, the common practice was to clearcut in large blocks, patches, or wide strips. These larger openings were justified as being more effective in controlling spruce beetles and in reducing logging costs. Slash and cull material were either broadcast burned, dozer-piled, or windrowed and burned. Hazards from fire and insects were reduced, but removal of all slash, cull material, and residual trees left the seedbeds devoid of shade, thereby creating a difficult microenvironment for the establishment of either natural or artificial regeneration (Roe et al. 1970, Ronco 1970a). Furthermore, the destruction of advanced reproduction was usually an unnecessary loss of valuable growing stock.

Today, after nearly 20 years of harvesting spruce-fir almost exclusively by clearcutting, there is a shift in cutting practices to either some form of partial cutting or a combination of partial cutting and small cleared openings without complete cleanup of slash and other logging debris (Alexander 1973). This shift was necessary because clearcutting large areas often (1) resulted in adverse visual and environmental impacts, (2) was incompatible with the objectives of other forest uses, and (3) led to regeneration failures.

DAMAGING AGENTS

Windfall

Windfall is a common cause of mortality after any kind of initial cutting in old-growth spruce-fir forests, but partial cutting increases the risk because the entire stand is opened up and therefore vulnerable. Windfall is usually less around clearcuts because only the boundaries between cut and leave areas are vulnerable, but losses can be substantial if no special effort is made to locate windfirm cutting unit boundaries (Alexander 1964, 1967b).

While the tendency of spruce to windthrow is usually attributed to a shallow root system, the development of the root system varies with soil and stand conditions. On medium to deep, well-drained soils, trees have a better root system than on shallow, poorly drained soils. Trees that have developed together in dense stands over long periods of time mutually protect each other, and do not have the roots, boles, or crowns to withstand sudden exposure to wind if opened up too drastically. If the roots and boles are defective, the risk of windthrow is increased. The presence of old windfalls in a stand is a good indicator of lack of windfirmness. Furthermore, regardless of the kind or intensity of cutting, or soil and stand conditions, windthrow is greater on some exposures than others (Alexander 1964, 1967b, 1973). Exposures where windfall risk is below average, above average, or very high have been identified as follows:

Below Average
1. Valley bottoms, except where parallel to the direction of prevailing winds, and flat areas.
2. All lower, and gentle middle north- and east-facing slopes.
3. All lower, and gentle middle south- and west-facing slopes that are protected from the wind by considerably higher ground not far to windward.

Above Average
1. Valley bottoms parallel to the direction of prevailing winds.
2. Gentle middle south and west slopes not protected to the windward.
3. Moderate to steep middle, and all upper north- and east-facing slopes.
4. Moderate to steep middle south- and west-facing slopes protected by considerably higher ground not far to windward.

Very High
1. Ridgetops.
2. Saddles in ridges.
3. Moderate to steep middle south- and west-facing slopes not protected to the windward.
4. All upper south- and west-facing slopes.

The risk of windfall in these situations is increased at least one category by such factors as poor drainage, shallow soils, defective roots and boles, and overly dense stands. Conversely, the risk of windfall is reduced if the stand is open grown or composed of young, vigorous, sound trees. All situations become very **high risk** if exposed to special topographic situations such as gaps or saddles in ridges at higher elevations to the windward that can funnel winds into the area.

Insects

Keen (1952) lists a large number of insect pests of Engelmann spruce. Of these, the spruce beetle (*Dendroctonus rufipennis* (Kirby)) is the most serious. It is restricted largely to mature and overmature spruce, and epidemics have occurred throughout recorded history (Hopkins 1909, Massey and Wygant 1954). The most damaging recorded outbreak was in Colorado from 1939-51, when beetles killed nearly 4 billion fbm of standing spruce (fig. 5). Damaging attacks have been largely associated with extensive windthrow, where down trees have provided an ample food supply needed for a rapid buildup of beetle populations (Massey and Wygant 1954, Wygant 1958). Cull material left after logging has also started outbreaks, and there are examples of heavy spruce beetle populations developing in scattered trees windthrown after heavy partial cutting. The

Figure 5.—Beetle-killed spruce stand. White River National Forest, Colorado.

beetle progeny then emerge to attack living trees, sometimes seriously damaging the residual stand. Occasionally heavy spruce beetle outbreaks have developed in overmature stands with no recent history of cutting or windfall, but losses in uncut stands that have not been subjected to catastrophic windstorms have usually been no greater than normal mortality in old growth (Alexander 1973).

Spruce beetles feed and breed in the phloem layer. The first evidence of attack is the red boring dust from entrance holes that usually accumulates in bark crevices on the boles and around the bases of infested trees. The needles of killed trees usually turn a yellowish green and fall about 1 year after attack, but they may remain green until the second year (Schmid and Beckwith 1971).

Overmature trees are attacked first, but if an infestation persists, beetles will attack and kill smaller diameter trees after the larger trees in the stand are killed. In the central Rocky Mountains, susceptibility of spruce stands in relation to location decreases in the following order: (1) trees in creek bottoms, (2) better stands on benches and high ridges, (3) poorer stands on benches and high ridges, (4) mixed stands, and (5) immature stands (Knight et al. 1956, Schmid and Beckwith 1971). Analysis of past infestations suggests the following characteristics are associated with potential outbreaks: (1) single- or two-storied stands, (2) high proportions of spruce in the overstory, (3) basal area of 150 ft^2 per acre or more in the older and larger trees, and (4) an average 10-year periodic diameter growth of 0.4 inch or less (see footnote 3).

Natural factors such as nematodes, insect parasites and predators, and woodpeckers normally maintain beetle populations at low levels, but generally fail to control populations under outbreak conditions. Extremely low temperature can eliminate beetle infestations, however, if the insect has not developed cold-hardiness. Temperatures of -15° F under the bark will kill nearly all adults, while -30° F will kill the larvae (Schmid and Beckwith 1971). Chemical control is expensive and only a holding action until potentially susceptible trees can be disposed of. In infested stands, or those with potential beetle problems, felling and salvaging attacked or susceptible trees, and disposing of green cull material is the most effective silvicultural control. Partial cutting that removes the larger overmature trees and releases the younger trees is another way to reduce potential insect problems in stands with a good stocking of trees in the smaller diameter classes. "Trap trees" intentionally felled prior to beetle flight are highly attractive, and often provide an effective way of concentrating and trapping spruce beetles (Nagel et al. 1957). After the beetles enter the downed logs, they are usually salvaged, but may be chemically treated or burned (Schmid and Beckwith 1971). Lethal traps in which cacodylic acid is used to prevent brood development in trap trees appears to be a potentially useful refinement to the regular trap-tree approach (Buffam et al. 1973).

The western spruce budworm (*Choristoneura occidentalis* Freeman) is another potentially dangerous insect attacking Engelmann spruce (Whiteside and Carolin 1961). Subalpine fir is attacked by several groups of insects (Keen 1952), the most important of which are the western spruce budworm and the fir engraver (*Scolytus ventralis* Lec.). The western balsam bark beetle (*Dryocoetes confusus* Sw.) may at times be very destructive locally (Stevens 1971).

Diseases

The most common diseases in spruce-fir stands are caused by wood-rotting fungi that result in loss of volume (Hinds and Hawksworth 1966, Hornibrook 1950) and predispose trees to windthrow and windbreak (Alexander 1964, 1967b). In a recent study of cull indicators and associated decay in Colorado, Hinds and Hawksworth (1966) identified the major root and butt fungi in mature to overmature Engelmann spruce as *Fomes nigrolimitatus* (Rom.) Engel., *Pholiota alnicola* (Fr.) Singer, *Polyporus tomentosus* Fr., *Corticium radiosum* (Fr.) Fr., and *Coniophora puteana* (Schum ex. Fr.) Karst. Trunk rots which caused 88 percent of the decay were associated with *Fomes pini* (Fr.) Karst, *Stereum sanguinolentum* (Alb. and Schw. ex. Fr.) Fr., *S. sulcatum* Burt. and *S. chailletii* (Pers. ex. Fr.) Fr. Hinds and Hawksworth (1966) have provided a means of estimating defect in standing spruce based on the average amount of cull. Most cull was associated with specific indicators that were grouped into three classes. Cull deductions for these indicators are shown below:

Indicator type	Decay as a proportion of gross volume
	(Percent)
1. *Fomes pini* knots or sporophores	81
2. Broken tops with adjacent dead brooms	24
3. Basal wounds, dead broom rusts, dead leader, frost cracks, forks, joined at base, spiketop on trunk wounds	10

Decay in relation to age, diameter, and site quality have been determined for subalpine fir in Colorado (Hinds et al. 1960). Important root and butt rot fungi are *Corticium radiosum* (Fr.) Fr., *Coniophora puteana* (Fr.) Karst, *Armillaria mellea* (Fr.) Quel., *Coniophora olivacea* (Fr.) Karst, *Pholiota squarrosa* (Fr.) Kummer, and *Polyporus tomentosus* Fr. *Stereum sanguinolentum* (Fr.) Fr., *Fomes pini* (Fr.) Karst, and *S. chailletii* (Fr.) Fr. are responsible for most trunk rot.

Spruce broom rust (*Chrysomyxa arctostaphyli* Diet.) and fir broom rust (*Melampsorella caryophyllacearum* Schroet.) are also common in spruce-fir forests. They cause bole deformation, loss of volume, spiketops, and windbreak, and provide infection courts for decay fungi (Peterson 1963).

NATURAL REGENERATION REQUIREMENTS

A supply of viable seed, a suitable seedbed, and an environment compatible with germination and seedling establishment are the basic elements necessary for successful regeneration (Roe et al. 1970). If one of these elements is missing, regeneration fails (fig. 6).

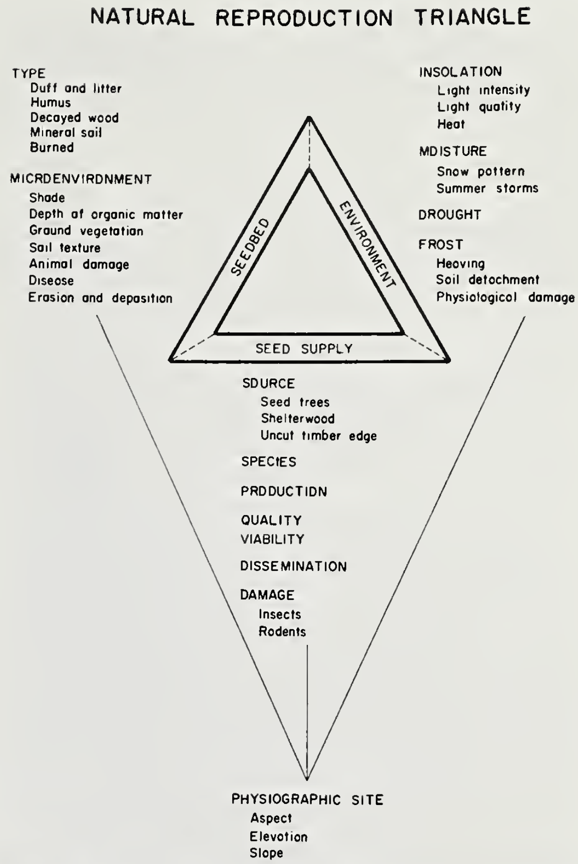

Figure 6.—Factors affecting spruce seedling survival and establishment (Roe et al. 1970).

Seed Supply

FLOWERING AND FRUITING

Male flowers of both spruce and fir ripen and pollen is wind disseminated in late spring or early summer. Cones mature and seed ripens from late August to early October the first year (Alexander 1958a, 1958b; USDA-FS 1948).

CONE-BEARING AGE

Although cones have been observed on open-grown spruces and firs when they are about 4 to 5 ft tall and from 15 to 40 years old, seed production does not become significant until the trees are larger and older. The most abundant crops in natural stands are produced on healthy, vigorous, dominant trees 100 to 250 years old (Alexander 1958a, 1958b; USDA-FS 1948).

TIME OF SEEDFALL

Natural seedfall in spruce stands begins in early September and continues through the winter, but only minor amounts of seed fall before mid-September. In 1 year on the Fraser Experimental Forest in Colorado, about half of the total sound seed was released before the end of September.[7] In a good seed year in the Intermountain Region, from two-thirds to three-fourths of the total sound seed was released by October 20 on two areas, but only about one-third of the total sound seed was released by that date on a third area (Roe 1967).

Subalpine fir seedfall begins in early September and is usually completed by the end of October (Alexander 1958b).

CONE-CROP PREDICTABILITY

The ability to estimate the size of the cone crop well in advance would be important to the forest manager, because it would provide the basis for scheduling harvesting operations, seedbed preparation for natural reproduction,

[7]*Unpublished data on file with study FS-RM-1201.24, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

and seed collection (Dobbs 1972). Several ways have been suggested as a means of estimating potential cone crop size for other species, but no method has been developed for spruce.

PRODUCTION AND PERIODICITY

Engelmann spruce is rated a moderate seed producer, and seed crops vary considerably from year to year. Infrequent seed crops means that natural reproduction cannot be expected every year.

In an early study in Colorado, average annual seed production on the White River Plateau for an 18-year period (1914-31) was 83,000 sound seeds per acre, while on the Uncompaghre Plateau, annual seed production for a comparable 15-year period (1914-28) averaged 350,000 sound seeds per acre (USDA-FS 1933). Good seed crops (100,000 or more sound seeds per acre) were produced on the White River only at 5- to 7-year intervals, with complete failures about every 2 years. On the Uncompaghre, good crops were produced every 2 to 4 years, with complete failures at about 3-year intervals. In a study on the Fraser Experimental Forest in Colorado, annual seed production averaged only 32,100 sound seeds per acre during the period 1956-65 (Alexander 1969). Only one good and two moderate (50,000 to 100,000 sound seeds per acre) crops were recorded. Seed production was also observed on five National Forests in Colorado for the period 1961-67. In one year (1967) a bumper seed crop was produced on all areas. Seed production, varying from 845,000 to 5,340,000 sound seeds per acre, was the highest ever recorded in the central Rocky Mountains (Ronco and Noble 1971). In the other years of the study, some seed was produced each year, but good crops occurred only once in 4 to 5 years on three of the areas, and in 2 of 6 years on the other two areas (Ronco 1970b). Furthermore, these good crops did not occur in the same years on all areas.

Similar results for spruce have been reported from the northern Rocky Mountains. Boe (1954) analyzed cone crops in Montana between the years 1908 and 1953. He reported that 22 crops observed during the 45-year period west of the Continental Divide were rated as 5 good, 8 fair, and 9 poor. East of the Divide, seed production was poorer; only 2 good, 4 fair, and 15 poor crops were reported for a 21-year period. Seed production in 1952 in western Montana was estimated at 953,000 sound seeds per acre (Squillace 1954), but this was in a bumper year. Seed crops in the other 4 years of record were failures. Seed production in a good year (1964) on three areas in the Intermountain Region ranged from 200,000 to 2 million sound seeds per acre (Roe 1967). Seed production in the other 4 years of observation were also rated failures.

Subalpine fir seed production has not been studied in the central and southern Rocky Mountains. Elsewhere in the Rocky Mountains, it has been rated a prolific seed producer, with good crops borne every 3 years with light crops in between (LeBarron and Jemison 1953, USDA-FS 1948). In one study in the Cascade Mountains of Washington and Oregon, fir produced light to very heavy cone crops about every 3 years with failures in the intervening years (Franklin 1968). Observations in the central Rocky Mountains indicate that fir is not that good a seed producer, and failures are more common than good seed years.

SEED QUALITY

Variability in seed quality accentuates differences in seed production. The proportion of sound seed is usually highest in years of highest seed production. In the central Rocky Mountains, 70 to 90 percent of the seed produced in the bumper seed year of 1967 was sound.[8] In years of moderate to good crops, 30 to 50 percent were sound, and in other years, 10 to 30 percent were sound.

DISPERSAL

Spruce seed is light, averaging about 135,000 seeds per pound, and disperses long distances. In one study in Colorado,[8] as many as 96,000 sound seeds per acre were dispersed as far as 400 ft from standing timber into a clearcut block. In western Montana, significant quantities of seed (60,000 sound seed per acre) were dispersed as far as 600 ft from timber edge into a large clearcut block (Squillace 1954). These dispersals occurred only during a bumper (1952) and record (1967) seed year, however (Ronco and Noble 1971, Squillace 1954). Seedfall into cleared openings in Colorado that varied from about 130 to 850 ft wide, diminished as distance from seed source increased; most seeds fell within 100 to 150 ft of standing timber (Alexander 1969, Ronco 1970b, Ronco and Noble 1971). Prevailing winds influenced the pattern of seedfall on areas larger than 200 ft wide. In years of significant seed production, about half of the total number of sound seeds dispersed fell within 150 ft of the windward timber edge. Seedfall then

[8]*Unpublished data on file with study FS-RM-1201.13, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

diminished steadily as distance increased to about two-thirds of the way across the openings. At this distance the average number of sound seeds falling was about 10 percent of the number released in the uncut stands. Beyond this point, seedfall gradually increased toward the leeward timber edge (fig. 7).

In the Intermountain and Northern Rocky Mountain Regions, spruce seed dissemination on four areas in good seed years also diminished from timber edge into openings (Roe 1967). Seed was dispersed in significant quantities (0.5 to nearly 5 percent of the total released under the uncut stand) as far as 660 ft where a heavy seed source was present, (193 ft^2 of basal area in Engelmann spruce trees 10.0 inches d.b.h. and larger), but the dispersal winds were too variable to show definite directional patterns. Lighter seed sources, 70 ft^2 of basal area or less, dispersed fewer seeds for shorter distances. Smaller openings are required with lighter seed sources to insure adequate seedfall on all parts of the opening, otherwise the areas beyond the reach of adequate natural seeding must be artificially reforested (Roe 1967).

Just because seed can be dispersed long distances is not enough. Large quantities of seed will not restock harsh or incompatible environments (Roe et al. 1970). For example, seedfall that averaged 1.8 million sound seeds per acre over the entire opening on one area in Colorado did not result in adequate restocking because of unfavorable seedbeds and adverse environmental conditions: intense solar radiation and high temperatures, low temperatures and frost heaving, and drying winds (Ronco and Noble 1971).The effective seeding distance, defined by Roe et al. (1970) as the distance over which sufficient sound seed is dispersed to stock an area to an acceptable level under prevailing conditions, is more meaningful than mere seed dispersal distance.

A current study[9] of field germination on the Fraser Experimental Forest in Colorado has indicated that, on north slopes under favorable seedbed and environmental conditions (shaded, mineral soil), at least 20,000 sound seeds per acre are needed to provide 1,000 seedlings surviving at the end of the first growing season. That seedfall is not likely to occur beyond about 300 ft from a windward seed source except in years of bumper seed production. Furthermore, seedling mortality will continue to reduce initial first-year stocking for at least 5 years. Therefore, adequate restocking is not likely to result

[9]*Unpublished data on file with study FS-RM-1201.20, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

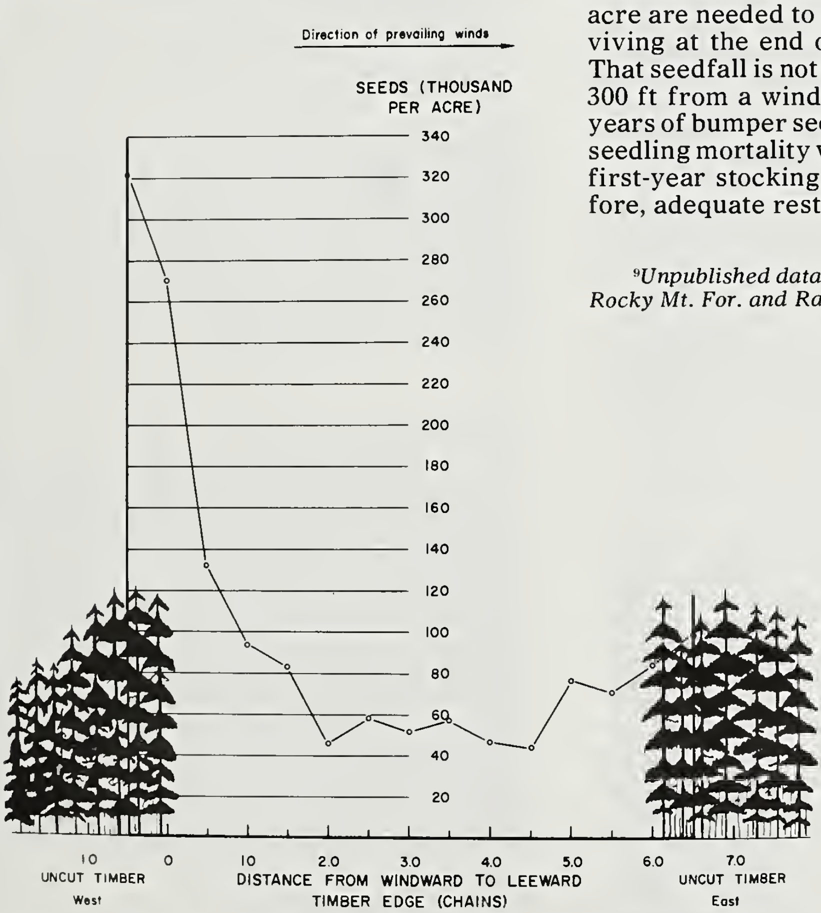

Figure 7.—Total 10-year Engelmann spruce seedfall into clearcut openings in relation to distance from windward timber edge.

from only one good seed crop. This suggests that the maximum width of opening that can restock over a period of years under favorable conditions is about 450 ft or five to six times tree height. On south slopes under the same seedbed and environmental conditions, at least 100,000 sound seeds per acre will be required to provide 1,000 first-year seedlings. Effective seeding distance is about 100 ft from the windward seed source. On the other hand, on north slopes 200,000 sound seeds per acre will be required to provide 1,000 first-year seedlings on unprepared and unshaded seedbeds, while no amount of seed will restock these seedbeds on south slopes (see footnote 9). Under average conditions in the Rocky Mountains, the distance of effective seed dispersal is likely to be 150 ft or less (Alexander 1969, Jones 1967, Roe and Schmidt 1964, Ronco 1970b).

Effective seeding distance may be greater in the northern than in the central Rocky Mountains. In one study in northern Idaho, a peripheral strip 660 ft wide around a large patch cutting was restocked naturally (Roe and DeJarnette 1965). Roe et al. (1970) have suggested that an effective seeding distance of 660 ft may be possible on northerly aspects with about 200 ft^2 of basal area in seed trees in the uncut timber edge, but only 200 to 400 ft is likely on south slopes. Effective seeding distances with a light seed source, 70 ft^2 of basal area or less, will vary from 0 to 200 ft on north slopes and 0 on other aspects.They concluded that the longer a favorable seedbed persists the greater the effective seeding distance.

Subalpine fir seed is larger than spruce, averaging about 37,500 to the pound (Alexander 1958b, USDA-FS 1948). Practically all seed is wind disseminated, but there are no data on dispersal distances.

SOURCE

There are several ways of providing a seed source for both spruce and fir. In cleared openings, the principal seed source is the trees left standing around the perimeter of the opening. Minor amounts of seed are available from the smaller unmerchantable trees left on the area, and some seed is also produced by the trees cut on the area. On partially cut areas, the residual trees are the principal seed source, but some seed is produced by trees cut on the area. One of the significant considerations in the kind of seed source to leave is resistance to windthrow. Situations and conditions where windfall risks were high, above average, and below average around the margins of cleared openings have been identified in Colorado, and recommendations developed for locating windfirm boundaries on clearcut units (Alexander 1964, 1967b). These recommendations have been modified to identify the kinds of trees and residual volumes that can be successfully retained in partial cutting for different stand conditions and windfall risk situations (Alexander 1973).

VIABILITY

The viability of spruce is rated both good (average germinative capacity is about 70 percent the first year) and persistent (average germinative capacity 30 to 50 percent after 5 years) if stored properly (Alexander 1958a, USDA-FS 1948, Van Dersal 1938).Spruce does not normally require pretreatment to break dormancy, and germinative capacity is not improved by stratification (Curtis 1958). Under natural conditions, seed overwinters under the snow and germinates the following spring. Occasionally some germination is delayed until the second year (Ronco 1967, see also footnote 9).

Subalpine fir seed viability is rated only fair (average germinative capacity is 38 percent) and the vitality transient (Alexander 1958b, USDA-FS 1948, Van Dersal 1938). However, observations and limited studies in the Rocky Mountains indicate that germinative capacity is often less than 30 percent (Shearer and Tackle 1960). Some lots of stored seeds exhibit embryo dormancy, which can be broken by stratification in moist sand or peat at 41° F for 60 days (USDA-FS 1948). Under natural conditions, fir seeds lie dormant under the snow and germinate the following spring.

SEED LOSSES

Observations on the Fraser Experimental Forest indicated that a substantial part of the 1972 spruce seed crop was lost before seedfall to cone and seed insects.[10] A number of cone and seed insects of spruce and fir have been identified by Keen (1958), but their relative importance, frequency of occurrence, and the magnitude of losses are not known.

Pine squirrels (*Tamiasciurus hudsonicus fremonti* Audubon and Bachman) are a major consumer of spruce and fir cones and seeds, as evidenced by the large caches common to spruce-fir forests. These caches have been the principal source of seed for reforestation.

[10]*Personal communication with Daniel L. Noble, Forestry Technician, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

After seed is shed to overwinter under the snow, small mammals are the principal source of seed losses. The most important seedeaters include deer mice (*Peromyscus maniculatus* (Wagner)), red-backed mice (*Clethrionomys gapperi* (Vigors)), mountain voles (*Microtus montanus* (Peale)), and western chipmunks (*Eutamias minimus* Bachman). All spruce-fir forests support populations of these small mammals, and any disturbance that initiates understory plant succession favors a buildup of populations, particularly if slash and other down material is present to provide cover. Undoubtedly these mammals eat considerable seed, but the magnitude of losses is not known for the central and southern Rocky Mountains, and results from studies elsewhere are conflicting. In western Montana, for example, spruce seedling success was little better on protected than unprotected seed spots (Schopmeyer and Helmers 1947). On the other hand, protection of seed from rodents was essential to spruce and fir regeneration success in central and southern British Columbia (Prochnau 1963, Smith 1955).

Factors Affecting Germination

Viable seeds of spruce and fir that survive overwinter normally germinate following snowmelt in June or early July in the central Rocky Mountains, when seedbeds are moist and air temperatures at least 45° F. On the Fraser Experimental Forest in Colorado, field germination of spruce seeds has ranged from 0 to 28 percent, depending upon seedbed, weather, and aspect (see footnote 9).

Seedbed is one of the keys to spruce germination success (Roe et al. 1970). Germination is usually better on exposed mineral soil than other seedbed types because of more stable moisture conditions (Clark 1969, Day 1964, Day and Duffy 1963, Roe and Schmidt 1964,see also footnote 9). Germination is often good on mineral soil with incorporated organic matter if a constant supply of moisture is available (Clark 1969; Day 1963, 1964). Germination on burned seedbeds has been variable. Success has been associated with the severity of burn and the depth of loose ash (Clark 1969, Roe et al. 1970, USDA-FS 1943). The natural forest floor, duff, litter, and undecomposed humus are generally poor seedbeds even when moist because seeds cannot absorb sufficient water to germinate (Barr 1930, Smith 1955). Germination may be high on decayed wood (Day 1964, Day and Duffy 1963), but without overhead shade many of these seedlings die when the seedbed dries out (Roe et al. 1970).

The effectiveness of the seedbed is influenced by such factors as weather, shade, and soil texture that operate primarily through their effects on moisture and temperature. Dead shade may increase germination by reducing temperatures, thereby conserving moisture. Low temperatures on shaded seedbeds in the spring following snowmelt may delay germination, however, so that by the time seedbeds are warm enough they are too dry. Germination can also be delayed if precipitation is low or irregular in June or early July following snowmelt. Exposed seedbed surfaces are rapidly dried out and heated to high temperatures during periods of clear weather. Few seeds can imbibe sufficient water to germinate, and most newly germinated seedlings are killed by either drought or stem girdle (Day 1963, 1964; Roe et al. 1970). If germination is delayed until the late summer rains, the late-germinating seedlings are unable to harden off before the onset of cold weather (Ronco 1967, see also footnote 9). Ronco (1967) also found that germination followed definite storm periods.

Alexander and Noble (1971) studied the effects of amount and distribution of watering treatments — selected to represent precipitation patterns and temperatures likely to occur at 10,500 ft elevation on the Fraser Experimental Forest in Colorado — on the germination of spruce in the greenhouse. They concluded that, under favorable seedbed and environmental conditions: (1) more seedlings would emerge with frequent showers than with one or two larger storms when monthly precipitation is 1 inch or less, and (2) when monthly precipitation averages 1 inch or more, germination is completed in a relatively short time with frequent showers, whereas seedlings will emerge throughout the growing season if precipitation falls in only one or two storms.

Noble (1972) found no differences in spruce germination on two soil types in a greenhouse study in Colorado, but both soils were gravelly sandy loams. On the other hand, striking differences were found in germination on two soil types in western Montana (Roe et al. 1970). Seeds were sown in the spring on a droughty sandy loam and a black, moderately heavy loam soil that retained a high moisture content throughout the growing season. More than nine times as many seedlings germinated on the heavier soil. Apparently, rapid surface drying limited moisture for germination on the sandy soil.

Germination of subalpine fir is usually good on mineral soil seedbeds (Clark 1969, USDA-FS 1943). Fir is less exacting in its seedbed requirements than spruce, and will germinate and become established on a wider variety of seedbeds (Alexander 1958b; Day 1963, 1964).

Factors Affecting Initial Survival and Seedling Establishment

Most spruce seedling mortality occurs during the first growing season, but losses can be substantial during the first 5 years after germination (Ronco 1967, 1970b; see also footnote 9). The first growing season is considered here as the period of initial survival, and the second through the fifth growing seasons as the time of seedling establishment.

INITIAL ROOT GROWTH

The rate of root growth is an important determinant of initial survival of spruce seedlings. The further the root penetrates the soil, the better chance the seedling has of surviving drought, frost heaving, and erosion. Critical rooting depth depends upon seedbed type, weather, and soil properties.

First-year spruce seedlings (fig. 8), field grown on mineral soil seedbeds under partial shade on the Fraser Experimental Forest in Colorado, have a rooting depth of 3 to 4 inches, with a total root length of 5 inches (Noble 1973b). In an earlier study in the central Rocky Mountains, the root length of vigorous 1-year-old spruce seedlings averaged about 2.75 inches on seedbeds where the depth of humus was about 1 inch

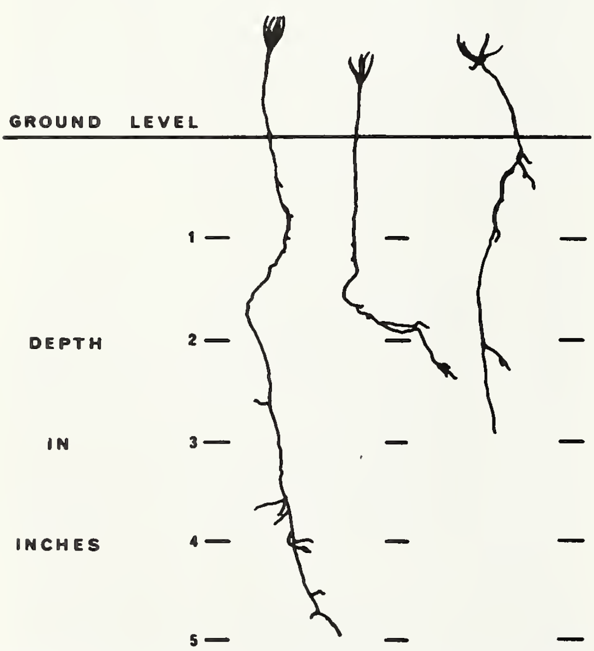

Figure 8.—Engelmann spruce seedling roots at the end of the first growing season.

(Roeser 1924). In eastern Arizona, average first-year spruce root penetration was 2.7 inches on shaded mineral soil (Jones 1971). In the northern Rocky Mountains and British Columbia, first-year root penetration of spruce seedlings under field conditions is only about 1.5 inches (Roe et al. 1970, Smith 1955).

No comparable data are available for subalpine fir in the central Rocky Mountains, but first-year root penetration of its variety, corkbark fir, in Arizona averaged 3.4 inches (Jones 1971). In British Columbia, first-year root length of subalpine fir averaged 2.7 inches (Eis 1965).

SEEDBED TYPE

In the undisturbed forest, spruce seedlings become established on a variety of seedbeds: duff, litter, partially decomposed humus, decaying and moss-covered wood, and on mounds of mineral soil upturned by windthrown trees (Alexander 1958a, Dobbs 1972). These same seedbeds are available after logging, with some additional mineral soil and mineral soil mixed with humus. Removal of the overstory, however, will produce new microhabitats, many of which will be unfavorable to initial survival and seedling establishment. Seedbed preparation is one way to modify limiting environmental factors sufficiently to enable seedlings to survive (Roe et al. 1970).

Spruce seedling survival and establishment after logging in the central Rocky Mountains have generally been better on prepared mineral soil seedbeds than on other seedbed types (USDA-FS 1943, see also footnote 9), because mineral soil provides a more stable moisture source than other seedbed types (Smith 1962). Exceptions have been on south slopes, where shade has been more important to initial survival than the seedbed type (see footnote 9). In some instances, subalpine fir has established more readily on mineral soil, while in others more fir seedlings were found on undisturbed seedbeds (Alexander 1966d, USDA-FS 1943).

In the Intermountain Region, Roe and Schmidt (1964) found that mechanically exposed mineral soil was superior to all other seedbeds for initial survival and establishment of spruce seedlings. Decayed wood, the natural forest floor, and undisturbed duff were poor seedbeds. In northern Idaho, spruce stocking after 5 years was better on scarified seedbeds where 40 percent or more of the area was exposed mineral soil than on the natural forest floor or areas where scarification had exposed only about 20 percent of the surface in mineral soil (Boyd and Deitschman 1969). In southwestern Alberta on the Crowsnest Forest, spruce seedling establishment was best on decayed wood, but success was associated with moist sites (Day 1963, Day and Duffy 1963).

Spruce seedling establishment on burned seedbeds has been variable. Stocking was poor or nonexistent in the central Rocky Mountain and Intermountain Regions on burned piles and windrows where burning left layers of loose ash several inches deep, or generated such great heat that rocks were fractured (Roe and Schmidt 1964, USDA-FS 1943). Under these conditions, burned seedbeds are not likely to support any plants for long periods of time (Roe et al. 1970). On the other hand, Boyd and Deitschman (1969) found that spruce stocking on seedbeds 5 years after prescribed burning was as good as on scarified seedbeds where 40 percent or more of the area was exposed mineral soil.

The length of time seedbed treatment remains effective also varies. On the Fraser Experimental Forest in Colorado, scarified seedbeds on light-textured gravelly, sandy, loam soils with a vaccinium ground cover were still discernible 8 to 10 years after treatment, whereas scarified seedbeds on more heavily textured soils with a ground cover of grasses and sedges were largely obliterated in 3 years (Alexander 1969). Seedbeds on the latter soils were not receptive long enough for seedlings to become established. Mechanically scarified and prescription-burned seedbeds did not last longer than about 5 years in northern Idaho, but that was sufficient time for seedlings to become established (Boyd and Deitschman 1969). The best results with natural or artificial seeding on scarified seedbeds in the interior of British Columbia were obtained in the first and second growing seasons after seedbed treatment (Arlidge 1967).

Spruce seedling survival and establishment on natural seedbeds are limited by the depth of organic matter, whether it is partially decomposed L, F, and H layers or an accumulation of litter, duff, or other debris (Roe et al. 1970). Although germination may have been good, few spruces became established in the Intermountain Region where the depth of organic matter on the seedbed exceeded 2 inches (Roe and Schmidt 1964). Poor establishment was attributed to first-year root penetration that was too shallow to keep pace with the rate at which the seedbed dried out during the summer. Even with a deeper first-year root penetration, seedlings in the central Rocky Mountains do not become established readily on seedbeds covered with heavy layers of duff, litter, or partially decomposed humus (Roeser 1924).

CLIMATE

The climate of the Rocky Mountain subalpine is characterized by extremes in insolation, temperature, and moisture (Alexander 1958a, 1958b). Some of these extremes limit regeneration success.

Insolation

Light intensity and total solar radiation are high where spruce grows. Solar radiation in the high mountains of Colorado can be as high as 2.2 $cal/cm^2/m$ on a clear day with scattered cumulus clouds (Gates and Janke 1966, Spomer 1962). On cloudless days, daily and weekly mean maximums of about 1.9 $cal/cm^2/m$ throughout the summer have been reported (Spomer 1962). Maximum air temperatures at 10,000 ft elevation rarely exceed 78° F, however (Roe et al. 1970).

Light is essential to seedling survival, but spruce does not establish readily in the open at high elevations in the Rocky Mountains. Seedlings develop a chlorotic appearance that is unrelated to nitrogen content (Ronco 1970c) and subsequently die. High light intensity (visible light can be as high as 13,000 footcandles (fc) from shortly after sunrise to shortly before sunset) is one of the factors contributing to the mortality of seedlings planted in the open (Ronco 1970d). Mortality can be reduced by shading planted seedlings (Ronco 1961b, 1970a, 1972). Ronco (1970d) also found that photosynthesis was higher for shaded than unshaded seedlings. He suggests that solarization — a phenomenon by which light intensity inhibits photosynthesis — leads to irreversible tissue damage and subsequent death of seedlings.

More natural seedlings were also established in the Intermountain Region in the shade of nonliving material than elsewhere (Roe and Schmidt 1964). Shade not only reduced light intensity, but lowered temperatures and conserved moisture, thereby improving the microenvironment for seedling survival and establishment.

On the other hand spruce seedlings cannot compete with subalpine fir in the low light intensities commonly found in dense natural stands.

Temperature

Engelmann spruce is restricted to high elevations because of low tolerance to high air temperatures (Bates 1923, Hellmers et al. 1970).

However, solar radiation at high elevations heats exposed soil surfaces and increases water losses from both seedlings and soil by both transpiration and evaporation. Drought or heat girdling may cause mortality, especially among first-year seedlings (Roe et al. 1970).

Tree seedlings in the succulent stage are particularly susceptible to stem girdling. The cortex is killed by a temperature of 130° F, but prolonged exposures to lower temperatures may also be lethal. On the Fraser Experimental Forest, soil surface temperatures have exceeded 150° F in the open on both north and south slopes at 10,500 ft elevation in the month of June (see footnote 9). Maximum air temperature during this period did not exceed 78° F. In western Montana, at lower elevations, soil surface temperatures exceeded 160° F on gentle north slopes several times during one summer (Roe et al. 1970). Early shade protection improved survival of newly germinated spruce seedlings; 30 to 50 percent of the seedlings were lost to heat girdling on unshaded plots, compared to 10 percent on shaded plots. Day (1963) studied heat and drought mortality of newly germinated spruce seedlings in southwestern Alberta, and found that when water was excluded nearly three-fourths of the mortality on four different unshaded seedbed types was caused by heat girdling. Surface temperatures as low as 113° F caused heat girdling, but losses were not high until soil surface temperatures were above 122° F. Shading reduced heat girdling on all seedbed types. Soil surface temperatures in excess of lethal levels for spruce seedlings, especially on burned seedbeds, have been reported in British Columbia (Smith 1955).

The growing season is short at 10,000 ft elevation in the Rocky Mountains, and frost can occur any month of the growing season (Alexander 1958a, Ronco 1967). Frost is most likely to occur in depressions and cleared openings because of cold air drainage and radiation cooling. Newly germinated spruce seedlings are susceptible to damage from early fall frosts. In a greenhouse and laboratory study, new seedlings did not survive temperatures as low as 15° F until about 10 weeks old (Noble 1973a). Terminal bud formation began at 8 weeks; buds were set and needles were mature at 10 to 12 weeks after germination.

After the first year, seedlings are most susceptible to frost early in the growing season when tissues are succulent. Shoots are killed or injured by mechanical damage resulting when tissue freezes and thaws. Frost damage has been recorded in most years in Colorado (Ronco 1967). In light frost years damage was minor, but heavy frosts either damaged or killed all new shoots of open-grown seedlings (fig. 9).

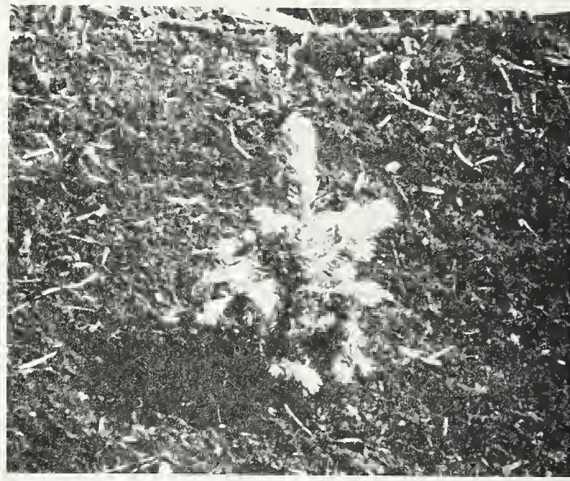

Figure 9.—Frost damage to an open-grown, planted Engelmann spruce seedling.

Furthermore, the loss of new shoots was at the expense of stored food reserves. Frost damage was nearly eliminated by shading the seedlings (Ronco 1967).

In the early fall, the combination of warm daytime temperatures, nighttime temperatures below freezing, and saturated soil unprotected by snow are conducive to frost heaving. On the Fraser Experimental Forest, these conditions have occurred in 2 out of the past 5 years (see footnote 9). Frost heaving has been one of the principal causes of first-year seedling mortality on scarified seedbeds on north slopes. Furthermore, seedlings continue to frost heave after four growing seasons. Shading has reduced losses by reducing radiation cooling.

Moisture

The moisture condition of the seedbed during the growing season largely determines first-year seedling survival.On some sites in the central Rocky Mountains, summer drought is responsible for substantial first-year mortality, especially in years when precipitation is low or irregular. On the Fraser Experimental Forest, drought and desiccation have caused more than half of the first-year seedling mortality in 4 years of observation on south slopes (see footnote 9). On north slopes during the same period, drought has accounted for only about one-third of first-year seedling mortality. On the other hand, frequent watering during dry summers did not increase first-year survival of planted spruce in central Colorado (Ronco 1967).

In the northern Rocky Mountains, late spring and early summer drought is a serious threat most years to first-year seedlings. In western Montana, all seedlings on one area were killed by drought in a 2-week period in late summer when their rate of root penetration could not keep pace with soil drying during a prolonged dry period (Roe et al. 1970). Late spring and early summer drought is also a serious cause of seedling mortality in the Southern Rockies.

The moisture provided by precipitation during the growing season is particularly critical to the survival of seedlings during the first year. Alexander and Noble (1971) studied the effects of amount and distribution of watering treatments on seedling survival in the greenhouse. Treatments simulated common summer precipitation patterns in north central Colorado. They concluded that, under favorable seedbed and environmental conditions: (1) At least 1 inch of well-distributed precipitation is needed monthly before seedlings will survive drought; (2) with this precipitation pattern, more than 1.5 inches of monthly rainfall is not likely to increase seedling survival; but (3) few seedlings will survive drought with less than 2 inches of rainfall monthly when precipitation comes in only one or two storms.

Summer precipitation may not always benefit seedling survival and establishment. Summer storms in the Rocky Mountains may be so intense that much of the moisture runs off, especially from bare soil surfaces. Moreover, soil movement on unprotected seedbeds buries some seedlings and uncovers the roots of others (Roe et al. 1970).

SOIL

Throughout the Rocky Mountains, spruce and fir grow on a wide range of soils — described by Johnson and Cline (1965) and Retzer (1962) — but there is little information about the soil requirements for regeneration. Noble (1972) compared first-year spruce seedling survival and growth on two soils in the greenhouse. One soil — Bobtail gravelly sandy loam — is a Sols Bruns Acides which developed in place under a mixed spruce-fir-lodgepole pine stand from mixed schists and gneisses that were metamorphosed from granitic rock. The other soil — Darling gravelly sandy loam — is a Podzol developed in place under a spruce-fir stand from coarse-textured materials weathered from mixed schists and gneisses. The Bobtail soil crusted and compacted when watered — as it did in the field — and root penetration was significantly less than on Darling soils. Consequently, 1.5 inches of water well-distributed monthly was required to obtain survival on Bobtail soils, whereas significant survival was obtained on Darling soils with 1 inch of water well distributed monthly. Top growth and total dry matter production after 24 weeks were about the same on both soils. Alexander (1958a) reported that spruce generally establishes and makes good growth on moderately well-drained silt and clay loam soils developed in place from volcanic and fine sedimentary rock, and on alluvial soils developed from a variety of parent materials, because these soils do not dry out rapidly. Spruce does not establish or grow as well on shallow, dry, coarse-textured sands, gravels, heavy clay surface soils, or saturated soils.

No information is available on the range of pH tolerated by spruce and fir, or their nutrient requirements.

High-intensity storms and runoff from snowmelt cause erosion that results in seedling mortality on mineral soil seedbeds (Roe et al. 1970). In the central Rocky Mountain and Intermountain Regions, seedlings are destroyed by either scouring that uncovers the roots or deposition that buries the seedlings (Roe and Schmidt 1964, see also footnote 9).

DISEASES

Newly germinated seedlings are killed by damping-off fungi (Ronco 1967, see also footnote 9). Losses normally occur early in the growing season before seedlings cast their seedcoats, and can be serious on all seedbed types if they remain damp for long periods of time. Damping-off was responsible for 17 percent of the first-year seedling mortality in central Colorado on both mulched and unmulched mineral soil seedbeds in a year when the growing season was particularly wet (Ronco 1967). Damping-off was the principal cause of mortality of newly germinated seedlings in the greenhouse when they were watered sufficiently to keep the soil surfaces from drying (Alexander and Noble 1971, Noble 1972).

Snowmold fungus (*Herpotrichia nigra* Hartig) occasionally damages or kills both natural and planted seedlings (Ronco 1967, 1970a; see also footnote 9). Losses are most severe when seedlings remain under the snow too long, as in years of heavy snowfall or when weather retards snowmelt in the spring, or in depressions where snow normally accumulates and melts slowly.

ANIMAL DAMAGE

A number of animals damage and kill young seedlings. Haig et al. (1941), Roe et al. (1970),

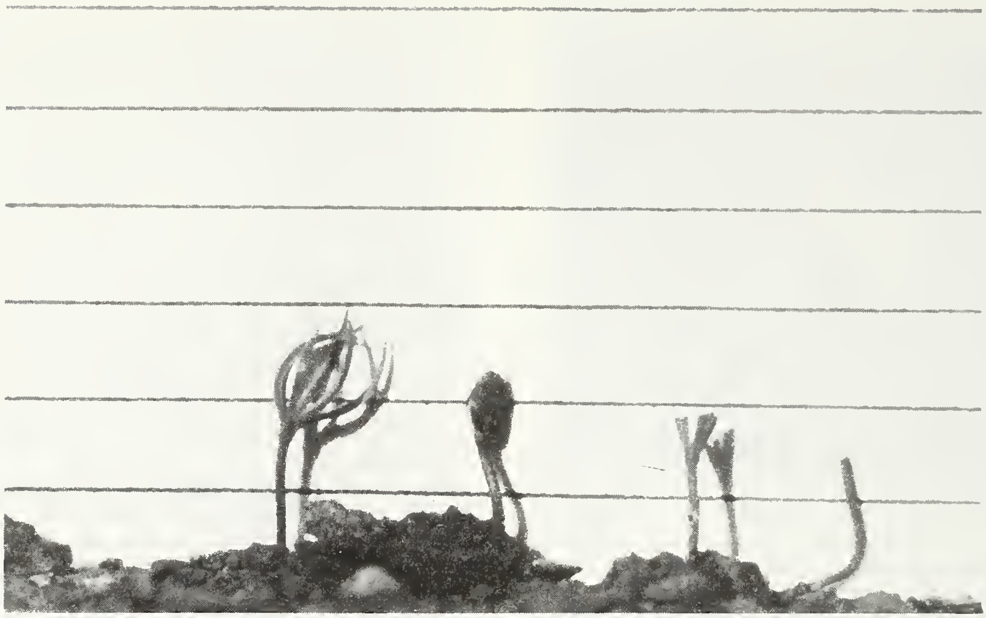

Figure 10.—Clipping damage to newly germinated spruce seedlings by juncos. Fraser Experimental Forest, Colorado.

and Ronco (1967) have suggested that mice consume cotyledonous seedlings as well as ungerminated seeds. Those workers based their conclusions on observations of seedlings that were clipped shortly after germination while seedcoats were still attached, but there is no documented evidence of mice actually doing the damage. A study by Noble and Shepperd (1973) indicates that the grey-headed junco (*Junco caniceps* Woodhouse) is probably responsible for clipping mortality and damage in the central Rocky Mountains previously attributed to mice (fig. 10). Established seedlings are not immune, however, to rodent damage. During some winters, established seedlings are debarked and killed by mountain voles, and mountain pocket gophers (*Thomomys talpoides* (Richardson)) periodically cause heavy mortality to spruce plantations up to 3 to 4 years after planting (Ronco 1967, 1970a).

The extremely small size of young spruce seedlings makes them especially vulnerable to damage by grazing and browsing animals. In western Montana, cattle — in one trip through a seedling survival study area — trampled or killed 10 percent of the marked first-year spruce seedlings. They were either buried or kicked out of the ground (Roe et al. 1970). Trampling damage by cattle and big-game animals is likely to be more severe on prepared seedbeds, especially if they have been plowed or disked, because the ground provides easy travel routes. Spruce is seldom eaten by these animals, but young subalpine fir is frequently browsed heavily by big-game.

GROUND VEGETATION

Understory vegetation can be either a benefit or a serious constraint to spruce seedling survival and establishment (Alexander 1966d, Day 1964, Ronco 1972). Observations of natural and artificial regeneration on several areas in the central Rocky Mountains have indicated spruce seedlings become established more readily on sites protected by such plants as willow (*Salix* spp.), shrubby cinquefoil (*Potentilla fruticosa* (L.) Rydb.), fireweed (*Epilobium angustifolium* L.), and dwarf whortleberry (*Vaccinium* spp.) than in the open. These plants shade seedlings without seriously depleting soil moisture. In contrast, mortality has been recorded when seedlings started near clumps or scattered individual plants of grasses or sedges, or herbaceous plants such as bluebells (*Mertensia* spp.) which spread to form a dense, solid cover with roots completely occupying the soil. Death is due to root competition for moisture and smothering by cured vegetation compacted under dense snow (Ronco 1972). The probability of regeneration success on an area with a complete cover of dense sod of grasses and sedges is low. In Utah, Pfister (1972) rated the environment for spruce regeneration success as severe in habitat types where the understory was dominated by *Ribes montigenum*, and moderate where the understory was dominated by *Berberis repens*. He concluded that natural regeneration success could be obtained in these habitat types only by maintaining a continuous forest cover.

SITE QUALITY

The evaluation of site quality is essential to the land manager as a means of identifying and intensifying management practices where timber production has the greatest potential.

Conventional Determination

Site index is the only method now available for estimating the potential productivity of spruce-fir forests in the central and southern Rocky Mountains. Alexander (1967a) prepared curves of the height and age relationship of dominant spruces that are suitable for estimating site index at base age 100 years in spruce-fir stands where age at breast height is at least 20 years (fig. 11). Data for these curves came from 2,100 dominant spruces with annual ring sequences showing no evidence of past suppression, on 350 plots in southern Wyoming and throughout Colorado. These plots were selected to represent the available range in density, site quality, and age.

Height measurements to the nearest foot and age at breast height from increment borings of at least six dominant spruce trees should be averaged when the site index curves are used. This will provide an integrated site index value that applies over the area occupied by trees aged and measured. Little improvement in sampling error is gained by measuring more than six trees (Brickell 1966).

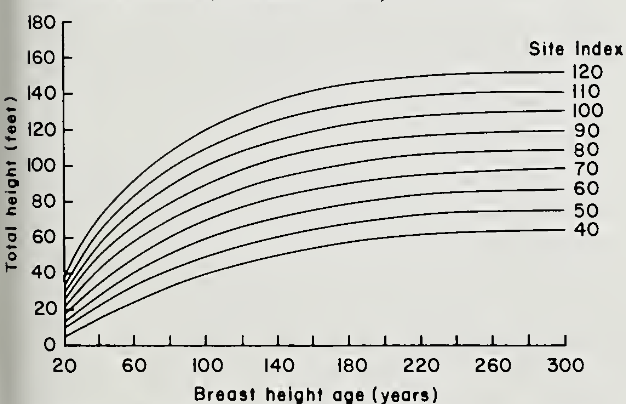

Figure 11.—Site index curves for Engelmann spruce in the central Rocky Mountains. Base age: 100 years, breast height.

In addition to being dominants, trees selected for measurement should meet the following criteria:

1. Even-aged — not more than a 20-year spread in the age of the dominant stand.
2. At least 20 years old at breast height — preferably 50 years old or older, because of the variability in height growth of trees on the same site at ages 20 to 50 years.
3. Show no visible evidence of crown damage, such as broken or forked tops, disease, or excessive sweep or crook.
4. Increment core shows a normal pattern of ring widths from pith to cambium, indicating no evidence of past injuries nor prolonged suppression.

Determination From Soil and Topography

The conventional method of height-age cannot be used to estimate site index if there are no trees present, or if trees are either too young or unsuitable for measurement. For example, the height-age curves developed by Hornibrook (1942) are not suitable for estimating site index because they were based on residual trees left after partial cutting, many of which were not dominants or codominants in the original stand.

Site index for granitic soils in northern Colorado and southern Wyoming can be estimated from the depth of soil to the top of the C horizon and elevation in feet (Sprackling 1972). Data came from 127 plots located on the Roosevelt, Arapaho, Medicine Bow, and Routt National Forests. The equation from which figure 12 is derived is shown below:

$$\hat{Y} = -106.64 + 62.46X_1 + 809.40X_2$$

where

Y = site index

X_1 = log of soil depth to top of C horizon, in inches

X_2 = 1000/elevation, in ft.

$$S_{\bar{y}\cdot x} = 9.00; \pm R^2 = 0.65$$

Site indexes estimated from these soil and topographic factors are strictly applicable only to the point sampled. The more variable the site, the more points must be sampled to precisely estimate site index over the area. In practice, however, site index sampled from what appear to be extremes on the ground for any given area is usually all that is needed.

Soil-topographic site indexes have not been developed for other areas in the central and southern Rocky mountains.

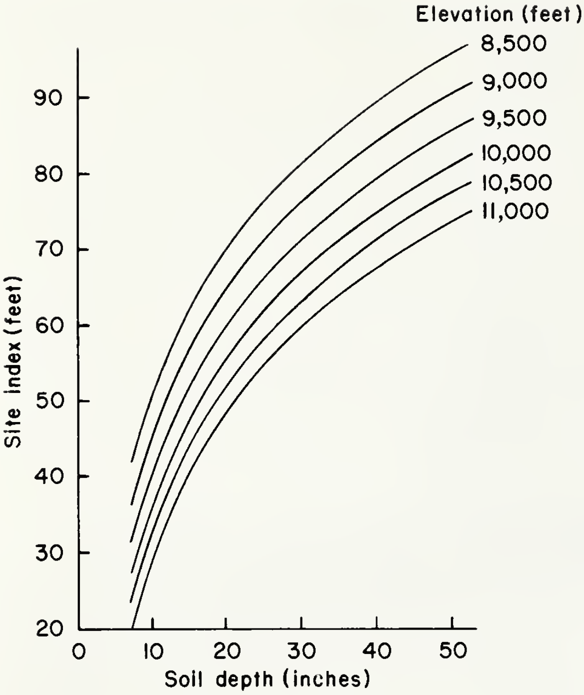

Figure 12.—Site index for Engelmann spruce on granitic soils in southern Wyoming and northern Colorado, from soil depth to the top of the C horizon and elevation (Sprackling 1972).

If we are to develop a true measure of site quality that includes potential productivity, regeneration capacity, and successional trends, the concept of "total site" that includes vegetation, soils, and landform appears to offer the best possibility of success.

GROWTH AND YIELD

Forest management in the spruce-fir type in the central Rocky Mountains is in a period of transition to more intensive management. Prediction of future yields and knowledge of individual tree growth are essential to the development of management practices for a variety of uses.

Growth of Individual Trees

Diameter growth is usually used to measure release because of its sensitivity to changes in stand density. Observations of diameter growth of residual spruce and fir left after partial or diameter-limit cutting show that individual trees respond to release, and the degree of release is related to initial diameter, tree vigor, and number of competitors (Hornibrook 1942, Roe and DeJarnette 1965, Stettler 1958). However, conventional thinning studies have not been made in spruce-fir forests in the central Rocky Mountains, partly because of the relatively few young stands and partly because spruce and fir do not grow in such dense stands as are common in lodgepole pine. A yield study[11] currently in progress in the central and southern Rocky Mountains will provide some of the data needed to determine the diameter growth of spruce and fir in relation to stand density, age, and site quality.

The height growth of individual trees is primarily important because of the relationship between site quality and height of dominant trees at index age. For tolerant species such as spruce and fir, height growth of dominant trees is unaffected over a wide range of stand density; consequently volume growth is also less affected by changes in stand density for any given site index and age. Dominant height is, therefore, a valid site index upon which to base yield prediction. The changes in the dominant height of spruce with age and site quality are shown in figure 11. At age 120 years, for example, dominant height varies from 46 to 130 ft in response to variations in site quality. Age at breast height is used as index age because the slow, variable height growth to 4.5 ft makes the use of total age meaningless.

Under stand conditions, the crowns of spruce tend to be parabolic in shape, while fir is more conical. The relationship of crown size to individual tree growth has been determined for spruce in the central Rocky Mountains (Alexander 1971). Figure 13 shows the relationship of the crown width of open-grown spruces to diameter at breast height.

New volume tables and point sampling factors have been prepared for Engelmann spruce in Colorado and Wyoming (Myers and Edminster 1972). The nineteen tables include: (1) gross volumes in total and merchantable cubic feet, (2) gross volumes in board feet, both Scribner and International 1/4 log scales, and (3) point sampling factors for merchantable cubic feet and board feet.

Volume on an area may be determined from either: (1) measurements of tree diameters and heights, (2) measurements of diameters and sufficient heights to convert the tables to local volume tables, or (3) tree counts obtained by point sampling (Myers and Edminster 1972).

[11] *Unpublished data on file with study FS-RM-1201.25, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

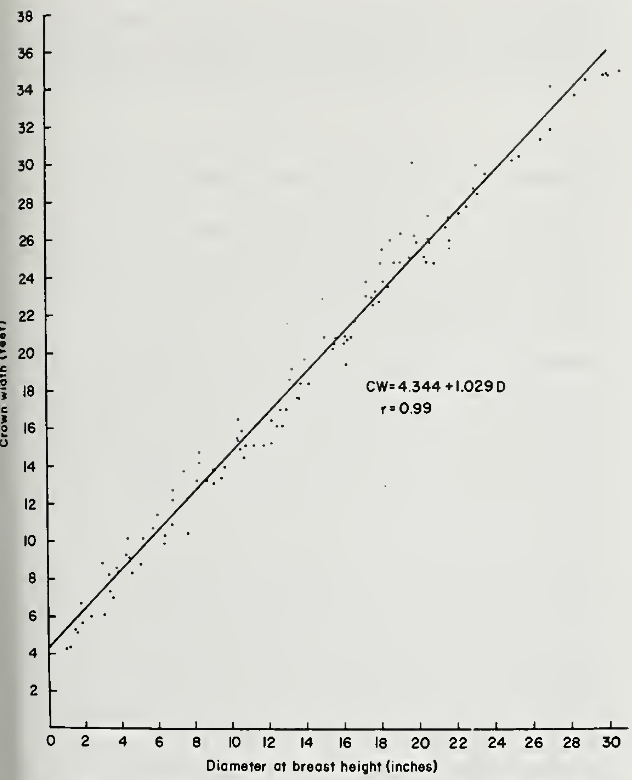

Figure 13.—Relationship of crown width to stem diameter at breast height for open-grown Engelmann spruce.

Yields Per Acre

NATURAL STANDS

With the high proportion of spruce-fir still in old-growth stands, the forest manager must largely accept what nature has provided during the period of conversion to managed stands. Growth estimates based on Forest Survey inventories, rather than detailed growth and yield studies, indicate that average annual growth over all sites in old-growth spruce-fir forests is only about 80 to 100 fbm per acre. Average volumes per acre vary from 5,000 to 15,000 fbm on poor sites to 25,000 to 40,000 fbm on better sites. Volumes as high as 80,000 to 100,000 fbm per acre have been reported (Pearson 1931, Thompson 1929, USDA-FS 1942).

MANAGED STANDS

Large areas of old-growth spruce-fir are being converted into stands that must be managed from the regeneration period to final harvest. The term managed as used here refers to control of stand density throughout the life of the stand. Yield tables for managed stands are essential to the land manager as a basis for decisions on:

1. Site quality classes that will repay the cost of thinning and other cultural treatments.
2. Levels of growing stock — including the frequency of thinning or intermediate cutting — to meet management objectives.
3. Length of rotation, cutting cycles, and allowable cut for different cutting methods, management goals, and utilization standards.
4. The place of timber management in mulitple-use management. Better decisions are possible regarding key uses when the timber potential of managed stands can be forecast.

Furthermore, yield tables that show what can be accomplished by different management practices will provide goals toward which conversion to managed stands can be directed.

The only growth-prediction tool now available for spruce-fir stands in the central Rocky Mountains was developed 30 years ago by Hornibrook (1942). However, it is for selectively cut stands, for sawtimber only, and for stand structures that are no longer management goals.

Most growth-prediction tools developed in the past have been either (1) normal yield tables, (2) empirical yield tables, or (3) experience or variable-density yield tables. Each method has deficiencies and limitations that make it unsuitable for developing growth prediction tools necessary to meet present and future needs in spruce-fir forests.

A method of yield table preparation for managed stands that avoids the limitations inherent in other methods has been developed by Myers (1971). It has been used to predict yields for managed stands of Black Hills ponderosa pine (*Pinus ponderosa* Laws.) and lodgepole pine (Myers 1966, 1967). Data are now being collected in the central Rocky Mountains and analyzed by Myers (1971) field and computer simulation procedures to develop yield tables for managed spruce-fir stands. The simulation program will generate tables derived from field data on past growth in relation to stand density, age, and site quality obtained from a large number of temporary plots in existing unmanaged but uniformly spaced spruce-fir stands. The program can produce a series of yield tables which show how projected outcomes will vary in response to changes in cultural treatments and/or variations in original stand and site conditions. With this series of yield projections, the manager can examine the probable results of his operations, make necessary changes in the management of his resources, and study the effects of these changes before money is spent on them (Myers 1971).

SILVICULTURE AND MANAGEMENT OF OLD GROWTH

Regeneration Silviculture

Spruce-fir forests can be harvested by clearcutting and shelterwood, and selection cutting, plus their modifications. The objective of each regeneration system is to harvest the timber crop and obtain adequate reproduction. The choice of cutting method depends on management objectives and environmental considerations, but stand conditions, associated vegetation, and windfall and spruce beetle susceptibility that vary from place to place on any area, impose limitations on how individual stands can be handled. Cutting to bring old-growth under management is likely to be a compromise, therefore, between what is desirable and what is possible. Management on many areas may involve a combination of several partial cutting treatments, clearcutting, and sanitation salvage cutting.

CLEARCUT AREAS

Clearcutting is a regeneration system that harvests the timber crop in one step. Since a large proportion of the spruce-fir type is in overmature sawtimber stands that offer little opportunity for future management because of their advanced age, relatively slow growth, and susceptibility to wind and insects, forest managers concerned with timber production have most often elected to convert old-growth to managed stands by clearcutting in strips, patches, and blocks. Harvesting and regeneration practices developed in the central Rocky Mountains have therefore been directed toward this objective. Much of the criticism recently leveled at clearcutting in spruce-fir has a valid basis, particularly where large openings were cut, geometric patterns were used that did not complement the landscape, unsightly logging debris was left on the ground, and areas did not regenerate. The cause of these criticisms can be eliminated if available knowledge is put into practice. From a silvicultural point of view, therefore, clearcutting is still an acceptable harvesting method in spruce-fir forests. In fact, under some conditions it is the only alternative to no cutting. Furthermore, a combination of cleared openings and high forests meets the needs of such key uses as water production and wildlife management. Consequently the following — taken chiefly from Roe et al. (1970) — will be directed at the practices needed to regenerate clearcuts. To restock these cutovers, the manager should first consider the cultivation of existing acceptable advanced reproduction before planning on subsequent restocking by natural or artificial means.

Management with Advanced Reproduction

Although many spruce-fir forests have an understory of advanced growth, wide variations in age, composition, quality, and quantity of advanced reproduction require careful evaluation of the potential for future management. This management potential must be determined before cutting. One course of action is followed if the advanced reproduction is to be managed, another if a manageable stand is not present, cannot be saved, or the manager chooses to destroy it and start over (Roe et al. 1970).

Prelogging Evaluation. — The initial examination must answer the following questions: (1) How much of the area is stocked with acceptable seedlings and saplings, and will that stocking insure a satisfactory replacement stand? (2) Can it be logged economically by methods that will save advanced reproduction? Is the timber volume too heavy to save advanced reproduction if it is removed in one cut? (3) How much of the area will require subsequent natural or artificial regeneration, either because advanced reproduction is not present or will be destroyed in logging?

Since any kind of cutting is likely to destroy at least half of the advanced growth, a manageable stand of advanced reproduction before cutting should contain at least 600 acceptable seedlings and saplings per acre of either spruce or fir. There are few data available on the growth response of advanced reproduction; the following criteria are therefore based largely on experience and observation. To be acceptable, reproduction must be of good form, able to make vigorous growth when released, and be free of defect or mechanical injury that cannot be outgrown. Trees over 4 inches d.b.h. may be acceptable, but they should not be included in the prelogging regeneration survey because they are more likely to be damaged or destroyed in logging or windthrown after logging. Stands or portions of stands not meeting these criteria will have to be restocked with subsequent natural or artificial regeneration (Roe et al. 1970).

Cutting and Slash Treatment to Save Advanced Regeneration. — Mature and overmature trees should be cut to release advanced reproduction and harvest merchantable volume. Seed sources need not be reserved from cutting unless required for fill-in stocking. If it is necessary to reserve trees for esthetic purposes or maintain high forests for other uses, some form of partial cutting that will release and protect advanced growth should be considered. The size, shape, and arrangement of openings cut is not critical from a regeneration standpoint, but to be compatible with other key uses, openings should be no wider than about five to eight times tree height, irregular in shape, and blend into the landscape. Not more than one-third of any drainage or Working Circle should be cut over at any one time.

Protection of advanced reproduction begins with a well-designed logging plan (Roe et al. 1970). Logging equipment must be suited to the terrain. Skidding, movement of equipment, and other activity must be rigidly controlled. To minimize damage to advanced reproduction and disturbance to soil, skid roads must be located and marked on the ground before cutting. They should be at least 200 ft apart. Movement of skidding equipment must be confined to these skid roads to eliminate indiscriminate travel over the area. Trees should be felled into openings where possible at a herringbone angle to the skid road so as to reduce disturbance when logs are moved onto the skid road (Alexander 1957a, Roe et al. 1970). It may be necessary to deviate from a herringbone felling angle in order to drop the trees into openings. If this is the case, the logs will have to be bucked into short lengths to reduce skidding damage. Furthermore, there must be close coordination between the felling and skidding operations, because it may be necessary to fell and skid one tree before another is felled. Dead sound material and snags that are felled should be skidded out of the area to minimize the amount of slash and unmerchantable material to be disposed of after logging.

Slash treatment should then be confined to areas of heavy concentrations as required for protection from fire and insects or preservation of esthetic values (Roe et al. 1970). Slash must be treated carefully to avoid unnecessary damage to advanced reproduction — care taken in logging is wasted if advanced reproduction is destroyed in slash disposal. If trees are felled into openings as much as possible, a minimum of turning and travel with brush dozers will be needed to concentrate the slash for burning. Sufficient piles should be made so that burning is confined to the smallest area possible.

Postlogging Reevaluation. — Regardless of how much care is taken in logging and slash treatment, a certain amount of advanced reproduction will be damaged or destroyed. The area must be surveyed to: (1) Determine the extent of damage to the reproduction. At least 300 acceptable seedlings and saplings per acre must have survived to consider the area adequately stocked plus whatever trees larger than 4 inches d.b.h. survive intact (fig. 14). Areas that do not meet these standards will need fill-in

Figure 14.—Adequate stocking of advanced spruce and fir reproduction after clearcutting and slash disposal. Fraser Experimental Forest, Colorado.

or supplemental stocking. (2) Plan stand improvement — cleaning, weeding, and thinning — to release crop trees. Guidelines are available to aid in marking trees to be cut or left (Alexander 1957b).

Cutover areas should not be considered in an adequate growing condition until the crop trees are free to grow and the necessary fill-in planting or natural regeneration is complete (Roe et al. 1970).

Management for Reproduction After Cutting

If advanced reproduction is not adequate, the area must be regenerated by natural or artificial means after logging.

Cutting unit layout, logging plans, slash disposal, and seedbed treatment should be designed to (1) facilitate seed dispersal, (2) promote seedling survival and establishment, and (3) create favorable growing conditions. If natural regeneration fails, plans must then be made to use artificial regeneration (Roe et al. 1970).

Clearcutting can be by patches, blocks, or strips. Such cutting can be readily adapted to multiple use land management by judicious selection of size, shape, and arrangement of openings in combination with other high-forest cutting practices.

Size of Cutting Unit. — Requirements for seed dispersal and site preparation will influence the size of opening that will restock to natural regeneration. The best seedbed preparation is wasted if the seedbed does not receive sufficient seed; likewise, any quantity of seed is wasted if it does not fall on a receptive seedbed (Roe et al. 1970). The cutting unit must therefore be designed so that seed from the surrounding timber margin reaches all parts of the opening unless supplementary artificial regeneration is planned. Effective seeding distance and aspect determine the size of opening.

The tabulations below are guides developed for the central Rocky Mountains. They are based on 12 years of seed production and dispersal data from six areas in Colorado (Alexander 1969, Ronco 1970b, Ronco and Noble 1971) and 5 years of spruce survival data from the Fraser Experimental Forest in Colorado in a *Picea engelmannii-Vaccinium* spp. habitat type (see footnote 9). Effective seeding distance as used here is defined as the distance to which sufficient sound seed is dispersed to provide an arbitrary minimum of 1,000 first-year seedlings on (1) mineral soil seedbeds where competition from competing vegetation has been eliminated, and 50 percent overhead shade and protection from rodents provided; and (2) natural seedbeds with only protection from rodents provided. The number of first-year seedlings expected to become established on two aspects is:

Seedbed and aspect	Seedlings per 1,000 sound seeds
Shaded, mineral soil:	
North	50
South	10
Unshaded, natural:	
North	5
South	0

The estimated maximum distance that can be seeded from all sides and size of opening that can be made on two aspects based on moderate to good seed production is:

Seedbed and aspect	Maximum — Distance that can be seeded (ft)	Maximum — Size opening (tree heights)
Shaded, mineral soil:		
North	450-500	5-6
South	150-200	2-2½
Unshaded, natural:		
North	50-100	1-1½
South	0	0

Based on these seeding distances, the following conclusions can be drawn:

1. Clearcutting for natural regeneration is most likely to succeed on north and east aspects, if the right combination of mineral soil and shade has been created. Even then, more than one good seed year will likely be required to obtain adequate restocking.
2. Clearcutting on south and west aspects is not likely to result in an acceptable stand of new reproduction in a reasonable period of time, even with favorable seedbed and environmental conditions, without fill-in planting to bring reproduction to the minimum acceptable standard.
3. Where larger openings than shown are cut on north and east slopes, it will be necessary to plant the area beyond effective seeding distance.
4. Where the seed source is of poor quality, plan to plant the cutovers.

Similar guides developed for Intermountain Region conditions by Roe et al. (1970) show that larger openings than indicated here can be restocked if the seed source contains 200 or more ft^2 of basal area in spruce trees 10 inches d.b.h. and larger.

Windfall. — A significant consideration in the location of cutting unit boundaries is windfirmness. Not only are the trees along the margins of openings the source of seed for regeneration, but they also provide ideal breeding grounds for spruce beetles when windthrown. The following guidelines for minimizing windfall around the perimeter of clearcut openings were developed in Colorado (Alexander 1964, 1967b):

1. Protection from wind for the vulnerable leeward boundaries is most important.
2. Do not locate cutting boundaries where they will be exposed to accelerated winds funneling through saddles in ridges to the south and west of the cutover area, especially if the ridges are at high elevations. Success in reducing blowdown from that kind of exposure depends upon the ability of the forester who lays out the cutting-unit boundaries to recognize exceptionally hazardous situations.
3. Avoid locating cutting boundaries on ridges or near saddles in ridges, especially ridgetops of secondary drainages to the lee and at right angles to the main drainage when the latter is a narrowing valley with steep slopes. One cutting unit should straddle each ridgetop and extend downslope in both directions for a distance of at least 200 ft. That unit may be cut or uncut. Such an arrangement will avoid leaving a cutting boundary on the top of a ridge.
4. Lay out each unit so the maximum amount of cutting boundary is parallel to the contour or along a road where topography, soils, and stand conditions will permit.
5. Do not lay out cutting units with dangerous windcatching indentations or long, straight lines and square corners in the leeward boundary or in boundaries that are parallel to stormwinds. V- or U-shaped indentations in the boundary can funnel wind into the reserve stand. Long, straight cutting-boundary lines and square corners also deflect the wind and cause increased velocities where the deflected currents converge with others such as a windstream flowing over a crest. Irregular cutting boundaries without sharp indentations or square corners lessen the opportunity for deflection and funneling of air currents.
6. Do not locate cutting boundaries on poorly drained or shallow soils. Trees grown under these conditions are shallow rooted and susceptible to windthrow.
7. Locate cutting boundaries in stands of sound trees. Trees with decayed roots and boles or root systems that were cut or torn during road building or log skidding operations are poor windfall risks.
8. Locate cutting boundaries in immature stands when possible. Stands of young trees are usually less easily uprooted by strong winds.
9. Locate cutting boundaries in poorly stocked stands. Open-grown trees are more windfirm than trees grown in dense stands.
10. Avoid locating cutting boundaries in areas where there is evidence of old prelogging blowdowns.
11. Reduce blowdown in areas with exceptionally hazardous windfall potential by locating the vulnerable leeward boundaries where hazards are below average, or by eliminating those boundaries by progressive cutting into the wind.

Seedbed Preparation and Slash Treatment.—There are a number of things to consider when planning the treatment of spruce slash: (1) slash 8 inches in diameter or larger provides a habitat for spruce beetles; (2) it provides beneficial shade for germination and seedling establishment; (3) in heavy concentrations, it obstructs natural seedling establishment; and (4) it creates an adverse visual impact.

Burning slash in large concentrations such as windrows or piles often creates enough heat in the soil to inhibit the development of any kind of plant growth for an unknown period of time. Windrows or piles should therefore be small or narrow, and should cover a minimum proportion of the area.

Mineral soil can be exposed by mechanically scarifying the ground surface, sometimes in connection with slash disposal or by broadcast burning. To be effective, broadcast burning should accomplish certain objectives. It should consume most but not necessarily all of the duff or organic material on the ground, and it should burn hot enough to destroy some or all of the competing vegetation. On the other hand, it should not burn so hot that a deep layer of loose ashes accumulates, the mineral soil changes color, or the rocks fracture. It must leave cull logs, tops, and other large slash to provide shade and protection for soil and seedlings (Roe et al. 1970). Timing of the burn is exceedingly important. The spruce type is generally so cool and moist that times when effective broadcast burns can be achieved are limited. The key to the time to burn is the moisture content of the duff — it must be dry enough to be consumed. If only the surface is dry, a blackened organic layer that inhibits seedling establishment will remain (Roe et al. 1970).

Careful mechanical scarification will prepare a satisfactory seedbed if it exposes mineral soil and destroys some of the competing vegetation, but leaves shade protection. At least 40 percent of the area should be left as exposed mineral soil. It may be necessary, however, to rearrange some of the residual slash to provide adequate shade. Tractors equipped with brush blades should be used. A complete cleanup job is neither necessary nor desirable. There is a double advantage in not cleaning up too thoroughly: First, residual tops and slash shade the seedbed; second, residual organic material reduces soil erosion. Cut green spruce material over 8 inches in diameter should be removed or treated to prevent the buildup of spruce beetle populations, but true fir material may be left. On highly erodible soils, the duff layer should be removed along the contour, preferably in strips the width of the dozer blade, with untouched strips intervening. Some of the larger debris may then be pushed back on the scarified strips for protection from erosion, and the dozer walked over it at right angles to the strips to break it down (Roe et al. 1970).

Management for Artificial Regeneration

Planting. — Guidelines for planting spruce in the central and southern Rocky Mountains have been prepared by Ronco (1972). His recommendations are summarized here unless otherwise indicated.

1. *Need and Timing.* — Good sites should be planted **immediately** after logging where there is not a manageable stand of advanced reproduction, and where local experience has shown that natural regeneration is likely to take a long time. Areas logged and prepared for natural regeneration that fail to restock in 3 to 5 years should be planted before invasion by other vegetation has completely occupied the site. Experience has shown that a minimum goal should be about 300 well-established spruce seedlings in addition to whatever other species may have become established (Roe et al. 1970).

   Planting cutover areas has several advantages. By growing stock in nurseries, many of the vagaries of the natural regeneration system are avoided, such as unpredictable seed years, irregular seed dissemination, and high rates of early seedling mortality. Planting permits better control of stand density, tree distribution, and species and genetic composition of the stand. Planting, unlike natural regeneration, does not impose a restriction on size of cutting units, and it removes the necessity of reserving merchantable trees for seed. Furthermore, successful planting may shorten the regeneration period (Roe et al. 1970).

   There are, however, some disadvantages in planting. Field planting requires close coordination between cutting plans and the availability of planting stock. Delay in planting after logging may increase the costs of site preparation. Costs of surviving seedlings are frequently higher than those of natural regeneration. Close supervison is needed to assure planting of only large, vigorous stock, proper storage and transportation, proper handling of stock from the nursery until planted, and proper planting techniques. Furthermore, planting spruce requires just as much site preparation as natural seeding. Many planting failures in the Rocky Mountains can be traced to one or more of the disadvantages mentioned above (Roe et al. 1970).

2. *Site Preparation.* — Site preparation for spruce plantations probably requires more consideration than for most other species because of the complex relationship between the environment and seedling requirements. For example, warmer soils and increased moisture availability accompanying complete vegetation removal would benefit seedlings, but because of their sensitivity, seedlings would be more prone to severe injury from intense light and frost. Therefore, in the absence of logs or stumps, live vegetation such as willows, Potentilla, fireweed, Vaccinium, or other species of similar growth habit may be desirable as protective cover even though it competes with seedlings.

   Hand scalping will probably be adequate for most planting operations. Hand-scalped spots should not be smaller than 18 to 24 inches square. Above-ground parts of plants are totally removed, but lateral roots from vegetation surrounding the scalp usually remain active. Thus the zone of soil released from the competitive effects of vegetation tapers rapidly below the ground surface.

   Heavy concentrations of slash should be treated to reduce fire and insect hazards and adverse visual impacts, but slash disposal and seedbed preparation with heavy machinery should be minimized. Removing vegetative competition or treating slash can adversely affect plantation establishment by destroying microsites that afford protection for planted seedlings. Machines could be used, however, to obtain better distribution of favorable microsites over the plantation by rearranging logs. Exposure of mineral soil during such operations would also create favorable seedbeds, which might result in supplemental stocking from natural regeneration.

In areas where hand scalping is unsatisfactory because of dense sod-forming grasses and sedges or a heavy cover of herbaceous species such as Mertensia, vegetation may be controlled by such machine methods as disking, furrowing, mounding, ridging (berms resulting from plowing), and bulldozing. Where competing vegetation consists of relatively tall brush species that form dense cover, complete removal or cleared strips of bulldozer-blade widths may be desirable. Machine scalping with disks or plows (furrowing or ridging) should leave vegetation-free areas 1.5 to 2 ft wide.

Broadcast burning can be used on areas where there is no advanced reproduction or residual stand. Logs not consumed in the fire will provide shade for planted seedlings (Roe et al. 1970).

3. *Planting Stock.* — Plant only stock that meets the following specifications: (1) Tops should be no shorter than 3 to 4 inches; they should be well developed with not less than two or three branches. (2) Roots should not be shorter than 5 to 6 inches; they should be compact, fibrous, and well developed with several lateral roots. (3) Tops and roots should have a low shoot/root ratio.

4. *Planting Season.* — Plant spruce in the spring after snowmelt. Planting usually should be completed before June 25, but may be extended to July 10 if moisture does not become depleted or temperatures unseasonably high. Temporarily suspend planting during the regular season when temperatures are unseasonably warm, especially on clear days when the wind is blowing.

5. *Storage.* — Nearly all planting in the central and southern Rocky Mountains requires that seedlings be lifted while they are still dormant and stored at the nursery until planting sites are free of snow. Because of the incidence of mold and depletion of food reserves, spruce should not be held in storage longer than 3 months. Seedlings must be treated as dormant plants during transit to planting sites. If refrigerated transport is not available, cover the bundles or bags with canvas to maintain temperatures between 34° to 40° F. Storage problems are more severe in the field because limited facilities on the planting site make temperature control difficult. Well-insulated storage sheds that can be cooled by ice or snow can be used in the absence of mechanical refrigeration. If such storage is not available, cool, moist cellars or even snowbanks can be used. Seedlings can be held in storage locally up to 7 days if temperatures can be maintained below 40° F.; otherwise limit local storage to 3 days. When transferring seedlings from bundles or bags to planting containers, handle the seedlings carefully to prevent root breakage and do not expose roots to sun or wind.

6. *Spot Selection.* — Plant seedlings with roots in moist soil and only on those spots where seedlings are protected by stumps, logs, slash, or open cover of live vegetation, and only on the north and east side of protective cover (fig. 15). Avoid planting in depres-

Figure 15.—Good spot selection. Engelmann spruce seedling planted on the east side of a log where shade is fully utilized.

sions, frost pockets, on small mounds, in areas with an extensive cover of sod-forming vegetation, where advanced regeneration shows evidence of snow mold, and where skidding and slash disposal have buried trash in the soil.

7. *Planting Method.* — Use the hole method; dig holes with mattock hand tools or power augers. If power augers are used, do not dig holes too far in advance of planting.
8. *Plantation Protection.* — Protect new plantings from trampling by livestock until seedlings are at least 3 ft high. They may require fencing or other adjustments in grazing allotments. New plantings should also be protected from rodents. Sample the rodent populations on the areas scheduled to be planted. If populations are large, provide controls until seedlings become established.

9. *Records.* — Adequate data from detailed records are needed to (1) correct deficiencies causing failure, and (2) recognize good practices leading to successful plantations. Decisions affecting regeneration practices can then be based on quantitative information rather than conjecture. Follow the recommendations suggested by Ronco (1972).

Seeding. — Until reliable techniques have been worked out for the central and southern Rocky Mountains, direct seeding of spruce is not recommended as an operational regeneration practice.

PARTIAL CUT AREAS

Partial cutting here includes both shelterwood and selection cuts and their modifications. They are regeneration systems that harvest the timber on an area in more than one step. From a silvicultural point of view these are acceptable harvesting methods in old-growth spruce-fir. They are, in fact, the only options open to the manager where (1) multiple use considerations preclude clearcutting, (2) combinations of small cleared openings and high forests are required to meet the needs of various uses, or (3) areas are difficult to regenerate after clearcutting. However, windfall, insects, and stand conditions impose limitations on how stands can be handled. A careful appraisal of the capabilities and limitations of each stand is necessary to determine cutting practices. Furthermore, partial cutting requires careful marking of individual trees or groups of trees to be removed, and close supervision of logging.

A classification based on stand characteristics is needed to (1)identify the kinds of stands that can be partially cut, those that must be clearcut and started new, and those that should be uncut; and (2) develop partial cutting practices for different management objectives. Until such a classification is available, the following recommendations for partial cutting practices are keyed to broad stand descriptions based largely on experience, windfall risk situations, and insect problems (Alexander 1973). Practices needed to obtain natural reproduction are also discussed.

Single-Storied Stands[12]

Description. —

1. Stands may appear to be even-aged (fig. 16), but usually contain more than one age class. In some instances, the canopy may not appear to be of a uniform height because of changes in topography, stand density, or stocking.
2. Codominant trees form the general level of the overstory canopy. Dominants may be 5 to

[12]*Reproduction less than 4.5 ft tall is not considered a stand story in these descriptions.*

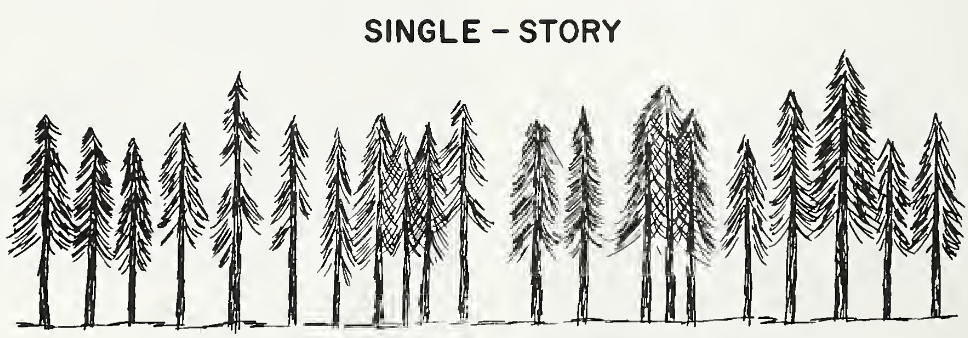

Figure 16.—A single-storied spruce-fir stand.

10 ft taller, and occasionally predominants may reach 15 to 20 ft above the general canopy level. Taller intermediates extend into the general canopy; shorter intermediates are below the general canopy level but do not form a second story.

3. The range in diameters and crown length of dominants and codominants is small.
4. There are few coarse-limbed trees in the stand; if two-aged or more, younger trees usually have finer branches and may not have diameters equal to the older trees.
5. Trees are more often uniformly spaced than clumpy.
6. A manageable stand of advanced reproduction usually is not present.[13]
7. If lodgepole is present in the overstory it is not a major stand component. Lodgepole pine reproduction is absent or sparse.

Recommended Cutting Treatments. — These stands are usually the least windfirm because trees have developed together over a long period of time and mutually protect each other from the wind.

1. **If the windfall risk is below average, and the trees are uniformly spaced —**

   a. The first cut should be light, removing about 30 percent of the basal area of the stand on an individual tree basis.[14] This type of cutting resembles the first or **preparatory cut** of a three-step shelterwood. Since all overstory trees are about equally susceptible to windthrow, the general level of the canopy should be maintained by removing some trees from each overstory crown class. Those trees with known indicators of defect should be removed first, but avoid creating openings in the canopy with a diameter larger than one tree height by distributing the cut over the entire area. Furthermore, do not remove dominant trees in the interior of the stand that are protecting other trees to their leeward if these latter trees are to be reserved for the next cut. In these and all other stands described where natural openings one to several acres occur, leave the trees around the perimeter for a distance of about one tree height until the final entry. These trees have been exposed to the wind and are usually windfirm, and protect the trees in the interior of the stand.

   b. The second entry into the stand should not be made for at least 5 to 10 years after the first cut in order to determine if the residual stand is windfirm. This cut should also remove about 30 percent of the original basal area on an individual tree basis. It simulates the second or seed **cut** of a three-step shelterwood. The largest and most vigorous dominants and codominants should be reserved as a seed source, but avoid cutting openings in the canopy larger than one tree height in diameter by distributing the cut over the entire area, even if it means leaving trees with poor seed production potential.

   c. The last entry is the **final harvest** and should remove all of the remaining original overstory. It should not be made until a manageable stand of reproduction has become established, but the cut should not be delayed beyond this point if timber production is one of the primary concerns because the overwood hampers the later growth of seedlings.

   d. The manager also has the option of removing less than 30 percent of the basal area at any entry and making more entries, but they cannot be made more often than every 5 to 10 years. This will spread the cut out and maintain a continuous forest cover for a longer period of time.

2. **If the windfall risk is below average, and the trees are clumpy —**

   a. The first cut should be a modified **group selection** that removes about 30 percent of the basal area. Harvesting timber in groups will take advantage of the natural arrangement of trees in clumps. Group openings should be kept small — not more than one to two tree heights in diameter — and not more than one-third of the area should be cut over (fig. 17). However, all trees in a clump should be either cut or left since they mutually support each other, and removing only part of a clump is likely to result in windthrow of the remaining trees.

   b. The second entry into the stand should not be made until the first group of openings has regenerated. This cut can also remove about 30 percent of the original

[13]*Since any kind of cutting may destroy as much as half of the advanced reproduction, even with careful logging, at least 600 spruce or fir seedlings and saplings per acre, of good form and vigor and free of defects, must be present to be considered a manageable stand.*

[14]*As a practical matter, small saplings that do not represent significant competition to the remainder of the stand may be excluded from the computation of basal area.*

Figure 17.—Group-selection cutting in spruce-fir. One-third of the area was cut in openings about one tree height in diameter. Fraser Experimental Forest, Colorado.

basal area without cutting over more than an additional one-third of the area. Openings should be no closer than about one to two tree heights to the openings created by the previous cut.

c. The final entry should remove the remaining groups of merchantable trees. The timing of this cut depends upon how the manager elects to regenerate the new openings. If he chooses to use natural regeneration the final harvest must be delayed until the regeneration in the openings cut earlier are large enough to provide a seed source.

d. The manager may choose to remove less than 30 percent of the basal area and cut over less than one-third of the area at any one time. This will require more entries, but each new cut should not be made until the openings cut the previous entry have regenerated. Furthermore, the last groups cannot be cut until there is either a seed source or the manager elects to plant these openings.

3. **If the windfall risk is above average, and the trees are uniformly spaced —**

a. The first cut should be restricted to a very light **preparatory** cutting that removes about 10 percent of the basal area on an individual tree basis. The objective is to open up the stand, but at the same time minimize the windfall risk to the remaining trees. This type of cutting resembles a **sanitation cut** in that the poorest risk trees — those of low vigor and with known indicators of defect — and predominants should be removed, but it is important that the general level of the overstory canopy be maintained intact. Provision should be made to salvage windfalls after spruce beetle flight at the end of July.

b. The second entry can be made in about 10 years after the first cut. This entry should remove about 15 to 20 percent of the original basal area on an individual tree basis. Any windfall salvaged after the first cut should be included in the computation of the basal area to be removed. The objective of this **preparatory cut** is to continue to open up the stand gradually while preparing the stand for the seed cut. Most of the trees marked for removal should come from the intermediates and small codominants, but maintain the general level of the canopy intact.

c. It will require another 5 to 10 years to determine if the stand is windfirm enough to make another entry. This will be the seed **cut,** and should remove about

20 to 25 percent of the original basal area including any windfalls salvaged since the last cutting. The largest and most vigorous dominants and codominants should be reserved as a seed source, but it is more important to distribute the cut over the entire area.

d. The last entry is the **final harvest** to remove the remaining original overstory. It cannot be made until a manageable stand of reproduction has been established. About 50 percent of the original basal area will be removed in this cut, and if this is more than 10,000 fbm per acre, it is probably too heavy to be removed in one harvest without undue damage to the reproduction. The manager must therefore plan on a two-step final harvest. The second step can begin as soon as the skidding is finished in the first step, providing that a manageable stand of reproduction still exists.

4. **If the windfall risk is above average and the trees are clumpy —**

a. The first cut should be light, removing about 15 to 20 percent of the basal area in a modified **group selection**. Group openings should be no larger than one tree height in diameter, and not more than one-fifth of the area should be cut over at any one time. All trees in a clump should be cut or left. In stands with small natural openings — about one tree height in diameter — the openings can be enlarged one tree height by removing clumps of trees to the windward.

b. Four additional entries into the stand can be made at periodic intervals, but each new entry should not be made until the openings cut the previous entry have regenerated. The last groups to be removed should be retained until the original group openings are large enough to provide a seed source. About 20 percent of the basal area should be removed over about one-fifth of the area at each entry. Group openings should be no larger than one tree height in diameter.

5. **If the windfall hazard is very high —**

The choice is limited to removing all the trees or leaving the area uncut. Cleared openings should not be larger than regeneration requirements dictate, and they should be interspersed with uncut areas of at least equal size. Not more than one-third of the total area in this wind risk situation should be cut over at one time.

Two-Storied Stands

Description. —

1. Stands may appear to be two-aged (fig. 18), but usually contain more than two age classes.
2. The top story (dominants, codominants, and intermediates) is usually spruce; resembles a single-storied stand.
3. The second story is often fir, and the trees are younger and smaller in diameter than the overstory. It may consist of small saw logs, poles, or large saplings, but is always below the top story and clearly distinguishable from the overstory. Trees in the second story are overtopped, but not suppressed.
4. There may be a manageable stand of advanced reproduction.
5. Arrangement of individual trees varies from uniform to clumpy.
6. If lodgepole pine is present in the stand it is usually a scattered component of the overstory. Lodgepole pine reproduction is absent or sparse.

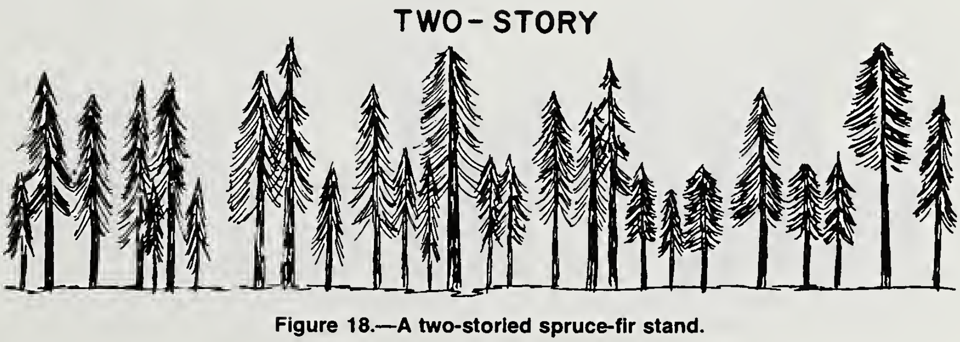

Figure 18.—A two-storied spruce-fir stand.

Recommended Cutting Treatments. — Same as for three-storied stands.

Three-Storied Stands

Description. —

1. Stand may appear to be three-aged (fig. 19), but usually contains more than three age classes. Occasionally two-aged, but is never all-aged.
2. If the stand is three-aged or more, the top story is usually predominantly spruce and resembles a single-storied stand except that there are fewer trees. The second and third stories are usually younger and smaller diameter trees (small saw logs, poles, and large saplings) that are usually fir. In a typical stand, the second story will be 10 to 30 ft below the top story and consist of small saw logs or large poles. Third story will be 10 to 30 ft below the second story and consist of small poles or large saplings. Although the second and third stories are overtopped, the trees are usually not suppressed.
3. If two-aged, the first two stories are old-growth with spruce in the top story and fir in the second story. The third story will be younger trees, largely fir, of smaller diameter.
4. Frequently contains a manageable stand of advanced reproduction.
5. More often clumpy than are single- or two-storied stands.
6. If lodgepole pine is present, it is usually a scattered component of the top story, but may occur in the second story. Lodgepole pine reproduction is usually absent or sparse.

Recommended Cutting Treatments (Two- and Three-Storied Stands). —Trees in the overstory are usually more windfirm than those in single-storied stands. The second and third stories are likely to be less windfirm than the top story.

1. **If the windfall risk is below average, and the trees are uniformly spaced —**
   a. The first cut can remove about 40 percent of the basal area where there is not a manageable stand of advanced reproduction. This type of cutting is heavy enough to resemble the first step or **seed cut** of a two-cut shelterwood, but the marking follows the rules for individual tree selection — mature trees are removed from each story. Since the overstory is likely to be more windfirm, selected dominants and codominants of good vigor and free of defect should be left. These trees are also the most desirable seed source. Avoid cutting holes in the canopy larger than one tree height in diameter by distributing the cut over the entire area. Furthermore, do not remove dominant trees from the interior of the stand that are protecting other trees to their leeward if these latter trees are to be reserved for the next cut.
   b. The second entry should be the **final harvest** to remove the remaining original stand and release the reproduction. It cannot be made until the new stand of reproduction is established. If the residual volume is greater than about 10,000 fbm per acre, the **final harvest** should be made in two steps to avoid undue damage to newly established reproduction. The second step can begin as soon as the skidding is finished in the first step, providing that a manageable stand of reproduction still exists.
   c. If there is a manageable stand of advanced reproduction, the first cut can be an **overstory removal** if the volume is not too heavy. Otherwise, the first cut can remove 40 percent of the basal area on an individual tree basis as long as the more windfirm dominants and codominants are left. The timing of the second cut is not critical from a regeneration standpoint,

Figure 19.—A three-storied spruce-fir stand.

providing a manageable stand of reproduction still exists after the first cut.

d. The manager has other options to choose from. He may elect to cut less than the recommended basal area, make more entries, and spread the cut out over a longer period of time by delaying the final harvest until the new stand is tall enough to create a continuous high forest. He may also elect to convert these stands to an uneven-aged structure by making a series of light cuts — 10 to 20 percent of the basal area — at frequent intervals — 10 to 20 years. Ultimately the stand will contain a series of age classes.

2. **If the windfall risk is below average, and the trees are clumpy —**

   a. The first cut should remove about 40 percent of the basal area in a modified **group selection** cutting. The group openings can be larger (two to three times tree height) than for single-storied stands, but the area cut over should be not more than one-third of the total. Furthermore, the group openings should be irregular in shape, but without dangerous windcatching indentations in the edges. All trees in a clump should either be cut or left.

   b. Two additional entries can be made. They should each remove about 30 percent of the original basal area in group openings up to two to three times tree height, but not more than one-third of the area should be cut over at any one time. If there is not a manageable stand of advanced reproduction, the manager must wait until the first group of openings is regenerated before cutting the second series. Furthermore, he must either delay the cutting of the final groups until there is a seed source or plan on planting these openings. If there is a manageable stand of advanced reproduction, the timing between cuts is not critical from a regeneration standpoint.

   c. The manager has the option of removing less than the recommended basal area and cutting less than the recommended area at any one time. This will require more entries and spread the cut out over a longer period of time.

3. **If the windfall risk is above average, and the trees are uniformly spaced —**

   a. The first cut should be a light **preparatory** cutting that removes not more than 20 percent of the basal area, on an individual tree basis, where there is not a manageable stand of advanced reproduction. Predominants, intermediates with long dense crowns, and trees with known indicators of defect should be removed first, but maintain the general level of the canopy. The objective of this cut is to open up the stand, but at the same time minimizing the windfall risk to remaining trees. Provision should be made to salvage windfalls after spruce beetle flight.

   b. The second entry into the stand should not be made in less than 10 years. This cut should remove about 30 percent of the original basal area, including the salvage of any windfalls that occur between the first and second cuts. The second entry is the **seed cut**, therefore the best dominants and codominants should be reserved as a seed source, but it is important that the cut be distributed over the entire area.

   c. The next entry is the **final harvest** to remove the remaining merchantable volume and release the new reproduction after it has become established. However, if the residual stand has too heavy a volume, the final harvest should be made in two steps.

   d. If these stands contain a manageable stand of reproduction and the volume per acre is not too heavy, the first cut can be an **overwood removal**. If the volume is too heavy for a one-step removal, the manager should follow the recommendations above because the wind hazard is too great to permit a two-step removal in a stand that has not been previously opened up.

4. **If the windfall risk is above average, and the trees are clumpy —**

   a. The first cut should be a modified **group selection** that removes about 25 percent of the basal area. Group openings should be kept small — not more than one to two tree heights in diameter — and not more than one-fourth of the area should be cut over at any one time. All trees in a clump should either be cut or left. Small natural openings can be enlarged one to two tree heights by removing trees in clumps to the windward of the opening.

   b. Three additional entries should be made. If there is not a manageable stand of advanced reproduction, about 25 percent of the original basal area should be removed on about one-fourth of the area in each entry. The interval between cuts will depend upon the time required to regenerate each series of openings. The manager must either delay the removal of the final groups until a seed source is available or plant the openings. If there is a manageable stand of advanced reproduction, the timing between cuts is not critical from a regeneration standpoint.

5. **If the windfall hazards are very high —**

   The choice is usually limited to removing all the trees or leaving the area uncut. Cleared openings should not be larger than regeneration requirements dictate, and should be interspersed with uncut areas. Not more than one-third of the total area in this windfall risk situation should be cut over at any one time.

Multi-Storied Stands

Description. —

1. Stands are generally uneven-aged (fig. 20) with a wide range in diameters.
2. If the stand developed from a relatively few individuals, overstory trees are coarse limbed and fill-in trees are finer limbed. The overstory trees may be relatively vigorous.
3. If the stand developed from the deterioration of a single- or two-storied stand, the overstory may be no limbier than the fill-in trees. Much of the vigorous growing stock is below saw log size.
4. There is almost always a manageable stand of reproduction as a ground story.
5. The fill-in trees may be clumpy, but usually the overstory trees are uniformly spaced.
6. Lodgepole pine may occur as a scattered component of the stand, usually in the overstory, but it may also occur in all stories including reproduction.

Recommended Cutting Treatments. — These are usually the most windfirm stands, even where they have developed from the deterioration of single- and two-storied stands, because by the time they have reached their present condition the remaining overstory trees are usually windfirm.

1. **If the windfall risk is below average —**

   There is considerable flexibility in harvesting these stands. All size classes can be cut, with emphasis on either the largest or smallest trees in the stand. For example, the first cut can range from removal of all large trees in the overstory to release the younger growing stock, to a thinning from below to improve the spacing of the larger trees. If the manager elects to make an overwood removal and the volume is too heavy, it should be harvested in two steps. Thereafter, cutting can be directed toward either even- or uneven-aged management, with entries made as often as growth and regeneration needs dictate.

2. **If the windfall risk is above average or very high —**

   The safest first cut is an overwood removal with a thinning from below to obtain a widely spaced, open-grown stand that will develop windfirmness. Thereafter, cutting can be directed toward either even- or uneven-aged management.

Modifications to Cutting Treatments Imposed by Spruce Beetles

1. If spruce beetles are present in the stand at an endemic level, or in adjacent stands in sufficient numbers to make successful attacks, and:

Figure 20.—A multi-storied spruce-fir stand.

a. Less than the recommended percentage of basal area to be removed is in susceptible trees, any attacked and all susceptible trees should be removed in the first cut. This will include most of the larger spruce trees and is a calculated risk, especially in above-average wind risk situations. Furthermore, the percentage of fir in the stand will increase. Provision should be made to salvage attacked trees. The remaining cuts should be scheduled in accordance with windfall risk, insect susceptibility, and regeneration needs.
b. More than the recommended percentage of basal area to be removed is in susceptible trees, the manager has three options: (1) remove all the susceptible trees, (2) remove the recommended basal area in attacked and susceptible trees and accept the risk of future losses, or (3) leave the stand uncut. If the stand is partially cut or left uncut, surviving spruce would probably make up at least half of the residual basal area, but most of the merchantable spruce would be small-diameter trees.

2. If the stand is sustaining an infestation that is building up and the manager chooses to either partially cut or leave the stand uncut because clearcutting is unacceptable, he must accept the risk of an outbreak that will destroy most of the merchantable spruce in the stand and spread to adjacent stands.

Cutting to Save the Residual

Before any cutting begins, the manager must determine whether he has an acceptable stand of advanced reproduction and if he is going to manage it. Furthermore, he must reevaluate the stand after the final harvest and slash disposal to determine the need for supplemental stocking. The same criteria used to evaluate advanced reproduction on clearcut areas apply here.

In partial cutting, protection of the residual from logging damage is of primary concern. The residual includes merchantable trees left after shelterwood cutting, and advanced reproduction in both shelterwood and group selection cutting where an acceptable stand is to be managed. Protection begins with a well-designed logging plan at the time of the first cut. To minimize damage, skidroads must be laid out — about 200 ft apart depending on the topography — and marked on the ground. These skidroads should be kept narrow, and located so that they can be used to move logs out of the woods at each cut. Close supervision of logging will be required to restrict travel of skidding and other logging equipment to the skidroads. In shelterwood cuttings, trees should be felled into openings as much as possible using a herringbone pattern that will permit logs to be pulled onto the skidroads with a minimum of disturbance. It may be necessary to deviate from the herringbone felling angle in order to drop trees into openings. If this is the case, the logs will have to be bucked into short lengths to reduce skidding damage. Trees damaged in felling and skidding should not be removed if they are still windfirm. In group-selection cutting, the felling pattern should be similar where there is a manageable stand of advanced reproduction. Otherwise all trees should be felled into the openings. Both shelterwood and group-selection cuttings require close coordination between felling and skidding because it may be necessary to fell and skid one tree before another tree is felled.

Slash Disposal and Seedbed Preparation

Some slash disposal will probably be needed after each cut, but it should be confined to concentrations and that needed to reduce visual impact because most equipment now available for slash disposal is not readily adaptable to working in shelterwood cuttings. Furthermore, burning of slash will cause additional damage to the residual. Skid out as much of the down sound dead and green cull material as possible for disposal at the landings or at the mill. Some hand piling or scattering may be needed where slash disposal equipment cannot be used. In group-selection cutting, if there is not a manageable stand of advanced reproduction, dozers equipped with bush blades can be used to concentrate slash for burning in the openings. Piles should be kept small to reduce the amount of heat generated. Leave some of the larger pieces of slash and other debris in place to provide shade for new seedlings. Cut green spruce material larger than 8 inches in diameter should be removed to reduce the buildup of spruce beetle populations.

On areas to be regenerated by new reproduction, a partial overstory canopy or trees standing around the margins of small openings provide two of the basic elements necessary for regeneration success — a seed source within effective seeding distance, and an environment compatible with germination, initial survival, and seedling establishment. The manager must make sure that the third element — a suitable seedbed — is provided after the seed cut where shelterwood cutting is used, and after each cut where group selection is used. If at least 40 percent of the available ground surface is not exposed mineral soil after logging and slash disposal, additional seedbed preparation is needed. Until special equipment is developed, the same problem exists as with slash disposal. The equipment available today is too large to work well around standing trees. Smaller machines equipped with suitable attachments will have to be used, but they must be closely supervised to minimize damage to the residual.

Multiple-Use Silviculture

In addition to being the most productive timber type in the central Rocky Mountains, spruce-fir forests are also the highest water yielding, and are valuable wildlife, recreation, and scenic areas. Because of increasing demands on forest lands from a rapidly expanding population and the limited resource available, management must consider all key land uses. The kinds of stands that appear desirable for increased water yields, preservation of the forest landscape, maintenance of scenic values, and improvement of wildlife habitat have been suggested in a general way by both research and observation.

WATER

Water yield studies have indicated that the increase in snow depth in openings cut in spruce-fir forests is not additional snow but a change in deposition pattern (Hoover and Leaf 1967).Snow blows off adjacent standing trees and settles in the openings. The increased snow in the openings means that more water is available for streamflow. Research and experience suggest that a round or patch-shaped opening with a diameter about five to eight times the height of surrounding trees is the most effective for trapping snow (Hoover 1969). In larger openings, wind dips to the ground and scours and blows snow out of the opening. About one-third of the forest area should be in openings, which would be periodically recut when tree height reaches one-half the height of surrounding trees. The remaining two-thirds of the area would be retained as continuous high forest; trees would be periodically harvested on an individual-tree basis. Ultimately the reserve stand would approach an all-aged structure with the overstory canopy remaining at about the same height, although the original overstory could not be maintained indefinitely.

An alternative would be to make a light cut distributed over the entire watershed, removing about 20 to 30 percent of the basal area on an individual-tree basis or in small groups. The objective would be to open up the stand enough to develop windfirmness, and salvage low-vigor and poor-risk trees. Openings five to eight times tree height can then be cut on about one-third of the area. The remaining two-thirds of the area would be retained as permanent high forest, with trees periodically removed on an individual-tree basis or in small groups.

Another alternative that would integrate water and timber production would be to harvest all of the old-growth in a cutting block in a series of cuts spread over a period of 120 to 160 years. Each cutting block would contain at least 300 acres, subdivided into round or patch-shaped units approximately 2 acres in size or four to five times (in diameter) the height of a general canopy level. At periodic intervals, some of these units, distributed over the cutting block, would be harvested and the openings regenerated. The interval between cuttings could vary from as often as every 10 years to as infrequently as every 30 to 40 years. The percentage of units cut at each interval would be determined by Cutting cycle/Rotation age × 100. At the end of one rotation, each cutting block would be composed of groups of trees in several age classes ranging from reproduction to trees ready for harvest. The tallest trees would be somewhat shorter than the original overstory, but any adverse effect on snow deposition should be minimized by keeping the openings small and widely spaced.

WILDLIFE

Big-game use of spruce-fir forest lands can be improved by certain timber cutting practices, as shown in two recently completed studies. Openings of less than 20 acres cut in the canopy of spruce-fir forests in Arizona were heavily used by deer and elk, but use decreased considerably in larger openings (Reynolds 1966). Openings created by harvesting were preferred to natural openings because the vegetation that initially comes in on cutovers is more palatable to deer and elk. Reynolds suggested that openings be maintained by cleaning up the logging slash and debris, removing new tree reproduction, and seeding the area to forage species palatable to big-game. However, since natural succession on the cutover areas is likely to replace the more palatable species eventually, a more desirable alternative would be to cut new openings periodically while allowing the older cuttings to regenerate. That would provide a constant source of palatable forage and the edge effect desired, while creating an all-aged forest by even-aged groups. The openings created should be widely spaced, with the stand between openings maintained as high forest.

On the Fraser Experimental Forest in Colorado, deer use in spruce-fir forests was greater and forage more abundant on cleared openings than in the uncut forest. Clearcut openings 3 chains wide were used more than wider or narrower strips (Wallmo 1969, Wallmo et al. 1972). While no recommendations were made as to optimum size or arrangement of openings, the Fraser study suggests that they be kept small and interspersed with standing trees that could be periodically harvested on an individual-tree basis.

One alternative that would integrate wildlife habitat improvement with timber production would be to cut about one-sixth of a cutting block every 20 years in openings about four to five times tree height. Each Working Circle would be subdivided into a number of cutting blocks (of at least 300 acres) so that not all periodic cuts would be made in a single year on a Working Circle. Such periodic cutting would provide a good combination of numbers and species of palatable forage plants and the edge effect desired, while creating a several-aged forest of even-aged groups.

Wildlife other than big-game is also influenced by the way forests are handled. For example, with the curtailment of wildfires, some reduction in stand density by logging is probably necessary to create or maintain drumming grounds for male blue grouse (*Dendragapus obscurus* Say). Partial cutting that opens up the canopy enough to allow tree regeneration to establish in scattered thickets appears to provide the most desirable habitat. Cutting small, irregularly shaped openings (up to 10 acres) in the canopy may also be beneficial to blue grouse, if thickets of new reproduction become established in the cleared openings (Martinka 1972).

RECREATION AND ESTHETICS

Permanent forest cover at least in part is preferred in recreation areas, travel influence zones, and scenic view areas. Since old-growth spruce-fir forests will not maintain themselves in an esthetically pleasing or sound condition indefinitely, some form of partial cutting would maintain forest cover while at the same time replacing the old with a new stand. However, the visual impact of logging operations — haul roads, damage to residual trees, and slash and debris — must be minimized. In situations where there is no alternative to clearcutting, and the environmental impact of clearcutting is unacceptable, there is no choice but to leave the stands uncut.

To reduce the sudden and severe visual impact on the landscape viewer, openings cut in stands for timber and water production, wildlife habitat improvement, and recreation (ski runs) should be a repetition of natural shapes, visually tied together to create a balanced, unified pattern that will complement the natural landscape (Barnes 1971). This is especially important for those openings in the middle and background that can be seen from distant views. The foreground should be maintained in high forest under some partial cutting system.

Silvicultural practices must be developed that will incorporate the maintenance of scenic values and provide the combination of continuous high forest and cleared openings necessary to integrate all land uses. This development will include: (1) classifying existing stands into categories of similar stand characteristics as a means of identifying management potentials, and (2) testing silvicultural systems and cultural practices in stands of different characteristics for a variety of management objectives.

THE LODGEPOLE PINE TYPE

CHARACTERISTICS OF THE TYPE

The lodgepole pine type is generally pictured as an even-aged, single-storied, overly dense forest, varying in age from place to place but uniform in age within any given stand. This is true only where favorable fire, seed, and climatic conditions once combined to produce a large number of seedlings at one time (Lexen 1949). Elsewhere, lodgepole pine grows on a wide range of sites with a great diversity of stand conditions. It can occur as two-aged, single- or two-storied stands; three-aged, two- or three-storied stands; and even-aged to broad-aged multi-storied stands (Tackle 1954a, 1955). Multi-storied stands, and to a lesser extent, two- and three-storied stands, generally resulted from either scattered trees that produced seed for subsequent stand development, or the gradual deterioration of old-growth stands from wind, insects, and diseases (Alexander 1972). The diversity complicates the modification of silvicultural systems for multiple use.

Lodgepole pine stands are frequently pure pine over much of the area it occupies, especially where stands originated after repeated fires and there is no seed source for other species (Tackle 1961a, 1965). However, mixed stands of lodgepole pine and other species are not uncommon. In pure stands of lodgepole pine of medium to high density, there is seldom an understory of reproduction; in low-density

Figure 21.—Heavy blowdown in lodgepole pine after partial cutting that removed 60 percent of the original basal area. Fraser Experimental Forest, Colorado.

stands there may be younger trees in the understory. If this advanced growth has not been suppressed for long periods of time it will respond to release.

In mixed stands, the overstory can either be pure pine, or pine, spruce and/or fir at higher elevations, and pine and Douglas-fir at lower elevations, with the climax species in the understory. Advanced growth of the climax species will respond to release when the overstory is removed (Alexander 1972).

PAST CUTTING HISTORY

Cuttings in lodgepole pine forests date back almost 100 years. Some of the earliest were clearcuttings to provide stulls, lagging, and charcoal for mining operations. Pioneer ranchers used lodgepole pine for fuel, fences, and corrals. Later, millions of cross ties were hewn for the railroads. Following World War I, some form of partial cutting became standard practice on the National Forests of the central Rocky Mountains, even though early studies suggested that clearcutting satisfied the silvical requirements of the species (Bates et al. 1929, Clements 1910, Mason 1915b). The usual practice was to mark stands for the selective removal of special products. Cutting was often heavy because everything salable was frequently marked for removal. Most skidding was done with horses, and seedbed preparation was limited to the disturbance associated with logging and slash disposal. Slash was either lopped and scattered or piled and burned (Thompson 1929).

Heavy partial cutting in general (removal of more than 50 percent of the total basal area), and under some conditions any kind of partial cutting, was not successful as a means of arresting deterioration in old-growth stands or accelerating growth of the residual stand. For example, residual trees on the Fraser Experimental Forest suffered heavy mortality when about 60 percent of the total basal area was removed by either individual tree selection or modified seed-tree cutting (Alexander 1966b) (fig. 21). Furthermore, net increment was less than in uncut stands. Similar results followed heavy partial cutting elsewhere in the central Rocky Mountains, and in the northern and Canadian Rockies (Blyth 1957, Hatch 1967, LeBarron 1952). Even where mortality was not a serious problem, heavy partial cutting often left the older, decadent stands in such poor condition that not only was there little or no growing stock available for another cut, but the stands had little appearance of permanent forest cover (Tackle 1965).

The principal cause of mortality was usually windfall, and it generally increased as the intensity of cutting increased. Mountain pine beetle (*Dendroctonus ponderosae* Hopk.) outbreaks caused heavy losses in some instances, and beetles continue to be a serious and often unpredictable threat to lodgepole pine forests. In addition, many stands were infected with dwarf mistletoe (*Arceuthobium americanum* Nutt. ex. Engel.). Partially opening up the stand intensified the infection on residual trees, which in turn infected the new reproduction, leading to infection centers in the next generation. These heavily dwarf mistletoe-infected stands are a serious lodgepole pine management problem (Gill and Hawksworth 1964).

Where substantial reserve volumes were left, partial cutting was successful in some instances in the sense that the residual stand did not blow down. On the Fraser Experimental Forest, windfall losses were light and other mortality negligible after partial cutting removed about 45 percent of the total basal area by a modified shelterwood cut, even though the stands were exposed to windstorms that nearly destroyed adjacent, partially cut stands with less residual basal area (Alexander 1966b). Net increment was no greater than in uncut stands, however.

There are numerous examples of early cuttings on many National Forests in Colorado and Wyoming where a light to moderate shelterwood cut that removed 30 to 40 percent of the total basal area did not result in excessive mortality. The openings created have regenerated to either new lodgepole pine or the climax species. Where dwarf mistletoe infection in overstory trees was light, the new pine stand is not heavily infected. Similar stands have originated from open-grown trees and stands that were opened up by mountain pine beetle infestations (Alexander 1972).

In 1939, Taylor developed a tree classification scheme for marking lodgepole pine for partial cutting that is still useful today (fig. 22). He based his classification on the area, length, and vigor of the crowns of individual trees:

Vigor class A

1. Crown area: 30 percent or more of the "extreme outline" of vigor class A.
2. Crown length: 50 percent or more of the bole length.
3. Crown vigor: Dense, full, good color, pointed.

Vigor class B

1. Crown area: Usually more than 30 percent but less than 50 percent of the "extreme outline" of vigor class A.
2. Crown length: Usually more than 50 percent but usually less than 60 percent of the bole length.
3. Crown vigor: Moderately dense, good color, pointed or slightly rounded.

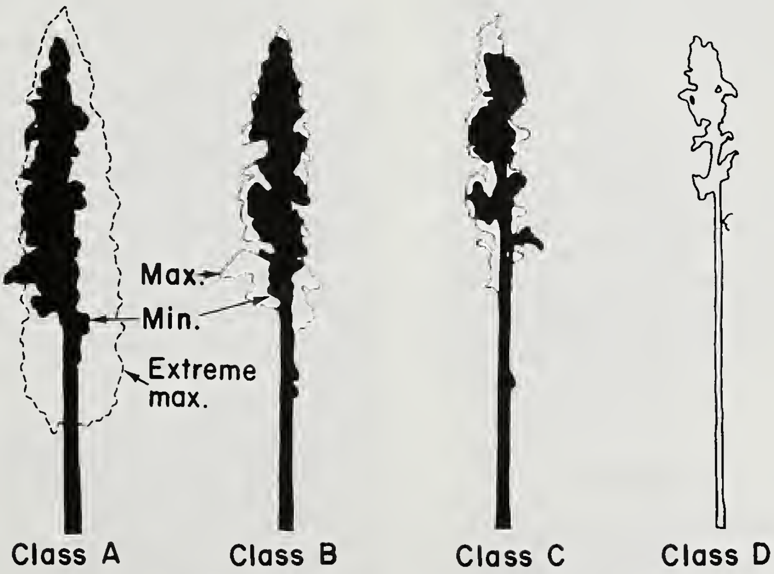

Figure 22.—Tree vigor classes (Taylor 1939).

Vigor class C

1. Crown area: 15 to 30 percent of the "extreme outline" of vigor class A.
2. Crown length: 40 to 50 percent of the bole length except for trees with above average vigor, when 20 percent of the bole length is sufficient.
3. Crown vigor: Sparse, bunchy, poor color, never pointed.

Vigor class D

1. All live trees of poorer vigor than class C. Includes trees in classes A, B, and C outlines but with dead or dying tops.

At the close of World War II, harvesting shifted back to clearcutting as the recommended practice (LeBarron 1952, Lexen 1949). Traditionally, stands have been clearcut in either blocks or strips (Alexander 1966b, LeBarron 1952, Lexen 1949, Tackle 1965). The pattern and size of opening depended upon the predominant cone habitat (serotinous or nonserotinous) and the occurrence of dwarf mistletoe (Tackle 1965). The common practice has been to cut all merchantable trees, followed by removal of the unmerchantable residual to reduce dwarf mistletoe infection. Slash and logging debris have usually been either (1) broadcast burned, dozer piled or windrowed and burned, or (2) roller chopped to reduce fire hazard and prepare seedbeds. Clearcuts have usually restocked naturally if logging slash bearing serotinous cones was carefully handled (Alexander 1966a; Boe 1956; Tackle 1964, 1965), or openings were small where cones were nonserotinous (Alexander 1966a). However, both artificial and natural regeneration efforts have failed where seed was burned in slash fires, openings were too large to be seeded in from the side, or opening up the site created difficult microenvironments (USDA-FS 1971).

Clearcutting is still the recommended practice for areas where timber production is the primary use, but openings must be smaller (40 acres or less) than in the past, and designed to blend into the landscape. Where the visual and environmental impacts of clearcutting are not acceptable, clearcutting is not compatible with other uses, or regeneration will be difficult, some form of partial cutting must be used (Alexander 1972).

DAMAGING AGENTS

Windfall

In the central Rocky Mountains, lodgepole pine is generally considered susceptible to windthrow after cutting. Partial cutting increases the risk because the entire stand is opened, whereas only the boundaries between cut and uncut areas are vulnerable after clearcutting (Alexander 1966b, 1972; Mason 1915b). While the tendency to windthrow is frequently attributed to a shallow root system, the development of the root system varies with soil and stand conditions. On deep, well-drained soils, trees have a better root system than on shallow or poorly drained soils. With the same soil conditions, the denser the stand the less windfirm are individual stems, because trees that have developed together in dense stands over long periods of time mutually protect and support each other and do not have the roots, boles, and crowns to withstand exposure to the wind if opened up drastically. The risk of blowdown is also greater in stands with defective roots and boles. The presence of old windfalls is a good indication of lack of windfirmness. Furthermore, regardless of how stands are cut or the soil and stand conditions, the risk of blowdown is greater on some exposures than others. The following windfall risk situations based on exposure have been identified by Mason (1915b) and Alexander (1964, 1967a, 1972):

Low Windfall Risk Situations

1. Valley bottoms except where parallel to the prevailing winds, and all flat areas.
2. All lower and gentle middle north- and east-facing slopes.
3. All lower and gentle middle south- and west-facing slopes that are protected by considerably higher ground not far to windward.

Moderate Windfall Risk Situations

1. Valley bottoms parallel to the direction of prevailing winds.
2. All lower and gentle middle south- and west-facing slopes not protected to the windward.
3. Moderate to steep middle and all upper north- and east-facing slopes.
4. Moderate to steep middle south- and west-facing slopes protected by considerably higher ground not far to windward.

High Windfall Risk Situations

1. Ridgetops.
2. Moderate to steep middle south- and west-facing slopes not protected to the windward, and all upper south- and west-facing slopes.
3. Saddles in ridgetops.

The risk of windfall in these situations is increased at least one category by such factors as poor drainage, shallow soils, and defective roots and boles. All situations become high risk if exposed to special topographic situations such as gaps and saddles in ridges at higher elevations to the windward that can funnel wind into the area.

On clearcut units the leeward cutting boundaries are the most vulnerable, especially if they are at right angles to the direction of windstorms.

Insects

Many species of insects infest lodgepole pine (Keen 1952), but the mountain pine beetle (*Dendroctonus ponderosae* Hopk.) is the most serious pest in mature to overmature lodgepole pine stands in the Rocky Mountains. Epidemics have occurred throughout recorded history (Roe and Amman 1970), and extensive outbreaks are now in progress in northern Wyoming. Less extensive, but severe outbreaks are underway in southern Wyoming and northern Colorado, where a large number of old-growth stands that have been protected from wildfires are now reaching a high degree of susceptibility to attack (Alexander 1972).

Mountain pine beetles feed and breed in the phloem layer. The first indications of attack are pitch tubes on the trunk where beetles have entered, and boring dust in the bark crevices and around the base of the tree. Trees successfully attacked in the summer usually begin to fade the following spring. Needles change from green to yellow green, sorrel, and finally rusty brown before dropping off (McCambridge and Trostle 1972).

Not all stands are equally susceptible to attack. Epidemic outbreaks are usually associated with stands that contain at least some vigorous, thick-phloemed trees 14 inches in diameter and larger (Cole and Amman 1969, Roe and Amman 1970). As the larger trees are killed, the beetles must attack smaller diameter trees until the outbreak finally subsides because the phloem of these trees is not thick enough to provide a food supply. Trees smaller than 6 inches d.b.h. are rarely killed. Although natural factors such as a sudden lowering of fall temperature or prolonged subzero winter temperatures, nematodes, woodpeckers, and parasites may reduce populations, they cannot be relied upon to control outbreaks (McCambridge and Trostle 1972). Chemical control is expensive and often is only a holding action until potentially susceptible trees can be disposed of by other means.

The only alternatives left to the manager in heavily infested stands where most of the trees are 10 inches in diameter and larger are to (1) fell and salvage the infested trees, burn the green culls and unmerchantable portions of trees, and regenerate a new stand, or (2) let the infestation run its course uncontrolled. On the other hand, in infested stands with a good stocking of trees in the smaller diameter classes, partial cutting that removes the vigorous, larger trees with thick phloem appears well adapted to regulating mountain pine beetle losses.

The pandora moth (*Coloradia pandora* Blake) (Carolin and Knopf 1968) and the lodgepole terminal weevil (*Pissodes terminalis* Hopk.) that produce distorted or forked crowns in young stands are other potentially serious insects attacking lodgepole pine.

Diseases

Dwarf mistletoe is the most serious disease affecting lodgepole pine (Hawksworth 1965) (fig. 23). Surveys in Colorado and Wyoming show that from 30 to 60 percent of the commercial lodgepole pine forests are infected to some degree by dwarf mistletoe (Hawksworth 1958). Dwarf mistletoe reduces growth, increases mortality (Hawksworth and Hinds 1964), and drastically reduces seed production. The mortality rate depends largely on the age of the host tree when attacked. Young trees die quickly, while older trees with well-developed and vigorous crowns may not show appreciable effects for years. Dwarf mistletoe is most damaging in stands that have been partially opened up by cutting, mountain pine beetles, or windfall, and of least consequence on regenerated burns following catastrophic fires (Gill and Hawksworth 1964). Heavily infected old-growth stands frequently have only about half the fbm volume of comparable uninfected stands (Hawksworth 1958).

The disease is difficult to detect in recently infected stands because trees show no abnormalities except for the inconspicuous shoots on branches and main stems. Where the parasite has been present for a long time, stands will have one or more heavily damaged centers characterized by many trees with witches' brooms, spike-tops, and an above-average number of snags with remnants of brooms (Gill and Hawksworth 1964).

Although optimum development is favored by a vigorous host, and the most vigorous trees are most heavily infected, the frequency of infection is usually higher on poor than good sites. Furthermore, where site index is 70 or greater (Alexander 1966c), only the middle and lower crowns of dominants and codominants are susceptible to heavy infection, while trees in the

Figure 23.—Dwarf mistletoe-infected lodgepole pine. Bighorn National Forest, Wyoming.

intermediate or lower crown classes are susceptible to heavy infection throughout their crowns. Where the site index is below 70, all crown classes are susceptible to heavy infection throughout the crowns.[15] In Colorado and Wyoming, dwarf mistletoe has an altitudinal limit about 300 to 500 feet below the upper limit of commercial lodgepole pine forests. This means that in some areas, considerable lodgepole pine lies in a dwarf mistletoe-free zone (Gill and Hawksworth 1964).

Separation of the old and new stands by clear-cutting and felling unmerchantable residual trees appears to be the best way to control dwarf mistletoe. In areas of high tree values, such as recreational, administrative, and homesites, infected branches can be pruned from lightly infected trees, but heavily infected trees must be cut. Partial cutting and thinning generally create ideal conditions for maximum damage, and should be avoided where possible unless the infection is light.

To quantify the severity of infection, Hawksworth (1961) developed the 6-class mistletoe rating system (fig. 24). The average stand rating can be estimated by determining the percentage of trees infected in the stand. The approximate relationship of average stand rating to proportion of trees infected in several mature stands was:

Average stand mistletoe rating	Percent of trees infected
1	50
2	70
3	90
4	97
5	99
6	100

Comandra blister rust, a canker disease caused by *Cronartium comandrae* Pk., occurs commonly in the central Rocky Mountains, but damage has been most extensive in northern Wyoming (Peterson 1962). Girdling causes dead tops and flagging branches, which are the most conspicuous symptoms until dead trees begin to appear. On larger stem infections, cankers with an abundance of yellow, dried resin are a conspicuous symptom (Mielke et al. 1968). The disease cannot pass directly from pine to pine but requires an intermediate host (*Comandra umbellata* (L.) Nutt.).

The damage from Comandra rust is usually not spectacular, but trees of all sizes and ages

[15]*Personal communication with Frank G. Hawksworth, Plant Pathologist, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

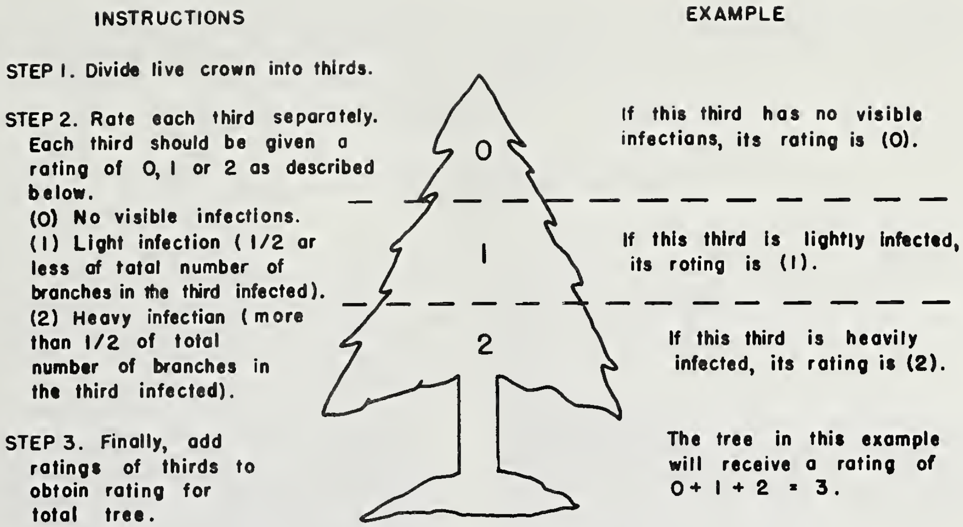

Figure 24.—The 6-class mistletoe rating system (Hawksworth 1961).

are susceptible (Peterson 1962). Seedlings may be killed in a relatively short time. In older trees, the time betwen initial infection and death may be 25 or more years because the infection enters the trunk by way of the branches and the rate of spread is slow. Under conditions favorable to the rust, stands may be heavily damaged over limited areas. In those stands, from 30 to 40 percent of the living and dead trees will have cankers, and about half the cankered trees will have spike-tops (Krebill 1965). Usually, however, the infection is lighter and scattered through the stand (Peterson 1962).

Sanitation salvage cutting is about the only practical way of controlling the disease in forest stands (Mielke et al. 1968). In areas of high tree values it may be possible to prune infected branches from lightly infected trees, but heavily infected trees should be cut. Partial cutting and thinning appear well adapted to the control or reduction of Comandra rust, even in heavily damaged stands, because the disease is not passed from pine to pine and only the trees with stem infections need to be removed.

Western gall rust (*Peridermium harknessii* Moore) occurs on lodgepole pine throughout the Rocky Mountains, but is not as distinctive as Comandra rust because most infections occur as galls on branches rather than on the trunk. Mortality in the seedling stage and loss of growth and cull are the principal forms of damage from this rust. Removal of infected trees in cultural operations is the only practical way to control gall rust damage in forests. Presence of a few galls is not sufficient cause to remove a tree. Only cankered trees need be cut (Peterson 1960).

The major root and butt fungi attacking lodgepole pine in the Rocky Mountains are *Polyporus circinatus* Fr., *Coniophora puteana* (Schum ex. Fr.) Karst, and *Armillaria mellea* (Fr.) Quel.; the principal trunk rot fungus is *Fomes pini* (Fr.) Karst (Hepting 1971, Hornibrook 1950).

NATURAL REGENERATION REQUIREMENTS

The basic elements necessary for successful natural regeneration are the same as for spruce: (1) an adequate supply of viable seed, (2) a suitable seedbed, and (3) environmental conditions compatible with initial survival and seedling establishment.

Seed Supply

FLOWERING AND FRUITING

Male flowers of lodgepole pine ripen and pollen is wind disseminated in late spring and early summer. Cones from the current year's crop mature and seed ripens in September and October (Tackle 1961a).

CONE BEARING AGE

Lodgepole pine begins bearing cones with viable seeds at a very young age — in open stands by trees 5 to 10 years old, in more densely stocked stands by age 15 to 20 years — and continues well past maturity (Crossley 1956b,

Table 3.--Variations in serotinous cone habit and estimated average sound seed per acre stored in serotinous cones on four areas in Montana and Idaho (Lotan 1967a, 1968)

Average age of stand, (yrs)	Cone habit: Predominately serotinous	Cone habit: Intermediate	Cone habit: Predominately nonserotinous	Average sound seed stored per acre
	Percent of trees			*Millions*
111 (uneven aged)	38	14	48	1.0
88 (even aged)	58	10	32	3.2
117	48	19	33	1.8
191	23	20	57	.8

Tackle 1961a). Seed from trees less than 10 years old can have as high a germination percentage as seed from mature trees.

CONE CHARACTERISTICS

The regeneration of lodgepole pine is greatly affected by its cone habit. Individual trees are classified as (1) **closed cone** if 90 percent or more of the cones are serotinous, (2) **intermediate** if less than 90 but more than 10 percent of the cones are serotinous, and (3) **open cone** if less than 10 percent of the cones are serotinous (Crossley 1956b; Lotan 1967a, 1968).

Throughout much of the Rocky Mountains, the closed cone habit is widespread (Alexander 1966a, Critchfield 1957, Tackle 1961a). In stands with the serotinous habit, trees bear an abundance of closed cones that remain unopened on standing trees up to 40 years (Lotan and Jensen 1970). That seed is available for release following fire or cutting. In one study over a 10-year period in central Colorado and southern Wyoming, the average amount of seed stored in closed cones was 2½ to 3½ times greater than the current crop (Bates 1930). The average number of sound seeds stored in closed cones ranged from 181,000 to 1,104,000 per acre.

Although most trees bear either serotinous or nonserotinous cones, the number of serotinous cones varies greatly from tree to tree, and the proportion of closed-cone types varies greatly between stands (Clements 1910, Mason 1915a, Lotan 1967a). Lotan (1967a, 1968) studied the variation in serotinous cone habit and estimated the number of sound seeds stored in closed cones on four areas in Montana and Idaho (table 3). Most trees produced almost entirely either open or closed cones. Only 10 to 20 percent of the trees were classified as intermediate. The estimated number of sound seeds stored in closed cones varied from 0.8 to 3.2 million per acre.

The fruiting habits of lodgepole pine in Alberta suggest a possible relationship of age to closed cone habit (Crossley 1956b). In young stands (17 years old) only 17 percent of the trees had closed cones, while in 55- and 250-year-old stands, 82 and 83 percent, respectively, of the trees bore closed cones.

In some areas the cone habit is known to be nonserotinous. For example, trees in northern Wyoming on the Bighorn and Shoshone National Forests bear largely open cones. Other areas reporting mainly nonserotinous cones are the Deschutes Basin and Blue Mountains in Oregon (Dahms 1963, Mowat 1960, Trappe and Harris 1958).

The variability in closed cone habit means that each stand must be examined before cutting to determine cone serotiny and estimate the number of sound seeds available in closed cones. Lotan and Jensen (1970) have developed such estimating procedures from data collected in mature and overmature stands in Idaho and Montana. They should also provide reasonable estimates of the number of sound seeds stored in serotinous cones in similar stands in the central Rocky Mountains, however. Seed from nonserotinous cones can be estimated from conventional seed traps.

TIME OF SEEDFALL

Natural seedfall in lodgepole pine occurs throughout the year, but not at a uniform rate. On two study areas in pure, overmature stands in Montana, only about 20 percent of the yearly crop shed was released during August and September in 3 out of 4 years; 60 to 70 percent was shed from October to June the following year, and the remainder fell in June and July (Boe 1956, Tackle 1964). In the subalpine forest region of Alberta, maximum annual seedfall during 3 years of observation in a 60-year-old stand occurred over a 4- to 5-week period, and was heaviest the first week in October (Crossley 1955). In eastern Oregon, most of the seedfall occurs before November (Dahms 1963, Mowat 1960).

PRODUCTION AND PERIODICITY

Lodgepole pine has generally been rated a prolific seed producer, with good crops borne at 1- to 3-year intervals and light crops produced in the intervening years (Bates 1930, Dahms 1963, Mason 1915a). On the other hand, Boe (1954) analyzed cone crop records in Montana, and rated the 16 crops observed during a 45-year period west of the Continental Divide as 1 good, 11 fair, and 4 poor. East of the Divide, seed crops were rated 2 good, 13 fair, and 5 poor for a 20-year period. Part of the apparent differences in seed production may be in definitions of what is a good seed year, however.

The number of fully developed seeds per cone varies widely. In one study on 9 National Forests in Colorado and Wyoming, cones averaged 26 seeds (Mason 1915a). Cones averaged 40 seeds in another study of large lots of cones in Colorado and southern Wyoming, but individual cones produced as few as one or two seeds (Bates 1930). The average number of sound seeds per cone in Montana and Idaho varied between 10 and 20 (Lotan 1967a, 1968).

Seed production by individual trees and by stands also varies considerably. Seeds from old and new cones together averaged 50,000 per tree in Idaho and 21,000 per tree in Colorado (Clements 1910). Annual variations in seed production on felled trees during a 10-year period (1912-21) ranged from 0 to 135,000 per acre in southern Wyoming, and from 55,000 to 827,000 per acre in central Colorado (Bates 1930). In central Oregon, where the cones are nonserotinous and the total crop is released each year, annual production in uncut stands varied from 178,000 to 572,000 sound seeds per acre during a 3-year period (Dahms 1963). In the other year of the study, only 14,000 seeds per acre were produced.

In Montana, annual seedfall in stands with predominately serotinous cones averaged 70,000 sound seeds per acre over a 4-year period (Boe 1956). Tackle (1964) observed this Montana area for 2 more years and another area nearby for 2 years, and reported average annual release of 65,000 to about 90,000 sound seeds per acre. In similar stands in Alberta, average annual seedfall varied from 10,000 to 30,000 seeds per acre during a 3-year period (Crossley 1955). Most of the seed released in the predominately serotinous stands probably came from nonserotinous cones, and represents only a small proportion of the annual seed production in these stands.

SEED QUALITY

Variability in seed quality affects sound seed production. Bates (1930) concluded that the percentage of sound seed was higher in years of good seed production than in years of poor production. Furthermore, more sound seeds were available from current cones than from old cones. On the other hand, a number of studies have indicated little difference in seed quality between new cones and those up to 10 years old (Ackerman 1963, Crossley 1956a, Lotan 1964b). About 50 percent of the stored seed was viable in one study (Lotan 1964b). No data are available for seed from nonserotinous cones.

DISPERSAL

Lodgepole pine seed is light, averaging about 100,000 seeds per pound, with about 1/3 to 1/2 pound of seed per bushel of cones (Bates 1930). Dispersal from standing trees is largely by wind, but wind is important only in stands where nonserotinous cones are abundant (Tackle 1961a). Seedfall into cleared openings has been studied in Montana and Oregon (Boe 1952, 1956; Dahms 1963, Tackle 1964). Seed dispersed from standing timber dropped off sharply at a distance of about 66 ft and continued to diminish as distance from the source increased. These authors concluded that the number of seeds dispersed beyond 200 ft from the source was inadequate to restock a cutover area regardless of the amount of seed released under the uncut stand. More seeds were dispersed from the north and west boundaries than from the south and east boundaries on most areas studied, but differences were too small to detect any influence of prevailing winds on seed dispersal.

In Alberta, Crossley (1955) found a somewhat different dispersal pattern. Although the number of seeds falling to the ground diminished as distance from standing timber increased, seedfall did not diminish as rapidly in the first 66 ft, and there was little difference in the number of seeds falling to the ground between 66 and 330 ft from standing timber. He also concluded, however, that the amount of seed falling into the opening was not adequate to restock the area.

Seeds released from cones attached to the slash and cones knocked from the slash and scattered on the forest floor are the most important in regenerating stands with serotinous cones (Tackle 1961a). Most seeds are released from this source the first year after exposure (Boe 1956, Crossley 1956a). Some seeds are released for as long as 6 years (Tackle 1954b) but the number is not likely to be significant after the second year because there is little further change in cone radiation, height above the ground, or ventilation (Crossley 1956a). Furthermore, seeds from cones lying on the ground for as long as 6 years have only about half the germinative capacity of seeds stored in cones above the ground for the same period of time (Tackle 1954b).

Fire is not a requisite for seed release from closed cones in the slash (Bates et al. 1929), but heat is necessary. Temperatures of at least 113° to 122° F are required to melt the resin bond and allow cone scales to flex and spread apart (Cameron 1953, Clements 1910). Crossley (1956a) investigated the effects of solar radiation on cone opening, and found that an air temperature of at least 80° F at 3.5 ft above the ground was necessary to provide the heat needed to rupture the bonds of cone scales. Furthermore, the cones had to be on or near the ground surface to open, because at heights above 7 inches from the ground or other reflecting surface, cone temperatures did not rise sufficiently to melt resin bonds. More cones open on south slopes than on north slopes, but the amount of residual overstory apparently has little effect on cone opening because only a short exposure to direct solar radiation is sufficient to raise temperatures to a critical level (Crossley 1956a, Lotan 1964b).

No data are available from the central Rocky Mountains on the number of sound seeds required to produce an established seedling under different seedbed and environmental conditions. Lotan (1964a, 1968) has suggested that, under favorable seedbed and environmental conditions in the northern Rocky Mountains, 30,000 to 50,000 sound seeds per acre are needed to produce 1,000 first-year seedlings.

In stands with serotinous cones, assuming that Lotan's figures are reasonable estimates, the amount of seed stored in closed cones appears to be more than adequate to insure regeneration success if logging slash bearing cones is carefully handled. In stands with nonserotinous cones, 30,000 to 50,000 sound seeds per acre are not likely to be dispersed as far as 200 ft from standing timber in any one year. This suggests that the maximum size of opening in a nonserotinous stand that will restock in a reasonable amount of time is probably no greater than 300 ft wide or about four to five times tree height.

SOURCE

There are several sources of seed available for natural reproduction (Tackle 1964). In clearcut openings, the principal sources are:

1. Serotinous cones in the logging slash (provides only a one-shot opportunity).
2. Nonserotinous cones on trees standing around the cleared opening (wind disseminated about 150 ft).
3. Nonserotinous cones on unmerchantable residual trees while they are still standing.
4. Nonserotinous cones on new reproduction 5 to 10 years old.
5. Some seed is also available from nonserotinous cones on trees cut on the area.

In partially cut areas, the principal sources of seed are from serotinous cones in the logging slash and from nonserotinous cones on residual trees left on the area. Some seed may also be available from nonserotinous cones on trees cut on the area.

One of the significant considerations in clearcutting in stands with nonserotinous cones is the resistance of the seed source to windthrow. Situations and conditions where windfall risk is low, moderate, and high have been identified (Mason 1915a) and recommendations developed for locating windfirm boundaries on clearcut units (Alexander 1964, 1967b). These recommendations have been modified to identify the kinds of trees and residual volumes that can be successfully retained in partially cut areas for different windfall risk situations and stand conditions (Alexander 1972).

VIABILITY

The viability of lodgepole pine is rated good. In a series of 413 uniform tests, an average germinative capacity of about 80 percent was obtained after 41 days at 6 to 10 percent moisture with fluctuating diurnal temperatures of 57° to 83° F (Bates 1930). Lodgepole pine will retain a good germinative capacity for long periods of time if properly stored. The germinative capacity of seed stored in serotinous cones is not seriously reduced even after 50 to 75 years (Clements 1910, Tackle 1954b). Lodgepole pine seed does not normally require pretreatment, but stratification may hasten germination (Tackle 1954b). In nature, lodgepole pine seed overwinters under the snow and germinates the following spring.

SEED LOSSES

Lodgepole pine seed crops are subject to losses before seedfall to cone and seed insects (Keen 1958), but their relative importance, frequency of occurrence, and magnitude are not known. Pine squirrels consume large amounts of seed and cones, as evidenced by the large caches common to lodgepole pine forests. After seed is shed to overwinter, small mammals such as mice and chipmunks undoubtedly consume considerable but unknown amounts of seed. In western Montana, lodgepole pine seedlings survived better on protected than on unprotected spots, but the differences may have been due to factors other than rodents (Roe and Boe 1952, Tackle 1961b). In the interior of British Columbia, protection from rodents was essential to lodgepole regeneration success (Prochnau 1963).

Factors Affecting Germination

Viable seeds of lodgepole pine that survive overwinter normally germinate in the early summer following snowmelt in the central Rockies. Optimum air temperature for germination is about 70° F (Bates 1930). Air temperatures of 70° F are usually reached in early June in the central Rocky Mountains, but snow frequently covers the seedbed until middle or late June. In one study in the northern Rocky Mountains, where seeds were sown in the fall to simulate natural seedfall, 90 percent of the germinating seedlings emerged the first 2 weeks in July following snowmelt in late June (Lotan 1964a). Field germination percentages were 74 to 84 percent for all seedbed conditions — considerably higher than reported for Colorado and Wyoming (Bates 1930).

Lodgepole pine is noted for its ability to germinate on burned surfaces after wildfire. Fire releases the seed from serotinous cones, creates a favorable seedbed, and reduces vegetative competition for light and moisture. However, site conditions and intensity of burn, as well as seed supply, influence germination on burned seedbeds. Some areas of the same burn will be overstocked, while other parts will be poorly stocked or nonstocked (Horton 1953, 1955; Stahelin 1943).

Germination has also been variable on seedbeds prepared by burning. In Colorado, good germination occurred in full sunlight on seedbeds where slash was burned in small piles (USDA-FS 1943). Good germination occurred on burned seedbeds in Alberta, but mortality on the black surfaces was high in full sunlight (Crossley 1956c). On the other hand, poor germination has been reported on burned seedbeds by Ackerman (1957), Boe (1956), and Crossley (1952). These authors did not indicate, however, whether poor success was due to high temperatures and surface drying, deep layers of loose dry ash, or loss of seed supply when cone-bearing slash was burned. In a greenhouse study, leached burned soil provided the highest germination, but unleached burned soil with a high ash content inhibited germination (Gayle and Gilgan 1951).

Germination has usually been better on exposed mineral soil and on disturbed duff and mineral soil than on other seedbed types, presumably because of more stable moisture conditions (Ackerman 1962, Bates et al. 1929, Boe 1956, Crossley 1956c, Tackle 1964, Trappe 1959). Germination has frequently been good on the natural forest floor (Boe 1956, Crossley 1956c), but the initial germination is often offset by heavy mortality when the seedbed dries out (Ackerman 1962, Prochnau 1963).

The effectiveness of the seedbed is influenced by any factor that affects temperature and moisture, as well as depth of slash and distribution of the slash-borne seed supply.

On clear days in early summer, exposed soil surfaces are rapidly dried out and heated to high temperatures. Few seeds can imbibe sufficient water to germinate, and many newly germinated seedlings are killed by stem girdle or drought. Shade either from light slash or a residual overstory reduces excessive heating and drying of the soil surface, thereby improving germination on both burned and mineral soil seedbeds (Crossley 1956c, Day and Duffy 1963). On the other hand, slash may inhibit germination if it is too deep and a mat of needles and fine twigs several inches thick accumulates (Boe 1956, Lotan 1964a, Tackle 1954b). Furthermore, if germination is delayed until late summer rains, the late-germinating seedlings may not harden off before the onset of cold weather (Ronco 1967).

Factors Affecting Initial Survival and Seedling Establishment

Most lodgepole pine seedling mortality occurs during the first growing season after germination, but seedlings usually require about 2 to 3 years after germination to become established. The first growing season is considered here to be the period of initial survival, and the second and third growing seasons as the time of seedling establishment.

INITIAL ROOT GROWTH

The rate of root growth is an important determinant in the initial survival of lodgepole pine seedlings. The further the root penetrates the soil, the better the chance for the seedling to survive drought and frost heaving. Critical rooting depth depends upon the seedbed type, weather, and soil properties.

There is little information on the first-year rooting depth of lodgepole pine other than the growth is slow (Tackle 1961a). Lotan (1964a) excavated a few seedlings less than 8 weeks old in the northern Rocky Mountains, and found roots 5 to 6 inches long on mineral soil seedbeds, 4 inches long on undisturbed duff. Seedlings initially form a weak taproot but it does not persist. The initial root system is stunted or obscured by subsequent lateral root development (Horton 1958).

SEEDBED TYPE

In the undisturbed forest, lodgepole pine seedlings establish most readily in openings on mineral soil such as upturned mounds resulting from windfall. Seedlings will become established on duff, litter, partially decomposed organic matter, or decaying wood if they are under a canopy that provides sufficient light while preventing the seedbeds from heating and drying out. Lodgepole pine seedlings do not become established in significant numbers on any seedbed type under a closed canopy.

The same seedbeds are available after logging and slash disposal, but with some additional mineral soil, and burned mineral soil and mineral soil mixed with organic matter. Removal of the overstory modifies the microhabitat, however, and such factors as organic seedbeds and competing vegetation frequently become limiting to natural regeneration success. Seedbed preparation to create a more favorable moisture source can modify limiting factors sufficiently to enable seedlings to survive.

Serotinous Cones

In stands with serotinous cones, the effect of seedbed type on survival and establishment is frequently confounded with slash disposal treatments because the seed supply is largely in the slash-borne cones. Furthermore, natural reproduction with seed from serotinous cones is a one-shot opportunity, and if the slash is not carefully handled, good seedbed conditions are wasted.

Lodgepole pine survival and establishment after logging and slash disposal in the central Rocky Mountains has generally been best on prepared mineral soil seedbeds (Alexander 1966a, USDA-FS 1943). In fact, the combination of dozer piling or windrowing slash for burning, and mechanically exposing mineral soil has frequently resulted in so much reproduction that early thinning is required to control stand density (Alexander 1966a).

Seedling survival and establishment have been good on burned seedbeds (Alexander 1966a, 1966b; USDA-FS 1943) except on fully exposed south slopes or where the seed supply has been destroyed in slash disposal. In one study in southern Wyoming, however, seedling establishment was nearly optimum on seedbeds where slash was broadcast burned or the concentrations burned, and the seed supply in serotinous cones was largely consumed by the slash fires. Seed for restocking these small (400 ft wide) openings came from nonserotinous cones on trees standing around the perimeter (Alexander 1966a).

Seedling survival and establishment has been variable on undisturbed seedbeds. On some areas it was only fair (USDA-FS 1943), but on other areas, satisfactory numbers and stocking were obtained on natural seedbeds with only a light cover of duff and litter. On the latter areas, slash was either lopped and scattered, or untreated slash was less than 1 ft deep and covered less than 40 percent of the area (Alexander 1966a, 1966b).

In the northern Rocky Mountains and Alberta, initial survival and establishment were better on mechanically scarified mineral soil and a combination of disturbed mineral soil and duff than other seedbeds (Ackerman 1957, 1962; Boe 1956; Crossley 1952, 1956c; Johnson 1968; Tackle 1965). In fact, these seedbeds were usually overstocked. Good establishment was obtained on undisturbed seedbeds on comparatively dry sites with a minimum of unincorporated organic matter and a paucity of competing vegetation, and on disturbed seedbeds where slash was lopped and scattered. Satisfactory numbers and stocking of reproduction were obtained on seedbeds with unburned slash concentrations and windrows, and where slash was piled or windrowed and burned. Burning in general created less favorable seedbeds than mineral soil unless they were shaded, however, because of excessive heating and drying. Furthermore, on burned seedbeds, seedling establishment was frequently slow during the first few years after treatment because too much of the seed supply was destroyed in slash fires (Boe 1952). Survival and establishment did not improve until the new reproduction was large enough to provide a seed source.

On clearcut areas where slash was left untreated, seedling survival and establishment have been better on disturbed mineral soil, disturbed duff, and areas where the depth of slash was less than 1 ft than on undisturbed duff, undisturbed soil, brush and grass, and areas where the depth of slash was greater than 1 ft (Tackle 1956).

Nonserotinous Cones

Observations of seedling establishment in stands with nonserotinous cones in northern Wyoming indicate that regeneration success on cleared openings within effective seeding distance has been satisfactory on mechanically scarified mineral soil and on burned soil seedbeds where slash was either broadcast burned, or piled or windrowed and burned. Seedbeds prepared by rolling and chopping slash have been about as effective as dozer scarification. Exceptions have been on south slopes and at lower elevations, where shade appears necessary to reduce temperatures and conserve moisture.

CLIMATE

The climate of the lower subalpine and upper montane where lodgepole pine grows in the central Rocky Mountains is warmer and drier than the higher spruce-fir zone, but the climate is still characterized by extremes in solar radiation, temperature, and moisture that can limit regeneration success.

Light and Solar Radiation

Light is essential to lodgepole pine seedling survival and establishment. Seedlings do not become established in less than 10 percent full sunlight, and development is poor in less than 20 percent full sunlight (Clements 1910). Early seedling development is usually considered best in full sunlight (Day 1964, Tackle 1961a), but lower radiation levels may be necessary on severe sites to reduce mortality (Armit 1966). Under full exposure, radiation intensities can create critical temperature and moisture conditions for first-year seedling survival.

In one study on the Fraser Experimental Forest in Colorado, more than twice as many seedlings survived the first growing season on all seedbed types with 60 percent shade than in either full sunlight or 30 percent shade (USDA-FS 1943). Similar benefits from overhead shade have been observed on south slopes, and at lower-elevation tension zones between timber and grasslands. On the other hand, first-year survival of planted lodgepole pine seedlings was equally good whether shaded or exposed to full sunlight on some of the most severe sites in the central Rocky Mountains (Ronco 1970d). Furthermore, full exposure to high light intensities did not adversely affect the rate of photosynthesis. Apparently, full exposure to high radiation intensities is more critical to newly germinated seedlings than to older stages.

Temperature

Temperature has been suggested as the least important of the environmental factors limiting regeneration success (Clements 1910), but the characteristic zonal pattern of occurrence of lodgepole pine in the Rocky Mountains is usually attributed to temperature at the upper limits (Tackle 1965).

Bates (1923) rated lodgepole pine as highly resistant to heat damage, but evidence of heat injury seems to be conflicting. Temperatures of 125° to 140° F combined with a restricted moisture supply will seriously damage or kill newly germinated seedlings in the succulent stage, and heat alone will cause mortality from stem girdling when temperatures rise to 140° to 160° F (Armit 1966). When air temperature reaches 80° F in the Rocky Mountains, direct solar radiation is capable of heating exposed soil surfaces to these levels (Crossley 1956a, Day 1964). In Alberta, Ackerman (1957), Crossley (1956c) and Day (1964) indicate that early shade protection, particularly on burned and mineral soil seedbeds, would improve survival, presumably by lowering temperatures and reducing water loss from both seedlings and soil.

In the northern Rocky Mountains, however, heat girdling of newly germinated seedlings did not occur as frequently as expected, although soil surface temperatures commonly exceeded 138° F for several hours and temperatures of 150° to 163° F were observed occasionally on the surfaces of undisturbed and burned seedbeds (Lotan 1964a). At the same time, seedlings were dying from drought. In Colorado, only 2 to 3 percent of the first-year seedling mortality over a 3-year period was from heat girdling on exposed sites where surface temperatures frequently exceeded 135° F and reached as high as 160° F (Ronco 1967). Soil moisture was sufficient to prevent drought losses.

Frost can occur any month of the growing season where lodgepole pine grows, especially in depressions and cleared openings because of cold air drainage and radiation cooling. Newly germinated seedlings are especially susceptible to damage from early fall frosts. In a laboratory study, first-year seedling susceptibility to frost damage was affected by age as well as minimum temperature (Cochran and Berntsen 1973). Seedlings 6 weeks old were more susceptible to frost damage at night temperatures of 18° F than were seedlings 1 to 4 weeks old. At 2 months of age, all seedlings were killed by night minimums of 15° F. Previous exposure to near-freezing temperatures reduced mortality when seedlings were exposed to night minimums of 20° F or less.

Frost damage after the first year has not been observed or reported in the central Rocky Mountains (Ronco 1967).

The combination of warm daytime temperatures, nighttime temperatures below freezing, and saturated soils unprotected by snow cover in the early fall are conducive to frost heaving. In one study in central Colorado, these conditions were observed in 1 out of 3 years, and frost heaving was the principal cause of first-year seedling mortality on exposed mineral soil (Ronco 1967). Seedlings continue to be susceptible to frost heaving after the first growing season. Shading seedlings reduced mortality by reducing loss of radiant energy from both seedlings and soil.

Moisture

The moisture condition of the seedbed during the growing season largely determines first-year seedling survival. In the Rocky Mountains, summer drought can be a serious threat to seedling survival and establishment on some sites. For example, mortality to both natural and planted seedlings on south slopes in northern Wyoming has been attributed largely to drought. In Montana and Idaho, approximately 90 percent of the first-year seedling mortality in one study was caused by drought (Lotan 1964a). On the other hand, Ronco (1961b, 1967) observed the survival of newly germinated and planted seedlings over a period of years, and concluded that drought was not a serious cause of mortality in the subalpine of central Colorado. However, his studies were at a higher elevation in the spruce-fir zone where moisture is generally more abundant.

Precipitation during the growing season is particularly critical to the survival of seedlings. Lotan (1964a) found that from 50 to 70 percent of the total mortality in 1 year occurred between June 22 when germination started and July 13, a period when precipitation was negligible. Mortality was substantially reduced after more than 1 inch of rain fell beginning on July 13. The relatively few losses to drought recorded by Ronco (1961b, 1967) were attributed to frequent showers after germination began or seedlings were planted.

Summer precipitation is not always a benefit to seedling survival and establishment, especially if storms are so intense that most of the moisture runs off and soil movement on unprotected soil surfaces either buries the tops or uncovers the roots of seedlings.

SOIL

Lodgepole pine grows on a wide range of soils throughout the Rocky Mountains (Johnson and Cline 1965, Retzer 1962), but little is known about how soils affect establishment and growth (Tackle 1965). In general, lodgepole pine becomes established most readily and makes best growth on moist, light, well-drained, sandy or moderately acid gravelly loam soils derived from granites, shales, sandstones, and coarse-grained lavas (Tackle 1961a, 1965). It does not establish readily in the central Rocky Mountains on soils derived from limestone or fine-grained igneous rocks (Bates 1917a). The former are too dry, and the latter break down into clays that are too poorly drained. Lodgepole pine is generally better able to establish on dry, rocky soils, on excessively drained light-textured soils, and severe exposures than are associated species, but it does not establish readily on sites with impeded drainage or heavily acid soils.

DISEASES

Newly germinated seedlings are killed by damping-off fungi. Losses normally occur early in the growing season before seedlings cast their seedcoats, and can be serious on all seedbed types if they remain damp for long periods of time. In one study, about 14 percent of the newly germinated lodgepole pine seedlings were killed in 2 consecutive years by damping-off on mineral soil seedbeds (Ronco 1967). Snowmold fungi occasionally damages or kills both natural and planted lodgepole pine seedlings. Ronco (1967) found little damage on pine plantings except during 1 year when snowmelt was retarded and seedlings remained under the snow too long. About 20 percent of the seedlings suffered damage, which was about equally divided between shaded and open-grown seedlings.

ANIMAL DAMAGE

Ronco (1967) found that mountain pocket gophers destroyed some planted seedlings each year, but losses were highest during a population peak the third and fourth winters after planting. Nearly all seedlings destroyed by gophers were clipped just above the ground level, but a few died from root destruction caused by burrowing. Clipping damage to newly germinated seedlings while the seedcoat is still attached frequently has been attributed to mice, but there is no documented evidence of mice having actually done the damage. A recent study of clipping damage and mortality to spruce seedlings on the Fraser Experimental Forest in Colorado has demonstrated that the gray-headed junco is responsible (Noble and Shepperd 1973). It seems likely that juncos or other seed-eating birds are responsible for similar damage to lodgepole pine. The mountain vole, however, will debark and kill established seedlings.

Young lodgepole pine seedlings are vulnerable to trampling damage from grazing and browsing animals. In one study of natural reproduction in southern Wyoming (Alexander 1966a), seedbed and slash disposal treatments created easy travel routes, and cattle frequently were observed to trail through the study area. While few seedlings were trampled to death, they were either deformed or damaged to the extent that they were susceptible to woodrotting fungi.

GROUND VEGETATION

Most studies of lodgepole pine regeneration have indicated that competing vegetation is a major constraint to successful establishment (Ackerman 1962, Boe 1956, Crossley 1956c, Lotan and Dahlgreen 1971, Tackle 1964). No benefits from understory vegetation of the kind that would provide protection for newly germinated seedlings has been reported.

SITE QUALITY

Site quality is commonly used to express the productive capacity of different forest environments. Determination of productivity is basic to the prediction of yields, the establishment of optimum levels of growing stock, and consequently, the level of management that can be profitably applied to any area.

Conventional Determination

The measure of tree growth usually found most independent of stand factors, and therefore the most reliable index of site quality, is the average height of dominant trees in relation to age. The relationship of height and age, when expressed as dominant height in feet at some specified reference age, is the familiar "site index" that has come into general use as the conventional measure of site quality.

The height growth of most conifers is independent of stand density over a wide range of stocking. The family of site-index curves developed for those species simply expresses the relationship between height growth and the independent variables of site quality and age. The rate of height growth of lodgepole pine, however, is influenced by stand density probably more than any other North American conifer (Holmes and Tackle 1962, Smithers 1956). For lodgepole pine, therefore, a third variable — stand density — must be considered.

Curves and tables of the height, age, and density relationships of dominant lodgepole pine (Alexander 1966c, Alexander et al. 1967) are suitable for estimating site index at base age 100 years where total age is at least 30 years and density ranges from CCF (Crown Competition Factor) 125 or less to CCF 500 (Krajicek et al. 1961) (fig. 25). Data for these curves came from the stem analyses of 1,048 dominant lodgepole pines on 262 plots in the western United States, sampled to represent a wide range of age, site quality, and density.[16]

[16]*Equations and computer subroutines for estimating site quality have been developed by Brickell (1970) from these curves, but the base age was changed to 50 years.*

Figure 25.—Site index curves for lodgepole pine at CCF levels of 125 or less. Base age: 100 years total age.

When these site index curves or tables are used, the steps below should be followed (detailed procedures are outlined by Alexander 1966c):

1. Determine average height and age of the stand. Select four or more dominants (site trees) and measure heights and ages in the conventional manner. Average total age may be approximated by adding 9 years to the average age at breast height.
2. Determine the density of the stand in which the "site trees" developed, either by estimating CCF from (1) measurements of stand diameters or (2) measurements of basal area and average stand diameter.
3. Determine site index from the appropriate curves or tables, based on the average height and age determined in step 1 and the CCF determined in step 2.

Trees — in addition to being dominants — and stands should meet the following specifications:

Stands

1. Even-aged — not more than 20 years spread in the age of dominant trees.
2. At least 30 years old, but not more than 200 years old (at least 50 years old in Pacific Northwest).
3. Apparent site the same throughout the stand. Site will be considered the same if all trees are growing on similar topography, slope, aspect, and soils.

Site Trees

1. Located in an area in the stand where present density is uniform, and there have been no abrupt changes in past density.
2. Increment cores show a normal pattern of ring widths from pith to cambium.
3. Reasonably free of dwarf mistletoe or other diseases or injuries that may reduce height growth.
4. Sound enough for ring counts.
5. Show no visible evidence of crown damage, or tops that are broken, forked, and so forth.

Determination from Soil and Topography

Conventional methods of site determination cannot be used on lands that are nonforested or contain trees either too young or unsuitable for site determination. An alternative approach is to evaluate environmental factors that influence site productivity, and combine these into a predictive equation.

Site index of lodgepole pine in north-central Colorado and south-central Wyoming can be estimated from environmental factors using procedures developed by Mogren and Dolph (1972). Data came from 72 plots in pure, even-aged (70- to 150-year-old) stands on the Medicine Bow, Roosevelt, and Arapaho National Forests. The prediction equation is:

$$Y = 64.99 - 0.345X_1 \text{ to } .339X_2 - 0.458X_3 \pm 0.436X_4$$

Where

Y = site index in feet,

X_1 = percent by weight of particles larger than 0.25 mm in diameter in the A horizon,

X_2 = total soil depth to the C horizon in inches,

X_3 = estimate of surface stoniness in percent, and

X_4 = average annual precipitation in inches.

$S_{\bar{y}\cdot x} = \pm 8.0$ ft, $R^2 = 0.78$

Estimates of site index from these environmental factors apply only to the point sampled, but in practice site index sampled from what appears to be the extremes on the ground for any given area is usually all that is needed.

Site indexes for lodgepole pine from environmental factors have not been developed for other areas in the central Rocky Mountains.

Productivity indexes for lodgepole pine based on vegetation, soils, or landform, or a combination of these factors have been developed in Canada and the Pacific Northwest by Duffy (1964), Illingworth and Arlidge (1960), Stanek (1966), Youngberg and Dahms (1970) and others, but productivity in relation to these factors has not been investigated in the central Rocky Mountains.

GROWTH AND YIELD

Forest management in the lodgepole pine type in the central Rocky Mountains is in a period of transition from unmanaged to managed stands. Management is based on silvicultural control over (1) growth and development of individual trees and (2) growth and yield of stands for different products. The most powerful silvicultural control available to the manager is the manipulation of the amount and distribution of growing stock by thinnings and other intermediate cuttings.

NUMBER OF STEMS

Lodgepole pine often reproduces so abundantly following fire or clearcutting that competition for growing space does not permit good development (fig. 26). Although shade-intolerant, lodgepole pine does not thin well naturally, and severe crowding of young trees of the same size leads to stagnation of growth. In Colorado, for example, 10 small plots established in a young stand after fire supported an average of 44,000 trees per acre (Mason 1915a). In Montana on burned areas, there were as many as 300,000 1-year-old seedlings per acre, and up to 175,000 8-year-old trees per acre (Tackle 1961a). Initial stocking largely governs reduction in number of stems per acre in natural stands as development progresses. In one study, very heavy mortality (10,200 stems per acre) occurred in a 35-year-old stand over a 20-year period (Alexander 1960). Even with fewer stems per acre and crown classes well differentiated, however, too many trees persist to make good use of available growing space, and artificial thinning is needed to concentrate growth on fewer stems.

Lodgepole pine stands are also characterized by extreme variation in number of trees per acre. Variations in stocking are associated more with such factors as differences in fire intensity and seedbed condition, previous age and stand density, and available seed supply than with site quality (Smithers 1961). Dense stands remain dense regardless of site quality.

Thinning generally reduces mortality in proportion to the number of stems removed (Alexander 1960, 1965; Barrett 1961). Mortality in thinned stands is little affected by age or initial size.

DIAMETER

Because of its response to changes in stand density, diameter growth is usually used in thinning studies to measure release. Diameter growth of lodgepole pine is usually considered slow, but slow growth is due largely to overcrowding.

Most thinning studies show that diameter growth is greatest at the lowest density and slowest at the highest density (Alexander 1956b, 1960, 1965; Barrett 1961; Dahms 1967, 1971a, 1971b; Smithers 1957, 1961). This relationship holds whether all trees or the largest 100, 200, 300, and so forth, trees per acre are compared. In contrast, Daniel and Barnes (1959) reported that, when stand density was 2,500 stems per

Figure 26.—Dense 60-year-old stand of second-growth lodgepole pine. Medicine Bow National Forest, Wyoming.

acre or less, the diameter growth of the 400 largest trees per acre was only moderately improved by heavy thinning. Furthermore, average diameter of the 400 largest trees decreased more rapidly than for all trees as stand density increased above 2,500 stems per acre.

In central Oregon, diameter growth was poorly correlated with initial diameter (Dahms 1971a, 1971b). Alexander (1960) found, however, that for comparable stand density in the central Rocky Mountains, the larger the initial diameter the larger the average stand diameter at any periodic interval after thinning. He also found in an earlier study (Alexander 1958c) that average diameter growth per tree in stands 30 to 80 years old was greater in younger than older stands at any stocking level from 200 to 20,000 stems per acre (fig. 27). In all stands examined over long periods of time, there was a tendency for diameter growth to slow with increasing age (Alexander 1960, Dahms 1971b).

The effects of stand density on diameter growth are well documented, but there is little information on the effect of site quality on diameter growth. Smithers (1957) suggested that the diameter growth of the 200 largest trees per acre was more rapid on good than poor sites in stands of comparable density over a range of ages. Myers' (1966) yield tables for managed stands indicate a similar relationship between diameter growth and site quality.

HEIGHT

The response of height growth to thinning has been variable. In Colorado and Wyoming, no consistent relationship was found between the height growth of either all trees or the 100 largest trees per acre and age, average stand diameter, or stand density (Alexander 1960, 1965). On some plots, height growth was greater

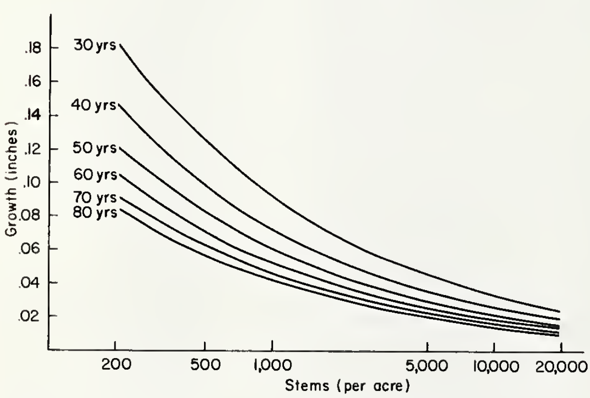

Figure 27.—Relationship of average annual diameter growth per tree to age and number of stems per acre.

in thinned than unthinned stands, in others the reverse was true, and in still others there were no differences. In central Oregon, the height growth of all trees and 100 largest trees per acre was increased by reducing stand density, but the differences between levels of stocking were slight (Barrett 1961, Dahms 1967, 1971b). In Montana, the height growth of dominant and codominant trees was greater than for intermediate and suppressed trees within treatments, but there was no difference in height growth between treatments for comparable crown classes (Lotan 1967b).

In unthinned stands, the effect of stand density on height growth has been well documented (Holmes and Tackle 1962, Smithers 1956, 1957). For that reason the dominant height of lodgepole pine does not constitute a valid site index unless it is adjusted for any reduction due to stand density (Alexander 1966c, Alexander et al. 1967). The changes in dominant height of lodgepole pine with age and site quality are shown in figure 25 for the range of stand density — measured as CCF — where height growth is unaffected. At age 50 years, for example, dominant height varies from 20 to 64 ft in response to variations in site quality. At CCF 300, the dominant height of trees in a 50-year-old stand varies from 16 to 50 ft (Alexander 1966c). Here the response to changes in site quality are confounded by stand density. Without the adjustment in site index, the estimate of site quality would not be valid.

BASAL AREA

Most thinning studies have shown that total basal area growth per acre is related to stand density. The greater the initial basal area or number of stems the greater the basal area at any periodic interval (Alexander 1960, 1965; Dahms 1971a, 1971b). These studies also show that basal area increment per acre decreases with increasing age, but there is less agreement on the rate of basal area increment in relation to stand density. In a study in the central Rocky Mountains, basal area increment in stands averaging 1 inch in diameter increased with an increase in number of stems up to 1,200 per acre, while in stands where the average d.b.h. was 5 inches, basal area increment decreased when the number of stems per acre increased above 300 or when basal area per acre was about 80 ft^2 (Alexander 1960). In another study on the Fraser Experimental Forest in Colorado, there were no differences in basal area increment between thinned and unthinned stands despite drastic reductions in stand density (Alexander 1956b, 1965). Elsewhere, Barrett (1961), Dahms

(1971a, 1971b), and Daniel and Barnes (1959) reported that basal area increment increased with an increase in basal area per acre.

VOLUME

Volume per acre is the ultimate objective of yield prediction; in young stands ft^3 volume is of most interest. Thinning studies in Colorado show that total ft^3 volume per acre increases with an increase in stand density (Alexander 1965), but in Oregon and Alberta, an increase in the number of stems reduced total ft^3 volume in densely stocked stands (Dahms 1971b, Smithers 1956). There is also disagreement on the relationship of total ft^3 volume increment to stand density. In some studies, thinning resulted in a temporary reduction in total ft^3 volume increment (Alexander 1965, Dahms 1971a). Thereafter, total ft^3 increments of thinned and unthinned stands were comparable. In other studies, total ft^3 volume increment increased with an increase in stand density measured as either basal area or CCF (Dahms 1966, 1967). In most studies, however, net total ft^3 volume was greater in thinned than unthinned stands except at very low densities. Furthermore, regardless of whether thinning increased total ft^3 volume increment, growth on thinned plots was concentrated on fewer, larger, and more usable stems (Alexander 1965; Dahms 1967, 1971b).

Crown Size

Under stand conditions, the crowns of lodgepole pine tend to be conical. The relationship of crown size to individual tree growth has been determined for open-grown trees in the Rocky Mountains (Alexander et al. 1967). Figure 28 shows the relationship of the crown width of open-grown pines to diameter at breast height for the central Rocky Mountains, Intermountain area, Pacific Northwest, and the three areas combined. Dahms (1971b) investigated the effect of stand density on crown length and width in thinned young stands. He found that 10 years after thinning, crowns were wider and longer for trees of comparable diameters at the lowest stand densities observed.

Volume Tables

Volume tables and point sampling factors have been prepared for lodgepole pine in Colorado (Myers 1964, 1969). These tables include:

1. Gross volumes in total and merchantable ft^3.
2. Gross volumes in fbm, both Scribner and International ¼-inch log rules.
3. Point sampling factors for merchantable ft^3 and fbm.

Volume per unit of area may be determined from either:

1. Measurements of tree diameters and heights,
2. Measurements of diameters and sufficient heights to convert tables to local volume tables, or
3. Tree counts obtained by point sampling.

Yields of Unmanaged Old-Growth Stands

Although the proportion of lodgepole pine stands still in old-growth is not as high as in

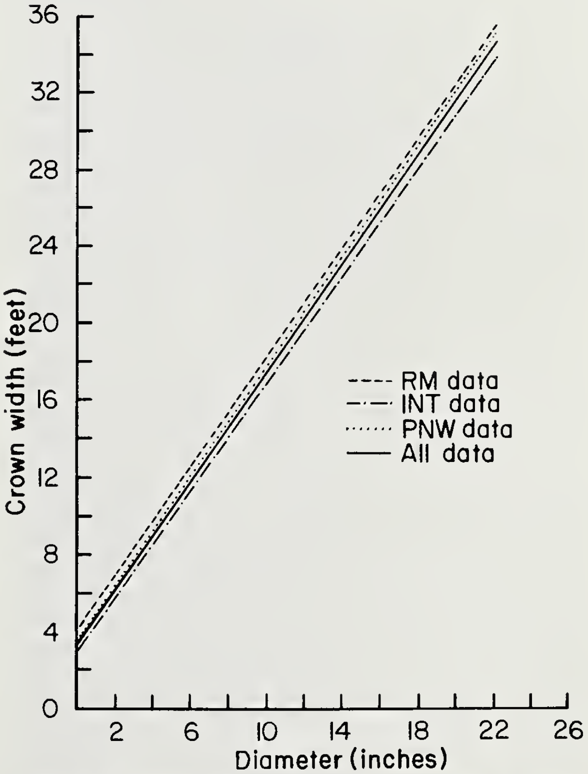

Figure 28.—Relationship of crown width to stem diameter at breast height for open-grown lodgepole pines. (RM = Rocky Mountain; INT = Intermountain; PNW = Pacific Northwest.)

spruce-fir forests, many of the poletimber-sized stands are also overmature. The manager, therefore, must largely accept what nature has provided during the period of conversion to managed stands. Forest Survey data indicate that average annual growth over all sites in old-growth lodgepole pine is about 25 to 40 fbm per acre. This low productivity is largely due to the great number of small trees.

Average volumes per acre in unmanaged old-growth stands in the Rocky Mountains depend on both density and environment. For example, in a 100-year-old stand, maximum volume was 20,000 fbm with 800 stems per acre, and only 1,500 fbm with 1,800 stems per acre (Tackle 1961a). In Colorado and Wyoming, yields of 12,000 to 15,000 fbm per acre are generally considered good; yields of 20,000 to 25,000 fbm per acre are exceptional (Thompson 1929).

Thinning studies have shown that, by reducing stand density at a young age, it is possible to obtain production comparable to ponderosa pine in the Black Hills — net annual increment of 150 fbm per acre on average sites — and distribute this growth over fewer and larger stems.

Yields of Managed Stands

Old-growth lodgepole pine sawtimber- and poletimber-sized stands are being converted into stands that must be managed from the regeneration period to final harvest. Furthermore, there are many stands of young growth that must be brought under management. Some of these stands have been thinned once but are in need of a second thinning.

Yield tables for managed stands are the basis for timber management planning. They report probable wood yields that will result from specified combinations of such factors as site quality, utilization standards, and frequency and intensity of thinning. They also provide an important part of the information needed for determining the influence of timber treatments on all forest resources. Yield tables for lodgepole pine are useful regardless of the current level of management. Well-managed forests can benefit from refinements in operations that are guided by comparisons of actual conditions with a good standard. Where conversion to managed stands is underway, yield tables provide goals toward which conversion can be directed. Furthermore, a manager should not be restricted to only one yield table per working group or series of stands managed under the same silvicultural system. He must have the opportunity to examine the probable results of his operations, to make necessary changes in the management of any of his resources, and to study the effects of these changes before money is spent on them (Myers 1967).

Field and computer procedures for preparing yield tables for managed stands, including those infected with dwarf mistletoe, realistically simulate (1) stand growth, (2) response to thinning, and (3) reproduction cutting by any of the even-aged systems (Myers, 1967, 1971; Myers et al. 1971). These procedures were developed from field data on past growth in relation to stand density, age, and site quality obtained from a large number of temporary plots in existing thinned stands of lodgepole pine.

To use the procedures in stands ready for final harvest and conversion to managed stands, the manager must decide on (1) the regeneration system — clearcutting, group selection or shelterwood — with natural or artificial regeneration, (2) the site index, (3) initial stocking (between 1,500 and 2,000 stems per acre at age 10 years are recommended because lodgepole pine requires some crowding at early ages to obtain height growth) and (4) age of initial thinning. He can then use the computer simulation program to produce a series of yield tables for different combinations of growing stock levels, cutting cycles, and rotation ages that will show how project outcomes will vary in response to different cultural treatments. The manager can then examine the probable results of different courses of action, and select the one that best meets his particular management goals.

To use the procedures to put existing stands not yet ready for final harvest under management, the manager must develop the necessary working tools from information obtained on age, diameter, height, site quality, stand density, and past growth. He can then use the computer simulation program to produce a series of yield tables for different combinations of growing stock levels, cutting cycles, and rotation ages that will show how project outcomes will vary with intermediate cutting treatments and past site and stand conditions. The manager can then select the one that best meets his management goals.

Cole (1971) has developed a stand volume equation for even-aged stands of lodgepole pine in Montana and Idaho that gives direct estimates of gross total ft^3 volumes from measurements of stand basal area and the height of dominant trees, and provides conversion factors to estimate merchantable ft^3 volumes. This equation should be substituted when Myers' (1967, 1971) computer simulation program is used to estimate yields of managed stands of lodgepole pine in the northern Rocky Mountains.

SILVICULTURE AND MANAGEMENT OF OLD GROWTH

Regeneration Silviculture

Harvest-cutting methods applicable to old-growth lodgepole pine forests include clearcutting, and shelterwood and group selection cuts. Seed-tree and individual-tree selection cutting are usually not applicable. The objective of each regeneration system is to harvest the timber crop and obtain adequate reproduction. The choice of cutting method in lodgepole pine stands depends upon management goals, but stand conditions, windfall, disease and insect susceptibility, and the risk of potential fire damage that vary from place to place on any area limit the options available for handling individual stands. Furthermore, the economics of harvesting, manufacturing, and marketing wood products from a large number of small diameter trees in the central Rocky Mountains further limits cutting practices. Cutting to bring old-growth lodgepole pine under management is likely to be a compromise between what is desirable and what is possible. Management on many areas may involve a combination of clearcutting small areas, several partial cutting treatments, and no cutting.

CLEARCUT AREAS

Clearcutting is a regeneration system that harvests the timber crop in one step. Forest managers concerned with timber production have most often elected to convert lodgepole pine to managed stands by clearcutting in strips, patches, or blocks. There are several reasons for this: (1) Lodgepole pine, a pioneer species, is shade-intolerant and reproduces best in most instances when overstory competition is removed or drastically reduced. (2) Dwarf mistletoe — present in many stands in varying degrees — is best controlled by separating the old stand from the new. (3) Windfall and mountain pine beetles, while variable, are always a threat. (4) The potential for future growth is limited because of the generally low vigor of mature and overmature stands and the suppressed condition of many smaller trees. Furthermore, many natural stands appear to be even-aged, having developed after catastrophic fires or other disturbances.

Harvesting and regeneration practices developed in the Rocky Mountains have been directed toward clearcutting. Much of the criticism directed at clearcutting in general has been associated with concern about (1) the large openings cut, (2) geometric patterns that did not complement the landscape, (3) logging slash and unmerchantable debris left on the ground, (4) failure of areas to regenerate, and (5) the unknown effect of roadbuilding and logging on other forest resources. In some cases the objections are valid, but with some critics, clearcutting has unjustifiably become synonymous with devastation.[17]

From a silvicultural point of view, clearcutting is still an acceptable harvesting method in lodgepole pine where timber production is a major objective, providing the knowledge available is put into practice. Under some conditions clearcutting is the only alternative to no cutting. Furthermore, a combination of cleared openings and high forest is desirable for increasing water yields and improving wildlife habitat. The following section will therefore consider the practices needed to regenerate clearcut areas with natural or artificial regeneration.

Management with Advanced Regeneration

There is seldom a manageable stand of advanced regeneration under pure lodgepole pine, or if present it has been suppressed for so long that it has no future management potential. In mixed stands, where the associated species are spruce and fir, there is frequently a stand of advanced reproduction. Procedures developed for spruce-fir stands should be followed to (1) evaluate the potential for management before logging, (2) set up cutting and slash disposal controls necessary to save the advanced reproduction if the manager decides to use it, and (3) evaluate the adequacy of stocking and need for fill-in reproduction after logging (Roe et al. 1970).

Management with Reproduction Following Cutting

Most lodgepole pine areas will be regenerated with either natural or artificial reproduction after logging. Cutting unit layout, logging plans, and slash disposal and seedbed treatment should be designed to (1) facilitate seed dispersal, (2) promote seedling survival and establishment, and (3) create favorable growing conditions. If natural regeneration fails, plans should be made to use artificial regeneration.

[17] *Lotan, James E. The clearcutting controversy and management of lodgepole pine. (Manuscript in preparation at Intermt. For. and Range Exp. Stn., Ogden, Utah.)*

Clearcutting can be by patches, blocks, or strips. Those cutting practices can be readily adapted to multiple-use land management by judicious selection of size, shape, and arrangement of openings in combinations with other high-forest cutting practices.

Size of Opening.—Successful natural regeneration in lodgepole pine depends upon an adequate supply of seed falling on a receptive seedbed. In the central Rocky Mountains there are no data on seed-to-seedling ratios, but Lotan (1964a) estimated that from 30 to 50 sound seeds would be required to produce one first-year seedling on mineral soil seedbeds with abundant moisture and favorable temperatures. Assuming that an arbitrary minimum of 1,500 first-year seedlings are sufficient to allow for normal mortality and still provide the density necessary to obtain early height growth, between 45,000 and 75,000 sound seeds per acre will be needed before the seed supply can be considered adequate.

The size of opening that is likely to receive sufficient seed to restock receptive seedbeds is influenced by whether the seed is dispersed by open or closed cones. The manager cannot assume that the cone habit is either serotinous or nonserotinous. He must examine each area and classify the stand as (1) closed cone, (2) open cone, or (3) intermediate. If the stand is classified as closed cone, the manager must then determine if he has sufficient sound seed stored in closed cones to provide an adequate seed source for natural regeneration, using the procedures developed by Lotan and Jensen (1970).

1. *Stands with Serotinous Cone Habit.*—The size and shape of openings cut in these stands that will restock is highly flexible if there is an adequate supply of seed. Natural regeneration is a one-shot opportunity, however, because the seed supply is in the slash-borne cones. There is no advantage to cutting openings larger than 30 to 40 acres, even for dwarf mistletoe control,[17] and openings 10 to 20 acres would be more compatible with other uses. On south slopes and other difficult regeneration chances, it may be desirable to cut openings smaller than 10 acres to provide a supplemental seed source in trees standing around the perimeter. If there is not an adequate supply of seed in closed cones, follow the recommendations below.

2. *Stands with Nonserotinous or Intermediate Cone Habit.*—The cutting unit must be designed so that seed from the surrounding timber margin reaches all parts of the opening unless artificial regeneration is planned. Effective seed dispersal distance from standing trees has not been studied in the central Rocky Mountains, but studies elsewhere (Boe 1956, Dahms 1963, Tackle 1964) indicate that, with favorable seedbed and environmental conditions, the effective seeding distance in lodgepole pine is about 150 ft. The maximum width of opening likely to restock to natural reproduction is therefore 300 ft, or about four to five times tree height. Furthermore, it is not likely that sufficient seedfall to provide adequate stocking will be obtained from only one seed crop. On south slopes openings should be smaller — 150 ft wide or about two to three times tree height. If larger openings are cut, plan on planting the area beyond effective seeding distance.

Windfall.—Windfirmness must be a significant consideration in the location of cutting boundaries, especially in stands with nonserotinous cones. Guidelines for minimizing windfall around the perimeters of clearcut openings in spruce-fir forests (Alexander 1964, 1967b) should also be used when locating boundaries for lodgepole pine clearcuts.

Seedbed Preparation and Slash Disposal.—There are a number of things to consider in planning the treatment of lodgepole pine slash: (1) in stands with serotinous cones, careful handling of slash is required to avoid destruction of seed-bearing cones, (2) heavy concentrations of slash obstruct seedling establishment and are a fire hazard, and (3) slash creates an adverse visual impact.

1. *Stands with Serotinous Cone Habit.*—Dozer piling or windrowing dry slash over the entire area has usually resulted in overly dense stands of reproduction because abundant seed is shaken out of cones onto exposed mineral soil seedbeds (Alexander 1966a, Boe 1956, Tackle 1964). Dozer piling and windrowing slash, then burning the concentrated slash, has frequently resulted in poor stocking, especially when the slash fires burned over much of the area and destroyed most of the seed. Broadcast burning usually results in little or no restocking because most of the seed is destroyed. Disposal of slash by lopping and scattering, and by rolling and chopping have resulted in adequate restocking if sufficient mineral soil (about 40 percent of the area) has been exposed and the seed-bearing cones are placed near the ground. Fire hazards and visual impact are usually not reduced sufficiently, however.

Concentrations of slash must be treated. If these concentrations are piled or windrowed for burning, the piles and windrows must be kept small (1/20 acre or less) and well distributed so that the burned area does not occupy more than 25 percent of the total area. The lighter areas of slash — less than 40 percent of the area covered with slash less than 1 ft deep — can be either lopped and scattered or rolled and chopped. This combination of treatments will reduce fire hazards and visual impact, provide exposed mineral soil, scatter the cone-bearing slash over the area, and place the cones near or on the ground.

2. *Stands with Nonserotinous or Intermediate Cone Habit.*—Slash can be handled in the same way as in stands with serotinous cones, or it can be broadcast burned. If slash is piled or windrowed for burning, the piles should be kept small and well distributed because burning in large concentrations often heats the soil enough to inhibit subsequent plant growth. To be effective, broadcast burning should cover about 75 percent of the area. It should consume most, but not necessarily all, of the logging slash, other debris, and duff or organic material on the ground, and it should burn hot enough to destroy most of the competing vegetation. It should not burn so hot, however, that a deep layer of loose ash accumulates. Areas with light slash can be lopped and scattered or rolled and chopped. It may be necessary to do some additional mechanical scarification on lopped and scattered areas. Tractors with brush blades should be used, and about 40 percent of the area should be left with exposed mineral soil.

Management for Artificial Regeneration

Planting.—Guidelines for planting lodgepole pine are not available in the central Rocky Mountains, but many of the recommendations for spruce planting prepared by Ronco (1972) are applicable to lodgepole pine.

1. *Need and Timing.*—Sites scheduled for planting should be reforested immediately after logging and slash disposal. Areas prepared for natural reproduction that fail to restock in 3 years should be planted, otherwise additional seedbed preparation is likely to be needed. A minimum goal should be 1,200 well-established seedlings per acre where timber production is a primary objective. If the manager intends only to hold the site, a minimum of 600 seedlings per acre is sufficient.

2. *Site Preparation.*—Planting will ordinarily require just as much seedbed preparation as natural seeding. Exceptions are areas where slash has been broadcast burned or completely cleaned up by dozer piling or windrowing and burning within 3 years of planting. However, burned areas with deep layers of loose ash will require ground preparation. Hand site preparation will probably be adequate on small planting jobs and for fill-in planting. Hand-scalped spots should not be smaller than about 18 to 24 inches square. Aboveground parts of competing vegetation should be totally removed. On large areas, or where hand scalping is unsatisfactory because of dense grass or herbaceous vegetation, mechanical site preparation should be used. Machine methods include disking, plowing (furrowing, mounding, and ridging), and dozing. Complete scarification is not necessary, but vegetation-free areas should be about 2 ft wide and lie on the contour. Where competing vegetation consists of brush, tractors equipped with angle dozer blades should be used to either completely clear the area or remove the brush in strips the width of the dozer blade.

3. *Planting Stock.*—Plant only stock that meets the following specifications: (1) stem caliper, ⅛ inch, (2) tops no shorter than 3 inches, (3) roots at least 9 inches long, and (4) top-root ratio no more than 3 to 1.

4. *Planting Season.*—Lodgepole pine should be planted in the spring after snowmelt. Planting should be completed by June 25. Temporarily suspend planting during the regular season when temperatures are unseasonably warm, especially on clear days when the wind is blowing.

5. *Storage.*—Lodgepole pine planting stock must be lifted while seedlings are still dormant, and stored at the nursery until the planting sites are free of snow. Storage should not be extended for longer than 3 months. During transit from nursery to planting site, the seedlings must be treated as dormant plants. If refrigerated transport is not available, the bundles or bags should be covered with canvas to protect them from the sun and wind. Temperatures should be maintained between 34° and 40° F. Packages should be arranged to provide air circulation under the covering. Water trees in bundles before loading. Storage problems are more

severe in the field because limited facilities on the planting site make temperature control difficult. Well-insulated storage sheds that can be cooled by ice or snow can be used in the absence of mechanical refrigeration. Trees in bundles should be kept moist and care taken not to lower temperatures below freezing. If storage sheds are not available, cool, moist cellars or snowbanks can be used. Seedlings can be held in local storage up to 7 days if temperatures can be maintained below 40° F. Otherwise, local storage should be limited to 3 days. When transferring trees from bundles or bags to planting containers, handle the seedlings carefully to prevent breakage and keep the roots covered with moist spaghnum moss.

6. *Spot Selection.*—Plant seedlings in moist mineral soil. On areas that have been hand scalped, seedlings should be planted to take advantage of dead shade wherever possible. The north and east side of stumps, logs, and rocks are favorable locations. Avoid planting in deep layers of loose ash, adjacent to shrubs or other live vegetation that competes for soil moisture, near cut banks and under logs where sloughing action can injure or kill seedlings, and trails or stock concentration areas where trampling damage may occur. Choice of planting spot is less critical on areas that have been plowed or stripped; there is little opportunity for individual spot selection when using tree-planting machines.

7. *Planting Method.*—Use the hole method for hand planting. Dig holes with mattock hand tools or power augers. If augers are used, do not dig holes too far in advance of planting or they will dry out.

8. *Plantation Protection.*—New plantations should be protected from trampling damage by livestock until seedlings are at least 3 ft high. This will require fencing or other adjustments in grazing allotments. New plantings should also be protected from rodents. Sample the rodent population on the areas to be planted. If populations are large, provide controls until seedlings become established.

9. *Records.*—Adequate data from detailed records are needed to (1) correct deficiencies causing failure, and (2) recognize good practices leading to successful plantations. Decisions affecting regeneration practices can then be based on quantitative information rather than conjecture. Follow the recommendations suggested by Ronco (1972).

Seeding.—Techniques have not been worked out in the central Rocky Mountains, but direct seeding of lodgepole pine on prepared seed spots has been successful in the northern Rocky Mountain and Intermountain regions. In a study in an *Abies lasiocarpa-Vaccinium scoparium* habitat type in northwestern Wyoming, 12 seeds (90 percent viable) were sown in June on hand-prepared seed spots and covered with ⅛ inch of soil (Lotan and Dahlgreen 1971). Rodents were controlled by poison baits. After 3 years, viable seed-to-seedling ratios were 5:1 on scalped 12-inch-square spots on the level and along the slope; 12:1 on scalped 5-inch-square spots along the slope; and 60:1 for seed sown in the ash and duff left by broadcast burning of logging slash. The percentages of stocked spots were: 72 percent for scalped 12-inch squares on the level; 64 percent for scalped 12-inch squares on the slope; 38 percent for scalped 5-inch squares; and only 10 percent for ash-duff seedbeds.

Roe and Boe (1952) and Tackle (1961b) also successfully spot seeded lodgepole pine on scalped 6- to 12-inch areas in central Montana. Seed-to-seedling ratios were about 5:1 for 10-year-old seedlings.

Spot seeding usually results in better success than broadcast seeding because the seed is placed in a more favorable environment and covered with soil (Lotan and Dahlgreen 1971).

PARTIAL CUT AREAS

Shelterwood and group-selection cutting and their modifications can be used in old-growth lodgepole pine. These regeneration systems harvest the timber on an area in more than one step. From a silvicultural point of view they are the only acceptable options open to the manager where (1) multiple-use considerations preclude clearcutting, (2) combinations of cleared openings and high forest are required to meet the needs of various forest uses, or (3) areas are difficult to regenerate after clearcutting. However, windfall, insects, diseases, and stand conditions impose limitations on how stands can be handled. A careful appraisal of the capabilities and limitations of each stand is necessary to determine cutting practices. Furthermore, partial cutting requires careful marking of individual trees or groups of trees to be removed, and close supervision of logging. The following recommendations are for partial cutting practices keyed to broad stand descriptions, windfall risk situations, and disease and insect problems (Alexander 1972). Practices needed to obtain natural reproduction are also discussed. Stands are pure pine unless otherwise indicated.[18]

Single-Storied Stands[19]

Description.—

1. Stands may appear to be even-aged (fig. 29), but often contain more than one age class, occasionally may even be broad-aged.
2. Codominants form the general level of the canopy, but the difference in height between dominants, codominants, and intermediates is not as great as in spruce-fir stands.
3. If even-aged in appearance:
   a. There is a small range in diameter class and crown length.
   b. Live crown length of dominants and codominants is generally short to medium (30 to 60 percent of the total tree height and boles are generally clear for 10 to 40 percent of total tree height).
   c. There are few coarse-limbed trees in the stand.
4. With two or more age classes, the younger trees usually have finer branches, smaller diameter, longer live crown, and less clear bole than older trees.
5. Stocking is generally uniform.
6. A manageable stand of advanced reproduction is usually absent.
7. In **mixed stands**, the overstory is either (a) pure pine or(b) pine and Engelmann spruce, subalpine fir, or Douglas-fir, with advanced reproduction of species other than pine that may or may not be a manageable stand.

[18]*In a mixed stand, either less than 80 percent of the overstory basal area is lodgepole pine, or the overstory is pine with an understory of a different species.*

[19]*Reproduction less than 4.5 ft tall is not considered a stand story in these descriptions.*

Recommended Cutting Treatments.— Single-storied stands are usually the least windfirm because trees have developed together over long periods of time and mutually protect each other from the wind.

1. **Low windfall risk situations—**

   The first cut can remove about 30 percent of the basal area on an individual tree basis. This initial entry is a **preparatory cut** that resembles the first step of a three-cut shelterwood, since it probably does not open up the stand enough for pine reproduction to become established in significant numbers. Overstory trees are all about equally susceptible to blowdown, therefore the general level of the canopy should be maintained by removing some trees in each overstory crown class. The cut should come from C and D vigor class trees, but openings larger than one tree height in diameter should be avoided by distributing the cut over the entire area. Do not remove dominant trees that are protecting other trees to their leeward if these latter trees are to be reserved for the next cut. In **mixed stands**, if the overstory is pure pine, handle as a pure stand; if the overstory is of mixed composition, cut as much of the basal area recommended in pine as is possible to release the climax species.

   The second entry into the stand should not be made until 5 to 10 years after the first cut to permit the stand to develop windfirmness.

SINGLE-STORY

Figure 29.—A single-storied lodgepole pine stand.

The second cut should also remove about 30 percent of the original basal area on an individual tree basis. It simulates the second or **seed cut** of a three-step shelterwood. The largest and most vigorous dominants and codominants should be reserved as a seed source in stands with the nonserotinous or intermediate cone habit, but avoid cutting openings in the canopy larger than one tree height in diameter by distributing the cut over the entire area even if it means leaving trees in the C and D vigor classes with poor seed production potential. In **mixed stands** cut as much of the recommended basal area in pine as is possible without creating openings larger than one tree height. The last entry is the **final harvest** and should remove all of the remaining original overstory. It should not be made until a manageable stand of reproduction has become established, but the cut should not be delayed beyond this point if timber production is the primary concern because the overwood (1) hampers the later growth of seedlings, and (2) if infected with dwarf mistletoe, will reinfect the new stand (fig. 30).

The manager also has the option of removing less than 30 percent of the basal area at any entry and making more entries, but they cannot be made at more frequent intervals. The cut will be spread out and continuous high forest cover maintained for a longer period of time. This option is not recommended where mountain pine beetles and dwarf mistletoe impose limitations on how stands can be handled.

The usual uniform arrangement of individual trees in single-storied stands is not well adapted to removing trees by **group-selection cutting.** Occasionally, however, natural openings do occur when stands begin to break up. Also, small openings may be desirable to meet management objectives. An alternative to removing trees on an individual basis would be to remove about 30 percent of the basal area in groups. Openings should be kept small, not more than one to two times tree height in diameter; not more than one-third of the area should be cut over at any one time. **This kind of cutting should be used only in stands where insect and disease problems are minimal.**

The second entry into the stand should not be made until the first openings have been regenerated. This cut should also remove about 30 percent of the original basal area without cutting over more than an additional one-third of the area. Openings should be no closer than about one to two tree heights to the original openings.

The final entry should remove the remaining groups of merchantable trees. The timing of this cut depends upon the cone habit and how the manager elects to regenerate the openings. If he chooses to use natural regeneration and the stand is classified as nonserotinous or intermediate cone habit, the final harvest must be delayed until the trees in the original openings are large enough to provide a seed source.

The manager may choose to remove less than 30 percent of the basal area and cut over less than one-third of the area at any one time. This will require more entries, but each new cut should not be made until the openings cut the previous entry have regenerated. Furthermore, in stands with nonserotinous or intermediate cone habit, the last groups cannot be cut until there is either an outside seed source or the manager elects to plant these openings.

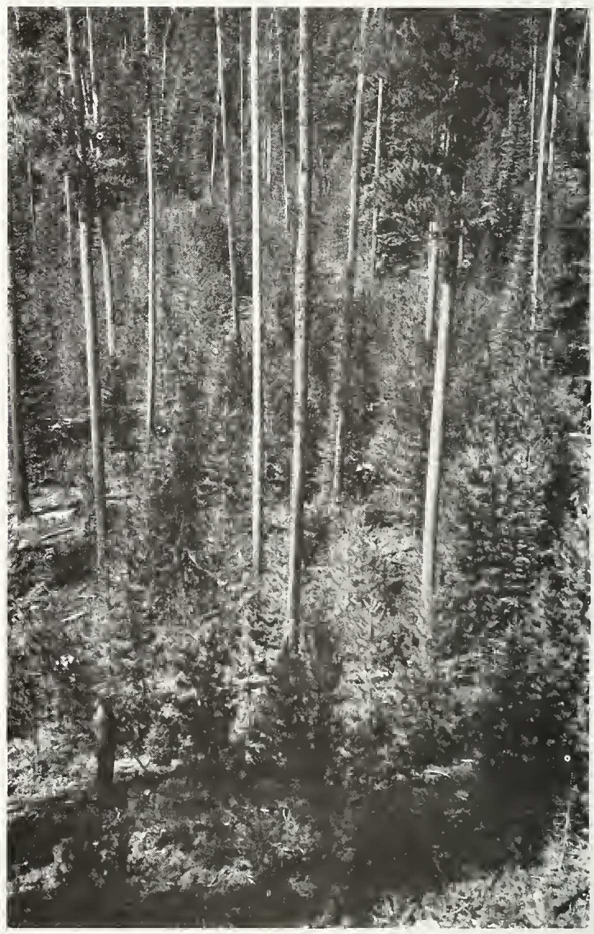

Figure 30.—New reproduction established after the seed cut of a shelterwood system in lodgepole pine. Overwood should have been removed earlier to release the reproduction. Fraser Experimental Forest, Colorado.

2.**Moderate windfall risk situations—**

The first cut should be limited to a light **preparatory** cutting that removes about 20 percent of the basal area on an individual-tree basis. The objective is to open up the stand, but at the same time minimize the windfall risk to the remaining trees. Provision should be made, however, to salvage blowdowns. This type of cutting resembles a **sanitation cut** in that the lowest vigor and poorest risk trees should be removed, but it is important that the general level of the overstory canopy be maintained intact. **Mixed stands** should be handled the same as in low windfall risk situations, except that less basal area should be removed.

The second entry can be made in about 10 years after the first cut. This entry should remove about 20 percent of the original basal area on an individual-tree basis. Windfalls that were salvaged after the first cut should be included in the computation of the basal area to be removed. The objective of this **preparatory cut** is to continue to develop windfirmness while preparing the stand for the seed cut. Most of the trees marked for removal should come from the smaller crown and poorer vigor classes, but maintain the general level of the canopy intact. In **mixed stands** cut as much of the recommended basal area to be removed in pine as is possible.

It will require about another 10 years to determine if the stand is windfirm enough to make another entry. This will be the **seed cut,** and should remove about 20 percent of the original basal area including any windfalls since the last cutting. The largest and most vigorous dominants and codominants in **mixed stands** and pure stands with non-serotinous or intermediate cone habit should be reserved as a seed source, but it is more important to distribute the cut over the entire area.

The last entry is the final harvest, which should remove the remaining original overstory. It cannot be made until a manageable stand of reproduction has been established. About 40 percent of the original basal area will be removed in this cut, and if it is too heavy (10,000 fbm or more per acre) to be removed in one harvest without undue damage to the reproduction, the manager must plan on a final harvest in two steps. The second step can begin as soon as skidding is finished in the first step, if a manageable stand of reproduction still exists.

The manager also has the option of removing less than 20 percent of the basal area at any entry and making more entries, but they cannot be made at more frequent intervals.

3. **High windfall risk situations—**

The choice is limited to removing all trees or leaving the stand uncut. Cleared openings can be up to about 5 acres, interspersed with uncut areas. Cutover areas should not exceed about one third of the total in this risk situation.

Two-Storied Stands

Description.—

1. Stands may appear to be two-aged (fig. 31), but can contain more than two age classes.
2. Top story — dominants, codominants, and intermediates — resembles a single-storied stand.
3. Second story is composed of younger trees of smaller diameter — small saw logs, poles, or saplings — than the top story, but it is always

Figure 31.—A two-storied lodgepole pine stand.

below and clearly distinguishable from the overstory. Trees in the second story are overtopped and may or may not be suppressed.

4. If more than two-aged, the overstory usually contains at least two age classes. The younger trees are finer limbed and may be smaller in diameter than the older trees. The second story may also contain more than one age class.
5. Stocking of the overstory may be irregular, but overall stocking is usually uniform.
6. A manageable stand of advanced reproduction is usually absent.
7. In **mixed stands,** the overstory is usually pure pine, but occasionally it may be pine with spruce or Douglas-fir. The second story is usually spruce and fir at the higher elevations, and Douglas-fir at the lower elevations.
8. Stocking in **mixed stands** may vary from uniform to irregular.
9. **Mixed stands** may have a manageable stand of advanced reproduction of species other than pine.

Recommended Cutting Treatments.—Same as for three-storied stands.

Three-Storied Stands

Description.—

1. Stands may appear to be three-aged (fig. 32), but they can contain more than three age classes, although stands are seldom broad-aged.
2. Top story resembles a single-storied stand except that there are fewer trees.
3. The second and third stories consist of younger, smaller diameter trees. Second story may be small saw logs or large poles, while the third story is likely to be composed of small poles or saplings. Second and third stories are overtopped, and some trees may be suppressed.
4. Overall stocking is likely to be uniform, but stocking of any story may be irregular.
5. A manageable stand of advanced reproduction is usually absent.
6. In **mixed stands** the top story may be either pure pine or a mixture of pine and other species. The second story is usually spruce and subalpine fir at the higher elevations, and Douglas-fir at the lower elevations. The second story may occasionally contain some pine, but it is rarely pure pine. The third story is almost always composed of species other than pine.
7. Stocking in **mixed stands** can vary from uniform to irregular.
8. **Mixed stands** often have a manageable stand of advanced reproduction of species other than pine.

Recommended Cutting Treatments (Two- and Three-Storied Stands).—Trees in the top story are usually more windfirm than those in a single-storied stand. Trees in the second and third stories are usually less windfirm than trees in the top story.

1. **Low windfall risk situations—**

   The first cut can remove up to 50 percent of the basal area in **two-storied stands** (providing not more than half of the basal area removed comes from the top story), and up to 40 percent of the basal area from **three-storied** stands. This cutting is as heavy as the first or seed cut of a two-cut shelterwood, but marking follows the rules for individual-tree selection. Heavier cutting may be possible in three-storied stands, but

Figure 32.—A three-storied lodgepole pine stand.

the appearance of a continuous overstory is not likely to be retained. Trees removed should be in vigor classes C and D insofar as possible, but since the top story is likely to be more windfirm, selected dominants and codominants should be left even when they are in vigor classes C and D, if they do not have dead or dying tops. Avoid cutting holes in the canopy larger than one tree height in diameter by distributing the cut over the entire area. Do not remove dominant trees that are protecting other trees to their leeward if these latter trees are to be reserved for the next cut. In **mixed stands**, if the top story or, rarely, the first and second stories are pure pine, handle as a pure stand. If the top story is of mixed composition, cut as much of the basal area to be removed in pine as is possible to release the climax species, but do not cut all of the pine if it is needed to maintain the overstory.

The second entry should be the **final harvest** to remove the remaining original stand and release the reproduction. It cannot be made until the new stand of reproduction is established. If the residual volume is greater than about 10,000 fbm per acre, the final harvest should be made in two steps to avoid undue damage to newly established reproduction. The second step can begin as soon as skidding is finished in the first step, if a manageable stand of reproduction still exists.

If there is a manageable stand of advanced reproduction under **mixed stands**, the first cut can be an **overstory removal** if the volume is not too heavy. Otherwise, the first cut can remove 40 to 50 percent of the basal area on an individual-tree basis as long as the more windfirm dominants and codominants are left. The timing of the second cut is not critical from a regeneration standpoint so long as a manageable stand of reproduction still exists after the first cut and can be saved.

The manager has other options to choose from. He may elect to cut less than the recommended basal area, make more entries, and spread the cut out over a longer period of time by delaying the final harvest until the new stand is tall enough to create the appearance of a high forest. **This is not recommended where mountain pine beetles and dwarf mistletoe limit how stands can be handled.**

In **pure** or **mixed** stands with irregular stocking that may have resulted from the breakup of single-storied stands, old beetle attacks, or windfall losses, an alternative first cut can remove about 40 percent of the basal area in a modified group selection. The group openings can be larger (two to three times tree height) than in single-storied stands, but the area cut over should not exceed about one-third of the total. Openings should be irregular in shape without wind-catching indentations in the borders. This kind of cutting is not applicable in pure stands where mountain pine beetle or dwarf mistletoe impose limitations, because the interval between initial cutting and final harvest is likely to be too long to prevent serious mistletoe infection of new reproduction and/or loss of beetle-susceptible trees.

Two additional entries can be made in the stand. They should each remove about 30 percent of the original basal area in group openings up to two to three times tree height, but not more than one-third of the area should be cut over at any one time. If there is not a manageable stand of advanced reproduction, the manager must wait until the first openings are regenerated before cutting the second series. Furthermore, in **mixed stands,** or **pure** stands with the nonserotinous or intermediate cone habit, he must either delay cutting the final groups until there is a seed source or plan on planting these openings. If there is a manageable stand of advanced reproduction, the timing between cuts is not critical from a regeneration standpoint.

The manager has the option in **mixed stands** of removing less than the recommended basal area and cutting less than the recommended area at any one time. This will require more entries and spread the cut out over a longer period of time.

2. **Moderate windfall risk situations—**

The first entry should be **a preparatory cut** that removes not more than 30 percent of the basal area on an individual-tree basis. Predominants, and codominants and intermediates with long live crowns should be removed first. The remaining cut should then come from trees in vigor classes C and D. Maintain the general level of the canopy by not cutting holes larger than one tree height in diameter in the canopy. Provision should be made to salvage blowdowns. **Mixed stands** should be handled as in low wind risk situations, except that less basal area should be removed.

The second entry should not be made in less than 10 years. This cut should remove about 30 percent of the original basal area, including the salvage of any windfalls after the first cut. The second entry is the **seed cut.**

The best dominants and codominants should be reserved as a seed source in stands with the nonserotinous or intermediate cone habit, but it is important that the cut be distributed over the entire area.

The next entry is the **final harvest** to remove the remaining merchantable volume and release the new reproduction after it has become established. However, if the residual stand has too heavy a volume, the final harvest should be made in two steps.

In **mixed stands** that contain a manageable stand of reproduction, and if the volume per acre is not too heavy, the first cut can be an **overwood removal**. If the volume is too heavy for a one-step removal, the manager should follow the recommendations for pure stands because the wind hazard is too great to permit a two-step removal in a stand that has not been previously opened up to develop windfirmness.

3. **High windfall risk situations—**

The choice is limited to either removing all the trees or leaving the stand uncut. Cleared openings can be up to about 5 acres, interspersed with uncut areas. The cutover area should not exceed about one-third of the total in this risk situation.

Multi-Storied Stands

Description.—

1. Stand is usually broad-aged (fig. 33) with a wide range in diameters.
2. If stands developed from relatively few individuals following disturbance, the overstory trees are coarse limbed. Fill-in trees are better formed and finer limbed. Vigor of the overstory trees varies from poor to good.
3. In stands that developed from deterioration of single- or two-storied stands, the overstory trees may be no limbier than the fill-in trees. Nearly all of the healthy, faster growing trees are below saw-log size.
4. Stocking may be irregular.
5. A manageable stand of advanced reproduction may be present.
6. In **mixed stands**, the overstory may be either (1) pure pine, or (2) a mixture of pine, spruce, and fir at the higher elevations, or pine and Douglas-fir at lower elevations. Understory trees have the same characteristics as pure stands except that the composition is likely to be other than pine.
7. Stocking in **mixed stands** is more likely to be irregular.
8. **Mixed stands** frequently have a manageable stand of advanced reproduction of species other than pine.

Recommended Cutting Treatments.—These are usually the most windfirm stands, even where they have developed from the deterioration of single- and two-storied stands. By the time they have reached their present condition, the remaining overstory trees are likely to be windfirm.

1. **Low to moderate windfall risk situations—**

There is considerable flexibility in harvesting these stands. All size classes can be cut, with emphasis on either the largest or smallest trees in the stand. The first cut can range from an **overwood removal** to release the younger growing stock to a **thinning from below** to improve the spacing of the most vigorous of the larger trees. Thereafter, cutting can be directed toward either even-aged or uneven-aged management. In **mixed**

Figure 33.—A multi-storied lodgepole pine stand.

stands the first cut should be an overwood removal of the pine to release the climax species. The understory trees should be thinned to improve spacing.

2. **High windfall risk situations—**

The safest first cut is an overwood removal with a light thinning from below to obtain a wider spaced, more open stand that can develop windfirmness. Thereafter, cutting can be directed toward either uneven- or even-aged management.

Modification to Partial Cutting Practices Imposed by Disease and Insect Problems

Dwarf mistletoe.—

1. Cut only in stands where the average mistletoe rating is two or less (see fig. 24), and remove only the percentage of basal area recommended for the stand description and windfall situation. In **single-storied** stands, where site index is 70 or above, trees in the intermediate and lower crown classes should be removed first in preference to dominants and codominants. If site index is below 70, trees in all crown classes are about equally susceptible to infection. In **two-** and **three-storied** stands, as much of the first cut as is possible should come from the second and third stories because these trees are likely to be more heavily infected than the top story. In **single-**, **two-**, and **three-storied** stands, the final overstory removal can be delayed until the new reproduction is tall enough to provide a forest aspect. To minimize infection of new reproduction however, time interval should not exceed 30 years after the **regeneration cut** when the average mistletoe rating is one, or 20 years when the rating is two. Provision should be made to sanitize the young stand at the time of final harvest. In **multi-storied** stands, the safest procedure is an overwood removal with a cleaning and thinning from below.
2. In old-growth stands with an average mistletoe rating greater than two, any partial cutting, thinning, or cleaning is likely to intensify the infection. The **safest** procedure, therefore, is to either remove all of the trees and start a new stand or leave the stand uncut. If the manager chooses to make a partial cut for any reason, the initial harvest should be heavy enough to be a regeneration cut. All residual trees must be removed within 10 years after the first cut, and provision made to sanitize the young stand at that time.

Comandra Blister Rust.—Cut as many trees with stem cankers and spike-tops as possible in the first cut without removing more than the recommended basal area or cutting large openings in the canopy. Since the rate of spread in mature trees is relatively slow and the disease is not transmitted from pine to pine, leaving a few infected trees is less of a risk than opening up the stand too much.

Mountain Pine Beetle.—

1. If the insect is present in the stand at an endemic level, or in adjacent stands in sufficient numbers to make successful attacks, and:
   a. Less than the recommended percentage of basal area to be removed in the first cut is in susceptible trees, any attacked tree and all of the most susceptible trees should be removed in the first cut. This will include most of the trees 12 inches d.b.h. and larger, and all trees 10 to 12 inches d.b.h. in vigor classes A and B. Provision should be made to salvage attacked trees, and the second cut should be made within 10 years of the first cut.
   b. More than the recommended percentage of basal area to be removed in the first cut is in susceptible trees, the manager has three options: (1) remove all the trees, (2) remove the recommended basal area in attacked and susceptible trees and accept the risk of future losses, or (3) leave the stand uncut. If the stand is partially cut or left uncut, some trees from 7 to 12 inches d.b.h. and most trees below 7 inches d.b.h. will survive.
2. If the stand is sustaining an infestation that is building up, and the manager chooses to either partially cut or leave the stand uncut, he must accept the risk of an outbreak that could destroy most of the merchantable stand.

Cutting to Save the Residual

In **mixed stands** and to a lesser extent pure stands, the manager must determine whether he has an acceptable stand of advanced reproduction and decide if he is going to manage it before any cutting begins. Furthermore, he must reevaluate the advanced reproduction after the final harvest and slash disposal to determine the need for supplemental stocking. The same criteria used to evaluate advanced reproduction on spruce-fir clearcuts applies here.

In partial cutting, protection of the residual from logging damage is of primary concern. The residual includes merchantable trees left after shelterwood cutting, and advanced reproduction in both shelterwood and group-selection cutting where an acceptable stand is to be managed. Protection begins with a well-designed logging plan at the time of the first cut. To minimize damage, skidroads must be laid out — about 200 ft apart depending on the topography — and marked on the ground. These skidroads should be kept narrow, and located so that they can be used to move logs out of the woods at each cut. Close supervision of logging will be required to restrict travel of skidding and other logging equipment to the skidroads. In shelterwood cuttings, trees should be felled into openings as much as possible using a herringbone pattern that will permit logs to be pulled onto the skidroads with a minimum of disturbance. It may be necessary to deviate from the herringbone felling angle in order to drop trees into openings. If this is the case, the logs should be bucked into short lengths to reduce skidding damage. Trees damaged in felling and skidding should not be removed if they are still windfirm. In group-selection cutting, the felling pattern should be similar where there is a manageable stand of advanced reproduction. Otherwise all trees should be felled into the openings. Both shelterwood and group-selection cuttings require close coordination between felling and skidding because it may be necessary to fell and skid one tree before another tree is felled.

Slash Disposal and Seedbed Preparation

Some treatment of logging slash and unmerchantable material will probably be needed after each cut. Treatment should be confined to concentrations and that needed to reduce visual impact, however, because most equipment now available for slash disposal is not readily adaptable to working in shelterwood cuttings. Furthermore, burning slash will not only cause damage to the residual, but may destroy the seed supply in stands with serotinous cones. Skid out as much of the down sound dead and green cull material as possible for disposal at the landings or at the mill. Treatment in stands should be limited to lopping and scattering, chipping along the roadway, and hand piling and burning to minimize damage. In group-selection cutting, if there is not a manageable stand of advanced reproduction, dozers equipped with bush blades can be used to concentrate slash for burning in the openings. Piles should be kept small to reduce the amount of heat generated. Stands with the serotinous cone habit should not be treated until the cones have had time to dry out and open up.

On areas to be regenerated by new reproduction, a partial overstory canopy or trees standing around the margins of small openings provide two of the basic elements necessary for regeneration success in stands with the nonserotinous or intermediate cone habit — a seed source within effective seeding distance, and an environment compatible with germination, initial survival, and seedling establishment. In stands with the serotinous cone habit, the seed supply is largely in the cones attached to the slash or scattered on the ground. The manager must make sure that the third element — a suitable seedbed — is provided after the regeneration cut where shelterwood cutting is used, and after each cut where group selection is used. Unless at least 40 percent of the available ground surface is exposed mineral soil after logging and slash disposal, additional seedbed preparation is needed. Until special equipment is developed, seedbed preparation as well as slash disposal will pose problems. The equipment available is too large to work well around standing trees. Small dozers or other machines equipped with brush blades will have to be used, but they must be closely supervised to minimize damage to the residual.

Multiple-Use Silviculture

Timber production is only one of the key uses of lodgepole pine forests in the central Rocky Mountains. They occupy areas that also are important for water yield, wildlife habitat, recreation, and scenic beauty. Forest managers must consider how these areas are to be handled to meet the increasing demands of the public. The kinds of stands that appear desirable for increased water yields, preservation of the forest landscape, maintenance of scenic values, and improvement of wildlife habitat have been suggested in a general way by both research and observation.

WATER

Snowfall is the key to water yield in lodgepole pine forests. Comparisons on the Fraser Experimental Forest in Colorado have shown that more snow accumulates in cutover areas than under adjacent uncut stands. Accumulations are greatest on plots that are clearcut (Wilm and Dunford 1948, Hoover and Leaf 1967). The increased snow depth is not additional snow, however, but a redistribution of snow. Wind transports the snow intercepted on the surrounding trees and deposits it in the openings. Some of the increase in water equivalent in the openings is available for streamflow (Hoover and Leaf 1967).

Research and experience suggest that a round or patch-shaped opening, about five to eight times trees height in diameter, is the most effective for trapping snow (Hoover 1969). In larger openings, wind is likely to dip down to the ground and blow the snow out of the openings. About one-third of the forest area in openings distributed over the watershed appears to be the best arrangement. These openings could either be maintained permanently or regenerated to new growth that would be periodically recut when trees reach about half the height of the surrounding trees. The remaining two-thirds of the area should be retained as continuous high forest, since the taller trees control snow deposition. Trees would be periodically harvested on an individual-tree basis or in small groups (one to two times tree height) to gradually replace the old with a new stand. Ultimately, the reserve stand would approach a broad-aged structure with the overstory canopy remaining at about the original height.

An alternative would be to make a light cut distributed over the entire watershed, removing about 20 to 30 percent of the basal area on an individual-tree basis or in small groups. The objective is to open up the stand enough to develop windfirmness, and salvage low-vigor and poor-risk trees. Openings five to eight times tree height can then be cut on about one-third of the area. The remaining two-thirds of the area would be retained as permanent high forest, with trees periodically removed on an individual-tree basis or in small groups.

Another alternative that would integrate water and timber production would be to harvest all of the old growth on a watershed with a series of cuts spread over a period of 120 to 160 years. At intervals of about 20 to 40 years, a portion of the area would be harvested in small openings — four to five times tree height — distributed over the watershed. The number of openings cut at each interval would depend on the size of the watershed and the length of rotation and cutting cycle selected. These openings would be regenerated (fig. 34) so that at the end of one rotation, the watershed would contain groups of trees in several age classes from reproduction to those ready for harvest. The tallest trees may be somewhat shorter than the original overstory, but the adverse effects on snow deposition should be minimized by keeping the openings small. At the end of one rotation, the forest manager has the option of following the same procedure through the next rotation, or selecting about one-third of the openings to be maintained as snow-trapping areas, and converting the remaining area into a broad-aged stand by periodically removing individual trees.

Figure 34.—New reproduction established in a cleared opening about four to five times tree height in lodgepole pine. Next series of group openings should be cut. Fraser Experimental Forest, Colorado.

WILDLIFE

The use of lodgepole pine forests by deer is influenced by timber cutting practices. On the Fraser Experimental Forest, there was more deer use and a greater abundance and selection of forage species on clearcut openings than under adjacent uncut stands (Wallmo 1969, Wallmo et al. 1972); openings 3 chains wide were used more than either wider or narrower openings. Forage production appears to decline about 10 years after cutting, however, as tree reproduction replaces forage species (Wallmo et al. 1972). Similar trends in forage production have also been observed on lodgepole pine clearcuts in Montana (Basile and Jensen 1971). Wallmo suggests that new openings be cut periodically.

An alternative would be to cut about one-sixth of a cutting block every 20 years in openings about four to five times tree height. Each Working Circle would be subdivided into a number of cutting blocks (of at least 300 acres) so that not all periodic cuts would be made in a single year on a Working Circle. Such periodic cutting would provide a good combination of numbers and species of palatable forage plants and the edge effect desired, while creating a several-aged forest of even-aged groups, thus integrating wildlife habitat improvement with timber production.

Observations on the Medicine Bow National Forest in Wyoming indicate that both natural and cleared openings in lodgepole pine forests are heavily used by elk for grazing and calving.[20] The size of opening does not appear to be critical, but openings interspersed with standing timber that can be used for ruminating, resting, and hiding are preferred. Since openings cut in the canopy are not likely to retain a high proportion of palatable forage species for long periods of time, new openings should be cut while allowing the older ones to regenerate.

Other wildlife, including nongame animals, living in lodgepole pine forests are affected by the way these forests are handled. In general, their habitat requirements include a combination of openings and high forest to provide food, cover, and edge. With protection from wildfires many stands have become denser, and reproduction has filled in the openings. Some reduction in stand density is needed to create or improve wildlife habitat. Small, irregular openings (about four to five times tree height) cut in the canopy at periodic intervals would open up the stand and provide the food, cover, and edge needed.

[20]Personal communication with A. Lorin Ward, Wildlife Biologist, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

RECREATION AND ESTHETICS

Permanent forest cover — at least in part — is preferred in travel influence zones, and in areas of high recreational value and outstanding scenic beauty. Unfortunately, old-growth lodgepole pine stands are not likely to persist in a sound condition indefinitely. Where stand conditions and wind, insect, and disease problems permit, some form of partial cutting will retain forest cover while at the same time replacing the old with a new stand. However, the visual impact of logging operations — haul roads, damage to residual trees, and slash and debris — must be minimized. In situations where there is no alternative to clearcutting, and the environmental impact of clearcutting is unacceptable, there is no choice but to leave the stands uncut.

To reduce the sudden and severe visual impact on the landscape viewer, openings cut in stands for timber and water production, wildlife habitat improvement, and recreation (ski runs) should be a repetition of natural shapes, visually tied together to create a balanced, unified pattern that will complement the natural landscape (Barnes 1971). Such a pattern is especially important for openings in the middle and background that can be seen from distant views. The foreground should be maintained in high forest under some partial cutting system (again, where stand conditions and wind, insect, and disease problems permit).

MANAGEMENT OF YOUNG GROWTH

Throughout the Rocky Mountains there are extensive areas of second growth. These stands, which resulted from past fires or cutting, are between 1 and 120 years old. Many are badly crowded and in need of thinning to bring them under management. Some have been thinned at least once, but all need further reduction in stand density to maintain or reclaim lost growth.

Stand Description

Young stands may be pure or mixed. Pure stands are usually single-storied and even- or two-aged. Two-aged stands are occasionally two-storied with pine in the overstory and spruce, subalpine fir, or Douglas-fir in the understory. Pure stands are most often overstocked, while mixed stands may be patchy. In the thinning practices described below, no distinction is made between species. Trees with the best form and vigor, and free of disease should be left.

Thinning Practices

In stands with less than 2,500 stems per acre, the first thinning can be delayed until age 30 years. If the stand is 10 years old and the stocking is less than 1,000 stems per acre, the manager should consider fill-in planting to raise stocking to 1,500 stems per acre. The level of growing stock to be retained at age 30 will depend upon management objectives. Use the procedures developed by Myers (1971) to examine the possible alternatives. Select the growing stock level and cutting cycle that best meet the management goals for the particular combination of age, diameter, height, site quality, stand density, and past growth.

If the stand contains more than 2,500 stems per acre, it should be thinned at age 10 to 20 years. The first thinning should leave about 1,500 stems per acre. This density is needed to promote height growth in young stands. The second thinning should be made at age 30 years. The spacing will depend upon management objectives. Use the procedures developed by Myers (1971) to examine possible alternatives. From past growth in relation to diameter, height, age, density, and site quality, determine future growth for different combinations of growing stock and cutting cycles. Select the appropriate combination that best meets management goals.

If stands are 40 to 70 years old, wider spacings are recommended because height growth has been established, and that lost by crowding cannot be recovered. Some of the diameter growth can be recovered, however. Develop the necessary working tools from stand examination, and use the simulation program developed by Myers (1971) to produce a series of yield tables for different combinations of growing stock levels and cutting cycles. Select the combination that best meets management goals for the particular site and stand conditions.

Thinning in stands older than 70 years is not recommended unless original stand density was less than 2,500 stems. Even then the value of thinning is questionable because the cost is not likely to be recovered in terms of increased volume production.

WHAT DO WE NEED TO KNOW

Silvicultural practices are needed that will establish and maintain subalpine forest stands with the form, structure, and arrangement needed to integrate all land uses. For the timber resource, these needs include: (1) the ability to classify subalpine forests into categories of similar characteristics as the basis for identifying management potentials in existing stands; and (2) tests of new and modified silvicultural systems and cultural practices in stands of different characteristics.

The classification of vegetation in subalpine forests is needed to guide the manipulation of stands for multiple use. For the timber resource, this classification should include: (1) what species grow together, and how to recognize the plant associations; (2) how these species reproduce, grow, and interact in a variety of situations; (3) successional trends and stability of various plant associations in response to different management prescriptions; and (4) the extent to which research results can be extrapolated.

Prediction of growth and yield of even-aged spruce-fir is needed to provide the basis for decisions on (1) site quality classes that will repay the cost of thinning and other cultural treatments; (2) levels of growing stock — including frequency of thinnings and intermediate cuttings — to meet different management objectives; (3) length of rotation cutting cycles, and allowable cut for different cutting methods, management goals, and utilization standards, and (4) the place of timber management in multiple-use management. Managers can make better decisions about key uses when they can forecast timber potential under alternative management systems. The field and computer simulation techniques now available for the management of even-aged stands must be expanded to include uneven-aged stands and irregular stand structures needed for multiple use.

Methods of obtaining natural and artificial reproduction of Engelmann spruce have been largely directed toward regenerating cleared openings. While adequate regeneration practice can be prescribed in most instances, information is still needed on: (1) relationships between the kind of seed source and the amount and periodicity of seed production; and (2) germination and survival under different environmental conditions to identify limiting factors and provide estimates of the probability of seedling establishment. These data, together with existing information on seed dispersal distances will permit simulation of the regeneration phase of spruce for different environmental conditions.

Methods of obtaining regeneration are usually adequate for lodgepole pine stands with serotinous cones. What is needed now are natural and artificial reproduction procedures for stands with nonserotinous cones, especially on south slopes and in tension zones.

There is a need to use quantitative data from existing knowledge in current resource and prediction response simulation models to aid multiple-use planning and decisionmaking. These models will also identify deficiencies in knowledge where additional work is needed to determine basic processes and interrelationships among various resources and management practices. We must pinpoint and fill in these gaps in our knowledge before we can develop more refined multi-resource response models.

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The status of our knowledge about the silviculture of subalpine forests in Wyoming, Colorado, and New Mexico is described. The ecology and resource of the Rocky Mountain subalpine are briefly described, followed by in-depth reviews of the spruce-fir type and lodgepole pine type. The relevant literature is included, along with unpublished research, observations, and experience. Research needs are considered as well as what is already known.

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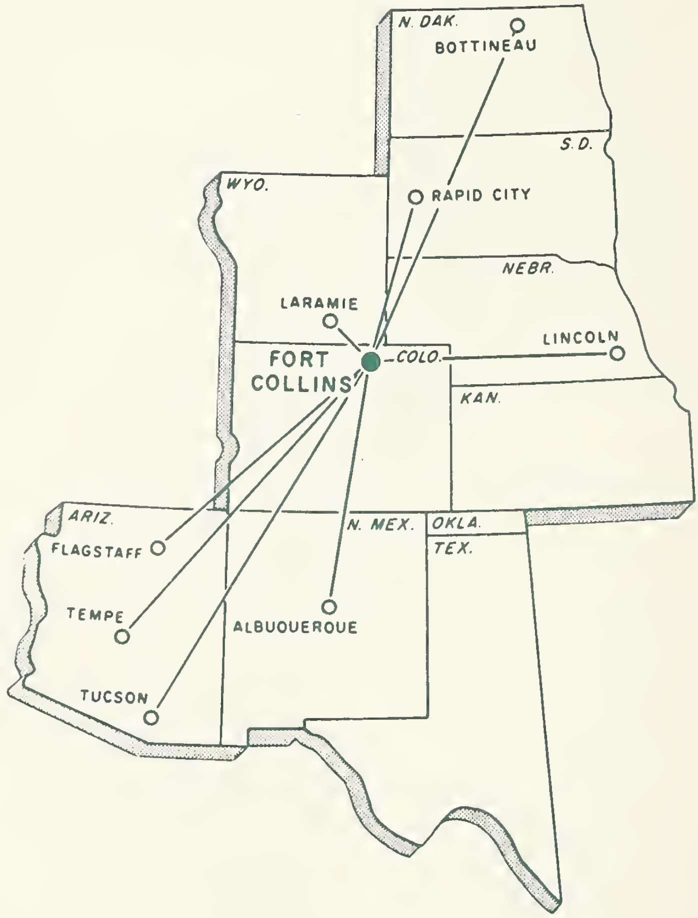
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