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Silvicultural Research and the Evolution of Forest Practices in the Douglas-Fir Region

Robert O. Curtis, Dean S. DeBell, Richard E. Miller,
Michael Newton, J. Bradley St. Clair, William I. Stein

Authors

Robert O. Curtis and **Richard E. Miller** are emeritus scientists and **Dean S. DeBell** is a research forester (retired), U.S. Department of Agriculture, Forest Service, Forestry Sciences Laboratory, Olympia, WA 98512; **Michael Newton** is an emeritus professor, Department of Forest Science, College of Forestry, Oregon State University, Corvallis, OR 97331; **J. Bradley St. Clair** is a research geneticist and **William I. Stein** is an emeritus scientist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3200 SW Jefferson Way, Corvallis, OR 97331.

Abstract

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Silvicultural practices in the Douglas-fir region evolved through a combination of formal research, observation, and practical experience of forest managers and silviculturists, and changing economic and social factors. This process began more than a century ago and still continues. It has had a great influence on the economic well-being of the region and on the present characteristics of the region's forests. This long history is unknown to most of the public, and much of it is unfamiliar to many natural resource specialists outside (and even within) the field of silviculture. We trace the history of how we got where we are today and the contribution of silvicultural research to the evolution of forest practices. We give special attention to the large body of information developed in the first half of the past century that is becoming increasingly unfamiliar to both operational foresters and—perhaps more importantly—to those engaged in forestry research. We also discuss some current trends in silviculture and silviculture-related research.

Keywords: Forest history, silviculture, Douglas-fir, forest research, *Pseudotsuga menziesii.*

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Chapter 1: Introduction[1]

Forestry is the science, art, and practice of creating, managing, using, and conserving forests and associated resources for human benefit to meet desired goals, needs, and values (Helms 1998). **Silviculture** is that portion of the field of forestry that deals with the knowledge and techniques used to establish and manipulate vegetation and to direct stand and tree development to create or maintain desired conditions. It is the application of knowledge of forest biology and ecology to practical forestry problems.

Modern forestry evolved over more than a century in the United States and over several centuries in Europe and elsewhere in the world. This long history is not well known to many people interested in forestry, and many natural resource professionals—including a good many foresters—know little of the scientific and social background that influenced the historical development of forestry and forest science. Yet, many modern questions and controversies are merely variations on those of the past. Any balanced consideration of current problems and possible solutions requires an understanding of how we got where we are today.

In the United States, a large body of information that was developed in the first half of the 20th century is becoming increasingly unfamiliar to both operational foresters and—perhaps more importantly—those engaged in forestry research. It is not unusual to see published papers whose authors are apparently unaware of pertinent information published many years ago, or who cite as sources recent papers without acknowledging original work done by researchers long before. This tendency is perhaps in part a result of generational turnover, but also stems from reliance on computerized bibliographic searches of relatively recent databases that do not include older work. The monumental *Selected Bibliography of North American Forestry* (Munns 1940)—largely unknown to the current generation of researchers—contains 21,413 North American forestry-related references prior to 1940. Most of these publications are not found in existing databases, yet some are of great value to anyone working in forest history, forest policy, or forest biology and silviculture.

A complete and detailed history of North American forestry and forestry research would be an enormous undertaking, far beyond our capabilities. We here confine ourselves to the much more limited subject of the development of silvicultural research and practice in the Douglas-fir region of the Pacific Northwest. In doing so, we take a broad view of silviculture, including silvics, nursery practice, seeding and planting, forest genetics, and those aspects of forest mensuration related to stand development. Our discussion will deal primarily with Douglas-fir as it occurs in western Washington and Oregon, but will also touch on important associated species. We concentrate on events and research in Washington and Oregon, only briefly touching on more or less parallel developments in adjacent Canada and California. We delve very lightly into the enormously important topic of fire and its effects. Likewise, we touch only briefly on the important role of silviculture in forest health issues such as prevention and control of root diseases, insect attacks, animal damage, and similar matters. We consciously bypass much of the large body of related work in physiology and ecology. Our main focus will be on the silvicultural research bearing on stand regeneration and stand management.

We give special attention to the period before World War II (WWII) and treat subsequent years in less detail, in part because the pre-WWII period is least familiar to the current generation of foresters. Most research in this early period was carried out by the U.S. Forest Service, the number of people involved was small, and they often worked on a variety of topics. The early researchers included some truly remarkable people who made enormous contributions. The memory of these people and their contributions should not be lost.

[1] By R.O. Curtis.

After WWII, there was a great expansion in the number of people involved in forestry research and in silvicultural research in particular (which peaked about 1975), and a broadening of activity by universities and a number of industrial organizations. In recent years, there has been a great increase in forest ecology research—some of it rather far removed from practical application—and a declining emphasis on research in practical silviculture. Boyce and Oliver (1999) described the history of the interplay between ecology and silviculture. It is impracticable to cover in detail the many individuals and individual studies involved. From about 1950 onward, we identify general trends, the major silvicultural research results, and a sampling of studies that are directly related to stand establishment and stand management. We also discuss their effects on current and future forest management practices.

We have organized our presentation into (1) historical background, (2) a brief outline in more or less chronological order of the general trends in silviculture-related research over time, (3) a series of more detailed chapters covering research on particular silvicultural or silviculture-related topics, and (4) a discussion of concurrent developments in practical forest management and the way in which they were influenced by formal forest research.

We also give an extensive list of references, which includes most of the important work prior to about 1950. It is impractical to list all of the greatly expanded literature from subsequent years, but we provide enough to indicate the general direction of research and to serve as entry points to the literature for those interested in particular topics.

Chapter 2: Historical Background[1]

European Experience

We do not know when forestry began any more than we can answer such a question for agriculture. Both agriculture and forestry initially evolved through practical experience, long before the days of land-grant colleges and professional publications. Some forms of intentional management of trees and forests probably antedate the written word. Both agriculture and forestry have been practiced in one form or another in different locations and at different times, with results strongly influenced by physical conditions and existing cultural, political, and economic factors.

The prerequisites for development and systematic application of forestry and silviculture are (1) a climate favorable to the establishment and growth of forests; (2) a stage of population and economic development in which pressure on forest resources creates an awareness of present or anticipated scarcity; (3) sufficient prosperity that concern for the future is not completely overshadowed by immediate problems of survival; and (4) a degree of cultural, political, and economic stability and social organization that makes concerted action possible.

Fragmentary evidence shows that techniques such as planting, coppicing, and thinning were known and practiced in the ancient Mediterranean world, together with some governmental efforts to control forest use (Mather 1990). But a climate not particularly favorable to forests, repeated wars and invasions and associated political and social instability, population pressures, and the goat combined over the millennia to destroy much of the region's forests.

The moist temperate climate of western and central Europe is much more favorable for establishment and growth of forests, and resembles the climate of portions of the Eastern United States. The roots of modern forestry and silviculture stem from developments in western Europe, from the late Middle Ages onward. We do not have a good up-to-date comprehensive history of European forestry in English; the closest to this is still Fernow (1911). There are a number of more recent publications in English that treat specific limited topics. Among these are Freeman (1994), James (1996), Klose (n.d.), Linnard (1974, 1999), Lowood (1990), Mantel (1964), Osmaston (1968) Smout (1997), Thirgood (1971, 1989), and Watkins (1998). This list is by no means comprehensive, and the synopsis given below is necessarily an incomplete and broad-brush treatment of the subject.

Like our North American forests, the composition of European forests changed over time in response to the changing climate of the glacial and postglacial period and to the effects of human activities. By the late medieval period, most of the forests of western Europe south of Scandinavia are thought to have been broad-leaved, primarily oaks (*Quercus* sp.) and beech (see appendix for scientific names of species). Higher elevations in Switzerland and the mountains of Germany and France contained much spruce and silver fir. Scots pine was abundant on drier sites in Germany, in the Scottish highlands, and in Scandinavia and the Baltic countries, whereas spruce and birch were extensive in northern Scandinavia.

The Europe of late medieval and early modern times was composed of numerous political and economic units, which gradually became consolidated. Wood was the only energy source for cooking and heating. Mining, glass making, brick making, and the metal working industries were dependent on wood or on charcoal made from wood. Shipbuilding and general construction all depended on wood. Transportation was rudimentary, and heavy or bulky commodities could only be transported by water. Consequently, timber shortages soon developed in the vicinity of population and industrial centers, even though there might be abundant supplies in other areas.

Timber was not the only or even the priority product of forests. The nobility put great value on their hunting privileges—both for sport and meat—and these privileges frequently took precedence over the interests of the majority

[1] By R.O. Curtis.

of the population. Cattle grazing was important. The widespread oak forests were valued for mast production, which supported numerous herds of swine.

Because fuel- and charcoal-wood and oak mast were two of the primary products in demand, much of the broadleaved forest was managed from an early date under coppice (regeneration by sprouts) or coppice with standards (some trees reserved to grow to large sizes) systems. The standards also provided some large timber for shipbuilding and construction as well as mast for swine production. These were relatively simple regimes, well adapted to the needs of the time, and continued in many areas until the introduction of coal in the late 18th century and the coming of the railroads in the early 19th century reduced markets for fuel wood while improving transportation and, hence, markets for large and formerly inaccessible timber. This, in turn, led to a gradual conversion of many forests from coppice or coppice with standards to high forest (originating from seed rather than sprouts), managed under several silvicultural systems.

Fragmentary records exist, dating at least from the 13th century, of the systematic forest management of some monastic and communal forests. By the 17th and 18th centuries, closely controlled forest administrative organizations had developed for royal and community forests in France and the German principalities, with timber production as a major objective.

Thus, in France, an ordinance of 1376 provided for regulation of cut and reservation of standards (trees held for further growth) on felled areas in the royal forests. The ordinance of 1669 reformed the forest administration and established a new and more comprehensive forest code for the royal and communal forests. After the disruptions of the revolutionary period, the present Ecole National des Eaux et Forêts was established at Nancy in 1824 and a new Code Forestier was introduced in 1827. The majority of French forests remained in hardwoods (beech and oak). Regeneration was primarily by coppice or by natural seeding, and there was a gradual conversion from coppice or coppice with standards to some form of the shelterwood system in most royal and communal forests (James 1996, Thirgood 1989).

Parts of Germany (such as the Black Forest) and France had large areas of derelict forest and poor pasture land (reminiscent of our eastern Appalachians of the early 1900s), and much of this passed into state ownership in the late 18th and early 19th centuries. There were extensive planting programs in the early 19th century, mostly with spruce in the mountains, Scots pine on poorer lowland sites, and maritime pine in the Landes region of southwestern France.

A number of texts on silviculture and forest management appeared in the late 18th and early 19th centuries, and the scientific study of forests and formal forestry education began in France and Germany. This, in turn, led to the establishment of specialized forest research institutions in the latter half of the 19th century. Similar developments took place in Denmark and Austria, and somewhat later in the Scandinavian countries. Various techniques for regulation of cut were introduced, aiming at the objective of sustained yield and establishment of a uniform ("normal") distribution of age classes. Thinning became a common practice in France, Denmark, and Germany. By the late 19th century, yield tables for the major species (which portray expected stand development and timber production) were in common use.

Of course, there was not a smooth continuum of progress everywhere. Major disruptions of forest management and damage to the resource accompanied the social and economic upheavals associated with events such as plagues, the Thirty-Years War, the French Revolution, and the Napoleonic wars.

In Britain, the early forest laws of 1184 and later were primarily concerned with protecting game for the use of king and nobility. An act of 1543 under Henry VIII was the first that defined a positive policy for timber production (Osmaston 1968), including provision for regeneration and reservation of standards. John Evelyn's *Sylva* (1664) is often cited as the first silvicultural text in English (Dengler

1964), along with other early writings. In the 1700s, tree planting became a common practice on estates.

Despite these early efforts, Britain had no overall forest policy. After a start in the 17^{th} and 18^{th} centuries, stimulated by the needs of naval construction and early industry, timber production forestry declined in the 19^{th} century, with an increasing emphasis on land use for shooting grounds and amenities. Factors responsible included the availability of cheap imported timber from North America and the Baltic, the substitution of coal for wood as an energy source, the shift from wood to iron in ship construction, the absence of any overall government forest policy, and the fact that many large landowners came to derive their income primarily from investments in manufacturing industries and overseas development rather than from their lands in Britain. Timber production forestry was resumed in Britain on a large scale only with the establishment of the Forestry Commission and an extensive afforestation program in 1919, as a response to wartime shortages. This was greatly expanded after World War II, with afforestation of large areas of poor grazing land and nonproductive moor land.

In contrast to the neglect of forestry in 19^{th} century Britain, an effective forest policy and administration was established comparatively early in British-ruled India and Burma. This work began in the 1850s and developed under three German foresters, Brandis, Schlich, and Ribbentrop (Fernow 1911). Professional staff were trained at Oxford and at the forestry college (and research institute) established in 1878 at Dehra Dun.

Forest management was introduced on some communal and other forests in Switzerland by the 17^{th} century, but was far from universal. Government was highly decentralized until the early 1800s. By the mid-1800s, severe flood problems were recognized, and toward the end of the century (1876) federal forestry programs were put in place that emphasized watershed protection on mountain lands. In 1902, federal oversight was extended to all forest lands. Further clearing of forests was restricted, and efforts were made to reforest poor mountain pasturelands. Most forests were and are managed under selection and shelterwood systems, with predominantly natural regeneration.

In the more remote and less accessible areas of northern Scandinavia and Finland, forest management remained largely extractive until the beginning of the 20^{th} century.

By 1900, German forestry was widely viewed as an outstanding success and a model for other countries to follow. Highly productive forests under systematic planned management had replaced the degraded forests of earlier times. Plantation forestry, particularly with spruce, was emphasized because of its high yields and favorable financial returns. But there were some rumblings of discontent, which have increased over time. A decline in growth of planted spruce stands occurred in some areas, now attributed to the attempt to grow spruce on warmer and drier sites than those on which it occurred naturally. Pure spruce stands suffered from windfall. Rising labor costs made the traditional dense planting and intensive early thinning increasingly questionable. There were movements in favor of mixed species, more “natural” regeneration methods, and more emphasis on amenity values (Plochmann 1992, Troup 1952: 193–207).

Public regulation of forest practices in varying degree has long been established in many European countries, and is often combined with extensive public assistance to private and communal owners through technical services, marketing services, owner cooperatives, and various forms of subsidy for socially beneficial activities that are not otherwise financially attractive to an owner (Gilfillan and others 1990; Grayson 1993; Klose, n.d.; Plochmann 1974).

Although European species are not identical with those of the United States, most of them are close relatives of and similar in behavior to those of the Northern United States. A number of species from the Pacific Northwest, including Douglas-fir, Sitka spruce, and lodgepole pine, have been introduced in Europe and have done extremely well. Weetman (1996) provided a useful discussion of European silvicultural experience and recent parallels with Pacific Northwest experience and problems.

Several lessons can be drawn from European forest history:

- Forestry and silviculture have a much longer history than most people realize.
- Objectives and practices evolve with changes in the social and economic environment.
- Forests have been managed for multiple objectives throughout history, although the emphasis has been different in different places and at different times.
- The moist temperate forests of central and northern Europe have shown great resilience and remain highly productive after 2000+ years of relatively dense human occupation and intensive use and abuse. Extensive areas that had been reduced to nonproductive wasteland have been successfully rehabilitated.
- Many of our present activities and problems have parallels in the past.

United States Beginnings[2]

The indigenous peoples of the Eastern and Southern United States cleared and cultivated substantial areas, but there were also vast areas of forest. The early European settlers were mainly agriculturists, who viewed forests as obstacles to be removed. It was the policy of both colonial governments and the later government of the United States to transfer public lands into private ownership as rapidly as possible, in the belief that agricultural development would naturally follow. This policy was not seriously questioned until the latter part of the 19th century.

The transfer of lands to private ownership was accomplished by large land grants to private parties in the colonial period; by direct sale; by the Homestead Act of 1862, which gave 160 acres (65 ha) of land to any citizen willing to cultivate it; by huge land grants to railroad companies in lieu of cash subsidies; various grants to the states; and assorted other acts, such as the Timber and Stone Act of 1878, the Timber Culture Act of 1873, and the Mining Act of 1872. Administration of the various laws governing land disposals was unavoidably loose and sometimes corrupt. Fraud and speculation were common and led to a number of scandals toward the end of the 19th century.

Results of this overall policy were reasonably satisfactory in the fertile lands of the Midwest and the Mississippi Valley. But it gradually became evident that agriculture on the eastern pattern would never be feasible in much of the arid West or in the rugged terrain of the Rocky Mountain and Pacific coast regions. Future values lay in timber, minerals, grazing, and the water that could make agriculture feasible.

By the latter half of the 19th century, a large lumber industry had developed that provided materials for the burgeoning economy as population grew and industrialization proceeded. At the time, this was a migratory industry that viewed the forests as fixed assets to be mined. Competition among numerous firms was intense, and the industry was highly cyclical. The center of activity shifted from New England to Pennsylvania to the Lake States as the resource was exhausted, then to the South and to a beginning on the west coast. These lumbering operations and the fires that often accompanied them left behind a trail of derelict lands and ghost towns.

From the Civil War onward, repeated warnings were voiced of the calamitous consequences of the progressive destruction of North American forests. An approaching timber famine, floods, and water supply problems were predicted. Notable figures in the efforts to obtain congressional action included George P. Marsh, Carl Schurz, Franklin B. Hough, and John A. Warder (who was instrumental in formation of the American Forestry Association in 1875). A committee of the American Association for the Advancement of Science, with Hough as chairman, prepared a statement asking Congress to address the issue (Hough 1873). President Grant presented this to Congress in 1874. As one result, Hough was appointed as forestry agent in the Department of Agriculture, in which capacity

[2] This section and related discussion are drawn from Dana (1953), Miller (2000), Rodgers (1991), and Steen (1977).

he prepared several extensive reports on the U.S. forest situation and recommendations for action (Hough 1913, Miller 2000, Steen 1977). His book *The Elements of Forestry* was the first general forestry text published in the United States (Hough 1882).

Efforts for reform and congressional maneuvering continued over subsequent years. We will not attempt to follow the details, but merely point out the results:

- A Forestry Division was established in the Department of Agriculture in 1881 with Hough as its first chief. He was succeeded for a brief period by Nathaniel Eggleston, and the division (later renamed the Bureau of Forestry) was made permanent in 1886, under Bernhard E. Fernow as Chief (Rodgers 1991). Fernow in turn was succeeded by Gifford Pinchot in 1898.
- The Forest Reserve Act of 1891 gave the President authority to establish forest reserves from the public lands. Presidents Harrison and Cleveland set aside some 40 million acres over the next few years, with protection and management responsibility assigned to the General Land Office in the Interior Department.
- The Organic Act of 1897 provided extended authority for creation and administration of the forest reserves, and established their purposes as “to improve and protect the forest. . . .to secure favorable conditions of water flows, and to furnish a continuous supply of timber for the use. . . .of citizens of the United States.”
- In 1905, the Interior Department functions in administration of the forest reserves were combined with the Department of Agriculture’s Bureau of Forestry to form the U.S. Forest Service and National Forest System, located in the Department of Agriculture, with Gifford Pinchot as Chief.
- The national forests were greatly expanded under the Theodore Roosevelt administration.

The Society of American Foresters was established in 1900, with an initial membership that included a number of people who were prominent leaders in American forest policy, forest science, and forestry education over the next several decades.

A forestry education program was established at Cornell University in 1898 under Fernow, but fell victim to political difficulties in 1903. Carl Schenck (a German forester) established and ran the independent Biltmore School from 1898 to 1913. The Yale School of Forestry was established as a graduate school in 1900, under Henry S. Graves, previously assistant to Pinchot in the Bureau of Forestry. A number of other professional programs were established at various universities within the next few years, including that at Oregon State in 1906 and at the University of Washington in 1907. These provided the cadres for the developing federal, state, and private forestry organizations.

Fernow and Schenck were German foresters who immigrated to the United States. Pinchot, Graves, and some others had studied forestry in France and Germany. Thus, they came to their tasks with a considerable knowledge of the European experience and the practices in use in Europe. Although American social and economic conditions were markedly different, their European forestry background had a considerable and generally beneficial influence on their thinking and choice of measures.

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Chapter 3: The Douglas-Fir Region [1]

As we use the term, the "Douglas-Fir Region" is the region lying between the crest of the Cascade Mountains and the Pacific Ocean in western Washington and western Oregon, plus a considerable area of similar conditions in southwestern British Columbia including Vancouver Island. This geographic area encompasses most of the range of coast Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), which extends southward more narrowly into northern California.

Annual rainfall is moderate in the Puget Sound basin and Willamette Valley (about 100 centimeters, 40 inches), somewhat lower in southwest Oregon, and very high along the Pacific coast and at higher mountain elevations (200 to 300 centimeters, 80 to 120 inches). Rainfall is strongly seasonal, with dry summers. Temperatures are mild and relatively equable although the climate becomes more severe with much greater snowfall at the higher elevations.

The Forests

The predominantly coniferous forests of the coastal Pacific Northwest are complex and are probably the most productive natural temperate forests in the world. The region takes its name from Douglas-fir, the most abundant and economically most important species. However, the region also includes a number of other important species and forest types, which have received considerably less attention.

Popular mythology has it that at the coming of Europeans, the region was an unbroken expanse of giant old-growth trees that had been present from the distant past. This is far from the truth. We cannot know exactly how much of the region was "old growth," but several estimates suggest it may have been about 50 percent (Ripple 1994). The proportion of old growth must have fluctuated considerably because of the periodic huge fires that we know occurred in presettlement as well as postsettlement times. The Native Americans of the region were not agriculturists and settled mainly along the seacoast and major rivers. The forests were therefore less affected by pre-European human activities, excepting fire, than those of the Eastern United States. Nonetheless, accidental and intentional burning by Natives had major effects. Camas (*Camassia quamash*) was a major food source, and extensive lowland areas were intentionally burned to promote growth of this plant as well as to facilitate hunting. These fires, combined with relatively low rainfall and excessively drained glacial outwash soils in some areas around Puget Sound, produced extensive areas of open prairie and oak woodland in the Puget Sound trough and Willamette Valley. Similarly, intentional as well as accidental fires in the mountains produced extensive huckleberry fields, much valued by the Natives.

Glaciers covered the northern part of the region until about 12,000 years ago. Pollen analyses and dating of organic debris indicate marked changes in climate and in species composition of the forests since retreat of the glaciers. The forests are thought to have reached approximately their present species composition only some 6,000 years ago (Brubaker 1991).

Present forest composition is closely related to elevation and rainfall. The forest can be subdivided into zones (adapted from Franklin and Dyrness 1973) more or less as follows:

- Western hemlock (*Tsuga heterophylla*) zone.
- Sitka spruce (*Picea sitchensis*) zone.
- Pacific silver fir (*Abies amabilis*) zone.
- Mountain hemlock (*Tsuga mertensiana*) zone.
- Willamette Valley.
- Mixed-conifer and mixed-evergreen zones (southwest Oregon and adjacent California).

Of these, the western hemlock zone is by far the most important in terms of both area and productivity. Despite the name (based on the successional "climax" species), most of the zone is dominated by Douglas-fir. This dominance is the combined result of past fires (historical and prehistoric), clearcut timber harvesting, and planting of burned or harvested areas; all of which favor the relatively shade-intolerant Douglas-fir. Important associated species

[1] By R.O. Curtis.

include western hemlock, western redcedar (*Thuja plicata*), and red alder (*Alnus rubra*), plus a considerable number of others common in parts of the zone. Productivity varies from moderate to extremely high, according to rainfall, elevation, and soils. The majority of research studies and most of the discussion in later portions of this paper are primarily concerned with Douglas-fir as it occurs in the western hemlock zone. We touch only briefly on the associated species and adjacent zones.

The Sitka spruce zone is a narrow belt along the Pacific Ocean, with mild temperatures, very high rainfall, and high productivity. It is a southern continuation of the extensive spruce-hemlock forests of southeastern Alaska and western Vancouver Island. Although it takes its name from the characteristic presence of Sitka spruce, western hemlock is the most abundant species. Other commercially important species present in lesser amounts include red alder, western redcedar, and Douglas-fir. This zone has received less research attention than the western hemlock zone, probably because western hemlock was seen as a relatively low-value species until quite recently.

The silver fir and mountain hemlock zones are at higher elevations, in which timber harvesting has a short history and in which relatively little silvicultural research has been done. Sites range from moderately productive to clearly noncommercial. Species composition is mixed, including—in addition to the Pacific silver fir and mountain hemlock that give the zones their names—Douglas-fir at the lower margins and such other species as western hemlock, western redcedar, Engelmann spruce (*Picea engelmannii*), western white pine (*Pinus monticola*), noble fir (*Abies procera*), lodgepole pine (*Pinus contorta*), and Alaska yellow-cedar (*Chamaecyparis nootkatensis*).

The Willamette Valley is an area of lesser rainfall, in the rain shadow of the Oregon Coast Range. At the time of settlement it consisted largely of prairie and open Oregon white oak (*Quercus garryana*) woodland. Associated species include Douglas-fir, grand fir (*Abies grandis*), ponderosa pine (*Pinus ponderosa*), and bigleaf maple (*Acer macrophyllum*).

The mixed-conifer and mixed-evergreen forests of southwestern Oregon and adjacent California (which include Douglas-fir as an important component) have considerable differences from forests to the north; the forests in the southern part of the region are associated with a warmer and drier climate and more frequent fire-return intervals.

Early History

The first permanent European settlements were the fur-trading posts of the Hudson's Bay Company and its U.S. competitors, established shortly after the Lewis and Clark expedition reached the Northwest coast in 1805. By the 1840s, there was substantial continuing immigration from the Eastern United States. A major area of settlement was the Willamette Valley, which attracted settlers because of its good agricultural soils and open prairie and oak woodland. The second and somewhat later area of settlement was the Puget Sound region, which was less attractive to the agriculturist but had the advantage of sheltered harbors and easy water transport on Puget Sound.

The California gold rush of 1849 suddenly created a large demand for lumber. Most of Puget Sound was bordered by forests, easily accessible to water transportation. The immediate result was establishment of a lumber industry shipping its products to California; a trade that soon expanded to include exports to Hawaii, Australia, and South America. This quickly became the principal industry in the area. A similar but considerably later development occurred in Oregon, where transport and access to shipping was much more of a problem. Completion of the transcontinental railroads in the 1870s, and the opening of the Panama Canal in 1914 provided access to Eastern U.S. markets.

Logging began at tidewater, and gradually moved inland up the valleys and lower slopes. The horse and ox teams that were originally used quickly proved inadequate for handling large timber over any distance. There was rapid development of an elaborate logging technology based on the steam engine, logging railroad, and cable yarding systems (Gibbon 1918).

In this early period, timber was obtainable either without cost (bluntly, by theft from public lands) or at minimal cost through the various land grants and land disposal laws (Ficken 1987, Yonce 1980). Timber was regarded as a fixed asset to be mined. No value was placed on future use of the land other than possible use for agriculture or town sites in some favorable locations. There was no effort at fire control beyond the immediate vicinity of mills and established communities. The combination of large-scale unregulated logging and repeated fires produced large areas of unstocked and derelict land, much of which (but not all) eventually restocked through natural processes.

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Chapter 4: Forestry Research—Origin and Direction[1]

Initial Explorations

The scientific study of Douglas-fir and associated vegetation started with the description of the species in 1792 by Archibald Menzies at Nootka Sound on the west coast of Vancouver Island (Hermann 1982). Doubtless, Native people had earlier knowledge of the ecology of Douglas-fir and other species. Slightly more than a decade after Menzies, the Lewis and Clark expedition made systematic notes on Northwest flora (Moulton 1983).

Other expeditions that included systematic observations of vegetation soon followed. David Douglas observed and collected plant and animal specimens in exploratory trips throughout the Pacific Northwest from 1825 to 1827, and 1830 to 1833 (Harvey 1947). John Fremont's expeditions from 1844 to 1852 involved some observations and collections in forest types of the Pacific Northwest (Welsh 1998). Railroad surveys followed, and as settlers arrived, systematic land surveys were begun that recorded the most prominent species present (Habeck 1961). Much information on forest types and conditions was developed by Leiberg, Plummer, and others during surveys of the forest reserves in the Pacific Northwest (Gannett 1900). These early observations for various purposes provided the first knowledge about species distribution and characteristics.

Figure 1—Thornton T. Munger came to the Pacific Northwest in 1908, became the first Director of the Pacific Northwest Forest Experiment Station (1924–38), and retired in 1946. He had a great influence on Northwestern forestry and forestry research.

Early Research: 1881–1920

The Division of Forestry established in 1881 (renamed the Bureau of Forestry in 1901) in the Department of Agriculture was authorized to undertake a variety of work, including making forest plans for private timberland owners, tree planting, and forest investigations. Its assigned functions thus combined education, forestry extension, and forestry research. Its chiefs, Hough and Fernow (chapter 2), both had a research orientation, and a large part of their activities were concerned with fact-gathering and research. Within a rather short period, the organization produced a considerable number of publications, despite (by present standards) a small staff and minuscule appropriations.

These activities continued after the Bureau of Forestry was merged with the forest reserve administration of the Public Lands Office to create the U.S. Forest Service within the Department of Agriculture under Pinchot, although Pinchot's efforts appear to have emphasized the promotion of forestry among landowners and the problems of organizing and administering the public forests. Raphael Zon promoted establishment of a series of forest experiment stations, the first of which was established in 1908 at Fort Valley, Arizona.

In 1908, a Section of Silvics was established in the newly organized District Forester's office in Portland. Its leader, Thornton T. Munger (fig. 1), soon became one of the outstanding figures in Northwestern forestry research.

[1] By R.O. Curtis.

Figure 2—Beginnings of the Wind River Nursery, about 1910.

Figure 3—The great Yacolt Fire and others prompted early emphasis on reforestation of burned areas. This 1913 photo of the 1902 Yacolt Burn was taken by Julius V. Hofmann near the Wind River Forest Experiment Station.

Figure 4—Wind River Nursery and Wind River Forest Experiment Station, 1919.

In 1913, the Wind River Experiment Station was established near Carson, Washington. (Herring and Greene, in press, give a detailed history). The location was originally chosen for its proximity to the recently established Wind River nursery (fig. 2), primarily because of the belief that the most pressing problems concerned nursery practice and reforestation of the extensive burned areas (fig. 3). This emphasis was soon replaced as the paramount interests by problems of slash disposal, fire control, and natural regeneration after cutting (Munger 1955). From 1913 to 1924, most silvicultural research was conducted at Wind River (fig. 4) by staff working there under Julius V. Hofmann. In 1915, 160 acres (65 hectares) of new plantations and young natural regeneration was set aside as the first unit of an experimental forest (Munger 1955: 229). This was later greatly expanded (1932) to form the present Wind River Experimental Forest. In 1926, a 280-acre (113-hectare) natural area was established in the Trout Creek drainage. In 1932, this was enlarged to 1,180 acres (480 hectares) to form the Wind River Natural Area within the Wind River Experimental Forest, later (1977) renamed the T.T. Munger Research Natural Area.

In 1915, Henry S. Graves, successor to Pinchot as Chief of the Forest Service, appointed Earle H. Clapp as chief of the newly established Branch of Research, a post he held until 1935. He established the position of research (including the Wind River Experiment Station) as an activity independent of national forest administration and responsible to the Washington Office rather than the regional foresters. He laid the groundwork for the McSweeney-McNary Act, discussed below.

Many of the small staff involved in research activities of the Bureau of Forestry and in the early years of the Forest Service went on to play prominent regional and national roles in forestry research, policy, education, and administration. Hereafter, we mention only those individuals, studies, and publications directly pertinent to the Douglas-fir region.

A major activity in the initial years was preparation of a series of monographs on the silvics and general characteristics of important timber species, as understood at the time. Among of the first of these was a bulletin on western hemlock by E.T. Allen[2] (1902), who later played a prominent role in the Western Forestry and Conservation Association (still extant) and in the promotion of industrial forestry. He also wrote a lengthy report on Douglas-fir,[3] which, among other things, recognized the role of fire in creating and perpetuating Douglas-fir forests, and the possibilities of future management of these forests.

Sudworth published (1908) *Forest Trees of the Pacific Slope*, a comprehensive text on the dendrology and silvics of Pacific Northwest species. This provided the first compiled information on seeding characteristics and reproduction of western trees and specifics about the geographic occurrence of individual species.

Another major early publication was Frothingham's (1909) monograph on Douglas-fir. Frothingham recognized the distinction between coast and Rocky Mountain forms, gave some information on European experience with introduced Douglas-fir, and discussed its geographic distribution and silvical characteristics in different parts of the region. He recognized the role of fire in perpetuating Douglas-fir, its inability to reproduce and grow under shade, and recommended clean (clear) cutting with burning of slash to expose mineral soil as the most appropriate form of management on the Northwest coast. Reading this today, one is impressed by the author's understanding and generally correct observations.

The first large field study was on growth and yield of Douglas-fir, and involved extensive field measurements in existing second-growth stands. The results were published, along with much other information, in *The Growth and Management of Douglas-Fir in the Pacific Northwest* (Munger 1911). This discussed silvics of the species, the possibilities of future production from logged-off land, the measures needed to ensure regeneration, associated costs, and prospective yields. It presented a volume table and a yield table, based on field measurements in the previous several years; these were the first of many such tables prepared in the Northwest. Munger argued that satisfactory regeneration could be secured with some fairly minor modifications of prevailing logging methods. He recommended:

- Clean (clear) cutting the area (except that provision must be made for seed trees),
- Clearing the area of debris by fire to prepare the seedbed,
- Protecting the area from subsequent fires.

In 1911, Allen published *Practical Forestry in the Pacific Northwest*, through the newly established Western Forestry and Conservation Association. This was a lengthy discussion of the problems and opportunities for forestry in the Pacific Northwest and a plea for action, based in part on the recently acquired silvicultural knowledge, in part on the economics of the lumber industry, and in part on extrapolation from European experience. From the standpoint of the

[2] E.T. Allen began as a ranger in Washington state under the Public Lands Office, joined the Division of Forestry in 1899, served briefly (1905–07) as State Forester of California, and was then appointed District Forester for District 6 in Portland, Oregon. He resigned in 1909 to become manager of the newly organized Western Forestry and Conservation Association.

[3] Allen, E.T. 1899. Red fir in the Northwest. 94 p. Unpublished manuscript. On file with R.O. Curtis.

present discussion, his two most important points were (1) the overriding importance of establishing adequate fire protection as a prerequisite for any type of forest management and (2) the importance of regeneration.

An early long-term research project was a provenance trial of Douglas-fir, begun in 1912 (chapter 7). Seed was collected at widely scattered locations in western Oregon and Washington, grown in the nursery, and then planted at five locations ranging from 1,000 to 4,600 feet (300 to 1400 meters) in elevation. Major differences among seed sources were found in survival, growth rate, and sensitivity to differences in local climate (Hofmann 1921, Morris 1934, Munger and Morris 1936).

A worldwide search for fast-growing exotic trees began in 1912, and specimens were planted to form the Wind River Arboretum. This work was initiated by T.T. Munger, continued by E.L. Kolbe, and later by Leo Isaac, and reported in detail by Silen and Olson (1992). Results demonstrated the superiority of native species over exotics. The progressive failure of initially promising exotics showed that long-term forest research findings can be very different from initial results.

From 1910 through 1940, a series of permanent sample plots was established in young-growth Douglas-fir stands (first reported in Munger 1915). The original purpose was to provide a foundation for growth and yield estimates for pure, well-stocked stands of Douglas-fir. These formed the basis for a number of publications, discussed later. Williamson (1963) described those plots still surviving in 1963. Several are still extant and have recently been used by university scientists interested in development of older unmanaged stands (Acker and others 1998).

In 1920, a set of three experimental thinning plots was established on Martha Creek at Wind River, in a 9-year-old naturally regenerated stand. One plot was left unthinned, and two were thinned to 8- by 8-foot spacing (2.4- by-2.4-meter) (chapter 6).

On the national scale, knowledge of artificial regeneration had accumulated to the point that J.W. Toumey published a detailed textbook on the subject (Toumey 1916), subsequently rewritten and considerably expanded (Toumey and Korstian 1931).

In this early period, there was debate over the use of natural vs. artificial regeneration methods. Rehabilitation of the extensive burned areas (Yacolt Fire of 1902 and others) was an urgent problem, and the Wind River nursery had been established (1910) to provide for this. There was little question about the need for planting such areas. But there was some difference of opinion over desirable practice for regenerating freshly logged areas. Munger (1912), in rebuttal of Kirkland's (1911) opinion that artificial regeneration would be both cheaper and more satisfactory than natural regeneration, advocated general use of natural seeding by the scattered seed tree method, after burning slash to expose mineral soil. He (optimistically) estimated that one large seed tree per 2 acres might be sufficient. As these could be selected from among damaged and defective trees, the cost would be materially less than with artificial regeneration. Greeley (1912) sided with Munger on the practical grounds that limited financial resources would be best directed at reforesting the huge existing area of nonstocked land.

Research: 1921–1960

The increased level of research activity and wide variety of topics make it impractical to adhere to a strictly chronological presentation in discussing this and subsequent periods, and instead we will review progress in a number of silviculture-related topics in a series of subsequent chapters.

In general, silviculture research in this period was directed primarily at the problem of securing prompt and adequate regeneration of cut areas mainly, though not exclusively, by natural seeding. There was also much work on Douglas-fir yield tables and growth prediction and a beginning on extensive thinning research.

A number of major events and organizational and technical changes in this period affected the course of forestry research. These included:

- The Pacific Northwest Forest and Range Experiment Station (now Pacific Northwest Research Station, PNW) was established in 1924 and absorbed the former Wind River Experiment Station. Headquarters was in Portland, Oregon, with Thornton T. Munger as its first Director. Extensive records of events at the Station are given in unpublished reports by Cowlin[4] and Wertz.[5]

- The McSweeney-McNary Act of 1928, for which Earle Clapp was largely responsible, established essentially the present system of forest experiment stations under USDA Forest Service. The act greatly elaborated research authorization and increased funding. The act provided clear direction that Forest Service research should serve the needs of all forest landowners and of the public, rather than functioning as a support organization for national forest administration. It also established the Forest Survey (now Forest Inventory and Analysis), as a continuing national inventory of forest resources.
- Although the Great Depression of 1929–1940 severely impacted the timber industry, the Civilian Conservation Corps program improved research infrastructure and provided manpower in support of research.
- The introduction of truck transport and tractor skidding provided increased flexibility in application of silviculture.
- Statistical methods were increasingly used, as a result of developments in applied statistics, education, and the introduction of mechanical calculating devices. The methods pioneered by R.A. Fisher in agronomy were introduced to forestry research (primarily through training efforts within the USFS research organization) by people such as Donald Bruce, F.X. Schumacher, J.G. Osborne, R.A. Chapman, and others (Bruce 1999).
- World War II shifted most research personnel to the military or to war-related work for the duration.
- After the war, forestry education expanded and the role of the universities in forestry research increased.
- Support for forestry research increased markedly as a result of postwar changes in the economy and the timber-related industries.

In 1934, the Forest Service established the Cascade Head Experimental Forest on the Siuslaw National Forest, north of Lincoln City on the Oregon coast. This experimental forest was primarily Sitka spruce and western hemlock. It was the site of considerable research in the type, including precommercial thinning trials in hemlock (Hoyer and Swanzey 1986) and in Sitka spruce comparing a range of spacings; work on spruce-hemlock regeneration; and harvest methods. Walter Meyer established 11 long-term growth plots in spruce and hemlock. In 1940, Briegleb added three Douglas-fir long-term plots at Cascade Head in the series begun by Munger. In 1935–37, a study was installed comparing growth of red alder and alder-conifer mixtures (Berntsen 1961a). In the late 1930s, experimental plantings were made of a number of introduced species, none of which were successful. Cascade Head Experimental Forest has also been the site of a considerable amount of more recent work in various aspects of forest ecology, by both PNW Research Station and Oregon State University.

Three experimental forests were established in 1947–49, specifically to study commercial thinning, and will be discussed further under that topic. These three—the Hemlock, McCleary, and Voigt Creek Experimental Forests—were established on industrial land under cooperative leases.

In 1948, the H.J. Andrews Experimental Forest was established on the Willamette National Forest, east of Eugene, Oregon. It has been the site of much research by PNW Research Station, Oregon State University, and others that continues to the present. Early work was concerned primarily with old-growth harvesting techniques, including

[4] Cowlin, R.W. 1988. Federal forest research in the Pacific Northwest Research Station. 244 p. Unpublished manuscript. On file with R.O. Curtis.

[5] Wertz, J.H. 1940. A record concerning the Wind River Forest Experiment Station, July 1, 1924–December 30, 1938, with supplements 1939 through 1943. Unpublished documents. On file with R.O. Curtis.

various forms of strip cutting, small group cuts, seed tree cuts, and conventional staggered settings. Emphasis then shifted to forest ecology and watershed questions, and in recent years there has also been work on thinning regimes and related topics.

Munger (1927), in *Timber Growing and Logging Practice in the Douglas-fir Region,* summarized then-existing information and recommendations for harvest and regeneration of old stands and protection of regeneration from fire.

In 1947, the PNW Forest and Range Experiment Station published *Management of Second-Growth Forests in the Douglas-Fir Region* (USDA FS 1947). This was a compendium of existing knowledge on all aspects of Douglas-fir silviculture and stand management prepared by a committee that included many individuals prominent in public and private forestry and in both research and administration. It had a major influence on the transition to permanent long-term management on industrial and other private lands.

In the late 1950s to early 1960s, there were substantial changes in the Forest Service research organization, under the leadership of V.L. Harper. The former geographically based research center organization adopted after World War II was abandoned in favor of a project organization that grouped people working on particular topics. Promotion of scientists was no longer dependent on acceptance of administrative responsibilities. Pioneering research units were established to provide wide scope for the abilities of selected outstanding researchers (Steen 1998). Research funding was increased and a laboratory construction program was undertaken.

Research: 1961–1985

Research in this period emphasized increasing growth rates of established young stands through such practices as density control and fertilization. There was also much work on artificial regeneration and the associated problems of site preparation and brush control. Extensive work was undertaken in genetics and tree improvement.

University research underwent a great expansion, supported in part by funding under the McIntire-Stennis Act of 1962. A number of corporations established substantial forestry research organizations (Staebler 1999). Forest research was no longer solely or even primarily a function of the federal government. Most foresters and much of the public saw the needs of public and private owners as broadly similar, and there was much cooperation and mutual support between the public and private sectors. This cooperation included establishment of a number of research cooperatives involving industry, public agencies, and educational and research organizations. The first cooperatives were in tree improvement and forest fertilization, but the approach expanded to other silvicultural and forestry matters.

Efforts in several research areas were greatly increased in the 1950s and 1960s. These included the initiation of comprehensive genetics studies in Douglas-fir, installation of numerous thinning studies, and expansion of artificial regeneration and vegetation management studies. Outputs from these programs had profound effects on silvicultural practices and on the conduct of future research.

Statistical designs were evolving rapidly, as were calculators and computer technology for handling large data sets. Statistical methods and designed experiments became routine. The advent of the electronic computer brought a revolution in data management and analysis, including the development of computer models to predict stand and tree growth and response to treatment. These became an important means of summarizing silvicultural knowledge and an important management tool. The new capabilities enabled scientists to address problems in ways that were not previously possible. They also had drawbacks in that they led some to place undue reliance on computer-generated numbers as substitutes for direct field observation and experience.

Some of the early experiments in nursery technology revealed needs for major changes in seedling density management, fertilization, and soil maintenance. Research in artificial regeneration showed that competition from native and invasive exotic plants, and herbivory by wildlife were major obstacles that needed regional attention. Agricultural chemicals adapted for selective weed control in agronomic crops were found to have major roles in controlling forest composition. By the 1970s, these early programs had developed the basis for large, well-designed experiments that have greatly strengthened the data base underlying many decisions in forest management, and provided the basis for using silvicultural strategies to accomplish a wide range of management goals.

Research: 1986 to the Present

The pressures associated with the rise of the environmental movement, the Endangered Species Act (1973), and the growing opposition of segments of an urbanized public to cutting trees and to clearcutting in particular, produced major changes in research direction in this period. Objectives and interests of private and industrial owners now often diverged from those of the public land managing agencies. The federal agencies, in particular, no longer saw commodity production as a primary objective.

Accordingly, research directed at enhancement of timber production was deemphasized by the Forest Service. The Northwest Forest Plan of 1994 placed the long-established Wind River and Cascade Head Experimental Forests in late-successional reserves, thus effectively halting any form of manipulative experimentation on these areas. Emphasis shifted to various aspects of forest ecology and to alternatives to the long-established clearcutting system that might be used to enhance wildlife habitat and scenic values.

In contrast, industrial and state ownerships remained strongly interested in practices to increase timber growth rates, an interest that was enhanced by impending timber supply shortages and the prospect of more caused by the Northwest Forest Plan's withdrawal of most Forest Service land from timber harvest. Nursery practices for producing seedlings with good storage tolerance, rapid early growth, and competitive ability emerged from a combination of research by commercial nursery interests and cooperative nursery technology programs. Research continued on aspects of production forestry such as fertilization, plantation density, and control of vegetative competition. There was a decline in in-house research by industry that was at least partially offset by the work of university-based cooperatives, which were financed mainly by industrial and state landowners.

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Chapter 5: Regeneration Systems

Natural Regeneration[1]

In the early days of Northwestern forestry, the priority problem (after fire control) was that of securing prompt and adequate regeneration. It was soon realized that most of the existing forest consisted of more-or-less even-aged stands that had originated after fire, and that Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) was a moderately intolerant species that grew best with full overhead light. There was consensus at the time within the Forest Service that natural seeding was the most economical and, in most cases, the only feasible means of regenerating harvested areas, with artificial regeneration to be used mainly on burns or other areas that were not restocking adequately.

It was initially assumed by almost everyone that the regeneration often found on logged or burned areas was from wind-borne seed produced by whatever few surviving trees were present. Hofmann conducted extensive surveys of the distribution of regeneration on old burns and logged areas, and found regeneration in locations far removed from any existing seed source (fig. 5). He concluded (Hofmann 1920, 1924) that Douglas-fir seed could survive for considerable periods in the duff, and that this was the main source of regeneration.

Figure 5—Natural regeneration in 1918 on a burn in the Wind River Valley. Natural regeneration at considerable distances from any existing seed source led Hofmann to conclude that regeneration originated principally from seed stored in the duff.

In 1918, Hoffmann installed a 1.5-mile (2.4-kilometer) transect across the Wind River Valley in a large freshly clearcut and burned area. Small plots located at intervals along this transect were periodically assessed (1919–46) for establishment of regeneration (Steele 1953), and aspect, topographic position and distance from uncut timber were recorded. Results showed that under favorable conditions, adequate regeneration could become established within 10 years for up to ¼ mile (400 meters) from uncut timber. Final results (as updated by DeBell[2] in 2003) showed that most of the area eventually restocked naturally.

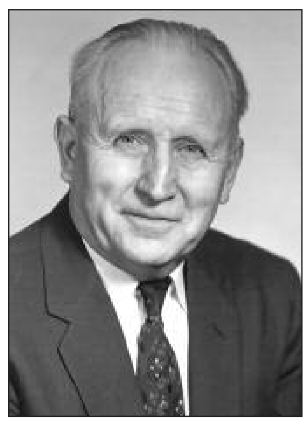


Figure 6—Leo A. Isaac joined the PNW Forest Experiment Station in 1924. He became the authority on natural regeneration and provided early impetus for tree improvement.

Hofmann left the Wind River Experiment Station soon after this transect was established, and went on to an academic career in the East.

In 1924, Leo Isaac came to Wind River, and thence to the newly formed Pacific Northwest Experiment Station (fig. 6). He devoted most of his working life to Douglas-fir silviculture, primarily research on the problems of natural

[1] By R.O. Curtis.

[2] DeBell, D.S. 2003. Historic transect across Wind River Valley. 4 p. Unpublished note. On file with R.O. Curtis.

regeneration. He became the recognized authority on the subject, and his findings are still relevant.

Hofmann's conclusion—that Douglas-fir seeds that survived for extended periods in the forest floor and germinated following cutting were the principal source of regeneration—was questioned by others who pointed to numerous large open areas that were not restocking.

Isaac conducted two experimental studies that settled the question of seedling origin. The first (Isaac 1930, Isaac and Fry 1972) consisted of experimental dispersal trials of seed released from a container attached to a kite or balloon, with varying altitudes of release and varying wind velocities. Results showed that dispersion was greater from the edge of uncut old (tall) timber than from second-growth timber, and was strongly related to wind velocity and topography. Most seed fell within 200 feet (60 meters) of the source, but substantial quantities could travel up to 1/4 mile (400 meters), and sometimes considerably more under favorable conditions. There were also differences among species, with hemlock seed traveling the farthest.

The second study (Isaac 1935) was a series of germination trials using Douglas-fir seeds stored in containers placed in soil or the duff for varying periods, under existing stands and in the open. In all cases there was negligible germination after the first year, refuting Hofmann's (1924) conclusions.

These results together with the Wind River transect observations provided the basis for Forest Service standards for maximum size of clearcut blocks.

In 1933, McArdle and Isaac briefly summarized available knowledge on natural regeneration, a subject covered in much greater detail in Isaac's later publications.

Isaac conducted extensive work on factors affecting establishment and early growth of Douglas-fir seedlings (Isaac 1938). Among the major conclusions reached were (1) high surface-soil temperatures following germination are a major cause of first-year mortality; (2) maximum temperatures are higher in the open than in shade, and higher on a fire-blackened soil surface than on an unburned surface; (3) frost is also an important cause of early mortality; (4) low soil moisture in summer is a major cause of mortality; (5) partial shading is favorable to early establishment because of its mitigation of high temperatures in summer and frost in spring; and (6) hot slash fires should be avoided where feasible, particularly on south slopes. "Dead" shade from slash and stumps was more favorable to initial establishment and early survival than shade from other vegetation, because of competition from the latter.

In 1943, Isaac published *Reproductive Habits of Douglas-Fir*, which summarized results of his and others' many years of research. It remains definitive. He recapitulated earlier results and also gave much quantitative information on other aspects of natural regeneration and associated recommendations. He estimated that about 8 pounds of seed per acre (9 kilograms per hectare) is needed for successful restocking within a reasonable time. Seed crops are sporadic, with complete failures in some years. He concluded that slash burning should be limited to that necessary for fire protection, and severe burns are best avoided as they have unfavorable effects on soils and aggravate heat mortality. Rodents are an important cause of mortality and seed predation. Partial shade is favorable to initial establishment but not to later growth. There are pronounced variations in local climate and soils within the Douglas-fir region, and these have a marked influence on behavior of regeneration and severity of brush competition. Height growth of regeneration is related to number of seed trees retained, with a noticeable slowing of growth at 11 reserve trees per acre (27 per hectare) and a pronounced difference at 20 trees per acre (49 or more per hectare). (Note: these were old-growth trees; numbers cited are not necessarily applicable to young-growth stands). Mortality of old-growth seed trees is erratic and very high, with more than half occurring in the first 5 years. If the seed-tree method is used, 6 to 10 seed trees per acre (15 to 25 per hectare) were recommended rather than the 2 per acre (5 per hectare) that had been common Forest Service practice. Clearcut blocks should be so arranged that no part of the area is more than a quarter mile (400 meters) from uncut timber.

Figure 7—William I. Stein examining 9-year-old Douglas-fir transplants grown in the Wind River Arboretum under (A) 25 percent of full sunlight and (B) in the open.

Isaac also gave extensive attention to the effect of shade on Douglas-fir survival and growth. After observing shade effects on natural regeneration, he initiated a controlled test of light requirements of Douglas-fir seedlings. Seven shade conditions were tested: in the open, under three 16- by 16-foot (4.9- by 4.9-meter) shade frames in the Wind River Arboretum, in light shade under young growth, under heavy shade of young growth, and under virgin timber. Light, medium, and heavy shade was achieved by varying the spacing of wooden slats making up the sides and tops of the shade frames. Sectional tops were removed each year before snow fell and put back on after snowmelt. Two-year-old seedlings were planted, and seeds were sown in spots in the spring of 1939. More spots were sown in fall 1939 and spring 1940. Early survival was best in light shade, but height growth of survivors was best by far in the open (Isaac 1943, 1963) (fig. 7). From these measurements and other information, he concluded that satisfactory development of Douglas-fir natural regeneration requires removal of 50 percent or more of the overwood or groupwise removals providing openings of 1 acre (0.4 hectare) or larger. Isaac (1955) gave a brief summary of these findings plus a variety of recommendations for practical application.

Although Isaac was the outstanding individual working on natural regeneration in this period, others were also active. We note a few without attempting a complete coverage.

Munger (1930) summarized the factors affecting establishment of second-growth forests.

Worthington (1953) compared natural regeneration 5 years after cutting in old-growth Douglas-fir in western Washington on six small group cuts ranging from 1.2 to 4 acres (0.47 to 1.6 hectares), and a nearby large clearcut. Stocking of Douglas-fir and hemlock was satisfactory on all group cuts, and seedlings were more vigorous than on the clearcut. The clearcut had satisfactory stocking within 500 feet (150 meters) of the timber edge, somewhat less at greater distances, with a reduced proportion of Douglas-fir at the greater distances. Slash burning apparently favored reproduction of both species.

Garman (1955) summarized results from extensive research in coastal British Columbia over a considerable period of years. This report is generally comparable to Isaac (1943), and very similar in many respects in its results and recommendations. There are some differences, possibly reflecting the more northerly location: the British Columbia work had somewhat better results with reserved seed trees, and slash burning had a generally favorable effect on Douglas-fir establishment, except on south slopes.

Lavender and others (1956) examined a series of clearcuts in western Oregon, that were less than 160 acres (65 hectares) and that ranged in time since cut from 4 to 11 years. They found little correlation between size of unit and regeneration, but some units contained scattered seed trees, and little of the area was more than 800 feet (240 meters) from uncut timber. Established regeneration was most abundant on areas that were unburned, on north aspects, with light slash and light herbaceous cover, and correspondingly, less on burned areas, south aspects, and with heavy slash or heavy herbaceous or woody plant cover.

Franklin (1963) compared seedling establishment in various strip and small patch cuttings, a seed-tree cut, and a conventional large clearcut. He found best establishment in east-west strips, small patch cuts, and in the one seed-tree cut examined. Differences in initial establishment were attributed to the effects of intermittent shading in mitigating high surface temperatures.

Prior to the late 1930s, most cutting on private land was essentially liquidation. Although often loosely referred to in popular writing as "clearcutting," this was quite different in motivation and practice from the clearcutting system long recognized in silviculture (a silvicultural system is a planned series of operations for tending, harvesting, and reproducing a stand or forest). However, if subsequent fires were excluded, defective trees and inaccessible groups of trees frequently provided an approximation to the seed-tree method.

Harvests on national forest land before the 1930s most commonly used the scattered seed tree method, with a rough standard of at least 2 seed trees left per acre (5 per hectare). Experience showed that seed trees were often lost to wind, and that seed production was often insufficient. The method was not dependable.

By 1930, the introduction of the motor truck and crawler tractor made partial cuts feasible on gentle terrain. This capability combined with the economic pressures of the Great Depression led to introduction of what was then termed "selective cutting." Logging cost studies showed that under the conditions of the time, small and low-quality logs could only be handled at a net loss, and profitability would be improved by removing only those trees that could more than pay the costs of logging and milling. Such selective cutting was simply high-grading (removal of the most valuable trees with little regard to the future), driven by the economic fact that under the depressed markets of the time, only the finest trees could be handled at a profit. Operators hoped to be able to return for the remaining trees when conditions improved.

Kirkland and Brandstrom (1936) advanced a considerably more sophisticated proposal in a detailed prospectus entitled *Selective Timber Management in the Douglas-Fir Region*. They proposed a light initial cut removing primarily defective and low-vigor trees and providing for establishment of a road system. Then, after one or more cycles of such light cutting, there would follow a gradual move into small patch cuts of the order of 2 to 10 acres (0.8 to 4.0 hectares) to obtain regeneration. Regional forester C.J. Buck and others adopted this idea as an alternative to clearcutting, and attempted to apply it in a series of sales in the mid to late 1930s.

There was considerable skepticism and controversy at the time, and apparently heated personal conflict between Buck on the one hand, and Munger and Isaac on the other. Some modifications were made in the Kirkland and Brandstrom proposal before publication, in response to objections raised by Munger. Buck in turn attempted to block publication of a critique by Munger (1938), a critique that today seems fair and restrained.

Isaac and others established a series of plots and transects in national forest sale areas, which were remeasured over a period of about 10 years. Results showed no growth response by the residual trees, heavy losses to wind and bark beetles, much logging damage, and no regeneration. The effort was judged a failure (Isaac 1956, Munger 1950, Smith 1970) and was often cited in later years as proof that under most circumstances there was no feasible alternative to clearcutting in management of Douglas-fir.

In retrospect, failure stemmed less from defects in the basic idea than in unavoidable (at the time) practical difficulties in application. These included (1) attempted application in over-mature stands of low vigor; (2) economic conditions that made removal of small, defective, and low-quality trees impractical; (3) equipment not well suited to the task; and (4) total reliance on natural regeneration. In effect, the attempt quickly degenerated into high-grading and never progressed to the small patch cuts that Kirkland and Brandstrom recognized as necessary for Douglas-fir regeneration (Curtis 1998). Munger (1938), although opposed to individual-tree selection cuts, recognized that large-scale clearcutting was not the only or necessarily the best way in all situations and specifically stated that group selection, area selection, and strip cutting should have a large place in Douglas-fir silviculture. Kirkland and Brandstrom's proposal had some similarities to several recently established experiments (chapter 12), and might well have been successful if applied in younger and more vigorous stands under more favorable economic conditions.

In the meantime, Isaac's work of the 1920s and 1930s had shown that scattered seed trees were generally an inadequate seed source and that wind dispersal of seed from uncut stands could extend up to 1,500 feet (460 meters) from old-growth stands and 1,000 feet (300 meters) from second-growth stands. These facts coupled with feasibility considerations in high-lead logging led to general adoption of the "staggered setting" system. "Staggered settings" were simply moderate-size clearcuts, often about 40 acres (16 hectares) interspersed with blocks of uncut timber that served as a seed source. Cut areas were so shaped and placed that no part of the area was more than the specified distance from the margin of the uncut stand. Slash was normally burned, primarily as a fire-protection measure but also for the presumed benefits of exposure of mineral soil and partial control of brush competition. This was the most common procedure in the 1940s and 1950s (fig. 8) and was a marked improvement over previous practices.

It was not, however, the final word. Prolonged delays or failures of regeneration occurred at times, because of the sporadic nature of Douglas-fir seed crops, damage by seed-eating rodents, and the effects of high surface temperatures on some sites. Summaries of age-class distribution from 1850 to 1940 (Teensma and others 1991) demonstrated the general recovery of Coast Range forests following fire or early cutting, all of which relied on natural regeneration. But, there were also major gaps in conifer distribution that were filled by noncommercial species when natural processes were left alone. During the 1950s, there was a general shift to planting in place of reliance on natural regeneration. It soon became standard procedure to clearcut, burn, and plant (usually Douglas-fir). This was relatively simple, not unduly expensive, and under most circumstances produced

R.O. Curtis

Figure 8—Excellent natural regeneration on a clearcut block, Cedar River Watershed, 1954.

prompt and adequate regeneration. It also removed the need to retain seed blocks and allowed use of large harvest areas, which reduced logging and management costs. The regeneration problem seemed to be solved. Everybody (almost) was happy, and many soon came to believe that this was the only way to do things. There was a corresponding loss of interest in alternative systems, other than some limited work with shelterwood on difficult-to-regenerate sites (Tesch and Mann 1991, Williamson 1973). Research and practice concentrated on fine-tuning the method of clearcutting with artificial regeneration. This concentration on a single system later came to severely hamper efforts to mitigate conflicts between timber production forestry and the environmental movement (chapter 12).

Although planting has largely replaced reliance on natural regeneration, the latter is still a factor. Natural seeding provides profuse regeneration of hemlock in some localities. Some natural fill-in occurs in many plantations and can lead to overstocking. Advance regeneration (mostly of shade-tolerant species) can sometimes be used as an important supplement to planting.

Artificial Regeneration[3]

Although natural regeneration was the first choice in the early years of the 20th century, planting and seeding were

[3] By W.I. Stein.

used to speed reforestation after large wildfires. Research on natural and artificial regeneration of Douglas-fir began and progressed concurrently in the early years. After mid-century, artificial regeneration and supporting research became dominant. From the earliest times onward, informal studies and trials in the nursery and field provided many of the improvements in reforestation practices. Key formal studies, however, provided new direction or the insight as to why some practices improved or impeded progress.

Research to support artificial regeneration efforts in the Pacific Northwest did not start from scratch. Researchers and practicing foresters alike drew guidance from a substantial body of published information, notably Toumey's manual on *Seeding and Planting* (1916 and subsequent editions). Early U.S. Forest Service publications such as Cox (1911) and Tillotson (1917a, 1917b) also made available the nationwide experiences from reforestation research and operations.

Components of artificial regeneration include seed characteristics and testing, seed and seedling production, and seeding and planting techniques. Needs and circumstances triggered uneven emphasis on these components at different times. We here consider the development of each component separately.

Seed Characteristics and Testing

Determining Seed Characteristics

Seed collection and trade in seeds of Northwest species developed long before formal regeneration research began in the Pacific Northwest. Knowledge was sought on seed quality, purity, and the intrinsic germination characteristics of each species. As domestic and international uses expanded, source identity, genetic traits, testing methods, storage, stratification, and other attributes were also investigated. The need for high-quality seed intensified when limited numbers were sown per container and when scarce genetically improved seeds were used. Despite recognized needs, no sustained program of seed research developed in the Pacific Northwest. Instead, individual researchers responded to particular interests or demands to produce, in the aggregate, a substantial array of information. Locally developed information was supplemented by results of many studies conducted in other parts of the world.

The earliest systematic methods for determining seed weight, purity, germination capacity, and germination rate of Northwest species appears attributable to Johannes Rafn (1915). He founded the Scandinavian Forest Seed Establishment in 1887 and reported on a 25-year accumulation of information gained from seed lots tested. Rafn's comments about the characteristics of Northwest species are remarkably insightful for those early times, and even include some performance comparisons of seed produced in Denmark and other European sources with seed of the same species collected in the Pacific Northwest.

The next data summary from testing commercial lots of Northwest species was reported by Toumey and Stevens in 1928. Seed weight, purity, apparent viability, and course of germination were determined systematically. Germination tests were conducted at Yale in soil and between wick-fed moist blotters. Slightly higher germination resulted from tests made in the germinator than in the soil—a result reported repeatedly in various studies over the years. Great variability was found between seed lots, as Rafn had also experienced.

Several more sets of summary statistics on seeds per pound, purity, germination percentage, and seed preparation and treatment that include Northwest species have since been compiled. To facilitate conservation plantings by the U.S. Soil Conservation Service, Swingle (1939) assembled information from 78 references in an unpublished report entitled *Seed Propagation of Trees, Shrubs, and Forbs for Conservation Plantings*. This report included much unpublished data from various Bureau of Plant Industry and Soil Conservation Service sources. Swingle's compilation and the contemporary publications by Mirov and Kraebel (1937, 1939) and Mirov (1940) are among the earliest sources to include data for shrubs and for less prominent tree species.

The *Woody-Plant Seed Manual* (USDA FS 1948) provided seed information known by 1941 on 444 species and varieties of trees and shrubs nationwide. In 1974, this manual was superseded by a greatly expanded Agriculture Handbook 450, *Seeds of Woody Plants in the United States* (Schopmeyer 1974). The handbook included a major compilation of test results from the Oregon State University Seed Testing Laboratory. A third edition is now in press and available on the Worldwide Web (http://nsl.fs.fed.us/wpsm/). Much seed information developed for some species during the lengthy intervals between compilations, and in one instance, an update based on the 1974 handbook was made and published privately (Young and Young 1992).

The statistics on seed purity, weight, germination capacity, and germination rate in the three seed manuals and their predecessors are broadly informative. They provide a general understanding of achievable purity, range in number of seeds per unit weight, likely germination rate, and total germination by species. However, these are pooled averages, based on good lots and poor lots from often undefined locations, subjected to various processing, storage, and testing methods. For species where data are limited, such summaries are the best available. But, for species where samples are abundant, averages based on best practices or developed for specific stands or populations are more useful and informative. A minor start in that direction is given in the statistics for Douglas-fir in the third edition of the seed manual.

Seed characteristics have also been studied for individual trees or for carefully defined populations or stands. The first and one of the most comprehensive studies for Douglas-fir was started at the Wind River Experiment Station in 1912 (Willis and Hofmann 1915). Cones were collected from all parts of the crown from 127 trees of different sizes and ages, growing on different soils on the west side of the Cascade Range from north-central Washington to south-central Oregon. Individual tree lots provided information on cone size, seed size, and seed quality. Data were developed for each lot as well as pooled averages for elevation, latitude, etc.—83 tables in all. Seedlings were grown from each lot, and provided the stock for the first genetic study of Douglas-fir. This single pioneering study, planned by Thornton T. Munger, provided the concepts and basic supporting data that guided cone collection, seed tree selection, and other genetic considerations for decades (discussed further in chapter 7), as well as practical knowledge on seed processing and seedling germination.

Several other early investigators contributed to knowledge of seed characteristics and testing. In California, Show (1917) determined rate and total germination for ponderosa pine, sugar pine, Jeffrey pine, and incense-cedar seeds subjected to various pretreatments. Boerker (1916) made extensive greenhouse studies of germination of many species under several levels of shade, soil moisture, soil texture, seeding depth, and seed size at Lincoln, Nebraska. These studies included Douglas-fir, Sitka spruce, and western hemlock from western Oregon and Washington. He found that Douglas-fir and ponderosa pine from west coast sources differed in germination characteristics from sources farther inland and that large seeds produced a better seedling crop than small seeds of the same lot.

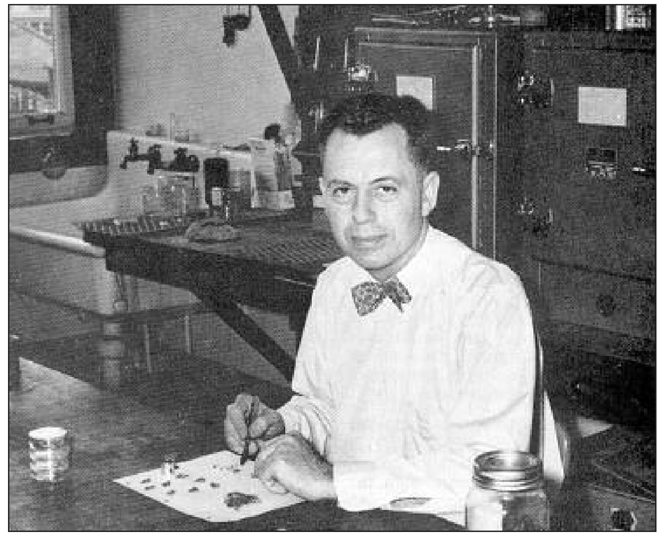
Surprisingly little was formally published on seed characteristics and seed testing of Northwest species from 1920 to 1950, even though seed use continued. Three researchers reported on the effect of heat on germination: Hofmann (1925) found that neither Douglas-fir nor western white pine seeds remained viable when subjected to high temperatures for lengthy periods, Wright (1931) demonstrated that some shrub seeds withstand high temperatures better than several conifers and grasses, and Morris (1936) determined the combined effect of moisture content with level and duration of temperature on germination of Douglas-fir and ponderosa pine. His study yielded basic information on seed characteristics as well as early guidelines for kiln-drying cones. Three publications reported on testing procedures: Heit and Eliason (1940) in New York provided information on many species, Flemion (1948) compared seed viability as determined by excised embryo and germination tests, and Allen (1941b) advocated a standard germination test for Douglas-fir. In subsequent decades, both Allen and Heit contributed repeatedly on the seed characteristics and testing of Northwest species.

Seed Testing

The first general instructions for testing seed of Northwest species were included in the bulletin *Forest Planting in the Douglas-fir Region* (Kummel and others 1944) that summarized available information gained from research and practical experience. Similar information for individual species was published in the *Woody-Plant Seed Manual* (USDA FS 1948).

Demand for information on seed characteristics and testing increased greatly as large reforestation projects, such as the Tillamook Burn, and increased harvesting accelerated the use of direct seeding and nursery stock. Common interests triggered formation of the Northwest Forest Tree Seed Committee in 1953, later titled the Western Forest Tree Seed Council (Stein 1975) and currently named the Western Forest and Range Seed Council, affiliated with the Western Forestry and Conservation Association. Improvement and standardization of forest tree seed testing was one of the committee's primary concerns. A consensus was reached eventually on some processing standards and testing techniques for Northwest tree seeds entitled *Rules for Service Testing Forest Tree Seed of the Pacific Northwest* (Bever 1959).

George S. Allen (fig. 9) was by far the most prolific individual contributor of seed information on Northwest species during the 1950s and 1960s. While at the University of British Columbia, he published on seed maturity and viability, stratification (moist prechilling), germination temperatures and moisture levels, processing effects, testing standards, and seed storage (Allen 1958, 1960, 1962b, 1962c; Allen and Bientjes 1954). Allen concluded that 25 °C (77 °F) provided the most satisfactory constant temperature for testing viability of Douglas-fir seeds. Meanwhile, at the Oregon State University (OSU) Seed Laboratory, where service testing Northwest conifers began in 1939, results of many comparison tests led to adoption of an alternating temperature regime for testing Douglas-fir–16 hours at 20 °C (68 °F) and 8 hours at 30 °C (86 °F) with light (Jensen and Noll 1959). In the early 1960s, while Director of the Weyerhaeuser Research Center at Centralia, Washington, Allen guided a collaborative test to identify the best testing method for Douglas-fir. The same tests were conducted on the same seed lots by six cooperating laboratories. These showed that the alternating temperature regime provided the most consistent results. This test procedure was recommended to the Association of Official Seed Analysts, who adopted and published rules for testing Northwest tree species in 1965. The new information was included in a booklet *Sampling and Service Testing Western Conifer Seeds* (Western Forest Tree Seed Council 1966). Because of variability among Douglas-fir lots in response to cold moist pretreatment (stratification) before germination, testing of dual samples, one prechilled and one not prechilled, continues to be part of the standard germination test.



Weyerhaeuser Archives

Figure 9—George S. Allen did extensive research on forest tree seed, served as dean of the Faculty of Forestry at the University of British Columbia, and became Director of Forestry Research for the Weyerhaeuser Company 1961–1966.

For more than half a century, the OSU Seed Laboratory has been the focal point for information on seed testing and related studies. The laboratory conducted comparison studies to identify better methods for service-testing tree seeds. To find faster alternatives to germination tests, "quick tests" focused attention on hydrogen peroxide (Ching 1959, Ching and Parker 1958), tetrazolium (TZ), and excised embryo

(Heit 1955) methods of determining seed viability. Primary development of several alternative methods occurred elsewhere, but the OSU laboratory kept abreast of improvements and made comparative tests. Laboratory Director, Ed Hardin (Hardin 1981) concluded that the hydrogen peroxide, tetrazolium, and x-ray tests, . . ."when properly performed and evaluated, can predict viability which correlates with the standard germination tests on the same sample (Douglas-fir, pines, spruce, bitterbrush), except in *Abies* species."

In recent decades, new information on seed characteristics and testing originated primarily from research with a genetic orientation, and from seed investigations in British Columbia. In Oregon, Sorensen (1980, 1996) reported that date of cone collection, seed stratification period, and sowing date affected coastal Douglas-fir germination and growth. Seed collected early was smaller and produced smaller seedlings. Sorensen and Campbell (1981, 1993) found that Douglas-fir seed orientation in the germination test can affect germination rate, and determined the genetic and environmental components affecting seed weight and seedling size. Seed research in British Columbia produced information on the interactive effects of light, temperature, and stratification on seed germination of many species (Leadem 1988, Li and others 1994). Information on seed characteristics of Northwest species continues to originate from other parts of the world.

Seed Production

Seed Source

Whenever tree seed is collected and used, questions arise regarding appropriate sources and parentage. The pioneering study of seeds and seedlings at Wind River (Willis and Hofmann 1915) produced the first information guiding use of Douglas-fir seed sources in the Pacific Northwest. Munger and Morris (1936) reported on continuing aspects of the same study. Soon afterward, broad zones or provenances were suggested by Munger and others to guide seed collection and use (Kummel and others 1944). Concentrating on the topic during a sabbatical, Isaac developed specific guidelines for choice of seed. He incorporated the available results of the Wind River study, domestic and foreign experience, and great personal knowledge to produce *Better Douglas-Fir Forests From Better Seed* (Isaac 1949). Isaac suggested tentative rules or limitations for collection and use of Douglas-fir seed and advocated seed certification and a research program to genetically improve the species.

The next step was geographic delineation of seed zones to provide guidance for seed collection and use. Preliminary statewide seed zone maps for the Pacific Northwest were produced by a committee of the Western Forest Tree Seed Council in 1966, and improved maps in 1973. The zones were based on latitude, longitude, temperature, moisture, and coniferous species composition, with seed lots identified by species within 500-foot elevation bands. Subsequent efforts to improve seed zones and seed transfer guidelines are covered in chapter 7.

Certification of species and origin of tree seed soon followed. Again, the Western Forest Tree Seed Council was the sponsoring group where the merits of certification were hotly debated and the mechanics of implementation developed. In 1966, the Northwest Forest Tree Seed Certifiers Association was founded (Hopkins 1968) and has since guided certifying efforts and standards. By late in the century, seeds, seedlings, and other reproductive materials were being certified (Schrumpf and Pfeifer 1993). The implementation of standards based on research and experience continues to have significant effects on all artificial regeneration in the Pacific Northwest.

Crop Forecasting and Stimulation

As demand for seed increased, forecasting and the evaluation of seed crops gained attention. George Allen (1941a) had an early and lifelong interest in seed-crop forecasting, particularly in flower initiation and development of seed maturity in Douglas-fir. After Allen's death, his detailed information was prepared for publication by John Owens who also drew on his own extensive experience in the monograph, *The Life History of Douglas-Fir* (Allen and Owens 1972).

Seed crops in the Pacific Northwest are cyclical or erratic. Causes of crop failures and means for better predicting seed crops have been sought occasionally by investigators (Eis 1973, Griffith 1968, Lowry 1966, Owens and others 1991, Silen 1967). Other authors documented the periodic nature of seed crops (Isaac 1943, McDonald 1992, Reukema 1982). Stimulation of seed production in ordinary young stands by thinning, fertilization, or other cultural means has received very limited study (Reukema 1982, Steinbrenner and others 1960), whereas means of stimulating seed production in tended orchards have been studied extensively in recent years (for example, Copes 1973, Ross and Currel 1989, Ross and others 1980, Wheeler and others 1985). Today most Douglas-fir seed and some of that for other conifers used in the Pacific Northwest comes from seed orchards.

Research on means to protect developing seed crops proceeded concurrently with studies aimed at crop stimulation. It was established early that insect depredation ruined many promising seed crops (Miller 1914). Subsequent information on cone and seed damage was summarized in *Insect Enemies of Western Forests* (Keen 1938), revised in 1952. Furniss and Carolin (1977) provided the most recent summarization of insect damage to cones and seeds. Topics of recent emphasis concerning insects and seeds include techniques for damage prediction, infection relationships, and physical and chemical means of reducing insect damage. Many of the research results appear in the proceedings of the second and third Cone and Seed Insects Working Party conferences held in Briancon, France, and Victoria, British Columbia, respectively, or in the Journal of Economic Entomology or Canadian Entomologist.

Collection and Processing

Among the components of artificial regeneration, seed collection, processing, and storage have received the least formal study. Following the preliminary guidelines by Willis and Hofmann (1915) and Willis (1917) for cone collection, drying, and extraction, little published information was added for several decades. Reports on planting and seeding provide evidence that collections were made and seed was used, but the technology developed mostly from practical experience rather than from research.

Willis (1917) provided the first insight on timing of collections by making weekly collections from nine Douglas-fir trees from early August until cone opening. Decades later, Finnis (1950) also made weekly collections and determined that specific gravity of Douglas-fir cones gave no guidance on initiation of seed maturity but length of embryo might. Subsequently, Allen (1958) studied periodic collections of both Douglas-fir and western hemlock and illustrated tree-to-tree variation in seed maturity. Studies and observations by Allen and Owens (1972) and others produced a good description of cone and seed maturity to guide timing of collections (Brown 1983).

Methods for after-ripening seeds in immature cones were investigated by Silen (1958), and collection time differences in Douglas-fir seed weight and germination were reported in a mass collection that spanned the entire season (Olson and Silen 1975). Seed lots collected within 10 days of seedfall yielded the best results; after-ripening in damp storage somewhat mitigated the effects of immature collection.

Winjum and Johnson (1962) seem to be the only ones who devised and tested a method for estimating the number of cones on young Douglas-firs. Cone crops of Northwest species have been rated in broad terms for many years, and those in the collection business have their individual estimation methods developed from practical experience and perhaps informal studies.

Only in the last half of the 20th century were improvements made in the time-honored ways of collecting cones by climbing the tree, felling it, or resorting to squirrel-dropped cones and caches. Power lifts of various kinds were tried and used in seed orchards and other machine-accessible locations. Successful tests were made of mechanical tree shakers under the direction of the U.S. Forest Service's Equipment Development Center in Missoula (USDA FS 1972) with later tests in an Oregon seed orchard (Copes 1985, Copes and Randall 1983). Cost-effective methods have been devised in Canada to aerially rake crowns or clip tops by helicopter (Camenzind 1990). A field guide for collecting cones in British Columbia by F.T. Portlock (1996) is the most recent and by far the most comprehensive regional guide to cone and seed collection.

Techniques for drying cones of Northwest species, extracting the seeds, and then dewinging and removing inert matter also progressed with limited research attention. In 1912, a USDA circular described the general sequence from cone storage to seed storage and discussed various options (USDA 1912). Willis and Hofmann (1915) were the first to describe cone drying and extraction techniques specific to Douglas-fir. Willis (1917) tested drying cones in a small kiln and concluded that 35 to 51 percent of the wet weight must be lost for Douglas-fir cones to fully open.

Early studies on effects of heat on seed by Wright (1931), Hofmann (1925), and Morris (1936) have already been noted under seed characteristics. The collection and extraction technology developed in the early years is described by Kummel and others (1944) and the major developments in the next 30 years by Stein and others (1974).

As seed use increased, various aspects of cone and seed processing received limited attention. Seed viability after prolonged storage in the cone was tested by Lavender (1958). Shea and Rediske (1964) and others examined the effect of fungal development in stored cones. Allen (1958) determined that commercial processing or blows simulating those that might occur in processing damaged or killed Douglas-fir seeds, altered germination, and produced weakened seedlings. He demonstrated that tree seeds are relatively fragile, hence the now-accepted dictum that cones and seeds need to be handled and processed as gently as possible. Silen and Osterhaus (1979) determined that separating seed by sizes can undesirably reduce the genetic base of a bulked lot. In recent decades, application of the flotation method of separating full and empty seeds has been applied to remove seeds infested with the seed chalcid (*Megastigmus spermotrophus* Wachtl) from Douglas-fir seed lots (Sweeny and others 1991).

Seed Storage

Seeds of Northwest conifers and some hardwoods have retained high viability for years when stored near 0 °F (-18 °C) at moisture contents of 5 to 9 percent. Again, current storage practices were arrived at largely from accumulated experience aided by some insights provided by research. Early experience with cellar storage of seeds of Northwest conifers is briefly described by Kummel and others (1944). The very rapid loss of viability by true fir seeds in room or cellar storage caused Isaac (1934) to investigate their storage at 15 °F (-9 °C). His favorable results were the first evidence that Northwest conifers store well at subfreezing temperatures. Barton (1954) added more insight on above- and below-freezing storage and packeting of Douglas-fir and western hemlock at different moisture contents. Allen (1957, 1962a) conducted storage tests at room temperature, 0 °F (-18 °C) and 32 °F (0 °C) of Douglas-fir seeds in sealed containers and when vacuum packed. Schubert (1954) showed that some conifer species and seed lots retain viability for 5 years or longer when stored at 41 °F (5 °C), but viability eventually declines to low levels. Forest nurseries and other organizations that maintain subfreezing seed storages retest lots in storage on a scheduled basis, and have extensive but unpublished records of long-term viability.

Storage of stratified (prechilled) Douglas-fir seed has recently gained attention (Malavasi and others 1985, Muller and others 1999). Stratified seeds have been re-dried and held as long as 17 months with better seedling performance reported than for seeds sown immediately after stratification.

Seedling Production

Bare-Root Seedlings

Organized production of bare-root nursery stock in the Pacific Northwest began with the establishment of the Silverton Nursery on the Snoqualmie National Forest in 1909 and the Wind River Nursery on the Gifford Pinchot (Columbia) National Forest a year later (Cameron 1979). Forest Service production was soon consolidated at Wind

River, which continued as the sole source of stock until the 1920s when four lumber companies operated small nurseries for several years. The city of Seattle built a forest nursery in 1925 to produce stock for the Cedar River Watershed, and the British Columbia Forest Service started an experimental nursery in 1926 that became the Green Timbers Forest Nursery in 1930 (Wells 1940). Federally aided nurseries were established in Pullman, Washington, Corvallis, Oregon, and later in Olympia, Washington. During the same period, small nurseries were operated by other federal agencies (Kummel and others 1944). The forest industries' first large cooperative nursery was established at Nisqually in 1942. In early years as well as in recent decades, nurseries were started and eventually closed as a result of technological advances and changing demands for nursery stock.

There is little in the published literature to indicate the role played by research during the first 50 years of nursery technology development. Because of its unique climate and soil, each nursery site poses its own set of problems and challenges. Nursery personnel tend to be innovators and experimenters. Thus, comparative trials and informal studies were a regular feature at many nurseries. Results were put to use, technology improved, and the information shared, but little was published. The first efforts at Silverton described by Cameron (1979) and the full chapter in Kumme and others (1944) probably provide the best insight into technological levels in the first 30 years. From 1948 on, nurserymen shared developing insights and experiences primarily at biennial nurserymen's meetings and in their proceedings, with *Tree Planter's Notes* a primary publication outlet.

Greatly expanded production and often less than desirable field performance triggered research studies on bare-root seedling technology from the 1950s onward. The physiology as well as the physical characteristics and condition of nursery stock received attention. Foremost early examples include (1) Edward C. Stone's studies in Berkeley on the absorption of dew (Stone and Fowells 1954) and investigations of root regeneration and lifting time on the survival of Douglas-fir, ponderosa pine, and other species (Stone and Schubert 1959, Stone and others 1962); (2) studies by Weyerhaeuser Company researchers in Centralia, Washington, on lifting date and storage of bare-root stock (Winjum 1963) and on seedling growth in controlled environments (Steinbrenner and Rediske 1964); and (3) Kenneth W. Krueger's research on food reserves and seasonal growth of Douglas-fir (Krueger and Trappe 1967), effect of packing material (Krueger 1968), seedling mineral content (Krueger 1967), and comparative photosynthesis and respiration (Krueger and Ferrell 1965, Krueger and Ruth 1969). Other early studies included effect of lifting date on survival of Douglas-fir seedlings (Lavender 1964) and the effect of mycorrhizae (Wright 1964).

Many aspects of bare-root seedling production have since been studied, involving numerous researchers and professionals at different laboratories and nurseries. Weed control, a large part of production costs in many nurseries, received particular attention. Control of weeds was first achieved by a combination of mechanical and manual means (Owston and Abrahamson 1984). For several decades, a petroleum distillate and other organic and inorganic chemicals, including fumigation for disease control, helped prevent weed emergence and early development. In the early 1970s, some promising herbicide treatments exhibited selective value in Douglas-fir bare-root operations (Newton and others 1976). As suitable herbicides became available, a large cooperative study was made involving 14 nurseries and 9 species to evaluate 6 herbicides for nursery weed control and conifer phytotoxicity (Stewart and others 1978). This screening test and subsequent followup studies formed the registration basis for use of several herbicides in Western forest nurseries.

In the early 1980s, van den Driessche (1984) published several articles involving fertilization, spacing, root wrenching, and their relation to field performance of Douglas-fir and other species grown in British Columbia nurseries. Seedling physiology was the focus of an entire technical session at the 1983 Society of American Foresters meeting in Portland (Duryea and Brown 1984). In the same year, a manual was published on the production of bare-root seedlings (Duryea and Landis 1984), and a workshop was held on evaluating seedling quality (Duryea 1985). In these publications, Northwest species are the primary but not exclusive backdrop to the technical presentations.

Research emphasis on bare-root seedling production peaked in the 1980s, but substantial new information has been produced since. Frost hardiness, involving hardening and dehardening of Douglas-fir seedlings, received attention (Schuch and others 1989a, 1989b). Widespread emphasis on seedling attributes led to the Target Seedling Symposium (Rose and others 1990). The accumulated experience from many studies at the Humboldt nursery was summarized by Jenkinson and others (1993). In recent years, the Nursery Technology Cooperative at Oregon State University has been in the forefront of supporting bare-root seedling research (Rose and others 1993, 1997).

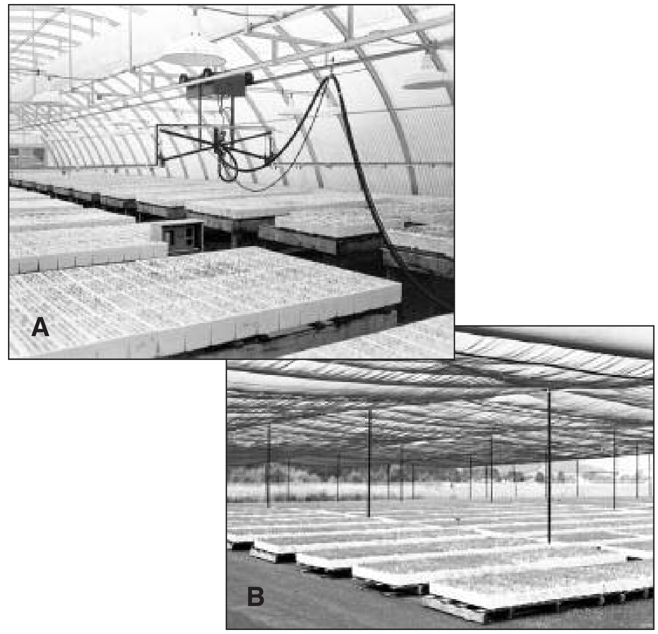


Figure 10—Container seedlings growing in a greenhouse (A) and outdoors under shade (B).

Containerized Seedlings

In the Pacific Northwest, large-scale production of containerized seedlings became a reality in the past 40 years. Unlike the technology for bare-root production that developed as much from practical experience as from research, container seedling technology developed from the start on the basis of forest and horticulture research information. Incentives for use of container stock included better control of the production environment, easier establishment and more flexibility of production facilities, and quicker production of stock not tied directly to local weather conditions (fig. 10).

Container stock was already in common use in other parts of the world before sustained interest developed in the Pacific Northwest. John Walters of the University of British Columbia stimulated local interest with his imaginative trials of bullet containers planted by gun or dropped aerially (Walters 1961, 1971). Although later trials proved seedlings developed best if removed from the container before planting, Walters' initial results stimulated sustained research on all facets of container seedlings—design and controls in the production facility, irrigation and fertilization schedules, size and shape of container, and sowing, storage, transport, and planting techniques.

The Canadian Forestry Service and British Columbia Forest Service worked cooperatively to rapidly advance and test the container seedling concept, leading to primary reliance on container stock in western Canada. In Oregon, Peyton Owston at the Pacific Northwest Research Station collaborated with the Siuslaw National Forest in investigating container production capabilities (Owston 1974, Owston and Kozlowski 1981). Private companies also investigated the technology and rapidly increased container seedling production. Information on container technology developed so rapidly in the Pacific Northwest and elsewhere that the North American Containerized Forest Tree Seedling Symposium (Tinus and others 1974) was organized to bring together and exchange available information, viewpoints, and thoughts.

Subsequent research that advanced production of containerized seedlings originated from many sources. Growing regimes are largely independent of local weather and site, and information developed in one location is often readily transferable to other regions or even other countries. Accumulated knowledge was summarized in the five-volume publication of the *Container Tree Nursery Manual* (Landis and others 1989, 1990a, 1990b, 1992, 1995). Since publication of the *Container Tree Nursery Manual*, container technology (and also bare-root technology) has expanded into the production of native shrubs, grasses, and other nontimber species (Steinfeld 1997).

The use of cuttings and other forms of vegetative propagation span facets of bare-root and container seedling technology. Plantations of black cottonwood established in 1893 (Brandstrom 1957) and 1901 (Kummel and others 1944) represent the probable first use of cuttings in the Pacific Northwest. Local research studies on poplar propagation appear to have started in the 1950s with determination of the effect of crown position and size of cutting on subsequent rooting and growth (Smith and others 1956). Subsequently, the culture and genetics of black cottonwood received much more research attention than its reproductive aspects, but occasional articles did appear (Heilman and Ekuan 1979).

In recent decades, efforts have been made to propagate Douglas-fir and other conifers by rooted cuttings (Copes 1992) and micropropagation (Hutzell and Durzan 1993), mainly to advance genetic objectives. Somatic embryogenesis, the production of plants from minute tissues, is getting substantial attention (Taber and others 1998). The results provide alternate methods to propagate conifer seedlings but have not led to commercial success.

Seedling Storage

Packing, storage, and shipment of nursery stock also evolved to meet local conditions and needs. Seedling storage was a minor consideration in the early days–most seedlings were shipped soon after lifting. Seedlings were packed for transport by railroad, wagon, and horseback. There was strong emphasis on packing seedlings with the tops toward the outside of the bundle or crate for good ventilation. Tillotson (1917a) summarized the packing techniques and variations then used at Forest Service nurseries.

Kummel and others (1944) described bundling techniques used at Wind River. Bundles were to be protected from sun and wind, and if held for more than a few days they were to be placed in a refrigerated building or cold cellar at temperatures between 35 and 40 °F (2 and 4 °C). A typical record was given of storage temperatures in the cellar at Wind River, and of moisture loss in storage from baled stock packed in tree moss or shingle tow. If transported in an open truck, bundles were to be covered by canvas, but were to be uncovered if the truck was stationary for any length of time.

The earliest research studies on seedling storage involved field comparisons of stored and nonstored stock. No growth differences were found for Douglas-fir seedlings stored in a cold room for 2 months at the Oregon Forest Nursery (Ruth 1953) or for 6 months in several tests at the Wind River Nursery (Deffenbacher and Wright 1954). These results formed the early basis for extensive and often lengthy storage of nursery stock. With improved storages and controls, temperatures were held between 33 and 35 °F (1 and 2 °C) and 90 percent or more humidity.

Introduction of polylined multiwall kraft bags or lined boxes for packaging tree seedlings (Duffield and Eide 1959) brought about major changes in storage and shipping methods. Packing in closed containers represented a major departure from the long-held tenet that seedling tops need "open air," and maintained better moisture conditions in and around seedlings.

Several decades after cold storage of conifer nursery stock in lined containers became common practice, storage of stock below freezing temperatures gained consideration. Weyerhaeuser company employees conducted the first broad-scale research on below-freezing storage of western conifer nursery stock (Gutzwiler 1978), although small trials or effects of accidental freezing may have been observed by others. Comparison trials of cold and freezer storage were accompanied by a careful look at how cold storage affects seedling physiology (Ritchie 1987). By 1986, Weyerhaeuser storage of bare-root and containerized conifer seedlings at -2 °C (28 °F) was a routine practice

(Hee 1987). Soon thereafter, guidelines for the cold storage of seedlings were issued in British Columbia, since updated (British Columbia Forest Service 2002). A recent study showed that variations in thawing regime did not affect container seedling survival or growth during two growing seasons (Rose and Haase 1997).

Over the past century, numerous improvements in the technology of growing seedlings have been accompanied by a complete change in how seedlings are stored, shipped, and handled at destination before being planted. Initially, it was common practice to lift seedlings, pack them in the field, and soon ship them; later, cellar or cold-room storage of short duration was used; then, short to lengthy storage in near freezing temperature was the norm; and now, below-freezing storage is used. Throughout, keeping seedlings cool and preventing desiccation has been emphasized. This is still the goal; the means of achieving it have become immeasurably better. Changes in shipping, made with little investigative research, amply illustrate the contrast—from open-ended bundles or crates shipped by railroad, wagon, or open truck and stored at destination in shade or even in a handy snowbank to shipment in closed, often refrigerated, trucks with storage at destination in coolers until the day of planting.

Planting and Seeding

Planting and seeding have been integral parts of reforestation efforts in the Pacific Northwest for nearly a century. In early decades, these were supplemental to natural regeneration, whereas today, artificial regeneration has the dominant role. Most early planting and seeding was done on federal land, where efforts to reforest denuded areas started soon after establishment of the national forests. Early accounts allude to experiments preceding large-scale reforestation, but little published information can be found on field comparisons of methods or techniques.

Direct Seeding

Numerous trials of broadcast seeding and spot seeding were made on the national forests starting in 1908 and concluding about 1913 (Kummel and others 1944), when early plantings proved to be more successful and reliable. A second peak of direct seeding studies and trials occurred at mid-century, triggered by the push to reforest the Tillamook Burn and meet more demanding regeneration requirements on a rapidly expanding acreage of cutovers. Again, use of direct seeding decreased as planting proved more reliable. Published accounts of the earliest seedings are fragmentary, being more in the nature of summaries of several trials, without specifics about exact location, site conditions, techniques employed, and level of data collection.

Rodent depredation of seed was a common hindrance in direct seeding, and C.P. Willis (1914) rather humorously described his futile efforts to protect seed in field and laboratory experiments. Munger (1917) briefly reported successful establishment of maritime pine (probably *Pinus pinaster* Ait.) in broadcast seeding, seed spotting, and planting trials to afforest coastal sand dunes on the Siuslaw National Forest. Reforestation bulletins by Cox (1911) and Tillotson (1917b) summarized experiences gained in early seeding and planting trials nationwide, including some specifics for the Pacific Northwest. The latter author provided a striking photo of a crew broadcast seeding in deep snow on the Siuslaw National Forest, as well as photos of reforestation efforts on several other sites. Summary accounts of forest planting by Kummel and others (1944) and of animal damage by Moore (1940) provide the most (but still limited) insight on early seeding trials in the Pacific Northwest. Apparently, Schenstrom's (1930) report on a seeding trial near Cowichan Lake in British Columbia was the first detailed published account of an experimental direct seeding.

Limited trials of direct seeding preceded the 1940s expansion as reported by Garman and Orr-Ewing (1949) for British Columbia and by Bever (1952) and Quintus (1952) for Oregon. A few trials yielded good stands of established seedlings, but most did not, with rodent depredation a primary cause of failure. These limited studies did identify problems and improve field techniques.

The ease of broadcasting rodent bait and tree seeds from the air stimulated a number of large aerial seeding trials in the Pacific Northwest around the mid-1900s. Early state of Oregon tests centered in the Cochran area that had burned repeatedly (Kallander and Berry 1953) and elsewhere in the Tillamook Burn (Woods and Bever 1952). There was also a U.S. Forest Service trial on the recent Forks Burn (Shaw 1953a) and a trial by MacMillan and Bloedel, Ltd. on an older burned area, Ash River (Allen and others 1955). Results on study areas indicated sufficient success to warrant further use of aerial seeding with suggestions for improvements in study and application techniques.

Direct seeding trials generally included concomitant evaluation of rodent populations and population control techniques. Members of the U.S. Biological Survey, notably Ned Dearborn and A.W. Moore (Moore 1940) made early studies of rodent populations and means to reduce seed depredation. Personnel of the Oregon State Board of Forestry that studied rodent control aspects of seeding trials included Edward Hooven (1958, 1966) and Denis Lavender (1952).

The accelerated use of direct seeding, especially by air, with attendant large-scale use of poison baits raised great concerns and demand for more selective baits and improved rodent control techniques or repellents. In response, the U.S. Fish and Wildlife Service established a temporary field headquarters in 1950 at the Wind River Experimental Forest, Carson, Washington, in cooperation with the Pacific Northwest (PNW) Forest and Range Experiment Station. Donald Spencer was the leader for the Fish and Wildlife Service assisted by Fred Eggert and later by Nelson Kverno, with Robert Steele and William Stein of the PNW assisting. Rodent census studies were started on local cutovers and in adjacent timber, as well as baiting and feeding trials. Meanwhile, screening of potential baits and repellents was accelerated at the Wildlife Research Laboratory in Denver. The project soon became a broad, cooperative regeneration research effort, regional or wider in scope, with many organizations and researchers participating. Seeding trials were conducted, rodent populations censused, existing poison baits evaluated, and several new candidates tested, with the eventual introduction of tetramine and then endrin applied directly on the tree seed. A series of publications (Spencer and others 1950, Spencer 1951, Spencer and Kverno 1952, 1953) reported the progress of this concentrated effort, and later publications by many authors reported different parts of the investigations (Dick and others 1958; Dimock 1957; Gashwiler 1959, 1969; Radwan and Ellis 1971; Shaw 1953b; Shea 1959; Stewart 1966).

Meanwhile, spot seeding received renewed but more limited attention. Good results were reported for spot seeding trials of ponderosa and sugar pine in southwestern Oregon. (Stein 1955b, 1957) and ponderosa and Jeffrey pine in central Oregon (Wagg 1958), though in later small-plot trials, artificial seeding in central Oregon was judged unreliable (Wagg and Hermann 1962).

The value of a nurse crop to aid establishment of newly germinated Douglas-fir seedlings also received attention. Some effects of India mustard (*Brassica juncea* (L.) Czern.), often used to quickly reestablish cover on burned areas, were evaluated, but the few studies provided only limited insights on the positive and negative aspects of a mustard nurse crop on seedlings and soil moisture levels (Chilcote 1957, McKell and Finnis 1957).

Despite reports of substantial successes for both broadcast and spot seeding, seeding use and supporting research soon declined. Planting could shorten the regeneration period and bypass many hazards to which tender young seedlings are subjected. Even though planting was more costly, the changing economics of timber production and increased restraints on rodent control increased the attractiveness of more rapid stand establishment by planting with attendant close control of genetic source and spacing.

But interest in direct seeding never completely ceased. Its status was summarized in a direct seeding symposium (Cayford 1974), and a historical perspective is provided in a summary publication on animal damage management (Black and Lawrence 1992). Studies on various aspects of direct seeding continue to appear with the most sustained effort by Thomas Sullivan in British Columbia investigating deer mouse populations and alternate foods to reduce depredation of conifer seeds (Sullivan 1979, Sullivan and Sullivan 1984).

Planting

Published results of field plantings in the early years are mostly summarized results of trials and experiences. Tillotson (1917b) described planting methods then in use on the national forests and suggested site priorities for planting or seeding Douglas-fir, noble fir, and ponderosa pine. Factors to consider in field planting were comprehensively covered by Kummel and others (1944). Included tables provide brief results of planting on good or rocky soil, survival by aspect, monthly moisture content at various soil depths, air and soil temperatures, and moisture content on denuded and brush-covered areas, and survival in brush and in the open. These limited data provide clear evidence that environmental factors were carefully considered in early planting trials.

The Douglas-Fir Heredity Study begun in 1912 was the first study that provided substantial information on growth and other long-term aspects of plantation development at different sites (Munger and Morris 1936) as well as evidence of genetic variation (see chapter 7). Munger (1943) pointed out that mortality continues in plantations after the initial losses: among 12 plantations, 1 was destroyed by fire, 2 were effectively eliminated by mountain beaver, and mortality in the other 9 averaged 35 percent 26 years after planting. Silen (1964) reported little correlation between seedling height and 50-year height. He wrote "Our experience, our techniques, and our concepts have changed in 30 years about as much as the plantations themselves." The development of these plantations continues to draw research attention.

The Wind River Arboretum, another unique field trial, was initiated by Munger in 1912 to test the suitability of trees from all parts of the world for forest plantings in Oregon and Washington. Over time, it became clear that native species far surpass introduced species in sustained vigor and growth, and that good early growth of a species is not necessarily assurance of its continued vigor and well-being (see chapter 7). Other early plantations that have yielded long-term results include a regional study of ponderosa pine races started in 1926 (Squillace and Silen 1962) and several spacing studies (see chapter 6).

The Oregon State Board of Forestry also initiated planting trials in 1912.[4] The first efforts involved introduction of new tree species for windbreaks, fence-posts, and fuel purposes in the eastern part of the state. Additional plantings were made in 1926 and 1927 using seedlings from the first crop produced at the state forest nursery in Corvallis. Some plantings of maritime pine were made at Coos Head in cooperation with the U.S. Coast Guard. Very successful plantings of Port Orford cedar were made in central Lincoln County in 1935 and 1937, with many trees measuring 14 to 16 inches in diameter in 1953. Over half a million seedlings, representing 23 species were planted in the late 1930s in the Hamlet State Experimental Forest located in Clatsop County. As with most early plantings, the results of these trials were not published; perhaps some reports exist in archives.

In an extensive research effort beginning in 1913, S.B. Show developed much information on planting stock performance of Douglas-fir, ponderosa pine, sugar pine, Jeffrey pine, incense-cedar, and white fir. Although stock was from seed of northern California sources and also compared there, much information was equally applicable to those same species in Oregon. Show compared age classes of planting stock, adaptability of species to various soils, influence of brush cover, survival in burned and unburned brush, relation of brush cover to rodent damage, and influence of slopes. After observation and testing in the nursery, seedlings of the same stock were field tested. In addition, repeated extensive observations were made on staked seedlings in numerous operational plantings. He reported that spring planting provided somewhat better survival than

[4] Lyon, H.G., Jr.; Berg, A.B. 1953. A forest history of Oregon. Salem, OR: Oregon Department of Forestry. 173 p. Unpublished manuscript. On file with: R.O. Curtis.

fall planting, and that large stock generally survived better than small stock of the same age class. Show's research constitutes the first and single largest effort to determine the stock characteristics and field capabilities of these six species. It is likely, but not documented, that his results undergirded early nursery and planting practices in the Pacific Northwest (Show 1924, 1930).

Isaac's shade study (described in "Natural Regeneration" section) showed very clearly that both planted and seeded Douglas-firs make their best growth and development in full sunlight. Strothmann (1972) repeated a modern-day version of Isaac's shade study under northern California conditions and arrived at essentially the same broad conclusions.

From the early 1950s onward, many researchers and organizations made short-term field studies with bare-root seedlings to serve a variety of objectives. One of the first was a survival and growth comparison of conifer species native to the Hemlock Experimental Forest in Gray's Harbor County, Washington (Worthington 1955). Among many other trials, plantings were made to evaluate timing effects of lifting or planting, and the influence of various nursery practices on seedling field performance (Duryea and Omi 1987, Jenkinson and others 1993, Owston and others 1986, Stein 1988, Strothmann 1971, Tanaka and others 1976, Walters and Soos 1961, Winjum 1963). Other plantings investigated the effect of seedling size and supplemental treatment on subsequent field performance (Edgren 1977, Newton and others 1993, Strothmann 1980, Van den Driessche 1992, Walters and Kozak 1965). The interaction between stock size and animal damage was also determined in a variety of studies (Hartwell and Johnson 1983, Newton and Black 1965, Schaap and DeYoe 1986, Staebler 1954). Test plantings were made to solve problems experienced on specific sites such as planting on steep slopes (Berntsen 1958), on droughty sites in southern Oregon (Hermann 1965), and to overcome severe conditions on the Dead Indian plateau (Williamson and Minore 1978). Strong interest led to a 1978 symposium on root form of planted trees in Victoria, British Columbia (Van Eerden and Kinghorn 1978).

Beginning in the late 1960s, field trials of container stock and comparisons with bare-root seedlings became part of the research effort. Early studies included a comparison of survival, growth, and root form of containerized Douglas-fir and noble fir (Owston and Stein 1978), how container and root treatments affected growth of ponderosa pine (Owston and Seidel 1978), and a regionwide effort to compare performance of bare-root and containerized seedlings (Owston 1990, Owston and Stein 1974). And, in British Columbia, the concerted effort to evaluate container seedling performance continued.

Several large retrospective investigations were also made in problem areas, generally to evaluate the success of both plantations and natural regeneration. Many cutovers were sampled by Halverson and Emmingham (1982) in the Pacific silver fir zone, by Minore and others (1982, 1984) and Stein (1981, 1986) in southern Oregon, and by Strothmann (1979) in the Klamath Mountains, to learn where regeneration succeeded or failed and identify the probable causes.

In recent decades, large-scale integrative studies spanning 5 years or more have been made to determine the combined effects of variables such as site preparation, stock type and species, protection, and competition on the survival and growth of planted trees. Perhaps the earliest of these is Strothmann's (1976) 10-year results of planting Douglas-fir by four methods in northwestern California. Michael Newton and associates, doing research in many aspects of site preparation and stock types, have reported results of two long-term studies (Newton and others 1993). In a unique retrospective effort, Richard Miller compared 35- to 38-year-old Douglas-fir stands on matched planted and naturally regenerated plots established on seven slash-burned areas in the Cascade Range (Miller and others 1993). William Stein and associates conducted three integrative studies in the Coast Range of Oregon. The first compared survival and growth of five Douglas-fir and two western hemlock stock types with and without protection

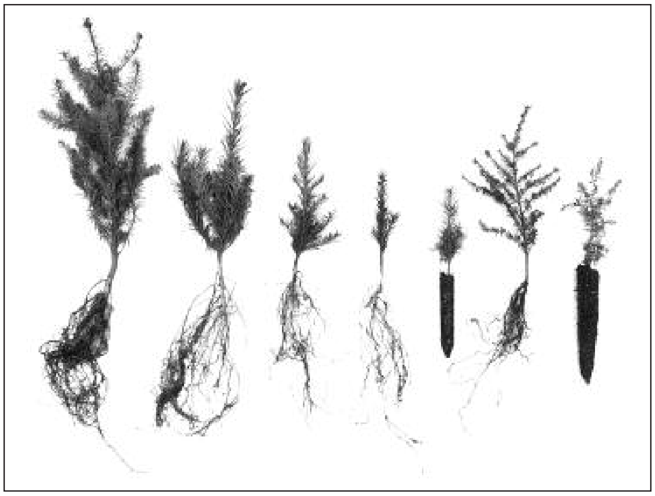


Figure 11—Stein (1990a) compared survival and growth of five Douglas-fir and two western hemlock stock types with different protection and site preparation treatments.

after four site preparation treatments (Stein 1990a) (fig. 11). The second determined growth of Douglas-fir and associated species for 10 years with and without protection after six site preparation treatments (Stein 1995), and the third, 6-year growth of Douglas-fir after manual or chemical release from competition (Stein 1999). Data from these studies and others underway have been the basis for predictive models (Knowe and Stein 1995, Knowe and others 1997).

Reforestation Evaluation

In all planting or seeding or natural reproduction there comes a time to ask if an area can be considered sufficiently stocked. Stocking can be determined by counting all qualifying trees on sample plots and then determining the average number per acre, or by determining presence or absence of one qualifying tree per plot of designated size, and then determining percentage of stocking and the distribution of stocked plots per acre. The stocked quadrat method, suggested by early researchers (Haig 1931, Lowdermilk 1927) has often been used, sometimes incorrectly. The strengths and weaknesses of the stocked quadrat and full count methods and possible alternatives have been considered and investigated over the years (Stein 1992).

Once stocking percentage or trees per acre has been determined, what do the numbers mean? The first attempt at defining stocking was produced by a subcommittee of the Western Forestry and Conservation Association (McKeever and Munger 1950). Consensus was reached by a committee that defined four classes of stocking by number of trees per acre, or by stocking percentage based on milacre (4.05-square-meter) or 4-milacre (16.2-square-meter) plots (Reynolds and others 1953). For several decades, these defined parameters for good, medium, and poor stocking were in general use, but they are seldom used today.

As state and provincial forest conservation laws were enacted, revised, and implemented, methods were prescribed for determining if minimum stocking requirements had been met. Designated standards for countable tree, sampling technique, and summary procedures differ greatly among states and provinces and change over time. Individual national forests as well as private companies set regeneration standards consistent with their management objectives. Not all evaluation methods in use are conceptually sound nor do they produce comparable data.

Unfortunately, there is at present no consensus on sampling methods and stocking standards. Therefore, broad comparisons of stocking percentage or numbers across or even within organizations involve a high risk of comparing noncompatible data. Valid comparisons are possible only when the countable tree, the sampling technique, and the summary procedures are comparable.

Overview

The literature cited and the many uncited publications of recent decades represent a vast store of knowledge and experience on artificial regeneration in the Pacific Northwest. This research has been summarized and interpreted periodically in comprehensive publications. The first of these modern summaries that merits attention is *Reforestation Practices for Conifers in California* (Schubert and Adams

1971). These authors delved deeply into reforestation publications for the entire Pacific Coast and provided good leads to many early publications.

The next summary, *Regenerating Oregon's Forests* (Cleary and others 1978), was the product of coordinated efforts involving many authors. A summary specific to the Klamath Mountains of Oregon and California was prepared by Strothmann and Roy (1984). Fire effects that relate to reforestation are covered in *Natural and Prescribed Fire in Pacific Northwest Forests* (Walstad and others 1990), and animal relationships in *Silvicultural Approaches to Animal Damage Management in Pacific Northwest Forests* (Black 1992). The output of the Forestry Intensified Research (FIR) Program was made available in many individual publications and in a comprehensive book, *Reforestation Practices in Southwestern Oregon and Northern California* (Hobbs and others 1992). Similarly, the reforestation aspects of the cooperative Coastal Oregon Productivity Enhancement Program (COPE) are included in the book *Forest and Stream Management in the Oregon Coast Range* (Hobbs and others 2002a). *Regenerating British Columbia Forests* (Lavender and others 1990) provided a guide specific for Canadian conditions.

Throughout most of the past century, reforestation efforts were aimed at achieving satisfactory results at minimum cost, and the supporting research was confined to the same objective. Initially, natural regeneration was expected to reforest denuded areas, and was only given a helping hand when very large denuded areas needed quick attention. Nature's uncertain timetable for regeneration establishment was good enough until land managers, and later forest practice regulations, set stocking goals to be achieved in specified lengths of time. Direct seeding then got much attention because it appeared to provide great flexibility at lower cost than production and planting of nursery stock. As the uncertainties and shortcomings of direct seeding surfaced and the reforestation targets became ever more pressing, primary emphasis shifted to bare-root nursery stock, and eventually also to container stock.

For far too many years, reforestation success was judged solely on the survival of an adequate number of seedlings. Eventually, both survival and actual or potential growth of seedlings was given attention. Only in recent decades, however, has maximizing both seedling survival and growth become an accepted reforestation objective. The knowledge, first reported by Show in 1930 and more recently affirmed by Van den Driessche, Newton, Stein and others, that large stock of good quality outgrows small stock in many reforestation situations is now being applied in practice. Likewise, much effort now goes to providing planted seedlings with nearly competition-free conditions. Increasing forest values, broader management objectives, and strong social pressures continue to drastically broaden the horizons and objectives of research on artificial regeneration.

The current state of nursery technology makes it possible to produce seedlings with specific physical (height, stem diameter, root density) and physiological (bud dormancy, cold-hardiness, root growth potential) characteristics as implied by the term "target seedling." The concept of a "target" seedling (Rose and others 1990) aims to provide silviculturists the seedling best suited to thrive in conditions on specific sites. This is a comprehensive, far-reaching concept that raises many challenges. The field performance of different-sized seedlings in various conditions has been determined in general terms. There is yet much to be done to learn how key characteristics, particularly the nonvisible physiological ones, govern seedling performance on specific sites.

The progress made in advancing reforestation practices through research, development, and experience is starkly illustrated by a comparison of the short, colorless planting instructions prepared by Munger (1942) versus the lengthy and colorful reforestation guide by Rose and Morgan in 2000.

Site Preparation and Control of Competing Vegetation[5]

Site preparation involves disposing of slash and unwanted vegetation and sometimes additional steps to prepare the seedbed. Control of competing vegetation may involve removing trees, shrubs, or herbaceous vegetation by various means to foster growth of the desired tree seedlings.

Site Preparation

The highest priorities in the early years of forest management were reduction of fire risk and provision for regeneration. Both objectives drove development of site preparation techniques. Requirements for meeting these needs eventually became part of forest practice regulations.

In the early years, most harvest operations were in old and often highly defective timber under economic conditions that prevented utilization of small and poor quality material. Defective logs and large branches produced slash accumulations in the hundreds of tons per acre. Because of the explosive nature of fires in heavy slash and the physical obstacles to regeneration represented by slash, early legislation required that slash be burned unless the landowner was granted permission by the state forester to do otherwise. On the steep terrain in most of the Douglas-fir Region, few alternatives were available. Snag felling within harvest units and in surrounding stands was also required in most circumstances. Broadcast burning was nearly universal (fig. 12). Burning greatly reduced short-term fire hazard, and exposed bare mineral soil for seedling establishment. Broadcast slash burns also reduced live brush and destroyed most weed seeds (Isaac 1963), although they also stimulated germination of many seeds in the sclerophyll brush areas of southwestern and central Oregon (Gratkowski 1962).

Movement of heavy logs and logging equipment caused soil disturbance in harvest of old-growth stands. Except for mass failures, soil disturbance was regarded as favorable to natural regeneration. Bare soil was an excellent medium for Douglas-fir, but also for red alder (Trappe and others 1968), and where hard-seeded species such as snowbrush *(Ceanothus velutinus* Doug. ex Hook.) had been present, the heat from slash burning stimulated seeds that had long lain dormant (Gratkowski 1962, Zavitkovski and Newton 1968). The herbaceous cover developing after either broadcast burning or clearcutting without burning was another major obstacle to seed or seedling survival and growth (Dyrness 1973, Krueger 1960, Petersen and others 1988, Yerkes 1960).

Figure 12—Until recently, broadcast burning was the usual method of fire hazard reduction and site preparation.

In general, natural regeneration was assumed to follow clearcutting with or without burning if some trees (usually culls) were left as a seed source. In many, but not all cases, this sequence produced adequate although irregular stocking of Douglas-fir, and is the source of most of the second-growth volume harvested in recent decades. It also initiated invasion by hardwoods and shrubs that could remain dominant for long periods (Newton and others 1968, Tappeiner and others 1991). Near the coast, hemlock also regenerated well after clearcutting and burning.

Considerable research was done in the 1920s and 1930s on fire danger, including rate of spread and resistance to control in slash burned vs. unburned conditions. There

[5] By M. Newton and W.I. Stein.

was concomitant work on the ecological effects of fire and vegetative succession after burning (Isaac 1940, Munger 1930) and on effects of fire on forest soils (Isaac and Hopkins 1937). This and other work was summarized by Munger and Matthews (1941), who made a variety of management recommendations. In the years 1946–52, Morris (1970) installed an extensive series of paired burned and unburned plots on national forest lands. Changes in vegetation cover and species were generally similar to those reported earlier, but the reduction in fire risk was of longer duration than reported by Munger and Matthews (1941), possibly reflecting the generally higher elevations sampled.

Although there was often little alternative to burning for site preparation and hazard reduction, it was shown that hot fires had some undesirable effects on soils and on establishment of reproduction (Isaac 1963, Isaac and Hopkins 1937). Reduction in fire danger usually lasted 15 years or less; thereafter, vegetative cover became the most important factor in fire risk, with continued low fire danger depending largely on successful establishment of conifers sufficient to shade out flammable brush species. Large freshly logged areas are much more hazardous than small units. There are large differences in fire danger and in the importance of slash burning within the region, associated with variations in climate: fire risk increases from north to south, and west to east away from the coastal fog belt.

Several variations of broadcast burning have been used in efforts to dispose of slash and vegetation with minimum damage to soil and threat of fire escape. Scheduling burns after fall rains sufficient to wet the soil or in spring became common practices. Where slash was lighter, as in harvest of young stands, only hand scalping was sometimes used during planting, and burning was only done at landings.

In coastal clearcuts, where much live residual vegetation may be interspersed with slash, "brown and burn" methods were found effective. Vegetation was desiccated with chemicals so slash and brush could be burned when surrounding vegetation was more fire resistant (Hooven and Black 1978, Hurley and Taylor 1974). Spraying with herbicides also reduced sprouting (Stein 1995). These methods provided control of slash hazards, physical access for planting, and control of competition in a single operation.

Major changes in environmental criteria for site preparation have emerged. Smoke management regulations, in particular, have had great influence on broadcast burning and development of alternatives. Rules on smoke emissions and visibility, managed through statewide determination of "burn-days," have severely curtailed burning opportunities and increased costs. Visibility regulations in wilderness areas are also major limitations on burning upwind from them. Many units cannot now be burned within the available time windows. Alternative site preparation methods became necessary even where broadcast burns would have been feasible, economical, and safe under earlier rules and would be preferred for a variety of reasons—some of which are environmental and at odds with environmental regulations that restrict use of fire. Now that most harvests are in second-growth stands, tree-length yarding and reduced amounts of large cull material have greatly simplified the slash disposal problem.

Controlled burning of piled slash is one alternative to broadcast burning to achieve both hazard reduction and site preparation (fig. 13). Piling slash to burn later under favorable conditions has long had limited use along roadsides, near structures, and other places or conditions where broadcast burning was too risky. The high costs of piling slash by hand generally limited use of piling and burning to situations where it was absolutely necessary.

Developments in mechanical site preparation equipment have made large changes in industrial site preparation. Recent adaptation of hydraulic excavators with multitined grapples has led to adoption of slash and brush piling in tall, narrow piles that can be burned in winter. Track-mounted machines can often pile brush and slash at lower cost per acre than would be encountered with broadcast burning under current regulations, even on "burn days." On steep slopes of up to 70 percent or more, machines known as "spiders" can be used; these are mounted on computer-controlled legs and can walk like an insect. Most of these machines have grapple-mounted booms that can reach 40 to 45 feet (10 to 14 meters). They can clear considerable

Figure 13—Broadcast burning has been greatly reduced in recent years. Partial disposal by piling and burning is now a common practice.

ground without moving, and when moving, they can clear a broad swath with little soil disturbance. They can maneuver around down logs left for wildlife habitat, uproot clumps of herbicide-resistant brush, and can make piles tall and narrow so that piles take up relatively little space and overheat relatively small patches of soil when burned. When covered with plastic before fall rains, piles can be burned during wet weather to minimize smoke hazards and soil damage. If unburned, planting around piles leaves little ground unplanted.

Thus, major advantages of machine piling are improved choices of planting spots, reduction of fire hazard, selectivity, and the ability to build or maintain certain kinds of wildlife habitat.

Disadvantages include safety limitations on use of tracked machines on steep ground and a relatively narrow seasonal window when soil does not pack readily. These are large, heavy machines. Despite low ground pressure, track-mounted machines may make several trips over a single track as they work, increasing the potential for soil compaction; the importance of this is currently under investigation (chapter 8). Despite these limitations, this equipment is finding wide use.

Machine piling exposes mineral soil on much of any unit. Although this is an advantage for natural regeneration or planting, it also is a favorable seedbed for weed species and red alder, all of which represent competition for the plantations that have almost universally replaced natural regeneration. Control of these competing species is therefore often necessary.

Other site preparation options include complete mechanical scarification; or mowing, chopping, crushing, shearing; or scalping slash and vegetation to prepare the seedbed. These methods have been used more to clear existing brushfields than to prepare fresh clearcuts. Site preparation methods have been well described in several comprehensive summaries (Helgerson and others 1992, Schubert and Adams 1971, Stewart 1978).

The extensive literature on use of prescribed fire and its consequences is summarized in the annotated bibliography of Loucks and others (1987) and the compendium *Natural and Prescribed Fire in Pacific Northwest Forests* (Walstad and others 1990).

Control of Competing Vegetation[6]

Major differences in composition and in species behavior exist within the Douglas-fir region, and are associated in a general way with the gradient from cool moist conditions in the northern part of the region to warmer and drier conditions in the south. Although Douglas-fir is an important component and grows reasonably well throughout most of the region, there are major differences in the associated species. Thus, the western hemlock, western redcedar, and red alder that are major components in the north diminish toward the southern part of the region, where other species such as ponderosa pine, sugar pine, incense-cedar, and white fir become important components.

[6] This section discusses research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides must be registered by appropriate state or federal agencies, or both, before they can be recommended. CAUTION: Pesticides can be injurious to humans, domestic animals, desirable plants, and fish or other wildlife—if they are not handled or applied properly. Use all herbicides selectively and carefully. Follow recommended practices for the disposal of surplus pesticides and pesticide containers.

Figure 14—Competition by undesired species often overwhelms desired conifers, as in this stand taken over by red alder.

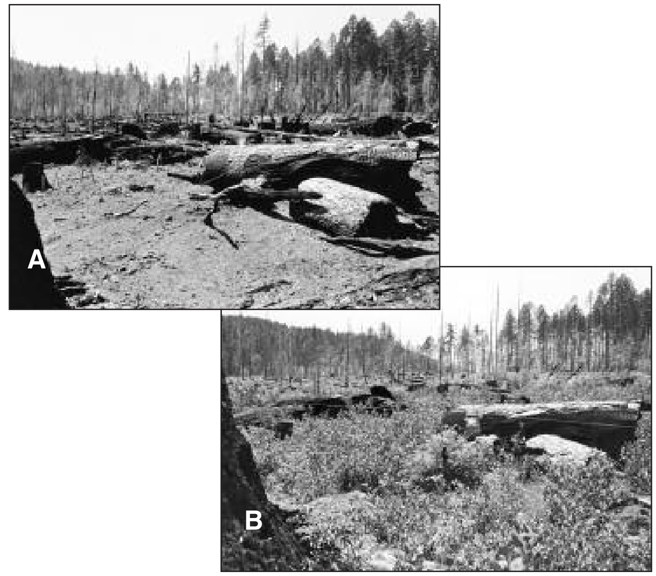


Figure 15— Broadcast burn on the Umpqua National Forest: (A) bare soil after the burn and (B) 3 years later showing 90-percent cover of snowbrush (*Ceanothus velutinus*).

There are associated differences in secondary vegetation that are important in silviculture. In the north, major woody competitors are red alder (which reproduces abundantly from seed) (fig. 14) and bigleaf maple (which sprouts abundantly). Shrub species important as competitors include salmonberry, salal, vine maple, Himalayan blackberry, scotch broom, rhododendron, and others. In the warmer and drier south, tree species important as competitors include madrone, tanoak, canyon liveoak, and chinkapin. The southern part of the region also has a number of evergreen shrubs (snowbrush, manzanita, etc.) that are adapted to summer drought and that sprout vigorously, making them severe competitors with Douglas-fir regeneration (fig. 15). There is a rapidly accumulating literature on the ecology of competing shrubs and hardwoods and their effects on conifer development (Halpern 1989, Harrington and Tappeiner 1991, Loucks and Harrington 1991, Loucks and others 1996, O'Dea and others 1995; Stein 1995, 1999; Tappeiner and others 1991, 2001).

The Tillamook Burn stimulated attention on all elements of regeneration, including site preparation and selective release treatments. In 1951, the state of Oregon issued bonds to pay for rehabilitation of the burned area, which totaled about 350,000 acres. This project involved a scale of operation beyond previous experience. Activities included —in addition to large-scale seeding and planting—removal of snags to decrease future fire risks, mechanical reduction of competition, and early testing of herbicides for control of competing vegetation arising in the years following the fires.

The Oregon Department of Forestry was given responsibility for implementing research and operational measures to reforest the Tillamook Burn. Larry Fick and Carl Smith led the rehabilitation effort in the field. The Oregon Forest Research Center was created and staffed with silviculturists, regeneration specialists, and a mammologist to evaluate efficacy of large-scale regeneration methods and the site preparation needed. The combined research and implementation of new forest practices by the Oregon Department of Forestry and Forest Research Center led to the first very-large-scale forest rehabilitation program in this country.

In 1962, the Oregon Forest Research Center became the nucleus of the Forest Research Laboratory of Oregon State University (OSU), with continuing emphasis on site preparation, regeneration, and control of vegetative competition.

Simultaneously, the PNW Forest and Range Experiment Station of the U.S. Forest Service initiated a research program to improve reforestation methods and evaluate chemicals for controlling hardwoods and shrubs. A major effort was begun in southwest Oregon in the early 1950s, stimulated by the need for rehabilitation of very large more-or-less permanent brushfields that had developed after past fires (Gratkowski 1961a). This effort, first led by Lloyd Hayes and later by William Hallin, was staffed by scientists working with both vegetation management and regeneration.

Several companies, notably Weyerhaeuser, also began investigations into combinations of thermal, mechanical, and chemical methods of site preparation and control of vegetative competition. The combined research and operational experiences from several groups yielded rapid improvement in reforestation techniques.

Vegetation management, including both site preparation and release, has a long history in Europe. There, inexpensive labor allowed dense planting that minimized influence of competing shrubs, and summer rains provided favorable moisture conditions. Vegetation treatments were generally applied with hand tools. In contrast, the Pacific Northwest's fertile residual soils and dry summers combine to provide excellent conditions for sclerophyll and deciduous shrubs and sprouting hardwoods, many of which support a frequent return of fires, especially in southwestern Oregon. The dry summers often meant that depletion of soil water by transpiration could threaten survival of natural and planted regeneration. Early studies that demonstrated the negative effect of competing vegetation include those of Dahms (1950) for manzanita and snowbrush, Ruth (1956) for salmonberry and alder, and Newton (1964) for herbaceous species. Developing vegetative competition was both a threat to regeneration and an increased fire hazard.

Safe chemical tools for managing species composition in forests are a development of the last half century, with the most rapid development between 1970 and 1990. After World War II (WWII), there was limited use of sodium arsenite for debarking pulpwood and controlling cull hardwoods in the Eastern United States. Arsenite was hazardous to wildlife and domestic animals, and never found wide use.

The beginning of effective large-scale chemical weed control followed the discovery of the phenoxyacetic acid herbicides 2,4-D and 2,4,5-T during WWII. Geoffrey Blackman in the United Kingdom discovered that these materials could remove broadleaf weeds from grain crops, and then discovered their selectivity in any grass-related crop such as corn. Within a few years, 2,4,5-T was shown to have great efficacy in controlling woody species, and to be selective in releasing certain conifers at dormant seasons. The phenoxy herbicides became the standard treatment for maintaining low cover along power line, rail, pipeline, and highway rights of way. The market was large, and these products soon became economical and well adapted in a range of products. Bovey and Young (1980) wrote a comprehensive history of this development, which had profound effects on management of forest vegetation.

Research to control brush competition on federal lands began in the 1950s, when Walter Dahms began work on controlling brush in ponderosa pine, and Robert Ruth and associates studied coastal types (Krygier and Ruth 1961 Ruth and Berntsen 1956). Dahms and James (1955) provided an early summary of existing information on chemical controls in forestry. The first aerial spraying of phenoxy herbicides in the Pacific Northwest was done in 1951 on the Waldport District of the Siuslaw National Forest (Hawkes 1953); red alder and several brush species were suppressed and conifers were relatively undamaged. Henry Gratkowski (1959, 1961b) began a long sustained research effort, primarily in southwestern Oregon (fig. 16), on brush control and methods for rehabilitation of the extensive brushfields that were a major problem.

At OSU, William Furtick did the first significant research on weeding in woody plant communities, in cooperation with G.H. Barnes. Shortly after, Virgil Freed of OSU explored modes of action, analytical techniques, and many other features, not only of phenoxy herbicides but

Figure 16—Henry Gratkowski pioneered vegetation management research in southwestern Oregon.

also of many pesticides. The first symposium on herbicides and their uses in forestry was held in 1961 by the College of Forestry (Kallander 1961).

By the end of the 1950s, a solid foundation had been established for this technology, relying mostly on 2,4,5-T. Bramble and Byrnes (1972) at Purdue University demonstrated that many similar treatments enhanced browse and cover for a variety of wildlife, and the application of selective synthetic chemicals was identified as a potential opportunity for large-scale habitat management while promoting commercial conifer crops. Scientists doing considerable field research in the Northwest on vegetation management included Gratkowski (1968, 1975, 1976, 1977, 1978), Newton (1969), Stewart (1974), Stewart and others (1978), and Dimock (1981). These and others evaluated both chemical and nonchemical control methods.

In the early 1960s, OSU research (Newton 1964) established that transpirational withdrawal of soil water from the surface layers by herbaceous cover could be substantially reduced by application of triazine herbicides. This speeded the registration of simazine and atrazine for herbaceous weed control in conifer plantations. By the late 1960s, chemical brush control methods were well enough established so there was seldom any excuse for failure of plantations because of vegetative competition. A national symposium, Herbicides and Vegetation Management in Forests, Ranges and Noncrop Lands, was held at OSU (Newton 1967). Walstad and Kuch (1987) provided a synthesis of information on forest vegetation management across the commercial forests of North America.

As practices developed, the scope of research broadened to include new chemicals, water quality, and the physiology and environmental chemistry for vegetation management chemicals. In the early 1960s, OSU's Department of Agricultural Chemistry developed a significant program to evaluate environmental aspects of vegetation management with chemicals and analytic methods for their investigation. By the late 1970s, this became a joint effort with Logan A. Norris and associates of the PNW Research Station. Oregon became a center of research activity dealing with forest chemicals. This cooperative effort contributed greatly to the efficacy and safety of site preparation and release programs. In the early 1970s, concern for public safety aspects of herbicides led to establishment of an extension toxicologist position in the Department of Agricultural Chemistry that remains active today. Newton and Dost[7] and Walstad and Dost (1984) made comprehensive summaries of available safety information for both herbicides and nonchemical methods of accomplishing the same objectives. McEwen and Stephenson (1979) compiled a comprehensive summary of the environmental consequences of such uses.

In 1981, the FIR Program and CRAFTS (now the Vegetation Management Research Cooperative, VMRC) were formed at OSU. These and other programs provided comprehensive field and laboratory investigations of vegetation management options in the Douglas-fir region (figs. 17, 18, 19). The synthesis by Hobbs and others (1992) gave detailed summaries of their findings for improving stand establishment following fires or harvesting in southwest

[7] Newton, M.; Dost, F.N. 1984. Biological and physical effects of forest vegetation management. Final report to Washington Department of Natural Resources. 423 p. Unpublished report. On file with: M. Newton, Department of Forest Science, Oregon State University, Corvallis, OR, and with Washington Department of Natural Resources, Olympia, WA.

Figure 17—Aerial spraying of appropriate herbicides can often provide cost-effective control of unwanted vegetation on large areas.

Figure 18—Small problem areas can be effectively treated by hand application of herbicides.

Figure 19—Growth acceleration of Douglas-fir after release from tanoak-Pacific madrone-manzanita competition.

Oregon and northern California. The VMRC has been the primary entity for cooperative vegetation management studies by private and government agencies, including evaluation of competition and growth concepts (Newton and Preest 1988, Rose and Rosner 2005, Rosner and Rose 2006).

The forest industry also made large advances in forest rehabilitation methods. The Weyerhauser Company began investigations of coordinated use of chemical, mechanical, and thermal methods of site preparation in the early 1960s. Their research program near the Washington coast undertook studies of manual methods and herbicides to facilitate fuel desiccation so that slash and brush could be burned when surrounding vegetation was fire resistant. The brown-and-burn approach provided control of slash hazards, physical access for planting, and control of competition in a single operation. It also reduced smoke. This proved an effective approach, which was later expanded and refined at OSU (Hooven and Black 1978, Hurley and Taylor 1974, Roberts 1975).

In the mid-1970s, the chemical industry developed several herbicide products that substantially improved vegetation management in forests. Whereas the phenoxy herbicides and atrazine had been used for selective control of shrubs, alder, and grasses since the early 1960s, these tools were neither broad enough in spectrum of activity nor free of controversy because of the use of herbicides for military purposes in the Vietnam war and the discovery of a dioxin contaminant in the military formulation. The advent of glyphosate, triclopyr, and hexazinone greatly increased managers' choices for selective control of plant species. A decade later, imazapyr, clopyralid, fluroxypyr, sulfometuron, and metsulfuron became available for forestry use and provided a highly effective set of vegetation management tools for both site preparation and release (Newton 2005).

By 1990, herbicides and technology were available for selective removal of all the major weed species in forest plantations. Perennial competitors could be controlled in advance of planting. Large, vigorous seedlings grown without significant competition had demonstrated the ability to reach 2 meters (6.6 feet) height within 2 years of planting, thus becoming more competitive and evading animal damage. This offered opportunities for shortened rotations for fiber production, and the same capability also offered opportunity to provide large trees in programs aimed at rapidly developing conditions approximating late stand development stages, and for establishment of mixed species. The International Forest Vegetation Management Conferences since 1992 have led to numerous publications outlining many options for yield enhancement, wildlife management, and other purposes that were not economically achievable a decade ago.

Research on vegetation management has increasingly become a cooperative, multiagency endeavor, with products presented in various publications. On a national basis, Stewart and others (1984) compiled an annotated bibliography on effects of competing vegetation on forest trees. A symposium in Vancouver, British Columbia, focused on several aspects of vegetation competition and responses (Hamilton and Watts 1988).

Today, among the many options for controlling vegetation, site preparation with broadcast ground applications of herbicides in understories is possible before logging, to prevent delay in replanting and the heavy use of postharvest chemical treatments.[8] The sophistication, selectivity, and safety of these tools is such that managers can favor many different arrays of vegetation concurrently with reforestation, ranging from zero competition to moderately productive populations of high-quality forage species for large ungulates, while leaving vertical structure of dead or injured shrubs and hardwoods intact for habitat purposes.

The ability to control demands on site resources has also provided opportunities for determining absolute site productivity for tree growth. Hanson (1997) and Newton and Hanson (1998) reported that juvenile-tree growth habits change markedly when plantations are established with negligible competition from herbs and shrubs. Sites identified by soil characteristics as having average productivity approach site class 1 capability or greater in their first 30 years if competition is controlled in the first few years and commercial thinning is done before live crown ratios are reduced below 45 percent.

Uses of chemicals in forests have encountered severe political obstacles that currently prevent use of herbicides on federal lands. These obstacles stem in part from attitudes engendered by opposition to the use of “Agent Orange” (a mixture of 2,4-D and 2,4,5-T) in the Vietnam war, and from demonstrated and well-publicized risks associated with certain specific insecticides (DDT, parathion), which have led to a public perception that any “chemical” is necessarily dangerous. These obstacles are exacerbated by conflicting federal laws and in-house regulations within federal agencies that give rise to procedural lawsuits that delay or prevent use of these tools (chapter 12).

Opposition of segments of the public to any use of herbicides—even where unsupported by scientific evidence—has caused most public owners to restrict or eliminate their use. Some private owners may also prefer to do so. Alternative means exist, although they are generally more expensive and often ineffective (Harrington and Parendes 1993, McDonald and Fiddler 1993). Other than prescribed burning and mechanical site preparation—discussed previously—these include controlled grazing, hand removal of brush clumps, mulching, and manual cutting.

Of these, manual cutting is the only method that has had much use. It is applicable to competing tree species

[8] Newton, M.; Cole, E.C.; Barry, J. “Waving wand” broadcast hand application of herbicides: technical basis and an example of usage. Manuscript in preparation. Department of Forest Science, Oregon State University.

Figure 20—Regrowth of brush competition (mostly *Ceanothus velutinus*) 3 years after manual cutting.

such as red alder and other hardwoods. Manual removal of tops of sprouting species has generally been ineffective in very young plantations (fig. 20), but is useful in stands at the precommercial thinning stage. Success is strongly influenced by time of cutting and physiological condition of the vegetation treated. Thus, best success with red alder was found by cutting in early summer, when food reserves were low (Belz 2003, DeBell and Turpin 1989).

Need for vegetation control can be reduced by use of large planting stock (Newton and others 1993); very large container stock preloaded with fertilizer is very competitive. Rapid early growth can enable planted trees to overtop competing vegetation, whereas broadcast fertilization increases vigor of the competition as well as that of desired conifers. Regimes that provide high stand density after crown closure and near the end of the rotation may reduce the vigor of understory shrub species (Tappeiner and others 2001).

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Chapter 6: Stand Density Control[1]

It has long been recognized in Europe that stand density has a marked effect on growth rate of individual trees, on stem quality, and at least some effect on yield per unit area. Common European practice was to establish a very large number of trees (either by natural seeding or planting), followed by early and frequent thinning to maximize volume production and stem quality while maintaining stand vigor and aiding in control of competing vegetation. Although this regime was appropriate under conditions of abundant labor and favorable markets for small material, in the United States labor was expensive and markets for small material were poor or nonexistent. These constraints raised questions about desirable stand density and feasible means of attaining it.

There are basically three possible means of controlling stand density: (1) in plantations, planting of some optimum number of seedlings (sometimes combined with treatments to control volunteer conifers); (2) early "precommercial" thinning, which removes excess small stems without generating immediate revenue; and (3) "commercial" thinning of older stands in which the stems removed are salable.

Plantation Spacing

Early Douglas-fir plantations were commonly established at close spacings, often 6 by 6 feet (1.8 by 1.8 m), still a relatively wide spacing compared to the then prevailing European practice. It was quickly realized that immediate costs could be reduced by planting fewer trees, and that this could be advantageous where early thinning would not be feasible. The uncertainties involved led to a number of experimental trials of alternative plantation spacing.

Wind River Spacing Trial

In 1925, a Douglas-fir plantation spacing test was established on the Wind River Experimental Forest. This was on a poor site (IV) that had been severely burned in two successive fires (fig. 21). Square spacings were 4, 5, 6, 8, 10, and 12 feet (1.2, 1.5, 1.8, 2.4, 3.0, and 3.7 meters). Results have been reported at intervals over the years, first by Eversole (1955) and more recently by Reukema (1979) and by Miller and others (2004). Although inferences are somewhat clouded by the lack of true randomization and replication, by soil variation that suggests that the 10- and 12-foot (3- and 3.7-meter) spacings may be on a slightly better site than others, and by planting stock of an unknown seed source, differences among spacings were and are striking and show generally consistent trends.

Figure 21—Wind River spacing test site at time of planting, 1925.

The closest spacings showed a slight advantage in height growth and much greater basal area and volume increment in the initial years. This changed markedly over time. Beginning about age 20, the wider spacings developed a marked superiority in height growth (contrary to a widely accepted expectation), and volume increment soon overtook that of the close spacings. Merchantable volume increment in the wide spacings soon far surpassed that in the close spacings, and it appears that mean annual increment in wide spacings will culminate later and at much higher levels than has already occurred in close spacings. Mortality (mostly weather-related) was severe in close spacings (fig. 22).

[1] By R.O. Curtis.

Figure 22—Wind River spacing test in 1997: (A) 12-foot (3.7-meter) spacing, (B) 4-foot (1.2-meter) spacing. Extensive windfall and snow breakage has occurred at close spacing, whereas the wide spacings have been unaffected.

These results led most owners to abandon the close spacings once commonly used in planting programs, in favor of 10-foot (3-meter) spacing if thinning was anticipated or even 12-foot (3.7-meter) spacing if thinning was not anticipated. There were correspondingly great savings in planting costs.

University of British Columbia Spacing Trials

The University of British Columbia established a series of spacing experiments in 1957 and following years on an excellent site (site I) on its research forest near Haney, British Columbia (Reukema and Smith 1987). These trials included Douglas-fir, western redcedar, and western hemlock. Unlike the Wind River trial, spacing had little effect on height growth of dominant trees on this excellent site. Spacing recommendations were generally similar, namely: 3.7 or 6.4 meters (12 or 15 feet) for lumber production, and 2.7-meter (8.9-foot) spacing to produce high yields where early thinning is economically feasible.

Other Spacing Trials

In the 1960s, additional spacing trials were established by ITT Rayonier Corp. and Pope and Talbot Corp., with generally similar results (Oliver and others 1986). There are also a number of spacing trials established by the British Columbia Ministry of Forests that date from the 1960s (for example, Omule 1988a). In the early 1980s, a much more extensive spacing trial (Bishaw and others 2003) was established on the Wind River Experimental Forest, with six replicates of six spacings for five conifer species, including Douglas-fir.

The Nelder design (Nelder 1962) is highly effective for demonstrating changes in tree growth and form over a wide array of spacings. Several industrial and public organizations have established Nelder plots with spacings ranging from 100 to 10,000 trees per acre (247 to 24,700 trees per hectare). Some have since been abandoned because of difficulties in maintenance and in statistical analysis of results, even though they provide striking visual demonstrations of spacing effects. Nevertheless, several sets exist today with some continuity of measurement. The first of these was installed by J.H.G. Smith of the University of British Columbia in 1965–66. Cole and Newton (1987) have several series of Nelder plots dating from 1978 to 1986 with both mixed species and pure stands. Hibbs and Radosevitch of Oregon State University established Nelder plots in red alder and mixed Douglas-fir–red alder at the H.J. Andrews and Cascade Head Experimental Forests. The Washington Department of Natural Resources has Nelder plots of several species in pure stands up to about 20 years of age, but most are not being maintained. In general, the Nelder experiments demonstrate clearly defined curves of diameter and crown response to crowding and identify thresholds of competitive interaction (Newton and Cole, in press). Unfortunately, the data for many of these studies are incomplete and confined to unpublished progress reports.

The Stand Management Cooperative established a new and extensive series of initial spacing trials in the 1990s, discussed later in connection with thinning.

All these trials have shown markedly greater diameter growth at wide spacings. The sharp reduction in height growth at close spacings observed in the 1925 Wind River trial has not generally been found in Douglas-fir trials on better sites. Similar effects have, however, been found with red alder (Bluhm and Hibbs 2006).

Scott and others (1998) reported on early growth of Douglas-fir plantations having a wide range of planting densities. These plantations showed a tendency for closely spaced stands to reach larger sizes (not only in height but also in diameter) in the first few years than more widely spaced plantings (Woodruff and others 2002). These observations have given rise to speculation that if early gains might be made by close spacing and preserved by a precommercial thinning program that would avoid severe competition, the practice might increase effective site index and productivity.

Aside from the effects on diameter growth, height growth, and volume growth that have been the primary objects of attention, initial spacing also affects wood quality and value (chapter 10) and development of understory vegetation.

Early Thinning Research: Pre-World War II

European experience dating from about 1800 had shown that thinning of young stands could be a beneficial practice, and thinning has been a common practice in Europe for the past two centuries. The possible benefits of thinning were recognized from the earliest days of American forestry. But thinning was long regarded as impractical under Northwest conditions because of the low or negative value of small material and the abundant supply of large high-quality mature timber. A number of pioneering and—at the time—visionary thinning studies were established in the period 1920–40. These were limited in scale and poorly designed by modern standards, and therefore are not amenable to statistical analysis. They have nonetheless provided valuable experience and insights into the effects of thinning in Douglas-fir, and the quantitative data have since been useful in construction of simulation models.

Wind River: Martha Creek and Lookout Mountain Road

Three plots established in 1920 in a 9-year-old stand at Martha Creek included a check and two thinning treatments. In 1933, three additional plots were established consisting of one check and two plots first thinned at age 22 and rethinned at age 42. Lookout Mountain contained two check plots and two plots thinned twice, in 1934 and 1953, at ages 31 and 50. Sites ranged from high IV to low III. There was considerable variation in initial stocking.

Three early reports were prepared by Meyer (1931), and by Steele (1955a, 1955b). Data summaries through age 81 are contained in an office report.[2] Lack of replication, variability in site, and stand damage prevented any clear conclusions about treatment differences, other than that thinning increased diameter increment.

Mount Walker (Olympic National Forest)

Four thinned plots and two check plots were established in 1934 and 1937 in a 60-year-old site IV Douglas-fir stand (Worthington and Isaac 1952) (fig. 23). The study was dropped after published results (Worthington 1966) indicated that response had been very slow and that thinned plots had greater diameters but less volume production than unthinned. However, the plots were remeasured in 1991 (Curtis 1995). At that time (age 117), the thinned plots appeared in good condition, with volume production not obviously different from the checks but with greater tree diameters. The most heavily thinned plot—which according

[2] Reukema, D.L. 1987. Final progress report on Wind River P.S.P.'s [permanent sample plots] 13, 14, 15, 16, 17, 18 (Martha Creek Flat) and 10, 11, 19, and 20 (Lookout Mountain Road). 60 p. On file with: Silviculture and Forest Models Team, Forestry Sciences Laboratory, 3625 93rd Ave. SW, Olympia, WA 98512.

Figure 23—Mount Walker thinning plots on a poor site (class IV), 1937: (A) unthinned stand; (B) plot 9, light thinning; (C) plot 7, heavy thinning. In 1991, plot 7 was in excellent condition with vigorous overstory trees and an understory of redcedar and hemlock. This was one of the earliest commercial thinning trials in the region.

to the establishment report had been thinned "far too heavily"—was in excellent condition and developing a layered structure with considerable redcedar and hemlock.

Schenstrom Thinning (Cowichan Lake, British Columbia)

This study consists of a check plot and five thinned plots, established in 1929 in an 18-year-old stand on an excellent site (Warrack 1979). Thinnings have been made repeatedly, although the originally planned differences in thinning treatments were more or less lost. Comparisons are clouded by lack of replication and minor site differences. There were no clear differences in volume production to age 67, although thinned plots had considerably great tree diameters than the check.

Kugel Creek (Olympic National Forest)

Four plots, three thinned and pruned, and one unthinned, were established in a 38-year-old stand in 1937. They were destroyed in the 1951 Forks Fire. Fire mortality was considerably less in thinned than in unthinned plots (Staebler 1955b). Initial growth response to thinning appeared favorable.

Summary of Early Trials

Results from these early thinning trials can be summarized as:

- Early (precommercial) thinning produced substantial increases in diameter growth.
- Thinning in older stands also increased diameter growth.
- Thinning effects on total volume production could not be well evaluated because of lack of replication and other defects, but it appears that such effects were small.
- An analysis using later data from these plots (Curtis 1995) indicates that none of the stands had reached culmination (maximum mean annual volume increment) at ages 73 and 81 (Wind River), 117 (Mount Walker), or 76 (Schenstrom).

Thinning Research: Post-World War II to the Present

Precommercial Thinning

Results from the spacing trials cited earlier, together with observations on existing young stands that were established either by natural seeding or by early planting at close spacings, made it apparent that many young stands were too dense for optimum growth. A few trials of very early thinning in dense young stands (Steele 1955a, 1955b) had shown that precommercial thinning could produce major increases in diameter growth and concentrate growth on future merchantable trees. Expected results were larger trees, merchantable volumes greater than in unthinned stands, and enhanced resistance to wind- and snow-breakage. In the pre-war period, however, such early thinning was not considered economically feasible. Views rapidly changed after WWII. Precommercial thinning became common by the 1970s.

In general, thinning was clearly beneficial, particularly in view of the prevalence of overstocked young stands. There were occasional instances of so-called "thinning shock"—temporarily reduced height growth accompanied by chlorosis—usually after heavy thinning of overstocked stands on poor sites (Harrington and Reukema 1983, Staebler 1956).

Reukema (1975) published guidelines for precommercial thinning, including procedures for estimating the desirable number of leave trees corresponding to the stand average diameter judged necessary for later commercial thinning to be feasible. He also gave estimates of the reduction in number of years to reach commercial thinning size that could be attained through precommercial thinning. Reukema and Bruce (1977) elaborated on the rationale of precommercial thinning and its expected results, concluding among other things that (1) ideally, thinning should be done when a stand is 10 to 15 feet (3.0 to 4.6 meters) tall, (2) number of trees left should be determined by average diameter at which commercial thinning is expected to be feasible and by a corresponding target basal area or relative density (Reukema 1975, Curtis 1982) that will avoid unacceptable reduction in crown development and diameter growth, and (3) the relative gain from precommercial thinning would be greatest on poor sites because of the more limited natural differentiation expected on such sites.

Commercial Thinning

The revival of economic activity after WWII, combined with the large and increasing acreage of second-growth stands and the foreseeable end of old-growth timber, stimulated interest in commercial thinning.

Soon after the war, the Pacific Northwest (PNW) Research Station undertook a number of operational-scale thinning experiments. These were conducted on industrial lands under cooperative agreements with the landowners. Three experimental forests were established for the primary purpose of thinning research:

The Hemlock Experimental Forest was established in 1949 near Hoquiam, Washington, on a tract belonging to

St. Regis Paper Company. Commercial thinning in 50-year-old western hemlock began in 1952 and ended in 1969. Treatments were high vs. low thinning on 3- and 6-year cycles. Thinning had little effect on gross volume production (change in live stand voume plus trees that died or were cut during the period of observation) but did increase diameter growth and allow salvage of mortality.

The McCleary Experimental Forest was established in 1948 on lands of the Simpson Timber Co., near McCleary, Washington. Thinning vs. no-thinning treatments were compared in a high-site 57-year-old stand. Four thinnings were made on a 5-year cycle. Results from the first three thinning periods (Reukema and Pienaar 1973) showed some gain in diameter growth, a reduction in gross growth, but a slight gain in net production because of salvage and forestalling of mortality.

The Voight Creek Experimental Forest was established in 1947 near Orting, Washington, in a stand of natural origin on a medium site, on land of St. Paul and Tacoma Lumber Co. (later St. Regis Paper Co.). Beginning at stand age 38, commercial thinnings were made on 3-, 6-, and 9-year cycles, designed to remove comparable volumes over an 18-year period. Unlike others, this followed a statistically valid randomized block design. The 21-year results (Reukema 1972) showed no effect of thinning cycle, small increases in diameter, some increase in growth percentage (annual net growth as a percentage of live volume), reduction in gross growth, and a slight increase in usable yield for thinning compared to no thinning. Three replicates were not enough to overcome the effect of within-stand variability, resulting in insensitive analyses.

Results of these studies markedly dampened interest in commercial thinning. They showed little or no short-term volume gain from commercial thinning in mid-age previously unthinned natural stands. This result, combined with financial considerations that impelled owners toward shortened rotations, led to abandonment of the experimental forests at the end of the lease period. In retrospect, this was unfortunate. Information on long-term effects of repeated thinning of older stands over extended periods would be extremely useful today in the present context of controversy and ecosystem management.

A number of other thinning studies were established in the 1950s by industrial owners. A number of firms established forestry research organizations and undertook extensive plot establishment programs. Most data remain proprietary and some have apparently been lost as a result of reorganizations and ownership changes.

Worthington and Staebler (1961) published an extensive review of information then available on commercial thinning, much of which remains pertinent.

Williamson and Price (1971) examined nine sets of thinned and unthinned plots established in 70- to 150-year-old stands over the years from 1928 through 1954. Although detailed analyses were hampered by the lack of a consistent overall study design, results appeared to show that (1) thinning reduced mortality from all causes; in particular, bark beetle mortality on thinned plots was only 40 percent of that on unthinned plots, and (2) these older stands were still making vigorous growth, although growth rates were slowly declining. Williamson (1982) reported further on one of these studies (Boundary Creek), established in a 110-year-old stand in 1952. He found little difference in gross volume growth for thinned vs. unthinned plots, but a large reduction in mortality on the thinned plots.

Allan Berg of Oregon State University established an extensive series of thinning trials in the 1950s on the Black Rock Forest near Corvallis. Although these show some striking contrasts and have had considerable use as demonstration areas, no formal report on the results has ever been published.

Reukema and Bruce (1977) synthesized knowledge of commercial thinning of Douglas-fir and hypothesized development of stands under repeated thinning regimes. They recommended that the interval between successive commercial thinnings should vary with site quality and age, and should not exceed 24 feet (7.3 meters) of height growth on site I to about 15 feet (4.6 meters) on site V. They made recommendations on residual stocking and other matters that are essentially the same as those adopted for the default regime incorporated in the DFSIM simulator (Curtis and others 1981) (chapter 9). They also concluded that relative gains in yield from commercial thinning would be greater on good sites, whereas those from precommercial thinning would be greater on poor sites.

Overall, the conclusions drawn from these trials of commercial thinning in mid-age, previously unthinned stands were that thinning such stands provided little gain in volume production, some gain in diameter growth of residual trees, and marked reductions in mortality. However, it was also apparent that most of these studies suffered from design defects and inherent variability that made comparisons quite insensitive. Most people concluded that the principal justification for thinning in such stands was reduction in mortality losses, which could be important in stands that would have to be carried for an extended period of years before final harvest. It was also realized that most of the above trials were begun in mid-rotation-age natural stands without early density control, and that these results did not necessarily represent the effects of thinning stands that had had density control from an early age.

There has been renewed interest in thinning in recent years. Reasons include improved markets for small material; emphasis on reducing the visual effects of harvests; the fact that some owners have unbalanced stand age distributions that necessitate holding some stands for considerable periods; wildlife habitat considerations; and the suspicion that results of thinnings begun comparatively late, after crown reduction has taken place, probably do not represent the potential of density management regimes begun at an early age. It was recognized that appropriate thinning could salvage or forestall most mortality losses while enhancing resistance of stands to damaging agents such as wind and snow and bark beetles. Another consideration is that maximum yield enhancement involves a commitment to relatively long rotations, with a sufficient period after the last thinning to allow stands to approach maximum density.

The marked differences between stands initially greatly overstocked compared to stands established with early spacing control, and with and without nonconiferous competition, showed the need for plantation-based thinning experiments. There are now several large-scale studies in the region that attempt to address these and related concerns.

Figure 24—George R. Staebler joined the newly established Puget Sound Research Center after WWII. He later moved to Weyerhauser Co., where he was Director of Forestry Research, 1966–79, and had a large influence on silvicultural research and industrial forestry.

The cooperative Levels-of-Growing Stock (LOGS) study in Douglas-fir is a joint study involving PNW Research Station, Washington Department of Natural Resources, Oregon State University, Weyerhaeuser Co., Canadian Forest Service, and British Columbia Ministry of Forests. This was begun in 1962 in 18- to 33-year-old stands with a wide range in site classes. Nine field installations are located in Oregon, Washington, and British Columbia. All follow a common design originated by George Staebler (fig. 24) and Richard Williamson, consisting of 27 plots containing 3 replicates of 8 thinning treatments plus a control, established at stand heights of 20 to 56 feet (fig. 25). Principal results to date are summarized by Curtis (2006) and Curtis and others (1997).

- Gross volume increment per unit area is related to growing-stock level, being highest in the densest stands. This is contrary to a belief widely held at the time the study was initiated.
- Volume increment per unit area is much more closely related to growing-stock level than is basal area increment, reflecting the effect of the rapid and continuing height growth—characteristic of Douglas-fir—on volume increment.

Figure 25—Iron Creek Levels-of-Growing-Stock (LOGS) installation in 1995, 46 years after planting. (A) untreated control; (B) treatment 7, repeated light thinning maintaining high level of growing stock; (C) treatment 2, repeated thinning to a low level of growing stock.

- Net volume increment per unit area of the unthinned control exceeded thinned stand net increment in early years, but there are indications that the relationship is reversing with advancing age and onset of competition-related mortality in the unthinned control, and that some thinning treatments will surpass the control.
- All thinning treatments markedly increased diameter increment.
- Thinning has had striking effects on understory composition and development.

The Stand Management Cooperative (SMC) studies include several series of spacing and thinning plots, some with superimposed pruning and fertilization, that extend over the full range of geographic and site conditions in the region. This is a large-scale cooperative effort established in 1985 and headquartered at the University of Washington (Chappell and others 1987). Its formation stemmed from the realization that existing data (1) did not provide adequate coverage of young stands with early density control, (2) did not provide coverage of a range of initial plantation spacings, and (3) were often of poor quality and inconsistent in standards. The effort required to develop a database adequate to support comprehensive modeling efforts was clearly beyond the capabilities of any one organization. The SMC involves most of the larger landowners in the region and uses standardized design and measurement procedures. Results to date are necessarily limited because of the short period of observation, but SMC data are rapidly becoming the major source of information on young stand development of Douglas-fir and western hemlock. Treatments include very early thinning to a wide range of initial densities, with later thinning to specified relative density targets; planting to a very wide range of initial densities; and superimposed fertilization and pruning treatments on subsets of the plots.

A number of **recently established studies** are concerned primarily with habitat development or integrated management for multiple objectives. In the 1990s, the U.S.

Forest Service and the Bureau of Land Management de-emphasized timber production in favor of efforts to promote development of stands with characteristics and structure thought to be favorable for wildlife and fisheries, including specifically endangered species such as the northern spotted owl (*Strix occidentalis caurina*). Research was also undertaken by PNW Research Station and the universities on regimes to develop old-growth-like structures, on alternatives to clearcutting that might be used to reduce conflicts and make timber production forestry more acceptable to the public, and on biodiversity and management of previously neglected species. These efforts do not fall readily into the conventional categories of regeneration systems and intermediate operations such as thinning and fertilization. Therefore we discuss them in a later section (chapter 12) under the heading "Silviculture for Multiple Objectives."

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Chapter 7: Genetics and Tree Improvement[1]

Selection for traits useful to man has been practiced for millennia in domestic animals and agricultural crops. Modern urbanized society would not be possible without the increased agricultural production provided by such improvements. Yet, the application of similar techniques to forest trees is relatively recent.

The first areas of investigation (based on European experience) were the possibility that exotic species might be superior to native species, and the probability that seed collected in one portion of the range of a species might not be suitable for other parts of the range. Later research focused on selection, testing, breeding, and seed production in tree improvement programs begun in the 1950s and 1960s.

Exotic Species

A number of exotic forest tree species had been introduced to Europe in the 19th century, with outstanding results in some cases. Exotics were and are valuable supplements to the relatively few native species available to European foresters. It was therefore natural for the early foresters to ask whether exotics might have potential in this country.

A worldwide search for fast-growing exotic trees appropriate for the Northwest began in 1912 at the Wind River Nursery and became known as the Wind River Arboretum. This work was begun and supervised for many years by T.T. Munger, and directed onsite in the early years by J.V. Hofmann, E.L. Kolbe, Leo Isaac, R.W. Steele, and in recent decades by R.R. Silen. A number of progress reports were issued over this period, and a comprehensive and probably final report was published by Silen and Olson (1992). Results demonstrated the superiority of native species over exotics. Introduced broadleaved species failed. Among conifers, there was a general similarity of growth among species from a given forest region. Although some introduced conifers appeared promising in the early years, over the 70-year period of observation, they gradually declined or succumbed to climatic and disease factors. None of the introduced conifers equaled either the growth or survival of native species. The study strikingly illustrated how inferences from early short-term results can be widely different from long-term forest research findings. The slow failure of initially promising exotics is the best example.

Provenance Trials, Geographic Variation, and Seed Zones

One of the first major long-term studies undertaken in the Northwest was a comparison of geographical races of Douglas-fir and its hereditary characteristics begun in 1912 and referred to as the Douglas-fir Heredity Study. The initial impetus was provided by Raphael Zon as a result of his knowledge of earlier European provenance investigations. Seed was collected from 120 parent trees of various ages and descriptions, at 13 widely scattered locations in western Oregon and Washington. Elevations ranged from 100 to 3,850 feet (30 to 1170 meters). Seedlings were grown in the Wind River nursery and then planted in six widely separated localities at elevations ranging from 1,000 to 4,600 feet (300 to 1400 meters). Survival and growth were recorded over many years. Physical characteristics of the parent tree (age, size, rot, competition) had little or no relation to performance of progeny (Hofmann 1921, Morris 1934, Munger and Morris 1936). Major differences among seed sources were found in survival, growth rate, and sensitivity to differences in local climate. Trees of several sources did not do well at sites differing markedly in climate from their source, indicating the importance of using seed adapted to local growing conditions. Some sources, on the other hand, made good growth over a wide range of elevations, showing inherently superior growth to other sources of similar climate and site. Collections from the Darrington and Granite Falls areas in Washington and Palmer in Oregon consistently out-performed others and showed a wide climatic tolerance. A widespread freeze in

[1] By J.B. St. Clair.

November 1955, however, damaged many of the larger trees from these and other provenances, illustrating the importance rare climatic events have to adaptation (Silen 1963).

While researchers were learning from the early Douglas-fir provenance trial, foresters were also gaining experience from operational plantations established in the first half of the 20th century. Stock of unknown seed origin was often used in early plantations. Many plantations failed or grew poorly, which was attributed to the use of seed sources not adapted to the conditions of the planting site. Isaac (1949) reviewed several examples of poor growth and survival of Douglas-fir plantations of known seed sources in which seed sources from lower elevations had poor growth and survival at higher elevations. Experiences with plantation failures as well as the results from the early Douglas-fir provenance trial led to the first delineation of seed collection zones (Kummel and others 1944) and seed collection guidelines (Isaac 1949). A system to certify the stand origin of forest tree seed was established by the mid 1960s, and in 1966, seed zone maps for Washington and Oregon were published (slightly revised in 1973).

Revised tree seed zone maps and guidelines were published in 1996 for western Oregon (Randall 1996) and in 2002 for Washington (Randall and Berrang 2002). The earlier seed zone maps were based on climatic, vegetative, and topographic information, and a single map was used for all species. Research over the past three decades, however, showed that tree species differ greatly in their distribution and patterns of genetic variation. Thus, the revised maps are specific for each species, and are less restrictive, particularly for latitudinal transfers within elevation bands.

Dissatisfaction with the sampling design of the early provenance trial and concern that seed movement guidelines were too restrictive led to the establishment of a second provenance trial of Douglas-fir in 1959 (Ching and Bever 1960). Seed was collected from 16 provenances across a wide latitudinal range from southern Oregon to northern Vancouver Island. Seedlings from all 16 provenances were planted at 16 sites in the same area of the seed collections plus a site near the northern California coast. Various problems reduced the number of study sites available for analysis to 10. Results for 10 sites at age 20 and the 5 fastest growing sites at age 25 showed that tree growth did not differ greatly among provinces, except that trees from the southern Oregon provenance were much smaller (Ching and Hinz 1978, White and Ching 1985). The provenance x site interaction was nonsignificant; trees from local provenances did not appear to grow best. White and Ching (1985), however, questioned the experimental precision of the study. Furthermore, the study sites presented in the 1985 publication represented a limited range of environments, and not enough detail is presented in the 1978 publication to determine the effect of moving seeds from low-elevation sources to the more challenging, high-elevation sites.

Provenance trials are expensive and long term by their nature. Because of practical and economic limitations on the size of tests, only a limited number of seed sources can be evaluated. Thus, provenance trial results have tended to be largely descriptive of geographic variation, rather than predictive. In the 1970s, Robert Campbell pioneered the development and use of predictive models of geographic variation to provide seed transfer guidelines and evaluate seed and breeding zones. In 1974, he published two papers (Campbell 1974a, 1974b) that predicted the seedling adaptive traits (bud burst or survival) in response to moving provenances between locations, from information on the environment of the seed source and the environment of the plantation site. Environments were characterized by surrogates such as elevation, latitude, or distance to the ocean. Later, he developed a methodology to estimate transfer risks as a function of the differences between sites and the genetic variation within sites (Campbell 1979, 1986). Short-term nursery tests facilitated the development of predictive models by allowing the evaluation of many seed sources from a large range of environments. Over the next couple of decades, Campbell and Frank Sorensen used this methodology to explore geographic variation and provide seed transfer guidelines for a number of conifer species in the Northwest (for example, Campbell 1986, 1991;

Campbell and Sorenson 1978; Campbell and Sugano 1987, 1989, 1993; Sorensen 1992, 1994).

Tree Improvement Programs in Douglas-Fir

Tree breeding work in the United States began with the establishment of the Institute of Forest Genetics in 1925 in Placerville, California (which emphasized work on pines), and the work of E.J. Schreiner, A.B. Stout, and R.H. McKee with poplars in the Northeast, begun in 1924. However, active tree-improvement work in Douglas-fir—beyond early efforts to determine appropriate seed sources—did not get underway until the 1950s.

In 1949, Leo Isaac made a strong case for an active tree-improvement program for Douglas-fir in his book *Better Douglas-fir Forests From Better Seed* (Isaac 1949). Two meetings were held in 1953 to review existing work in forest genetics and consider proposals to develop formal programs in basic biology and forest tree improvement. Participation included public agencies, the universities, the Industrial Forestry Association, and a number of the major industrial firms. This was a period when the major landowners were shifting from natural regeneration to planting, and they had a keen interest in securing well-adapted seed and in possible improvements through applied genetics. Consequently, there was wide support in both public and industrial organizations for tree improvement programs.

In 1954, the Industrial Forestry Association initiated a program of Douglas-fir tree improvement. John Duffield was hired to oversee the program. Superior parents were selected in wild stands, and the first clonal seed orchards were established by grafting. Also in 1954, a formal research project in forest genetics and tree improvement was founded at the Pacific Northwest (PNW) Research Station, directed by Roy Silen. In February 1955, a meeting, chaired by Leo Isaac, discussed the need for an organization of research workers in tree improvement, to be called the Northwest Forest Genetics Association (later renamed the Western Forest Genetics Association). This association was formally established in June of 1955, with Duffield as the first chairman. Over the next several decades, extensive research was carried out on the genetics of Douglas-fir and the practical problems of producing improved seed. This involved the PNW Research Station, universities in Oregon, Washington, and British Columbia, the British Columbia Forest Service, the Industrial Forestry Association, and major industrial landowners (Silen 1978).

As seed orchards became common in the early 1960s, a serious problem developed—many seed orchard trees died because of graft incompatibility. The result was a gradual disenchantment with Douglas-fir tree improvement. In 1966, Roy Silen proposed an alternative strategy to get around the problem of graft incompatibility. Silen advocated progeny testing of a large number of wind-pollinated families from less intensively selected roadside trees, followed by the establishment of seedling seed orchards using full-sib crosses of the parents in the field (Silen 1966, Silen and Wanek 1986, Silen and Wheat 1979). As information on the parents became available from progeny tests, the seedling seed orchards were incrementally rogued (culled) to provide greater genetic gains. Another feature of the program was small breeding zones to ensure that all planting stock would be locally adapted. This approach came to be called the "progressive" tree improvement program. Under the leadership of Roy Silen and Joe Wheat (of the Industrial Forestry Association), many local forest landowners, public and private, adopted the progressive approach as they came together to cooperate in tree improvement activities across their interlocking ownerships. The Douglas-Fir Heredity Study was often used by Silen to show the potential of tree improvement by pointing out the large differences among family row plots.

Grafted seed orchards, however, offer advantages over seedling seed orchards. Grafting mature branches from select trees onto rootstock provides seed production at younger ages and with greater certainty of the genetic worth of the parents. Don Copes of the PNW Research Station addressed problems in Douglas-fir seed orchards, in particular the problem of graft incompatibility. Copes developed a system to test for graft incompatibility and began a

Figure 26—Research to overcome graft incompatibility made high-genetic-gain seed orchards possible. Most Douglas-fir seed now comes from seed orchards, such as the Oregon Department of Forestry's J.E. Schroeder Seed Orchard, near St. Paul, Oregon.

Figure 27—Controlled pollination of Douglas-fir in a seed orchard. Tree breeding for wood production has become an important component of modern forest management.

breeding program to produce graft-compatible rootstock (Copes 1999, Silen and Copes 1972). As a result, the problem of graft incompatibility has mostly been solved, and most seed orchards today are clonal seed orchards from grafted parents (figs. 26, 27).

From 1967 to 1985, cooperative tree improvement programs using the progressive tree improvement approach were jointly guided by the PNW Research Station and the Industrial Forestry Association. After the retirement of Roy Silen and Joe Wheat, the leadership of the cooperative programs was passed in 1985 to an umbrella organization called the Northwest Tree Improvement Cooperative directed by Jess Daniels, hired as a contractor. In April 2000, the organization moved to Oregon State University and Keith Jayawickrama was hired as director.

By the 1980s, 125 Douglas-fir breeding programs involving over 30,000 parents tested in nearly 1,000 test plantations were in existence in western Oregon, Washington, and British Columbia (Johnson 2000b, Lipow and others 2003). Most of these programs are part of the Northwest Tree Improvement Cooperative, but several organizations have separate programs with their own approaches and history. Second-generation programs were initiated by Weyerhaeuser and the British Columbia Ministry of Forests in the 1980s and by the Northwest Tree Improvement Cooperative in the 1990s. Research at the PNW Research Station influenced breeding zone size, seed orchard layout, mating designs, and field-testing procedures (Johnson 1998). As a result, the second-generation breeding plan for the Northwest Tree Improvement Cooperative is very different from the first-generation strategy (Johnson 1998).

As reforestation relied less on natural regeneration and tree improvement programs began to advance, forest geneticists and forest managers recognized a responsibility to conserve the rich genetic heritage within our native forests (Ledig 1986, Namkoong 1984, Silen and Doig 1976). Efforts to evaluate and ensure the conservation of forest genetic resources were begun in the 1990s in western Oregon and Washington (Wheeler and others 1995) and in British Columbia (Yanchuk and Lester 1996). Conservation of genetic resources may be achieved by perpetuating native stands and processes at their original location, called in situ conservation, or by collecting and preserving the genetic material at some other location, called ex situ conservation. Yanchuk and Lester (1996) and Lipow and others (2004) considered population sizes of conifer species in in situ protected areas such as wilderness areas, national parks, and other reserves, and determined that genetic diversity is well represented.

Tree improvement populations may be considered a form of ex situ conservation. Yanchuk (2001) and Johnson and others (2001) reviewed the role of applied tree breeding programs in genetic conservation, including discussions of numbers of parents needed. They concluded that breeding populations are appropriately structured and populations are sufficiently large to ensure conservation of genetic diversity. The large number of first-generation Douglas-fir selections in the Northwest represents an important ex situ genetic resource (Lipow and others, 2003).

Today most Douglas-fir seed used in planting programs is produced in seed orchards from selected parents. This has clearly increased productivity in early stand development. There is uncertainty as to the magnitude of the increase in stand productivity over a rotation, because of the limited period of observation of operationally planted stands. Also, most genetic tests use mixed-family plantings, which involve uncertainties in genotype interactions and do not lend themselves to expansion to a stand basis (St. Clair 1993). Genetic gain trials are being established to compare realized gains in stand productivity under operational conditions with gains predicted from mixed-family genetic tests (St. Clair and others 2004).

Tree Improvement Programs in Other Species

Although Douglas-fir has received the most attention, a substantial amount of similar work has been done in western hemlock under the Northwest Tree Improvement Cooperative and the British Columbia Ministry of Forests (Daniels 1995). The USDA Forest Service and Bureau of Land Management have long had special breeding programs for western white pine and sugar pine, aimed at producing blister-rust-resistant planting stock (Johnson 2000a). The British Columbia Ministry of Forests has breeding programs for western white pine, western redcedar, Alaskan yellow-cedar, and Sitka spruce. Public agencies have tree improvement programs for ponderosa pine on the east side of the Cascades.

The University of Washington (Reinhard Stettler) and Washington State University (Paul Heilman) were active in developing hybrid poplars (usually crosses of the native black cottonwood with various other *Populus* species), and in recent years a number of industrial owners have undertaken extensive poplar planting programs.

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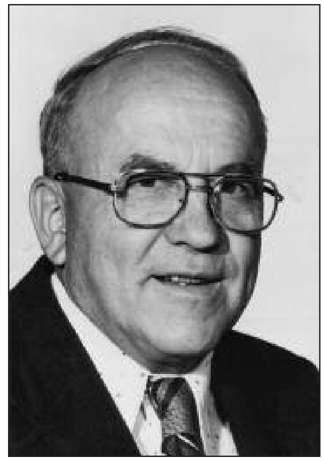
Chapter 8: Forest Fertilization and Long-Term Productivity[1]

Forest Fertilization

Forest soils in the Douglas-fir region have developed on a wide range of rock type, topography, and local climate. These soils differ greatly in their moisture-holding capacity, nutrient content, and physical environment for tree roots. Growth of forests can be limited when one or more nutrient elements are lacking or in low supply. Nutrient deficiencies can arise from deficiencies in the native soil and from losses caused by natural events (wildfire, erosion, landslides) and human activities (timber harvest, site preparation, prescribed fire).

Research on forest nutrition and use of commercial fertilizers to correct nutrient deficiencies in the forests of the Pacific Northwest began at the University of Washington in the late 1940s. The early research was conducted by Professors Stanley Gessel (fig. 28) and Richard Walker. Using field trials and greenhouse studies with potted seedlings, they demonstrated that tree growth on soils derived from glacial deposits was strongly stimulated by adding nitrogen (N) fertilizers (Gessel and Walker 1956, Gessel and others 1965). Subsequently, other organizations undertook research on tree nutrition and forest fertilization; these included Weyerhaeuser Company (Steinbrenner 1968), Crown Zellerbach Corporation (Strand and Austin 1966), the Pacific Northwest (PNW) Research Station (Robert Tarrant and Richard Miller), and Oregon State University (Chester Youngberg and Denis Lavender). By the mid-1960s, research results encouraged commercial application of fertilizers to industrial forests.

Recognizing the need for a wider geographical sampling and further quantification of stand response to fertilization, industry representatives to the Northwest Forest Soils Council (an informal organization that promotes use of soils information) proposed council sponsorship of a forest fertilization cooperative. A technical committee drafted a research design and plan of action that was accepted by the council. In 1969, the College of Forestry of the



University of Washington College of Forest Resources

Figure 28—Stanley P. Gessel pioneered research on fertilization of Northwestern forests. He was largely responsible for establishment of the Regional Forest Nutrition Research Program, now part of the Stand Management Cooperative.

University of Washington agreed to administer this cooperative, which became the Regional Forest Nutrition Research Program (RFNRP). Stanley Gessel was the first director, and Kenneth Turnbull (also of University of Washington) provided much technical guidance. The initial technical advisory committee to RFNRP included Gene Steinbrenner (Weyerhaeuser Co.), Robert Strand (Crown Zellerbach Corp.), Denis Lavender (Oregon State University), and Richard Miller (PNW Research Station).

The primary goal of the RFNRP was comprehensive testing and quantification of stand-level response to urea fertilizer in both Douglas-fir and western hemlock stands in western Washington and Oregon. The initial series of field trials in 1969–70 (Phase I) tested fertilization in fully stocked, unthinned stands, 10 to 50 years of age, usually of natural origin. Douglas-fir stands were stratified into six "provinces" or physiographic-climatic areas; western hemlock stands were located in three of these provinces. Within each province, stands were selected to represent four age classes and four site quality classes (I through IV). Six 0.1-acre (0.04-hectare) plots were installed in each stand, and three fertilizer treatments, (0, 200, or 400 pounds of N per acre (0, 224, 448 kilograms of N per hectare), were randomly assigned. A new series (phase II) was installed in

[1] By R.E. Miller.

1971–72 with the same treatments, except that fertilization was preceded by thinning that removed about 40 percent of the initial basal area.

Similar field trials were installed by the British Columbia Forest Service. Results from the U.S. and B.C. trials were reported by Miller and others (1986) and Chappell and others (1992). Practical experience in forest fertilization was shared at workshops (Anderson and others 1970, British Columbia Ministry of Forests 1991, Chappell and others 1992, Gessel 1965, Gessel and others 1979, and Miller and others 1986). About 70 percent of Douglas-fir stands in the U.S. and B.C. trials increased growth after fertilization. The average volume increase was about 300 cubic feet per acre (21 cubic meters per hectare) in the first 6 years after fertilization.

Trial results provided direct evidence on the average and range of response of Douglas-fir and western hemlock stands in western Oregon, Washington, and British Columbia (figs. 29, 30), and stimulated a marked increase in the area of operational fertilization of forest lands (Peterson and Hazard 1990, Turnbull and Peterson 1976).

Operational fertilization has been primarily of Douglas-fir stands with urea applied by helicopter at rates of about 200 pounds of N per acre (225 kilograms of N per hectare). Because response of hemlock stands in field trials has been erratic (especially in coastal areas), operational fertilization of hemlock has been much more limited. Both naturally regenerated and planted stands have been operationally fertilized. Decisions to fertilize plantations as well as naturally regenerated stands are largely based on results of RFNRP's phase III (1975) and phase IV (1980) installations in plantations of both species.

Figure 29—Relatively small and infrequent applications of nitrogen fertilizer often produce striking responses in tree vigor and stand development, particularly on poor sites: (A) typical diameter growth response, and (B) an extreme example of response shown by paired stem sections from trees on adjacent fertilized and unfertilized plots on a very poor site.

In 1991 the RFNRP was merged with the Stand Management Cooperative (SMC), which is also administered by the University of Washington. The SMC continues to install and maintain field trials involving density control, fertilization, and other stand management activities such as pruning.

Fertilization of established stands within a decade of harvest has usually been considered most attractive, because costs of fertilization can soon be recovered (Miller and Fight 1979). Potential financial gains from fertilization of Douglas-fir appear especially favorable when N is applied to thinned stands, because response is captured by trees that are expected to reach merchantable size and be harvested.

Research on effects of other forms of N fertilizer has been minor. Largely because of its higher concentration,

Figure 30—Research in forest fertilization led to extensive operational fertilization, usually with urea applied by helicopter.

urea (46 percent N) is preferred to other sources of N, such as ammonium nitrate (Miller and Harrington 1979, Miller and Tarrant 1983, Radwan and others 1984). Use of biuret (Miller and others 1988, 1996a) and concentrated N solutions applied as a foliar spray were also investigated (Miller 1981; Miller and others 1991, 1996a).

Some research has been conducted with elements such as phosphorus (P), potassium (K), and sulfur (S) as reported by Gessel and others (1981), Radwan and Shumway (1985), and Chappell and Miller (1988). Periodically, the effectiveness of combined or balanced fertilizers (N, P, K, S) has been investigated for improving survival and growth of recently planted seedlings or established stands. More recently, application of these other nutrients is being tested as a possible means for reducing damage from Swiss needle cast. There has also been some use of controlled-release fertilizers in containerized seedlings.

To optimize financial returns from operational fertilization, however, reliable site- or stand-specific prescriptions are needed. Which sites or stands should be targeted for fertilization? How can nutrient deficiencies be diagnosed to predict response to fertilization? Some answers have been reported (Carter and others 1992, Miller and others 1989a, Peterson and others 1984, Radwan and Shumway 1984, Shumway and Olson 1992).

With diagnostic techniques commonly used in agriculture, both foliar and soil analyses have been investigated as means for predicting nutrient inadequacies for optimum tree growth at individual sites. Except for identifying sites where one or more nutrients are in extreme shortage for tree growth, neither diagnostic tool has yet proved practical for operational use in the Pacific Northwest. Practicality has been limited by (1) costs of sampling soil or foliage of established stands (beyond the seedling stage), (2) great spatial and temporal variation in soil and tree foliage that necessitates careful and extensive sampling to obtain representative samples for analysis, (3) unreliable analytical results, and (4) the time and effort required to establish the biological linkage between observed growth and soil or foliar nutrient analyses.

There has also been considerable work on biological N fixation, mainly by red alder, in an effort to develop alternatives to commercial fertilizers for correcting N deficiencies, as discussed in chapter 11 in connection with alder silviculture. A number of other species also fix limited amounts of N (Gordon and others 1979).

Long-Term Site Productivity

An important and frequently raised concern is whether intensive management of forests—especially the short-rotation plantation management now common on industrial lands—may eventually degrade productivity of the land. Potential causes of site degradation include frequent losses of nutrients and organic matter in harvested wood or slash disposal, and cumulative effects of soil compaction and displacement by heavy logging equipment. This is a difficult concern to address, because of the need for controlled experimentation and long-term comparisons, and for sampling the wide range of soils and climates that exist in forested areas. We assume a priori that nutrient-poor sites, generally those of low site index, are most likely to be degraded by nutrient withdrawals and topsoil displacement.

Maintaining site productivity is a fundamental objective for all actively managed forest land, regardless of rotation length. For federal forests, the National Forest Management Act of 1976 directed the Forest Service to monitor its activities and to prevent "significant and permanent loss of land productivity." Subsequently, "land productivity" was defined as a soil's capacity to support plant growth as indicated by some index of biomass accumulation, and a "significant change" in productivity was defined as the minimal level of reduced growth detectable by current technology. Based on science available at the time, standards were set that defined "detrimental" soil disturbance (USDA Forest Service 1987). Hundreds of harvested sites have been monitored to determine if the areal extent of detrimental soil disturbance exceed standards.

Early research on aspects of long-term productivity (soil compaction and displacement) in the Northwest was reviewed in several symposia (Froehlich and McNabb 1984, Miller and others 1989b, Powers and others 2005). Some studies have been inconclusive because of short observation periods and existence of uncontrollable factors. Other studies have shown impacts ranging from no effect to some loss of productivity. There is little or no direct evidence of a general decline in productivity; on the contrary, because of improved silvicultural practices, many new stands are more productive than the stands they replaced. Yet, the period of observation is relatively short and comparisons may be confounded with climatic changes, site differences, changes in site preparation and planting practices, control of competition, and changes in genetic composition of the forest.

Nutrients and potential soil organic matter can also be lost or redistributed by prescribed burning or slash piling. Minore (1986) reported average 5-year height of several thousand Douglas-fir seedlings at each of 57 progeny test plantations in southwest Oregon. Slash was treated by broadcast burning at 23 plantations, and by piling and burning at 34 plantations. He concluded that site quality probably is reduced by piling and burning.

In 1986, Miller and Bigley (1990) reestablished paired plots at 44 of the original locations established by Morris (1970) in 1946–53. The paired plots at each location in the Cascade Range in western Washington and Oregon were adjacent and similar in size, slope, aspect, and logging disturbance. One plot in each pair was in that portion of the unit that could be protected from fire when slash was burned. The plots were not planted. No consistent difference in site index was found between burned vs. nonburned plots. Average volume on burned plots was similar to nonburned, although total numbers and volumes of Douglas-fir and hardwoods were greater on burned plots. At seven locations, a third plot was established in planted areas immediately adjacent to the broadcast burned and naturally regenerated plots (Miller and others 1993). At stand age 40 years, the planted plots on slash-burned areas averaged about 40 percent greater volume than naturally regenerated plots on slash-burned areas. Thus, differences among plots could be attributed to differences in species composition associated with fire and in type of regeneration rather than to changes in soil productivity.

Heavy equipment used to harvest trees or prepare sites for regeneration physically impacts soil, causing some degree of both displacement and compaction. Several studies evaluated the effects of skid trails on soil characteristics and tree growth in the Pacific Northwest. Steinbrenner and Gessel (1955) reported poor survival and growth of artificially seeded Douglas-fir on compacted and displaced soil of skid trails at nine clearcuts in western Washington. Froehlich (1979) also reported reduced height of Douglas-fir seedlings several years after planting on skid trails in western Oregon. In general, soil characteristics are altered by machine traffic, but tree growth may be decreased, unaffected, or increased depending on soil properties, degree of disturbance, and climatic stress (Heninger and others 2002; Miller and others 1996b, 2004).

In the early to mid 1990s, several long-term studies on soil productivity were initiated. These included the U.S.-Canadian Long-Term Soil Productivity (LTSP) study led by

Robert Powers of the Pacific Southwest Research Station (Powers and others 2005). Emphasis in that study is on the effects of changes in soil porosity, organic matter, and vegetative growth under controlled levels of organic matter retention and soil compaction (Holcomb 1996, Powers 2002). For example, in northern California, variability in tree growth responses to soil compaction was attributed to differences in soil texture and soil water retention after compaction (Gomez and others 2002). First results from this very large nationwide study (Powers 2002, Powers and others 2005) show that response to compaction differed widely among soils; effects on tree and total vegetative productivity could be positive or negative.

Pacific Northwest Research Station researchers initially declined to participate in the LTSP study because their limited resources were already committed to the Long-Term Ecosystem Productivity Program (LTEP). The LTEP is a long-term cooperative effort led by PNW Research Station and involves three national forests and the Washington Department of Natural Resources. The primary objectives are to determine the long-term effects of species composition and removal of organic matter on net primary production, although there are a variety of subsidiary objectives (Amaranthus and others 1995).

In 1999, the Fall River Long-Term Site Productivity study was started on a very productive site in western Washington (Terry and others 2001). This is a large study that was jointly designed and conducted by Weyerhaeuser Company, PNW Research Station, and the University of Washington. Objectives include evaluation of effects of organic matter removal, vegetation control, fertilization, compaction, and tillage on nutrient budgets, soil physical properties, microenvironment, vegetation development, soil and plant processes, and tree growth. Because some of the 12 treatments at Fall River are similar to those of the LTSP study (Powers and others 2005), Fall River is considered an affiliate installation. Early results indicate that soil moisture (and associated N availability) is the factor most closely tied to tree growth at this location, and that vegetation control has the greatest influence on soil moisture (Roberts and others 2005). Compaction of the silt loam soil increased available soil moisture and tree size at age 3 (Ares and others 2005). Amounts of logging debris retained on site influenced soil microclimate; the effects on tree growth were positive or negative depending on growing season precipitation. Although retention of large amounts of organic materials (and N) resulted in greater leaching of N, the amount lost was small relative to the total N pool (Strahm and others 2005).

The Fall River productivity research was expanded in 2002 with the establishment of two additional installations with different soils and climate. Although fewer organic matter removal and mitigative treatments are being tested at the Shelton and Mollala installations than at Fall River, vegetation control is also a main experimental factor. Each treatment combination is replicated four times. The expanded study involves the PNW Northwest Research Station, Port Blakely Tree Farms LP, Green Diamond Resource Company (formerly Simpson Resources), Oregon State University, and the University of Washington. Both the Fall River study and the expanded studies include research on soil and plant processes to understand and evaluate the mechanisms of tree response on large, replicated plots.

Although numerous studies have evaluated the effects of disturbance on soil properties, relatively few have evaluated tree growth response or the mechanisms of response to disturbance. It is incorrect to assume that if soil characteristics are altered or degraded, tree growth will necessarily also be reduced (Miller and Anderson 2002). Additional research is needed to identify situations where native or previously impacted soil is more or less at risk, and to prescribe appropriate stand and soil management practices for specific sites.

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Chapter 9: Growth and Yield/Mensuration[1]

Site index curves are the most widely used basis for productivity classifications. Volume tables and yield tables are not usually thought of as part of silviculture. But, volume tables and yield tables are essential tools in any quantitative silvicultural work. Yield tables (which evolved into the tree and stand simulators of today) portray the expected development of trees and stands over time. In their modern form of tree and stand simulators, they provide an important management planning tool, a quantitative summary of existing knowledge of average stand performance expected under specific silvicultural treatment regimes, and a means of exploring possible silvicultural alternatives.

The following discussion is far from a complete treatment of the subject, but lists several of the more important publications. Much more complete lists are given in Hann and Ritters (1982), Hann (1994, 1995), and Ritchie (1999).

Volume Tables and Equations

Munger (1911) produced a Douglas-fir volume table, which may well have been the first volume table published in the Pacific Northwest. In subsequent years, various authors developed a large number of similar tables for most of the economically important species. These tables were not always consistent in sampling and measurement standard or in methodology. Most of the earlier tables were developed by graphical methods, although regression methods were coming into use and eventually replaced the graphical methods. Prior to the electronic computer, relationships were generally expressed in tabular form.

With the advent of the electronic computer, a number of more elaborate, more flexible and more consistent systems of volume equations and taper equations were developed by regression methods, and soon replaced the older tabular formats. Hann (1994) provided an extensive bibliography.

Site Index Estimates

Site productivity is commonly expressed in terms of site index, the mean height attained by a specified stand component, such as dominant and codominant trees or a fixed number of largest trees per unit area, at a specified reference age. For many years, the height curves used to classify site quality were derived from tree measurements on temporary plots, by using the guide curve procedure or variations thereof. This procedure consisted of fitting an average curve of heights over ages and then drawing in a family of proportional curves, indexed by height at the reference age.

In the 1960s, stem analyses were widely adopted as a basis for height growth and site index curves, and largely replaced the older guide curve method. King (1966) provided the most widely used curves for Douglas-fir, although others later developed slightly different curves for specific subregions (Curtis and others 1974, Hann and Scrivani 1987). There has been some use of directly measured periodic height growth as a basis for such curves (Bruce 1981), a procedure that will probably become more common with the accumulation of high-quality repeated measurements from long-term plots.

It is often observed that site index estimates in plantations are higher than those from the prior stand or from adjacent stands, which presumably reflects some combination of effects of site preparation, vegetation control, genetic selection, and density differences. Flewelling and others (2001) prepared height-age curves specifically for planted stands, with adjustments for density. Newton and Hanson (1998) showed that early weed competition has considerable effects on early height growth and hence on site index estimates.

Normal Yield Tables

Methodology

A yield table portrays the expected development of a forest stand on land of specified site quality (usually expressed by

[1] By R.O. Curtis.

site index) under a specified form of management. In the early years of North American forestry, plot data showing actual growth rates of stands observed over time did not exist. Therefore, normal yield tables derived from temporary plots were adopted as an interim expedient. These tables were constructed from one-time plot measurements in subjectively selected stands judged to be well-stocked and representing a range of sites and ages.

Normal yield tables provided much useful information, but had major limitations: (1) they could be used only for even-aged stands, (2) their use to project development of stands of other than those of "normal" stocking was dependent on questionable assumptions about the "approach to normality" over time of initially over- or understocked stands, (3) they were not well suited to mixed-species stands, (4) they rested on the untestable assumption that the means of subjectively selected "well-stocked" plots at successive ages represented points on a true growth curve, and (5) they could not provide estimates of the response of stands to silvicultural treatments such as thinning. Despite these limitations, there was no viable predictive alternative under the conditions of the period.

Early yield tables and associated volume tables had been prepared for various species around the country, and a need quickly became apparent for some degree of standardization in data collection and analysis procedures. A committee including representatives of the Forest Service, Society of American Foresters, and Association of State Foresters was established for the purpose, under the chairmanship of E.N. Munns. Their report (Munns 1926) established the general procedures that were followed throughout the normal-yield-table era, which extended into the 1960s.

Douglas-Fir Yield

Beginning in 1909, some temporary tree and plot measurements had been collected and a few permanent growth plots established. The data formed the basis for yield estimates by Munger (1911) and Hanzlik (1914). This work was continued by Richard McArdle (fig. 31) beginning in 1925, who was joined by Walter H. Meyer in 1926. An extensive field program provided measurements from 2,052 temporary plots on 261 tracts, extending over a wide range of ages and site qualities. These provided the basis for USDA Technical Bulletin 201 (McArdle and Meyer 1930), which was reissued in 1949 and again in 1961 with minor changes and a supplement by Donald Bruce based on stand average diameters.

Figure 31—Richard E. McArdle (with Walter H. Meyer) developed the widely used Bulletin 201, *The Yield of Douglas-Fir in the Pacific Northwest* (1930). This publication and subsequent 1949 and 1961 revisions had a large influence on development of Douglas-fir forestry.

Bulletin 201 was a landmark publication (Curtis and Marshall 2004), which had a huge influence on Douglas-fir forestry and development of the Douglas-fir region. It documented beyond question the enormous productivity of Douglas-fir forests, and provided a basis for quantitative management planning. It was a major factor in convincing landowners to shift from forest liquidation to long-term management. Despite the limitations common to all normal yield tables, it was the bible of Douglas-fir managers until the advent of computer simulation models. The authors went on to distinguished careers; McArdle eventually became Chief of the Forest Service, and Meyer was for many years Professor of Forest Management at Yale.

An offshoot of the Douglas-fir yield table work was a set of average height-diameter curves classified by site and age, derived from the same data (Meyer 1936). The original intent was that these could be used for stand volume calculations in the absence of adequate direct measurements of height. In retrospect, their primary importance was that they clearly showed the progressive shift in position of height/diameter curves over time, which arises from age-related differences in the trends of diameter growth and height growth. (Similar shifts can arise from stand treatments such as thinning.) This is a point which even today is often ignored, although its neglect introduces substantial biases in volume growth computations.

Sitka Spruce and Western Hemlock Yields

Meyer (1937) carried out a similar study in spruce-hemlock stands in coastal Oregon and Washington and southeast Alaska.

In later use, some discrepancies appeared, attributed to differences in the Alaska data versus those from Washington and Oregon, associated difficulties with the site index curves, and to inclusion of some stands with a high proportion of spruce. Barnes (1962) subsequently produced revised tables from the same data, which provided separate estimates for Alaska and for Washington-Oregon, and excluded stands with less than 40 percent basal area in hemlock.

Red Alder Yield

Prior to the 1960s, red alder was generally regarded as a weed species and was the subject of little research. It had some limited commercial value (Johnson and others 1926) but was of interest mostly as an undesired competitor in conifer stands.

Worthington and others (1960) developed the first reasonably complete normal yield tables for red alder, in response to expanding markets and increased interest in the species. Subsequent developments in site evaluation and yield estimation were reviewed by Hibbs and others (1994) and Bluhm and Hibbs (2006).

Adjustment of Normal Yield Tables

Many existing natural stands differed from the "normal" stocking shown in normal yield tables, and there were a number of attempts at adjusting the yield tables to predict development of nonnormal stands.

Meyer (1928) described the permanent plots established in Douglas-fir up to that date, and discussed their relationships to the new normal yield tables then in preparation (McArdle and Meyer 1930) and the observed "approach to normality" in stocking over time. He (Meyer 1933) made a further analysis of "approach to normality" in various measures on permanent plots and found consistent though weak relationships, apparently tending toward values somewhat higher than those in the normal yield table.

Johnson (1955) subsequently examined the question with a subset of the same plots, and concluded that the simplest assumption for predicting future yields from the normal yield table was that understocked stands would make approximately the same volume growth as that indicated by the normal yield table.

Meyer (1930) compared various measures of stocking in an extensive sample of typical Douglas-fir forests. He concluded that basal area was preferable to number of trees as a measure of stocking, and that typical forest stocking was about 80 percent of normal yield table values. For comparable site index, highest volumes were found on approximately 40-percent slopes and on north and east aspects.

In the period 1972-80, Charles Chambers and Franklin Wilson of the Washington Department of Natural Resources produced a series of empirical yield tables for second-growth stands of Douglas-fir, western hemlock, and red alder. These were derived directly from the Department's inventory data (for example, Chambers 1980), without reference to normal yield tables.

Managed-Stand Yield Estimates

After World War II (WWII), markets for relatively small material developed and interest increased in active management of the large areas of second-growth stands that had developed on previously logged lands. Some means was needed to estimate yields to be expected under alternative treatment regimes, not only in volume but also in size and value of trees produced. The old normal yield tables were clearly too inflexible to describe stand development for such stands or to provide a basis for selection of thinning regimes.

Permanent-Plot Data

The earliest permanent (that is, remeasured) plot data in the region date from 1910. The early data were primarily from unmanaged young-growth stands, plus some from a very few experiments with early density control or later thinning. After WWII, there was a great expansion in permanent-plot work in thinning and—somewhat later—in fertilization trials and other aspects of forestry research. To facilitate consistency and comparability in such studies, Staebler and others (1954) provided a guide to recommended computational procedures for summarizing permanent-plot data.

Early Managed-Stand Yield Estimates

Heiberg and Haddock (1955) and Warrack (1959) developed yield forecasts for managed stands based on very small amounts of Pacific Northwest data combined with European data and experience.

Staebler (1955a) combined McArdle and others' (1949) net yield estimates with mortality estimates (Staebler 1953) derived from the permanent plots established earlier, to produce estimates of gross production for well-stocked Douglas-fir stands. Staebler (1960) then used these gross-yield estimates to produce estimates of yields of thinned stands, on the basis of the then-current belief that gross increment was independent of stocking over a considerable range of stocking and that moderate thinning would merely redistribute a constant increment. Although soon superseded by subsequent work, the procedure is of interest as the first attempt in the region at a quantitative model of development of thinned stands based on actual Pacific Northwest data. It was a precursor of the computerized growth and yield models that soon followed.

Simulation Models

There was a revolution in growth and yield research in the period 1960–2000, and the distinction between such research and quantitative silvicultural research became increasingly blurred. Two factors were primarily responsible: (1) the advent of the electronic computer and its evolution into the desktop personal computer, which placed computing power at the immediate disposal of all scientists; and (2) the gradual accumulation of massive quantities of growth data from remeasured plots, including data from designed silvicultural experiments that included a range of stand treatments. Another more recent advance has been the introduction of electronic devices that greatly improve the accuracy and lower the cost of height measurements.

The electronic computer made it possible to address the massive problems of record keeping, data storage and retrieval, editing, summarization, and analysis involved in working with very large data sets. By the early 1960s, these problems had exceeded the capabilities of traditional methods of computation. The computer also made possible the construction of simulation models representing the growth of trees and stands and their responses to treatment. Yields were now often estimated by numerical integration of growth functions, providing consistent estimates of growth rates and yields. Such models provide estimates of stand development and physical and economic yield under a variety of possible management regimes.

Simulation models have commonly been classified as stand-average models, individual-tree distance-independent models (which predict stand growth as the summation of individual tree predictions without reference to tree position), and individual-tree distance-dependent models (which make predictions for individual trees based on spatial position relative to other trees). Another common classification is empirical vs. process models, where the first is derived from fitting functions to observed tree or stand growth data and the second purports to represent underlying biological growth processes. In actuality, most existing models of practical usefulness are "mixed" models, which incorporate some features of both "empirical" and "process" models (Bruce 1990).

There is also a class of so-called "gap" models, popular with some ecologists interested in long-term successional trends. In general, these have not so far produced the detailed stand information needed by forest managers, and they are not discussed here.

There is an extensive literature on stand simulation models, which we necessarily skip over very lightly. Ritchie (1999) provided a good overall discussion of available simulators.

Possibly the first computer growth-and-yield simulation model in the Pacific Northwest was that of Newnham and Smith (1964), although this never had wide use. The first publicly available simulator to have any substantial use in the U.S. portion of the Douglas-fir region was DFIT (Bruce and others 1977), although there was some proprietary simulator development at about the same time by Jim Lin of Crown Zellerbach Corp. and possibly by others.

In the mid-1970s, Pacific Northwest (PNW) Research Station and Weyerhaeuser Co. undertook a joint effort to develop yield estimates for managed stands. This was a cooperative effort using data contributed by a number of public and private organizations. The result was DFSIM (Curtis and others 1981), a stand-average type simulator that had wide use in the Douglas-fir region.

The DFSIM development effort had a number of important offshoots. Massive quality control and consistency problems were found in much existing data. Also, despite their quantity, the existing data were extremely weak for young stands with early density control, and for stands with both fertilization and thinning, repeated thinning, or extreme thinning treatments. These concerns led to recommendations by a committee of Western Forestry and Conservation Association for standardization of plot measurements and record formats, and to a widely used publication on research plot procedures (Curtis 1983, Curtis and Marshall 2005). These concerns also provided motivation for establishment of the Stand Management Cooperative in 1985 (chapter 6).

Although stand-average models are relatively simple and work well for reasonably uniform stands predominantly of a single species, they are not capable of representing highly irregular stands or complex species mixtures. Therefore, most recent work has been directed at individual-tree-based simulators. Currently, the most important of these are TASS in Canada, and ORGANON and PROGNOSIS (and its FVS [Forest Vegetation Simulator] descendants) in the United States.

The PROGNOSIS model is an individual-tree distance-independent simulator originally developed by Stage and his associates (Stage 1973) for the northern Rocky Mountains. It has since been modified into many regional variants under the name of FVS. These are now the simulators most widely used by the Forest Service in the West. TASS (Goudie and others 2005, Mitchell 1975) has likewise gone through an extensive and continuing evolution, and is now the principal simulator used in British Columbia. ORGANON (another individual-tree distance-independent model), originally developed by Hann and his associates for southwest Oregon, has since been modified (Hann and others 1997) to extend its range of applicability by including data from other parts of the region. A number of proprietary models have also been developed. Monserud (2003) provided an up-to-date summary.

Recent supplementary developments include LMS (Landscape Management System) (McCarter and others 1998), which applies stand simulation projections based on FVS or ORGANON to landscape scales, and visualization software (McGaughey 1998).

These tree and stand simulators are not merely a means of updating existing inventories. They also represent the best available syntheses of existing silvicultural and biological data on stand development and response to silvicultural treatments.

Many current young stands differ markedly in origin and early history from the unmanaged stands and early plantations that supplied the data for presently available simulators. More intensive site preparation practices, improved nursery and planting practices, early control of competing vegetation, and use of selected genetic stock have produced young stands that commonly show early growth considerably exceeding past experience on similar sites. Thus, stand simulation is tracking a moving target as forest practices change.

Model Limitations

Current models have a number of shortcomings:

- Basic data are lacking for managed Douglas-fir stands grown to advanced ages (more than about 80 years), for a number of important secondary species, and for unconventional management regimes (for example, green tree retention or repeated thinning over extended periods). There are few stands available older than 30 to 40 years that developed under regimes with early and continued density control.
- They have very limited ability to predict early stages of stand development, or the development and effects of associated weed-tree or nontree competition (which involve measurements not customarily taken in the past).
- They do not satisfactorily incorporate the effects of genetic improvement programs.
- Flexibility and basic data needed to address new questions are limited. There is much current interest in wildlife habitat, visual effects, and the role of forests in carbon fixation, which require estimates of crown cover, layered crown structure, understory development, and total biomass. Existing simulators were originally developed to address timber management concerns, although some have been modified to produce at least some of the desired information.
- They do not satisfactorily incorporate the effects of vegetation control on juvenile growth. Recent data show that use of large seedlings and weed control reduce the time for trees to reach breast height by several years, and produce more rapid early height growth than indicated by the widely used height curves of King (1966) and McArdle and others (1961). Changes in growth trajectories lead to productivity predictions that increase well into merchantable size ranges (Hanson 1997, Newton and Hanson 1998).
- Changes continue in forest management objectives, management regimes, genetic composition, underlying biological knowledge, and perhaps in climate. Thus, no growth-and-yield prediction system can ever be complete. Continuing evolution and modification is to be expected.

Stand-Density Measures

Both thinning practice and construction of stand simulators necessarily involve some measure of stand density ("stocking" or "competition"). In ecological usage, "density" refers to number of individuals per unit area. This definition has limited usefulness in forestry, because trees increase in size and area occupied over time, within wide limits. A given number of stems has widely different meanings as an expression of competition, depending on the stage of stand development. Therefore, a number of other measures of stand density have come into use.

Basal area per unit of land area has been and is a widely used measure, primarily because it is easily determined. Considered alone, it has drawbacks similar to number, although perhaps to a lesser degree. However, basal area (or number) becomes meaningful in combination with site and age, or with other measures of stage of stand development such as average diameter or height. These are basic components of several measures that express density relative to some standard condition, thereby more or less eliminating the direct effect of tree size on area totals.

For many years, it was a common procedure to express stand density as a "normality percentage," the ratio of basal area (or number, or volume) to the corresponding value given by the normal yield table for the given site and age. This required the laborious and often inaccurate determination of site index and age for the particular stand. Therefore a number of relative density measures have been developed that do not require site index and age. In general, these are similar in nature and uses although differing in the particular form of expression (Curtis 1970, 1971).

The earliest of these was Reineke's (1933) stand density index (SDI), which is based on number of trees per unit area relative to quadratic mean diameter (QMD) adjusted to a value corresponding to a QMD of 10 inches (25.4 centimeters).

Another is Curtis RD (Curtis 1982), the ratio of basal area to the square root of QMD. This is basically merely a rearrangement of SDI, with a slightly different exponent of QMD. Reineke SDI is the measure of stand density used in the ORGANON and FVS simulators. Curtis RD is used in DFSIM.

A third common measure is Drew and Flewelling's (1979) relative density, which differs from the above in that it relates number per unit area to mean volume per tree rather than to QMD. They prepared a rather elaborate stand management diagram for Douglas-fir, which included a maximum density line and one representing the onset of mortality, as well as a lower density limit representing the point of crown closure. The addition of curves representing site height allowed estimation of corresponding stand volumes.

Long and others (1988) published a similar diagram using QMD rather than mean tree volume as the predictor. It is unclear whether QMD or mean volume is inherently more meaningful, but QMD is easier to use because it does not involve height measurements. Similar diagrams can be and have been prepared based on any of the common stand density measures. These are generally some combination of QMD or mean volume, number, and basal area. There is no great difference in practical results.

The various stand management diagrams or their numerical equivalents provide the silviculturist with convenient guides indicating the approximate limits within which stands should be maintained to avoid either substantial competition-related mortality or incomplete utilization of growing space.

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CONTINUE

Chapter 10: Silvicultural Influences on Wood Quality[1]

Background

General Overview

For many years, old-growth timber of the Pacific Northwest had great marketing advantages relative to its competitors: large stems, narrow rings, a high proportion of clear wood and—in the case of Douglas-fir—superior strength properties. Some of the region's advantages in the timber trade have been reduced, however, as the major source of wood supply shifted from old-growth timber to young natural stands and plantations grown on relatively short rotations. In young-growth stands, stems (and thus logs) are smaller in diameter, growth rings are generally wider, knots are more abundant, and strength properties are reduced. A larger proportion of the stem is composed of juvenile wood; this wood occupies the core of a tree (from the pith outward for various numbers of rings) and differs from mature wood in several basic traits—wood density (lower or higher, depending on the species), shorter fiber length, and greater microfibril angle. Juvenile wood generally has lower mechanical strength, greater tendency to shrink and warp, and lower pulp yield. Although manufacturing changes allow utilization of smaller, younger trees for many products, the traits previously associated with old-growth trees are still very important for other products and may command premium prices so long as mills capable of handling logs more than 30 inches (75 centimeters) in diameter continue operation. The number of such large-log mills has been declining rapidly.

Brief History of Wood Quality Research

Differences in wood properties (hence, quality) of Douglas-fir were noted in an early unpublished monograph (see footnote 3 in chapter 4) on the species by Allen in 1899. Allen commented that lumbermen recognized two varieties of Douglas-fir based on color of heartwood: yellow fir was somewhat lighter, softer and easier to work than red fir. Yellow fir trees were older (>75 years) than red fir trees (<70 years) and generally were growing on poorer sites and drier soils; at the time, some people believed the differences were caused primarily by age, but Allen considered the theory inconclusive because the oldest trees tended to occur on poorer sites.

One of the first activities after transfer of the Bureau of Forestry from the U.S. Department of the Interior to the U.S. Department of Agriculture involved the establishment of timber-testing laboratories in the Pacific Northwest at the University of Oregon (Eugene) and at the University of Washington (Seattle) about 1905–06 (Munger 1955; see also footnote 4 in chapter 4). Studies at the University of Oregon ended in 1907 (see footnote 4 in chapter 4), but work was continued for some time and eventually expanded at the University of Washington (Munger 1955). When the U.S. Forest Service established its Regional (then called District Forester's) Office in 1908 in Portland, Oregon, it included two small sections devoted to research—Forest Products and Silvics (Munger 1955). Wood properties of native species, including Douglas-fir, western hemlock, Sitka spruce, and western redcedar, were evaluated for structural and other purposes (for example, Cline and Knapp 1911). The Forest Products Laboratory at Madison, Wisconsin, was founded in 1910. Despite early recognition of the importance of both fields of scientific inquiry, it appears that little or no overlap or collaboration occurred between silviculture and forest products research; at the time, forest products and wood research was concerned primarily with the properties and use of the older, naturally-grown timber then being harvested. And during the first quarter of the 20th century, forest owners and managers were concerned primarily with reestablishment or regeneration of stands after harvest, and protection from fire. Munger's (1911) monograph on growth and management of Douglas-fir, however, did point out the significance of markets for small material (such as mining props and

[1] By D.S. DeBell and R.O. Curtis.

railroad ties) to yield and value obtainable from young stands, 30 to 70 years old. Management of young stands was limited and generally focused on high volume (quantity) production.

Although high volume production remained the primary management consideration for many years, quality as well as quantity of production gradually began to receive some attention. Paul (1932), a silviculturist at the Forest Products Laboratory in Madison, Wisconsin, published a thoughtful article in the *Journal of Forestry* titled "Improving the Quality of Second-Growth Douglas-Fir." He suggested that management of second-growth stands be focused on three objectives: freedom from large and loose knots, uniformity of growth rate, and production of both dense wood for special uses and nondense wood for other uses. To achieve these goals, Paul proposed silvicultural practices to influence stand stocking—interplanting in poorly stocked stands to reduce knot size and enhance natural pruning, thinnings in well-stocked stands to maintain uniformity of growth rate, and dense stocking plus longer rotations to produce dense wood. It is surprising that Paul did not mention pruning. Pruning studies established in 1930 in British Columbia (Schenstrom 1931) and in the mid to late 1930s in the United States (Stein 1955a, Meyer[2]) appear to be the first attempts to study the effect of silvicultural manipulations on wood quality. It was another 20 years before research foresters attempted to quantify relationships between branch or knot size and spacing or stand density in plantations (Eversole 1955) and natural stands (Grah 1961).

Except for a few reports from Canada (for example, Warrack 1948), research interest in the influence of silviculture on wood quality of Douglas-fir and other Northwestern species seems to have waned from the mid 1960s until the early 1980s. Several factors contributed to such decline in interest—a large portion of the wood supply continued to come from older forests, most economic analyses done between 1950 and 1980 indicated that there was little to be gained by pruning most species (Fahey and Willits 1995), and a general belief that in the future most wood-based products would be made from reconstituted fiber (for example, Zivnuska 1972).

The situation began to change rapidly in the last quarter of the 20th century. Forest area in young managed stands and the proportion of timber harvest from such stands increased, and it became apparent that very wide early spacing and very short rotations have undesirable effects on stem characteristics and wood properties, and therefore on timber or log values. Consumers encountered poorer quality lumber in lumberyards and home improvement stores, and experienced the negative performance of such wood in service. As a result, research concerning the effects of stand management on the quality and value of wood produced has greatly increased during the past 20 years. Considerable effort has gone into quantifying the basic relationships (Briggs 1989, Maguire and others 1991), estimating log and lumber values from tree characteristics (Briggs and Fight 1992; Fight and others 1987a, 1987b, 1988), and using recently developed stand models coupled with assumptions regarding stem and wood traits to estimate timber values produced under a variety of management regimes (Barbour and others 2003).

General Influences of Silvicultural Practices

Today it is well-accepted that the application and timing of several silvicultural practices can exert strong influence (of considerable economic importance) on stem characteristics and properties of wood produced in young managed forests:

Stand density management through initial spacing (plantations) and thinning (natural stands and plantations) can influence growth rates (ring widths), branch size and persistence (hence, number, size, and quality of knots), and the amounts and proportions of juvenile wood. Thus, wide spacings can produce large green branches and knots,

[2] Meyer, W.H. 1935. First report on Columbia thinning plots 4, 5, 6, 7, 8. Office report. On file with: Silviculture and Forest Models Team, Forestry Sciences Laboratory, Olympia, WA.

whereas breakage of dead branches during thinning can reduce the number of knots.

Pruning (sometimes called "artificial pruning" to contrast it with "natural pruning" or "self-pruning") can increase the production of clear wood, reduce the number and size of knots, possibly improve the form factor of the lower log(s), and accelerate the transition from juvenile to mature wood.

Fertilization or nutrient applications can influence growth rate (ring width) and basic wood properties, including density of and the transition between earlywood and latewood, and probably the size and persistence of branches (knots).

Genetic improvement (tree breeding) can affect many stem characteristics and growth traits such as early growth rate, stem form, branching patterns, and basic wood properties such as density.

Rotation length will strongly influence stem size (log diameters), amount of clear wood, heartwood/sapwood ratios, and the proportion of juvenile wood.

Essentially all of these practices or decisions can influence the uniformity of wood properties in logs harvested. Uniformity in raw material supply is extremely valuable in all manufacturing processes (Haygreen and Bowyer 1996); this is fortunate because this opportunity to affect wood uniformity is the major wood quality advantage that managed young-growth timber has over the old-growth resource that fueled the timber industry and economy of the Pacific Northwest for many years. Wood properties of the latter were already in place and, although the outer rings had excellent properties, substantial and abrupt changes in growth patterns from the pith to the outer rings were common.

The history of research on each of these practices as related to wood quality is summarized in the sections that follow.

Pruning

Old-growth Douglas-fir was highly valued for its large proportion of fine-grained clear wood, much in demand for the plywood industry as well as for a variety of other specialized uses. Paul (1932) pointed out the influence of stocking and stand density on size and looseness of knots in young-growth trees. It was early recognized that, even in well-stocked stands, natural pruning in unmanaged young-growth stands was a very slow process. Bransford and Munger (1939), Kachin (1940), and Paul (1947) conducted independent assessments on formation of knots, limb death, and production of clear wood; their reports estimated that production of substantial amounts of clear wood would require 100 to 150 years. It was therefore natural to consider pruning as one component of future management of young stands (fig. 32).

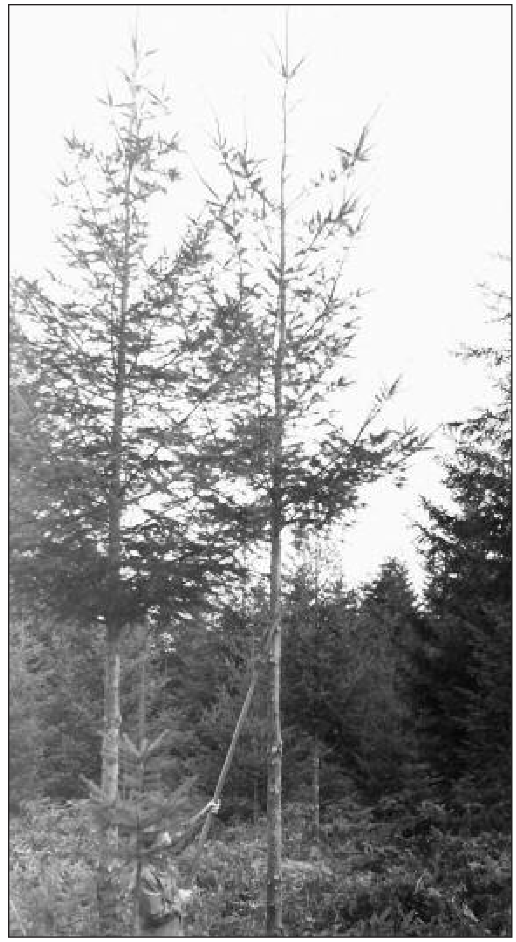

Figure 32—Early experimental pruning at Wind River.

Some small-scale trials date from the early 1930s (for example, Schenstrom 1931). A small amount of operational pruning was done by Civilian Conservation Corps crews on national forest land during the 1930s, although records are largely lacking. Pruning was one of the treatments in the Kugel Creek thinning study (established 1937, destroyed by fire in 1951). There was also some small-scale pruning done about 1940 on the Pack Experimental Forest of the University of Washington. A pruning study was established in 1937 (Stein 1955a) in a 28-year-old site IV stand on the Wind River Experimental Forest, comparing growth effects of different degrees of crown removal. The British Columbia Forest Service installed a combined thinning and pruning study in stands aged 14 to 20 years (Warrack 1948), and a pruning treatment was also superimposed on the Pacific Northwest Station's Voight Creek thinning study established in 1949.[3]

Early reports provided time and cost data (Welch 1939), healing times, and effects on stem growth. Anderson (1951) used material from the Kugel Creek and Wind River studies to show that healing time for pruned Douglas-fir was strongly influenced by diameter growth rate, bark thickness, and pruning technique as it related to stub length. Stein (1955a) evaluated stem growth in the Wind River study. He found that in this previously unmanaged naturally seeded 28-year-old stand, removal of 25 percent of live crown (length basis) produced a small increase in diameter and height growth, but that removal of 50 percent and 75 percent of live crown substantially reduced growth. Stein concluded that one could remove the lower third of live crown in previously unpruned stands without reducing growth. Staebler (1963) showed that early pruning removing one-third or more of the live crown altered bole form, producing more nearly cylindrical stems and reduced ring width in the lower bole.

Shaw and Staebler (1950, 1952) analyzed the effects of different factors on profitability of pruning, and concluded that diameter growth rate of pruned trees is crucial. Other important factors are price premium for clear wood, cost of pruning, and interest rate.

A general shortcoming of most early pruning research, aside from matters of experimental design and documentation, was that most trials were established beyond the optimal age and without the stocking control needed to ensure rapid diameter growth after pruning. Hence the potential gains in clear wood were generally underestimated.

Research and operational interest in pruning revived in the 1980s based largely on product recovery evaluations using Douglas-fir trees from a thinning/pruning study established in the early years (Cahill and others 1988) and development of simulation programs that allowed estimation of expected clear material and economic returns (Fight and others 1987a, 1987b; Mitchell 1995). The Stand Management Cooperative has installed an extensive series of new pruning studies in the last decade. The Mount Hood National Forest established an elaborate replicated trial in the early 1990s, and several other trials have been established by private owners.

The current state of knowledge about pruning Douglas-fir has been summarized by Oliver and others (1986), by O'Hara (1991), and in a later comprehensive symposium on pruning and wood quality in northwestern conifers (Hanley and others 1995). In sum:

- There is a large amount of published research on pruning Douglas-fir (and other species worldwide). The available information is adequate as a basis for operational applications.
- Simulations indicate pruning should be profitable on good sites under reasonable projections of current costs and price differentials.
- Pruning should be done at an early age and in conjunction with stand density control (or density control plus fertilization) to maintain rapid diameter growth, provided that the species is not susceptible to epicormic branching as a result of the combined

[3] Shaw, E.W. 1949. Pruning at the Voight Creek Experimental Forest. 6 p. Office report. On file with: Silviculture and and Forest Models Team, Forestry Sciences Laboratory, Olympia, WA.

treatments (Berntsen 1961b, DeBell and others 2006.)

- Pruning is best done on a limited number of trees that are expected to reach rotation age. Greatest benefits will be obtained on moderately long rotations.
- Some information is available on results of pruning Sitka spruce, western white pine, and red alder, but there is virtually no information available on results of pruning other major Northwestern coastal conifer species such as western hemlock and redcedar.

Operational application of this knowledge has so far been relatively minor, limited mainly to integrated companies in which owners and managers of the forest also control their own mills. A major obstacle to widespread application appears to be uncertainty as to whether a seller of pruned logs or stumpage will be able to command a premium commensurate with the increased value of the manufactured products, in the absence of any mechanism by which a buyer can be sure of pruning history and standards.

Initial Spacing and Thinning

Although Paul (1932) had identified opportunities to influence three aspects of wood quality (knots, growth rate, and wood density) by regulating stocking or stand density throughout the rotation, for the next two decades, research on relations between wood quality and stand management was limited primarily to the studies of branch mortality, natural pruning, and artificial pruning as discussed in the previous section. No one seems to have measured and reported the effects of stocking on branch (or knot) size or branch mortality in Douglas-fir until Eversole (1955) reported results from 27-year-old trees in a research plantation of various spacings. He showed that mean size of the largest limbs in whorls below breast height increased from 0.36 to 0.73 inches (0.91 to 1.85 centimeters) and height to live crown decreased from 19.5 to 6.7 feet (5.9 to 2.0 meters) as square spacing increased from 4 to 12 feet (1.2 to 3.7 meters). A few years later, Grah (1961) conducted work in natural, 20- to 40-year-old Douglas-fir stands on the relation of average spacing to knot diameter. Grah's linear regression may represent the first attempt to quantify and develop a predictive relationship between a silvicultural attribute (stand density) and a wood quality trait in Douglas-fir.

During the past two decades, effects of spacing on stem form, branch persistence and height to live crown as well as knot size have been investigated for Douglas-fir (Robbins 2000, Smith and Reukema 1986) and other species such as western hemlock and redcedar (DeBell and Gartner 1997, DeBell and others 1994a). Wider spacings increased stem taper, branch persistence, and knot size, but height to live crown was reduced. Studies in intermediate-aged stands specific to effects of thinning on wood quality are limited. Given that thinning generally tends to maintain or increase radial growth rate in the remaining trees, it appears to have little or mixed effects on average wood density of some species (for example, Douglas-fir, Briggs and Smith 1986) and reduce it somewhat in others (for example, western hemlock, DeBell and others 1994b, 2004). Regardless of the specific effects of maintained radial growth rate on density of subsequent wood, the more uniform growth rate and wood density from pith to bark is probably beneficial for most applications.

Fertilizer Application

The primary objective in fertilizing Douglas-fir stands is to enhance tree and stand volume growth. Soon after research trials demonstrated good growth response of Douglas-fir stands to added nitrogen, researchers at University of Washington (Erickson and Lambert 1958) began to assess effects of fertilizer on some wood properties.

As fertilization became operational in the late 1960s and 1970s, basic wood properties were assessed in some fertilized young Douglas-fir trees (for example, Megraw and Nearn 1972, Siddiqui and others 1972). Results indicated that whole ring density was slightly reduced, more so in the latewood than earlywood component, thus increasing uniformity throughout the ring. Work on fertilizer-wood quality relationships has not been extensive, and most hypotheses about the effects of fertilizer on other aspects of wood quality have been based on how increased growth rate, increased foliar retention, and longer branch persistence might increase size of the juvenile core and number and size of knots. Cahill and Briggs (1992) provided a comprehensive review of fertilization effects on wood properties and tree value, including an analysis of potential effects on specific wood and fiber products.

Genetic Improvement

Perhaps the earliest work related to wood quality and forest genetics of Douglas-fir occurred when Munger and others collected seed from mother trees for the 1912 heritability study (chapter 7) and diagrammed the form of each tree stem (Munger and Morris 1936). Although the outplanting trial established from this collection represents one of the oldest forest genetic trials in the world, there was little followup on wood quality traits, probably because Douglas-fir inherently has superior stem and wood characteristics. But as tree improvement or tree breeding programs developed in other regions, particularly in areas where pulp and paper dominated the industry, wood quality became an important consideration (Zobel 1961a, 1961b). Soon thereafter McKimmy (1966) collected increment cores from trees in the above-mentioned 1912 Douglas-fir heritability study and evaluated their specific gravity, presumably the first attempt in the Pacific Northwest to examine the tie between genetics and a specific wood property. McKimmy found that trees from different sources differed significantly in specific gravity, but differences were even greater among the four outplanting locations.

During the 1960s, interest developed in abnormal stem forms (forking, sinuosity, and ramicorn branching) sometimes observed in rapidly growing Douglas-fir plantations (Campbell 1965), but it received little attention in genetics research until the 1980s (Adams and Howe 1985). Recent work demonstrated that forking, sinuosity, and ramicorn branching are subject to genetic improvement (Schermann and others 1997). Also in the 1980s and continuing to the present, research increased on the genetic influences on wood density (specific gravity) and its components, including correlations of juvenile wood properties with those at later ages (McKimmy and Campbell 1982, Vargas-Hernandez and Adams 1992). Although the stem form traits and wood density are heritable, they are considered of secondary importance to volume and adaptability in current Douglas-fir breeding programs (Howe and others 2005).

Rotation Age

Tree and stand age have direct and indirect influences on wood quality: stem size and the length of branch-free bole increase, whereas the proportion of juvenile core wood, sapwood/heartwood ratio, and ring width decrease as stands become older.

The first scientific report related to age effects on wood quality is probably Allen's report on yellow vs. red fir in 1899 (footnote 3 in chapter 4). The amount of heartwood was recognized as important in western redcedar, where its resistance to decay was highly valued for outdoor applications. Various notes on self-pruning followed Paul's (1932) paper, which revealed that little clear wood is formed during the first 100 years of tree life. As the concept and properties of juvenile (or core) wood became more widely recognized (Wellwood and Smith 1962, Zobel 1961b), the negative properties associated with young rapidly-grown trees became apparent (Jozsa and others 1989). Juvenile wood usually comprises the first 10 to 20 rings outward from the pith (Di Lucca 1989). Compared to later "mature" wood, juvenile wood tends to have lower specific gravity, greater tendency to shrink and warp, lower mechanical strength, and lower pulp yield (Senft and others 1985). It is therefore less desirable for many uses. The amount of heartwood is important in some species, such as western redcedar where its resistance to decay is highly valued for outdoor applications.

Until recently, large trees were desirable for reasons beyond specific wood characteristics; harvest and hauling costs were lower for large trees than for small ones and manufacturing costs were reduced for many wood products, in part because recovery was higher. Recent changes in mill technology to handle small logs more efficiently and trends toward use of engineered wood products, however, have reduced or eliminated such advantages. At present, large trees may be difficult to market (Barbour and others 2002) and may actually incur a penalty of 25 percent or more (Mason 2002).

Simulation Estimates of the Effects of Silviculture on Wood Quality

In recent years, simulation techniques have been used to estimate the effects of management on the various factors of wood quality and value. In general, these techniques "grow" trees with individual tree simulation programs such as ORGANON and TASS that can predict quality-related values such as taper, crown dimensions, branch size, and juvenile wood core. These predictions can be combined with bucking and sawing simulators to generate estimates of product out-turn and value. Examples are TREEVAL (Briggs 1989, Briggs and Fight 1992), SYLVER (Mitchell and others 1989), and ORGANON + TREEVAL (Maguire and others 1991). Simulations have shown that regimes that produce the largest trees or the highest volumes are not necessarily those that produce highest value. Value criteria can lead to management decisions considerably different (higher planting density, longer rotation) from those made with volume as the primary criterion.

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Chapter 11: Silviculture of Associated Species[1]

The preceding discussions have been concerned primarily with Douglas-fir research. In this section we summarize the considerably shorter history of silvicultural research on the principal associated species.

Western Hemlock

After Douglas-fir, western hemlock is the most important species in terms of volume and area occupied. It occurs throughout most of the Douglas-fir region and is the climax species in most of the region—hence the designation of much of the region as the western hemlock zone. The species is most abundant and reaches its best development in the high rainfall areas along the Pacific coast (where it is associated with Sitka spruce) and at mid elevations in the western Cascades.

In the early years, hemlock was regarded as a low-value species with limited markets, influenced in part by the poor reputation of eastern hemlock and by the high defect common in old-growth western hemlock. Attitudes changed rapidly after World War II (WWII) as the combined result of depletion of timber supplies, expansion of the pulp and paper industry, increased use of hemlock in construction, and an expanding Asian market. However, prices for hemlock have historically been substantially lower than for Douglas-fir.

Prior to WWII, relatively little research was devoted to hemlock. Allen (1902) published a monograph on the species, summarizing available knowledge on the silvical characteristics of the species, its wood properties, and its potential for management. Watson and Billingslea (1914) published observational data on hemlock seed production, seed dispersal by wind, and the relationships between seedbed conditions, shading, and early growth of seedlings. It was early realized that hemlock can become established and can survive for long periods in dense shade, but good growth requires at least partial overhead light. Isaac (1930) measured wind dispersal of hemlock seed, along with that of Douglas-fir. Meyer (1937) prepared normal yield tables for mixed spruce-hemlock stands in Washington, Oregon, and Alaska. These were later reworked by Barnes (1962).

In 1935, twelve 0.4-hectare (1.0-acre) permanent plots were established in 83-year-old even-aged spruce-hemlock at the Cascade Head Experimental Forest. Briegleb (1940) reported results of the first six growing seasons. Fujimori (1971) examined biomass production on these plots and concluded that the values obtained were among the highest in the world. Smith and others (1984) gave a much more complete summary of 33 years of development. Results showed extremely high volumes and growth rates, with average net mean annual increment (MAI) of 17.6 cubic meters per hectare per year (252 cubic feet per acre per year) at age 83 and 16.5 cubic meters per hectare per year (236 cubic feet per acre per year) at age 116.

After WWII, there was a marked expansion of research on hemlock, both in the United States and in British Columbia. A commercial thinning trial established in 1952 in a 50-year-old stand at the Hemlock Experimental Forest showed a slight gain in volume production (mostly because of salvage of mortality) and increased diameter growth (Hilt and others 1977). Variation in initial stand conditions, departures from the original design, and 1962 storm damage precluded sensitive comparisons, and the experiment was abandoned. Graham and others (1985) reported results of light thinning in a 100-year-old stand at Cascade Head, and a number of other more-or-less similar hemlock thinning trials were established by other organizations in the 1950s and 1960s (for example, Omule 1988b). Results were generally similar, with some reduction in windfall and other mortality but little gain in overall production.

Several studies of plantation spacing or precommercial thinning were established in the same period. Thus, the University of British Columbia spacing trials established in the 1950s at Haney, British Columbia (Reukema and Smith 1987), included hemlock. Precommercial thinning trials established at Cascade Head in 1963 and at Clallam Bay in

[1] By R.O. Curtis and D.S. DeBell.

1971 showed striking response and very high growth rates (Hoyer and Swanzey 1986).

Shelterwood cuts have resulted in good natural regeneration (Williamson and Ruth 1976) and are a viable alternative to the prevailing practice of clearcutting, although growth of regeneration in the trials cited was inversely related to amount of overstory retained (Jaeck and others 1984).

Recent problems with Swiss needle cast on Douglas-fir in the Oregon coastal zone have reduced the formerly common practice of planting pure Douglas-fir after clearcutting, in favor of hemlock or mixed-species plantings.

Comprehensive summaries of past research and the state of knowledge as of the date of publication include Ruth and Harris (1979), Atkinson and Zasoski (1976), and Burns and Honkala (1990). We will not attempt to list here the many contributors, but only the major points that have been established by research as discussed in the above references.

- On suitable sites, hemlock volume production can exceed that of Douglas-fir.
- Hemlock is often abundant in the understory of older stands and advance regeneration frequently provides a hemlock component in areas planted to Douglas-fir.
- Artificial regeneration techniques are available.
- Hemlock often reproduces abundantly from natural seeding, but reproduction is often patchy and sometimes excessively dense, so precommercial thinning is often needed.
- Shelterwood regeneration has been successful but has not been widely used. The most common regeneration method in the past has been clearcutting, with or without slash burning, and either natural or artificial regeneration.
- As in other species, commercial thinning increases diameter growth but has no great effect on total volume production.
- A number of health problems affect management of hemlock: (1) hemlock is very susceptible to butt rots that enter through logging injuries; (2) it is susceptible to root rots, particularly laminated root rot (*Phellinus* root disease), similarly to Douglas-fir; (3) cut surfaces of stumps are often infected by spores of annosus root disease, and treatment of stumps has been recommended although not widely practiced; (4) dwarf mistletoe is common in older hemlock stands; (5) and hemlock is less windfirm than Douglas-fir.
- Dwarf mistletoe and susceptibility to butt rots and to windfall make selection systems—which would otherwise be well suited to this shade-tolerant species— questionable. The butt rot threat has caused some to question the merits of commercial thinning in hemlock stands.
- Hemlock has not shown consistent response to nitrogen fertilization.

Western Redcedar

Western redcedar is a high-value species with unique wood properties. Although it occurs throughout most of the Douglas-fir region, it is most abundant and reaches its best development in the high-rainfall areas along the northern Pacific coast and on the lower slopes of the western Cascades. Its abundance has decreased considerably since initial Euro-American settlement, primarily because of wildfire and the management regime of clearcut, burn, and plant Douglas-fir that prevailed until recently.

Despite its high value, there has been relatively little silvicultural experimentation with redcedar. This lack of interest probably arose from the common perception that redcedar is a relatively slow-growing species, compared to Douglas-fir and hemlock. This perception may stem from the fact that redcedar, as a shade-tolerant species and one that often has slower height growth in early life than its associates, commonly develops in a subordinate position. Most available information has been derived from observation of existing trees and stands (beginning with Jackson and Knapp 1914), plus empirical trials of seeding and planting techniques analogous to those used with other species. Manipulative experiments are few. The species has received less attention in the United States than in Canada, where it makes up a considerably larger proportion of the resource.

Pure redcedar stands of natural origin are rare. Nystrom and others (1984) located four fully stocked stands that had originated by natural seeding on areas cut about 1920. They examined patterns of height, diameter, and volume growth among crown classes and found stand volume production comparable to that of Douglas-fir on similar sites. Trees in these uniform well-stocked stands had excellent form, small limbs, and were free of the basal fluting common in redcedar grown in the open or in sparsely stocked stands.

Oliver and others (1994) reviewed the available information and suggested that redcedar grown in fairly dense pure stands (or possibly mixed redcedar-hemlock stands) could be expected to have good stem form, high yields, and reduced incidence of the large lower branches and basal fluting common in trees developing in an understory position. Kurucz (1978) developed site index curves from stem analyses of selected trees growing in mixed-species stands. There are no North American yield tables for the species.

Several plantation spacing trials have been established in recent years:

- The University of British Columbia spacing trials previously referred to (Reukema and Smith 1987) included fixed-area plots of redcedar and one Nelder plot with redcedar in addition to hemlock and Douglas-fir. At age 25 on this very good site, average trees of Douglas-fir were larger than the hemlock, which in turn were larger than the redcedar. Comparisons were somewhat obscured by damage, particularly browsing of the redcedar.
- A large spacing trial established at the Wind River Experimental Forest in 1982 included one block planted to redcedar. Results have not been reported to date, but the plantation is known to have suffered heavily from elk browsing.
- The Washington Department of Natural Resources established a redcedar spacing trial on the western Olympia Peninsula in 1984. Spacings were 4, 8, and 16 feet (1.2, 2.4, and 4.9 meters). In 2001, there were large differences in tree diameters among spacings, but the large trees in the wide-spacing plots had been severely damaged by bears.

A well-replicated study installed in 1980 in a 15- to 20-year-old dense poor-site stand on the Olympic Peninsula compared various combinations of precommercial thinning and fertilization (Harrington and Wierman 1990). Five-year results showed very strong response to fertilization and to fertilization combined with thinning, but limited response to thinning only.

Planting of redcedar has increased in recent years. It is a preferred species for use on areas heavily impacted by *Phellinus* root rot, because of its tolerance of root disease. There is also a considerable amount of planting as a secondary component of Douglas-fir-redcedar mixtures, motivated in part by a desire to ensure against root disease, and in part by biodiversity and wildlife concerns. Browsing by deer and elk remain serious problems, and mixed-species plantations are not easily established (Stein 1997).

The principal summary publications are Minore (1983, 1990) and Smith (1987). We will simply list the main points that have been established in reference to silviculture:

- Redcedar is better adapted to imperfectly drained soils than its coniferous associates.
- Redcedar foliage has high concentrations of calcium and may be important in nutrient cycling.
- Redcedar is very susceptible to fire and logging injury.
- Redcedar height growth trends differ from Douglas-fir and hemlock; Douglas-fir commonly overtops redcedar established at the same time.
- European plantation data indicate high potential yields compared to other species; high basal areas tend to offset somewhat lesser height growth.
- Seed production is usually abundant.
- Effective nursery and planting techniques are available.
- Redcedar is resistant to or tolerant of the coastal strain of *Phellinus* root disease.
- Redcedar is a preferred browse species for deer and elk.

High-Elevation True Fir–Hemlock

The forests above about 2,500 feet (800 meters) in the northern Cascades and Olympics and above about 3,500 feet (1100 meters) in the southern Cascades are composed of various mixtures of Pacific silver fir, noble fir, western hemlock, mountain hemlock (upper elevations), Douglas-fir (lower elevations), and various minor species, collectively referred to as true fir-hemlock. There was little active management of these forests until about 1960. Research has been limited and largely observational in nature; there have been few manipulative experiments.

Much of the silver fir zone and some lower portions of the mountain hemlock zone are quite productive (Franklin and Dyrness 1973). Although we have no U.S. yield tables, it is clear from observation and from European yield information that true fir stands can develop very high volumes. Noble fir in particular is a very impressive species (Franklin 1964a, 1964b) and is widely planted. Pacific silver fir often develops abundant advance regeneration; its behavior resembles that of the silver fir important in Europe. The true firs characteristically have slow early height development followed by a period of acceleration, with rapid growth continuing to advanced ages.

Hanzlik (1925) carried out a study that is probably the first study of noble fir growth, on Larch Mountain east of Portland, Oregon. This study brought out two points that have been confirmed by later work: (1) compared to both Douglas-fir and western hemlock, noble fir makes relatively slow growth in the early years; but (2) in later years it maintains rapid growth to advanced ages, exceeding (on this site) both Douglas-fir and western hemlock in growth rate.

Franklin's (1962) literature review showed that up to about 1960, the existing information on true firs was concerned principally with species distribution, botanical characteristics, and seeding habits. There was little information on applicable silvicultural methods.

Herman and others (1978) and Hoyer and Herman (1989) developed site curves from stem analyses of selected dominant noble fir and silver fir trees in old natural stands. Murray and others (1991) found that noble fir and silver fir established on clearcuts were making substantially faster height growth than indicated by stem analyses of old trees. Preliminary site curves exist for mountain hemlock. Managers have usually assumed that western hemlock will behave much as it does on the poorer sites at lower elevations.

The extensive ecology program of the Pacific Northwest Region of the USDA Forest Service developed an elaborate plant association classification that is useful in matching species and management practices to site (for example, Brockway and others 1983).

Early management attempts using the clearcut, burn, and plant (often Douglas-fir) practices used in the lowlands frequently failed (Franklin 1964a). The slow development and frequent failure of regeneration (often because of late spring frosts) on harvested areas was a major concern in the 1960 and 1970s, but with improved nursery and planting practices, less burning, better matching of species to site, and consequent higher survival, this was replaced with concern about the overstocking that frequently developed. In the 1980s, the Forest Service undertook an extensive precommercial thinning program in true fir-hemlock. Practices were based on experience with Douglas-fir because there were no quantitative stocking standards based specifically on experience with young true fir-hemlock stands.

Over the years 1987–94, an extensive series of spacing trials was established on national forest lands (fig. 33). In time, these trials should produce a basis for estimating yields of young true fir-hemlock stands under a range of stocking levels (Curtis and others 2000). The high values of true fir boughs for Christmas decorations can often cover the costs of precommercial thinning.

The principal available summaries of existing silvicultural information are Oliver and Kenady (1981) and Burns and Honkala 1990.

Prior to Euro-American settlement there were extensive areas of open land in the northern Cascades, maintained in part by burning by Natives. These lands were highly valued by the Natives for huckleberry production, and are now an

Figure 33—A precommercially thinned plot in a noble fir spacing experiment. Noble fir has been widely planted at higher elevations. Concern over some early establishment failures was later replaced with concern about overstocking in many areas.

important recreational resource. Concern over encroachment of forest on these open areas led to a small amount of work on huckleberry management (Minore 1972, Minore and Dubrasich 1978).

Currently, there is only limited formal research on true fir-hemlock in progress in the region. There is more emphasis on silver fir and mountain hemlock research and management in British Columbia, where the species occur at lower elevations and make up a greater proportion of the commercial forest land base.

Red Alder

Interest in silviculture of northwestern hardwoods is a fairly recent development. Examples are red alder, Oregon white oak, and poplars.

Red Alder as a Timber Species

Red alder is the most abundant and economically most important northwestern hardwood. It grows best on moist sites at low elevations, although it occurs on other sites. Alder is an intolerant and relatively short-lived pioneer species that reproduces abundantly on bare mineral soil exposed to direct sunlight. The large clearcuts and fires common prior to WWII are thought to have considerably increased the amount of alder, compared to presettlement conditions. Conversely, fire protection, the widespread planting of conifers on clearcuts, and conscious efforts in recent decades to convert alder and mixed-species stands to conifers have considerably reduced the area in alder and produced a shortage of young stands.

Prior to WWII, alder was regarded as a low-value weed species. Attitudes began to change after WWII. Causes were (1) increased use of alder for pulp and particle board, (2) increased use of alder for furniture and similar uses with correspondingly higher log prices, (3) recognition that alder's nitrogen-fixing ability had an important role in soil fertility, (4) recognition that rapid juvenile growth and early maturity made alder suitable for management on much shorter rotations than those appropriate for conifers, and (5) interest in the 1980s in short-rotation woody crops as a possible energy source. These factors partially offset the higher volume and value production obtainable with conifers. Interest in the possibilities of alder led to the establishment of the Hardwood Silviculture Cooperative at Oregon State University in 1987.

Two early publications on alder were Johnson (1917) and Johnson and others (1926). The latter was concerned mainly with utilization, but also included some discussion of silvical characteristics, yields, and management possibilities.

Little further work was done with the species until the 1950s. Beginning around 1960, an increasing number of publications appeared, and today there is a growing literature on alder biology and management, a considerable part of which is based on formal experimentation. Major summary publications are Worthington and others 1962, Trappe and others 1968, Briggs and others 1978, Heebner and Bergener 1983, Hibbs and others 1994, and Deal and Harrington 2006. DeBell (2006) gave an overall review of the history of red alder research and changing attitudes. The various papers included in Deal and Harrington (2006) showed that production in managed alder plantations considerably exceeds that in natural stands, and suggested that financial returns can be competitive with those from conifers.

To summarize the main points established by research:

- Compared to its conifer associates, alder makes much more rapid juvenile height growth but falls behind in later years. Consequently, it offers severe and often lethal competition to intermingled conifers in early life.
- Volume production per year on appropriate rotations is greater for conifers than for alder on most sites, but the rapid juvenile growth and correspondingly shorter rotations for alder reduce the financial advantage of conifers. The current weakness of volume and value yield estimates and of volume and taper functions specifically applicable to intensively managed young alder stands makes financial comparisons somewhat uncertain.
- Alder may have an important role in management of nitrogen (N)-deficient soils because of its N-fixing capability, albeit with recognition of its competitive potential.
- Early thinning trials were unsatisfactory, probably because they were not begun until after the period of rapid height growth. Thinning should be done early.
- Plantations with suitable density control can provide considerable increases over natural stands in volume, height growth, and stem quality. The regular spacing achievable by planting or thinning minimizes the lean and sweep common in unmanaged stands.
- Normal yield tables have been developed for unmanaged stands but are probably not applicable to stands with early density control, and may overestimate yields of older unmanaged stands.
- Site curves and alternative methods of evaluating site quality have been developed.
- Stocking guides for plantations and pure natural stands have been suggested.
- Suitable nursery and planting practices are available.
- Several plantation spacing trials exist, including both pure and mixed species.
- Alder's immunity to *Phellinus* root disease makes it suitable for planting on root-disease-infested areas.

Interest in alder management has been markedly stimulated by recent development of export markets and increasing log prices.

Red Alder as a Soil Improver

Johnson (1917) produced the first published reference on the role of red alder in the Northwest as a soil-improving species that actively fixes N. He observed apparent relationships between presence of red alder and increased soil fertility, which he interpreted as caused by alder, and referred to an analysis by the Forest Products Laboratory showing that the root nodules on alder contain N-fixing bacteria analogous to those in legumes.

Tarrant and others (1951) compared litter fall and nutrient composition of foliage of the major Northwestern species. They found that alder litter had much higher N content than other species, and suggested that it had value as a soil conditioner.

A severely burned site on the Wind River Experimental Forest was operationally planted to Douglas-fir in 1929. A strip within the plantation was interplanted with red alder in 1933. Tarrant (1961) and Tarrant and Miller (1963) found striking differences in stand growth and soil conditions between the Douglas-fir-alder mixture and the adjacent pure Douglas-fir plantation. The mixed planting had greater total yield, markedly better development of the Douglas-fir, greater soil organic matter content, lower bulk density, and greater N content. Miller and Murray (1978) reported subsequent development of this plantation and findings in other mixed stands, and suggested possible regimes to take advantage of alder N-fixation. The Wind River study had some unique features: (1) the alder was planted 4 years after the Douglas-fir, (2) there was some freeze damage to the alder, and (3) the site was very deficient in N because of previous severe burns. These findings stimulated research interest in alder.

Franklin and others (1968) and Cole and others (1978) compared mineral cycling and N accumulation in young red alder, Douglas-fir, and mixed stands. Soil organic matter and N accumulation were much greater in the alder, and greater in the mixed, compared to the pure Douglas-fir stands. Binkley and others (1994) reviewed the existing information and concluded that average N accumulation rates in pure red alder were generally in the range of 100 to 200 kilograms per hectare per year (88 to 178 pounds per acre per year). Newton and others (1968) measured N accumulations in scarified soils approaching 300 kilograms per hectare per year (267 pounds per acre per year), some of the highest accretion rates reported. They also warned of differences in growth habits of alder vs. conifers that lead to incompatibility in mixed stands.

A number of studies have attempted to evaluate mixtures of alder and conifers, as an alternative to chemical fertilizers. The primary problem encountered is that of keeping early alder competition with the conifers at an acceptable level while maintaining sufficient vigorous alder to provide meaningful amounts of N. Experiments are still ongoing, but it appears that the most feasible approach is either crop rotation (facilitated by the early maturity of alder) or groupwise plantings.

Research has made clear that alder substantially benefits soil productivity where N is deficient, and that N-fixation by an alder component can be an asset in stand management. However, similar benefits can also be obtained by direct application of N fertilizer, and the comparative costs are uncertain. Alder necessarily occupies growing space that could otherwise be used for higher yielding conifers. Potential soil benefits from alder have not generally been a primary consideration by managers who have direct fertilization available as an alternative.

Additional work on the basic biology of N fixation by red alder and on alder's effects on soils and on ecosystem productivity is discussed in symposium volumes edited by Trappe and others (1968), Briggs and others (1978), Hibbs and others (1994), and Deal and Harrington (2006).

Oregon White Oak

Oregon white oak (*Quercus garryana* Dougl. ex Hook), also known as Garry oak, is the only oak native to British Columbia, Washington, and northern Oregon. Other oaks are present in southern Oregon and northern California and may be associated. On most sites, Oregon white oak does not have the growth rates or maximum height potential of associated conifers and is thus overtopped and then succeeded by conifers. It is only considered to be climax on very dry sites.

At the time of initial Euro-American settlement, there were extensive areas of oak woodland and oak savannah and prairie in the Puget Sound region and in the Willamette Valley. These were maintained primarily by frequent burning by Natives, although natural fires were also important. Native Americans set fires to facilitate hunting, to favor food plants associated with the open environments (especially camas (*Camassia quamash* (Pursh) Greene), whose bulbs were an important food source), and to facilitate collection of other foods such as acorns and hazelnuts (Boyd 1999).

The areas of oak woodlands, oak savannas, and associated prairies have drastically declined. Reasons for this decline are (1) conversion to agriculture or urban development, (2) intentional conversion to conifers, and (3) invasion by conifers (primarily Douglas-fir) following fire exclusion. In recent years, interest has developed in the cultural and biological legacies associated with these areas. Although white oak is of negligible importance as a timber species, there are many plant and animal communities associated with these open habitats that are not found in conifer forests and several species considered to be threatened or at risk, including the western gray squirrel, several birds, the Mazama gopher, and various invertebrates. Current interests are in managing oak stands for wildlife habitat, biodiversity, or to keep or create open areas in the landscape.

Stein (1990b) summarized the then-available information on biology and management of Oregon white oak. Harrington and Kallas (2002) provided a more recent bibliography. Larsen and Morgan (1998) summarized information on the wildlife habitat values of oak and made management recommendations for maintenance and restoration of oak stands, as did Vesely and Tucker (2005) and Campbell (2003).

Most oak habitats are on private land, but some public agencies such as Department of Defense (Fort Lewis Military Reservation near Tacoma, Washington), Bureau of Land Management, U.S. Fish and Wildlife Service Refuges, Natural Resource Conservation Service, Washington Department of Fish and Wildlife, Washington Department of Natural Resources, and Oregon Department of Forestry have programs to preserve, restore, manage, or protect areas of oak and prairie. Nongovernmental agencies such as The Nature Conservancy, the American Bird Conservancy, the Oregon Oak Communities Working Group, and the Garry Oak Ecosystems Recovery Team are also promoting conservation activities. Researchers associated with the USDA Forest Service Pacific Northwest Research Station, University of Washington, and Oregon State University are studying various aspects of oak and prairie biology and management (Peter and Harrington 2002, Regan and Agee 2004, Thysell and Carey 2001, Tveten and Fonda 1999).

There are three key aspects to managing these systems: (1) releasing oaks from the overtopping conifers (and preventing future overtopping), (2) managing the understory to control species composition and development, and (3) establishing oaks and related species in areas where they are currently not present.

Many oak savannas or low-density woodlands have been invaded by conifers (fig. 34). Action to remove the conifers is time critical because the overtopped oaks and other vegetation are often of poor vigor and will not survive much longer. Because conifers will grow well on many of these sites, followup treatments will be needed to prevent future overtopping. Deciding to manage for oaks or open areas is a long-term commitment.

Currently, there are a number of research studies, management trials, and regular forest management activities aimed at improving the condition of the oak and prairie systems. Prescribed burning is an important tool in managing oak (Agee 1996) and is being used by some agencies to control understory conifers (as well as exotic weeds such as Scotch broom and Himalayan blackberry). However, the danger, cost, and smoke nuisance associated with burning make this a treatment that can only be used in limited areas. Where burning is not feasible, mechanical removal or herbicide treatment can be substituted.

Figure 34—Fire exclusion has led to widespread conifer encroachment and overtopping of remaining Oregon white oaks.

Black Cottonwood and Hybrid Poplars

Several small-scale but successful industrial cottonwood plantings were made along the Willamette and Skagit Rivers by paper companies (fig. 35), the earliest being a 60-acre plantation established in 1893 by Crown Willamette Pulp and Paper Co., the forerunner of Crown Zellerbach Corp. (Brandstrom 1957). However, these remained very small-scale efforts. Major interest in *Populus* is a recent development in the region.

Development of fast-growing *Populus* hybrids had been underway for many years in Europe and the Eastern United States. In 1939, two 1.0-acre (0.4-hectare) hybrid poplar plantations were established at the Cascade Head

Figure 35—T.T. Munger in 1914, in an early cottonwood plantation.

Experimental Forest and on Lady Island, near Camas, Washington (Silen 1947).

The energy crisis of the 1970s produced an interest in short-rotation plantations as a possible source of biomass for energy production. Department of Energy funding stimulated work with red alder and hybrid poplars in the Northwest, with projects at University of Washington, Washington State University, Seattle City Light, and the Olympia Forestry Sciences Laboratory. Clones and cultural information developed in these projects led to industrial investments in growing *Populus* for wood fiber.

With the passing of the immediate energy crisis, interest shifted from biomass energy to fiber production and—recently—to solid wood products. In the 1990s, considerable acreages of *Populus* plantations were established by industrial owners, much of it on former agricultural land (Hibbs and others 2004). Their economic viability is unclear at present.

Recent comprehensive summaries of the subject are Stettler and others (1996) and Dickmann and others (2001).

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Chapter 12: Changes in Society, Forest Management Objectives, and Supporting Silvicultural Research[1]

Over much of the history of northwestern forestry research, the primary, though not exclusive, interest was in timber production. This has changed markedly in recent decades. In this chapter, we briefly discuss some of the social changes and accompanying changes in public attitudes that have taken place in the Pacific Northwest and that have led to major changes in forest management objectives. We then discuss changes in research direction aimed at supporting current management goals.

Social Change and Silviculture

Many concerns that are today referred to as "environmental" influenced policy from the earliest days of North American forestry. Thus, the writings of Marsh (1864) and Hough (1873) and others warned of the need to do something about the state of the Nation's forests, and provided the stimulus for early legislation and establishment of the forest reserves (which became the national forests). The Organic Act of 1897 stated as objectives the preservation of the forests, improvement of water flows, and provision of a perpetual supply of timber. Activities and emphasis changed over time with changes in economic and political conditions and the development of transportation. Early efforts included rehabilitation of burns, fire protection, and exploration of regeneration methods after wildfire or harvest. Establishment of wilderness areas and research natural areas in the national forests began in the 1920s.

The selective timber management episode (Kirkland and Brandstrom 1936, Curtis 1998) (chapter 5) was an early—though unsuccessful—effort at a silvicultural alternative to large-scale clearcutting. The subsequent adoption of staggered settings (dispersed moderate-size clearcuts with intervening timber retained as a seed source) was an improvement over previous practices from the environmental as well as the timber standpoint, beneficial to populations of deer and elk and some other species. Efforts were directed toward control of insects and diseases, enhancement of tree and stand growth, and improvement of wildlife habitat.

Although timber production had been one of several public land management objectives from the beginning, its importance increased greatly during the economic boom following World War II (WWII). Improved transportation and research in logging engineering helped to reduce the impacts of harvest operations on soils and streams, and provided greater flexibility in application of silviculture. With improved access and increased disposable income and leisure time, public concerns about recreation and wildlife assumed increased importance and influence on management of public lands. Many, though not all, of the environmental concerns we hear today were addressed under the name of multiple use (Fedkiw, n.d.). Thus, the emphasis given to the various uses of forest land has been and is continually changing.

Great changes took place in the social and economic structure of the Douglas-fir region over the last half of the 20th century. Prior to the 1950s, much of the population lived in rural or small-town settings. Much of it was employed in natural-resource-based industries—agriculture, forestry, and fishing—and had direct contact with practical resource management. Many people were generally supportive of efforts to place timber production on a permanent basis as a mainstay of the economy, and realized that planned management with timber production as a major, though not exclusive, objective was a vast improvement over the forest liquidation and widespread fires of the not very distant past. There was little or no opposition to efforts in this direction. Many people were also keenly interested in management of game fish and wildlife species, although problems with salmon had not yet been generally recognized and nongame wildlife received little attention.

In the post-WWII period, there was a great and continuing influx of people from other parts of the country. Many

[1] By R.O. Curtis, D.S. DeBell, and M. Newton.

of the new immigrants came from urban backgrounds and had little direct contact with and little understanding of natural resource management or of regional history. Most settled in the expanding cities and found employment in urban-based industries such as aircraft, computers, and supporting services. Many saw little connection between their own well-being and the use of forests for commodity production. With increasing affluence and mobility, many came to value forests primarily for scenery and recreational use and as wildlife habitat. Many did not understand that forests are dynamic entities that are perpetually changing, with or without human intervention, and that it is not possible to perpetuate a given condition indefinitely. A substantial number regarded timber harvests as forest destruction and exerted increasing political pressure for withdrawal of public lands from commodity production and for restrictions on commercial forest operations. To some, large trees and old forests had unique spiritual values. A fringe element found in these attitudes a convenient excuse for disruption and vandalism, including criminal actions such as the arson fires that destroyed the Department of Natural Resources Land Management Center and Animal and Plant Inspection Service facilities in Olympia, Washington, in 2000 and the University of Washington Center for Urban Horticulture in 2001 and caused extensive damage to various facilities elsewhere.

Several developments in Douglas-fir silviculture exacerbated the conflicts among groups interested in the regions's forests. The shift to planting (primarily of Douglas-fir) as the primary regeneration method meant that it was no longer necessary to limit the size of clearcuts and retain seed blocks. Many owners used larger clearcuts to save on road and logging costs. Concurrently, there was a progressive reduction in rotations by many industrial and other private owners, motivated primarily by the desire to maximize net discounted timber values. The combined effect was creation of landscapes with extensive areas of unsightly recently cut land, with the rest of the landscape largely occupied by uniform young stands of a single species that are the least productive condition for many species of wildlife and that are regarded as unattractive by many people. Public reaction to these visual effects was an important factor in the developing opposition to clearcutting as a silvicultural system and to forestry operations in general.

The rise of the environmental movement in recent decades as a factor in Northwestern forestry is associated with these social and management changes. It has exerted an increasing influence on public policies, and has had major effects on both forest land management and silvicultural research. It has stimulated silviculturists and land managers to adopt broader perspectives, including increased consideration of social and ecological values. It has been a significant factor in directing more research toward management for multiple objectives including wildlife habitat, scenic values, biodiversity, and long-term sustainability, in addition to traditional commodity production goals. On the other hand, increased pressures and considerable sensational and often misleading propaganda from activist groups and individuals have at times overshadowed the efforts of more moderate groups. Conflicts and extreme positions often receive more attention in the news media than do constructive accomplishments. Contributing factors include (1) the difficulty that many people have in grasping the range of management options that exist and the timescales involved in forest development, (2) the increasing and sometimes exclusive public emphasis on wildlife, often directed at single species—as exemplified by the spotted owl recovery effort (mandated by court decisions); and (3) a romanticized and unrealistic view of "untouched nature" as an ideal condition, necessarily degraded by any human intervention. To some degree, the differences in viewpoints, values, and underlying philosophy extend into the scientific community, (for example, Salwasser and others 1997 vs. Noss 1995) and have been accentuated by lack of communication and mutual understanding between specialized disciplines.

Namkoong (2005) provided a wide-ranging discussion of the historical and cultural origins of the different conceptions of the nature and role of forests and the differing objectives, which range from short-rotation plantation forestry aimed exclusively at wood production at one extreme, to restoration of a mythical untouched nature at the other.

The tunnel vision evident in many land management disputes is not limited to the usual pressure groups and segments of the public. We like to think that "science" is unbiased, and no doubt it is, in the long run. But individual scientists have their own biases, whether they be silviculturists, ecologists, wildlife biologists, or whatever. They also can become preoccupied with pet topics, and are often unaware of existing knowledge and historical experience outside their immediate and sometimes narrow range of expertise. Also, the behavior of forests is influenced by the wide variations that exist within the region in soil and local climate, and by short-term weather fluctuations. Therefore, generalizations derived from individual studies that are not replicated in space and time can easily be misleading. Answers to many forestry questions are dependent on well-designed and well-replicated long-term experiments, which are expensive (and therefore few in number), dependent on continuity in funding and personnel, subject to disruption by pests and climatic events, and likely to be lost to the pressures for quick answers to the question of the moment. There is therefore, at best, considerable uncertainty in interpretation of existing science.

Incomplete knowledge and conflicting viewpoints and objectives have resulted in land management policies that are increasingly driven by political considerations and judicial decisions, some of which have had considerable effects on research.

Several factors affecting research on federal lands are associated with the Northwest Forest Plan (FEMAT1993), Record of Decision (ROD) (USDA FS 1994) These include:

- Inadequate funding and other limitations to conducting large-scale manipulative research over a sufficient range of conditions and practices.
- The near-failure of the adaptive management areas (AMAs) of the Northwest Forest Plan. The AMAs were intended to encourage federal land managers to try new and bold approaches, but have not generally been effective. Obstacles have resulted from lack of organizational support and from an institutional and regulatory environment that stymies innovation and makes managers unwilling to accept risks of failure and unwilling to try nonstandard practices that may provoke conflicts with segments of the public (Haynes and Perez 2001; Stankey and others 2003, 2006).
- Single-purpose set-asides or constraints that have curtailed or shut down ongoing research and negated the very purposes for which long-time research areas were dedicated. For example, inclusion of the Wind River and Cascade Head Experimental Forests in late-successional reserves.

Allied to these problems is the difficulty and frequent inability to conduct experiments on federal lands because of delays and disruptions associated with the regulatory and appeals processes (which can destroy the validity of an experiment), exclusion of large areas from any manipulation, and reluctance of managers to allow treatments that might provoke opposition or that conflict with existing guidelines. These difficulties are manifestations of what has been variously termed the "process predicament" and "analysis paralysis," in which the multitude of overlapping and sometimes conflicting laws, regulations, and court decisions render timely and effective action on anything almost impossible (Thomas 2000, USDA Forest Service 2002). One result is that some researchers in the Pacific Northwest, have abandoned attempts to work with the national forests in favor of state agencies and industrial owners.

Contributing factors include the general tendency of regulations, guidelines, and policies—necessarily based on incomplete knowledge and often influenced by political factors and judicial decisions—to become fixed dogma. Likewise, the tendency under the Endangered Species Act to direct effort toward individual species to the exclusion of other considerations, including the habitat needs of many other species.

The current prohibition on most uses of herbicides on most federal lands in the Pacific Northwest is an example of a policy driven by public attitudes that has had serious effects on land management and considerable impacts on silvicultural research. Segments of the public are opposed to any use of "chemicals," an attitude that initially stemmed from harmful effects on wildlife of widespread use of the persistent insecticide DDT and was reinforced by the military use of "Agent Orange" as a defoliant and crop destruction tool in the Vietnam War. Negative perceptions have been reinforced by the tendency of the public and the media to lump all such materials under the generic term "pesticide," without recognizing that there are a wide variety of such materials, and that these differ in persistence, mode of action, environmental effects, and uses.

Alleged human health effects from use of 2,4,5-T on the Siuslaw National Forest (Newton and Young 2004, US EPA 1979, Wagner and others 1979) led to suspension of use of herbicides on most federal lands in the Pacific Northwest in 1983. Subsequent development of herbicide technology and herbicide use continued elsewhere. Despite convincing evidence that currently used herbicides are often less expensive and more effective, safer, and more benign in their effects on the environment than alternative methods of controlling unwanted vegetation, that amounts used in forestry are very small compared to those routinely used in agricultural and other applications (Kimmins 1999: 129–138), and that currently used herbicides have not been shown to have harmful effects, advocacy groups opposed to any herbicide use have been successful in preventing nearly all use of herbicides on federal lands. This is a major limitation in cost-effective restoration of forests on burns and other nonstocked areas and in the control of invasive species and vegetative competition.

Dogmas do not all originate outside the forestry community. Historically, one may cite the clearcut-burn-plant-Douglas-fir regime that was nearly universal from about 1950 to the 1990s, as an example of silvicultural dogma. This regime was highly successful as a means of establishing prompt regeneration, and came to be accepted by a generation of foresters as **the** regime for management of Douglas-fir. But, its near-universal application in combination with progressively shortened rotations has had undesirable effects on public attitudes, scenic values, and many species of nongame wildlife. And, because of its very success in the context of the timber-oriented needs of the time, very little research was done on possible alternative regimes until quite recently.

Another forestry dogma was the goal of total elimination of wildfire, almost universally accepted until quite recently. This had only limited effects in the northern portion of the Douglas-fir region, but considerable effects in the drier climate of southwest Oregon and northern California.

There are older examples of historical interest. Thus, Fernow's 1903 attempted application of practices widely accepted at the time in his native Germany was halted, and the Cornell forestry program terminated, because of public reaction to visual effects (Dana 1953, Rodgers 1991). Lesson: public attitudes can and often do override science and economics and must be considered in silvicultural decisions.

Ernst (1998) recounts the conflicts over early introduction of block clearcutting and regeneration in Germany, which was prohibited by a court decision in one jurisdiction in 1764. Despite conflicts, it was widely adopted and was highly successful in rehabilitating extensively degraded forests, though considerably modified in more recent times. Lesson: the clearcutting furor of the recent past is nothing new!

The environmental historian Radkau (1996), reviewing the changes in German attitudes to forestry over the past several centuries, concluded with the statement:

> . . .even those foresters who have the good will to think ecologically do not find a common basis with environmental fundamentalists who want to ban economic considerations from the woods. . . If environmental history is able to produce any practical benefit, it could do so by overcoming the

> estrangement between forestry and the environmental movement. . .by criticizing dogmatic tendencies on both sides and arguing against the trend of playing off ecology against economy.

Lesson: North American problems are not unique.

Sustained Yield, Multiple Use, Ecosystem Management, and Sustainable Forestry

By the 1990s, differences in attitudes and understanding had created a degree of polarization that drastically impacted forest management and the economy of many small timber-based communities. It also produced marked changes in direction of research by public agencies. These changes included a great expansion in wildlife- and wildlife-habitat-related research, and initiation of research—most of it necessarily long-term—on silvicultural practices and regimes designed to promote scenic and wildlife values. Particularly, on those characteristics commonly associated with late-seral conditions and old-growth-dependent wildlife. There was also renewed interest in selection systems, natural regeneration, and species other than Douglas-fir.

Traditional commodity-oriented areas of research such as regeneration, pruning, fertilization, and tree improvement continued, but were now carried out primarily by the various landowner-supported research cooperatives at the universities. There was also considerable research by major industrial owners, some of it in cooperation with the universities and public agencies.

In this period, a number of new terms were added to traditional forestry terminology, ostensibly to describe changing management objectives.

Sustained yield is a long-established term for a management objective that dates from the early 19th century or earlier in Europe, and was increasingly adopted in the United States from the 1930s on. Originally, it denoted organization and management of a forest property for continuous timber production with the aim of achieving—at the earliest practicable time—an approximate balance between growth and harvest. By the late 20th century, the larger ownerships in the region were far along in conversion to continued production, although attainment of a balance between growth and harvest was often delayed by unbalanced stand age distributions and by disruptions associated with ownership changes in the private sector and land use allocation changes in the public sector.

The historical definition of sustained yield was broadened in its application to the national forests by the Multiple Use-Sustained Yield Act of 1960, which stated (Sec. 4):

> Multiple use means the management of all the various renewable surface resources so that they are utilized in the combination that will best meet the needs of the American people;. . .and harmonious and coordinated management of the various resources. . .without impairment of the productivity of the land, with consideration given to the relative values of the various resources, and not necessarily that combination of resources that will give the greatest dollar return or greatest unit output.
>
> Sustained yield of the several products and services means achievement and maintenance in perpetuity of a high-level annual or regular periodic output of the various renewable resources without impairment of the productivity of the land.

Ecosystem management and **sustainable forestry** are terms of recent origin. To us, they appear little different in meaning from the 1960 definitions given above. These terms appear to have come into use as an attempt to distinguish between certain past practices (particularly, large-scale clearcutting) and current practices and proposals, and to offset the perceptions of some to whom "sustained yield" and "multiple use" have connotations of a primary emphasis on timber production. Shifts in emphasis include de-emphasis of timber production in favor of a more holistic view emphasizing—in addition to the traditional multiple-use concerns for game animals and recreation—maintenance of biodiversity and ecosystem function, visual effects, and avoidance of hypothesized deleterious long-term effects from some forms of management (Hobbs and others 2002b).

This collection of ideas is also associated with the closely related term "new forestry," common in the 1990s.

There remains a wide gulf between those environmental groups philosophically opposed to any form of active management, and more moderate enviromental groups who believe that "do nothing" policies are neither biologically nor economically feasible in the long run. Unfortunately, concentration for the past half century on a single form of management—clearcutting, planting one species, and steadily decreasing rotation lengths—has provided the public with few on-the-ground examples of the long-term effects of alternative practices.

Over the past 15 years or so, there has been a great increase in research by ecologists and wildlife biologists on the relations between forest conditions and populations of small mammals, birds, lichens, and other organisms (Bunnell and others 1997). The main conclusions appear to be (1) large woody debris and large snags have a role in maintaining populations of certain small vertebrates and birds, (2) large trees and snags have value as refugia for organisms such as lichens that may have difficulty in recolonizing large open areas, and (3) different species have different requirements, and no one condition is favorable to all. Quantitative relationships between amounts of woody debris, snags, residual trees, and size and distribution of openings on the one hand, and their effects on the various wildlife and plant species on the other, are not well defined. Because species differ in their habitat requirements, maintenance of all species also requires provision of a wide range of habitat conditions (DeBell and Curtis 1993, Kohm and Franklin 1997). The current emphasis on "biodiversity" does not necessarily require diversity within each stand; biodiversity may be better achieved by a mosaic of diverse conditions at the landscape level (Boyce 1995, Kimmins 1999).

The emphasis on development of stands with late-seral characteristics arose in part because old growth was perceived as in short supply. In turn, this implies that on some portion of the land base, management should strive to create conditions with some of the attributes of late-seral stages—large trees, large snags, down wood, and layered structure (McComb and others 1993). Silviculture can accelerate the rate of development of these characteristics to a degree that is not generally realized. Much current silvicultural research is directed at accomplishing this acceleration, through changes in thinning regimes, harvest and regeneration practices, and rotations. This includes both new work and reinterpretation of work done in the past.

Curtis and others (1998) synthesized existing knowledge related to silviculture for multiple objectives and showed that the knowledge base is far greater than generally known outside the field of silviculture. Several papers included in Monserud and others (2003) and in Hobbs and others (2002b) also reviewed knowledge and ongoing research in multiple objective management, including specifically the promotion of biodiversity.

The change in emphasis has increased interest in silviculture of Northwestern hardwoods, associated in part with the new concerns with biodiversity. There is also more emphasis on the visual effects on the landscape, on public perceptions of silvicultural practices, and on the possibilities of using alternative silvicultural systems.

Visual Effects and Public Perceptions

The conflicts that have developed in recent years between the perceptions and desires of an urbanized public primarily interested in scenic, recreational, and wildlife values, and the economic needs for efficient commodity production and support of the rural economy, constitute the most serious problem in Northwestern forestry today. To a considerable extent, these conflicts arise from the high visibility of forestry operations on the landscape. There is thus a growing interest in silvicultural measures that may reduce conflicts while maintaining some reasonable level of commodity production. Such measures include different sizes, shapes, and arrangements of harvest areas; different amounts of green-tree retention on harvest areas; and extended rotations combined with increased emphasis on thinning. A number of studies over the past two decades have addressed the questions of (1) visual acceptability of alternative practices and (2) the costs involved (Clausen and Schroeder 2004).

Visual acceptability questions are often addressed by surveys in which respondents are asked to rate examples of typical practices, presented either as on-the-ground examples or—more frequently—as photographs or pictorial images. Typical examples are work by Brunson and Shelby (1992), Shelby and others (2003), Bradley and others (2004), and Ribe (2005). An important aid in such studies is visualization software (McGauhey 1998), which can create images of anticipated conditions. In general, results indicate that acceptability decreases with increased size of openings, with decreased number of retained trees in partial cuts, and with increased amounts of slash and down wood.

A drawback of many visual acceptability studies is that they tend to concentrate on conditions shortly after harvest rather than average condition over the life of the stand, or the landscapes produced by application of a regime over an extended period. Unfortunately, we have at present no concrete examples of the landscapes that can be expected from long-term application of regimes (including "do-nothing") other than conventional short-rotation even-age management.

Figure 36—It is now common practice to leave scattered green trees or groups of trees and snags on harvest areas for wildlife and other purposes. Although superficially resembling past seed-tree cuts, the trees are not retained for regeneration purposes.

Green-Tree Retention

Retention of scattered overstory trees, either as groups or scattered individuals, for presumed, though largely unquantified, wildlife and ecological benefits (Aubry and others 2004, Franklin and others 1997, Mitchell and Beese 2002) is now a common and in part a legally mandated practice, superimposed on even-age management (fig. 36). As amount of growing stock retained increases, there is a transition from more-or-less conventional even-age management to uneven-age management with either two-aged (reserve shelterwood) or patch- or group-wise uneven-aged structures.

There have been several attempts to evaluate the effect on timber production of retention of overstory trees (green-tree retention). Lacking permanent-plot data, most studies have been retrospective in nature (examples: Wampler 1993, Zenner and others 1998) or simulations (example: Birch and Johnson 1992). These indicate—as would be expected—that green-tree retention reduces growth of the understory, with reduction increasing as number of trees retained increases. It may also increase the difficulty of controlling competing vegetation.

The recently established DEMO study (Demonstration of Ecosystem Management Options) is a large regional study with six replications, designed to examine the ecological effects of several amounts and physical arrangements of green-tree retention after a single harvest operation (Aubry and others 2004, Franklin and others 1999). As originally planned, it made no provision for postharvest vegetation management or density control and therefore does not mesh well with other research and applications aimed toward sustainable management regimes.

Nontraditional Thinning

The LOGS (Levels-of-Growing-Stock) study in Douglas-fir (Curtis and others 1997) and a variety of other less elaborate thinning trials have shown that early and repeated uniform thinning can produce dramatic increases in individual tree growth and understory development. On good sites, large trees can be produced at relatively young ages.

Retrospective studies of operationally thinned and unthinned mid-age stands, and of age distributions and stand structures in old-growth and young-growth forests, have shown that appropriate thinning of mid-aged stands hastens the development of multistory stands (Bailey and Tappeiner 1998, Poage and Tappeiner 2002) and that many existing old-growth stands were established at much lower densities and with a much greater range in ages than young growth established following harvest. The marked differences in developmental trends suggest that in the absence of active management, many existing young stands will not develop into stands similar to existing old growth (Tappeiner and others 1997). Muir and others (2002) provided a comprehensive review on the potential of thinning for shaping stand development and suggested general guidelines for thinnings in young Douglas-fir forests to promote biodiversity and development of late-seral characteristics.

Most older thinning studies in Douglas-fir have applied uniform thinning to uniform even-aged stands. Treatments have usually been either low thinning or crown thinning, differing only in amount of growing stock retained and frequency of thinning. Several thinning studies have been established recently to examine techniques for promoting development of diverse stand structures through unconventional irregular thinning. Associated with these trials are efforts to maintain or establish secondary species.

One such study in young Douglas-fir plantations compares development of unthinned stands with stands treated with regular thinning, irregular thinning to create gaps, and with and without supplemental planting of other species in the gaps (Reutebuch and others 2004) (fig. 37). The first block was installed in a large area of uniform plantation in the Mount St. Helens blast zone.[2] An additional block was subsequently installed on the Willamette National Forest, and a very similar trial was established by Washington Department of Natural Resources[3] in the Forks area.

A second large-scale study involves irregular thinning in several mid-aged stands on the Olympic National Forest (Harrington and others 2005). A third study is in mid-aged stands on the Fort Lewis military reservation (Carey and others 1999). A fourth somewhat similar study was established at about the same time by Oregon State University and the Willamette National Forest. All recent studies use much larger treatment areas than the small plots (0.4 hectare or less, 1 acre or less) typically used in early thinning studies.

A large study at Oregon State University is designed to evaluate silvicultural practices to promote understory structure and diversity combined with overstory maturation, as stands mature in a two-story system. Several reports have described overstory effects on understory (Brandeis and others 2001a, 2001b, 2002) and damage to understory in rethinning (Newton and Cole 2006). Several other trials with broadly similar objectives, recently established by a number of organizations, are listed in Hunter (2001).

It has been commonly thought that old trees will not respond to thinning, a belief that probably stems in part from the unfavorable results of early selective cutting (chapter 5), in which choice of residual trees was largely dictated by immediate economic rather than silvicultural considerations. Recent work (Latham and Tappeiner 2002) has shown that, in many cases, removal of understory and less vigorous

[2] Lead scientist is Connie Harrington, Forestry Sciences Laboratory, Olympia, WA.

[3] Lead scientist is Richard Bigley, Washington Department of Natural Resources, Olympia, WA.

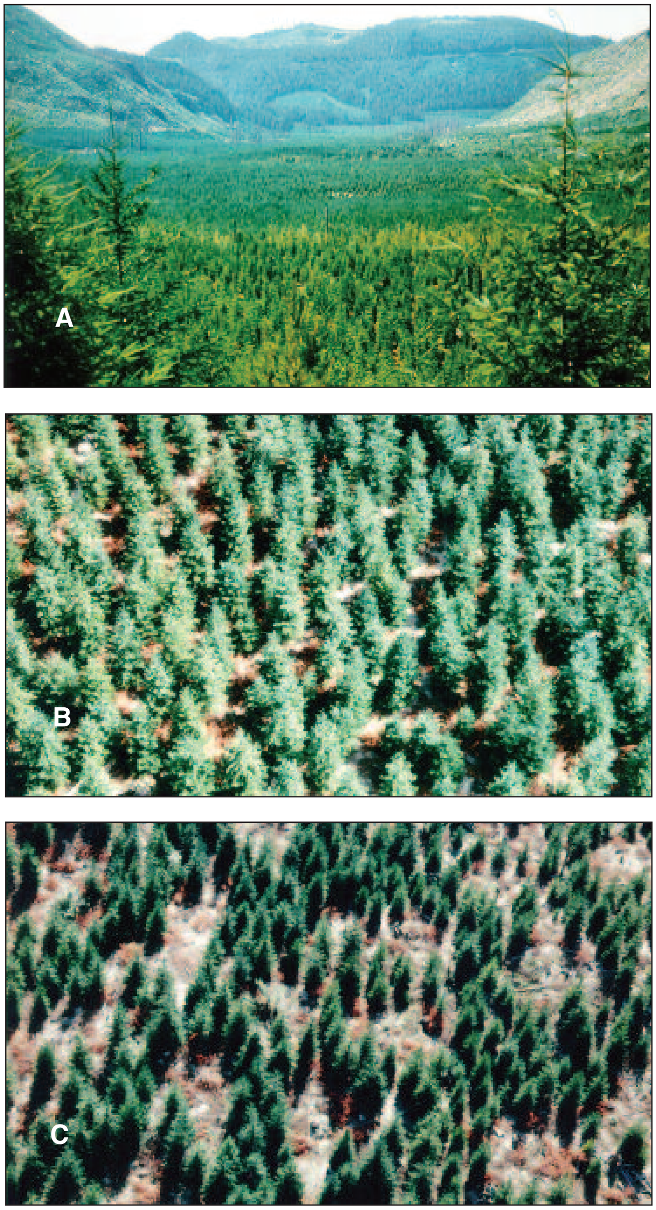

Figure 37—Experimental thinning in a plantation in the Mount St. Helens blast zone, aimed at creating irregular stand structure to enhance biodiversity: (A) uniform plantation, (B) uniform stand created by conventional precommercial thinning, and (C) irregular thinning.

trees accelerated growth of trees 200 or more years old. This not only promotes development of larger trees, but can be expected to reduce susceptibility to bark beetle attack, and possibly somewhat reduce the risk of stand-replacing fires.

Forest Health Issues

Sporadic minor damage from weather, insects, and diseases is a normal part of stand development, and in recent years the Douglas-fir region has been largely free from catastrophic damage. This is due at least in part to the prevalence of vigorous young stands, in contrast to the overstocked and low-vigor stands that are currently a major problem in forests east of the Cascade crest. Silviculture is the principal means of preventing or controlling a variety of damaging agents (Curtis and others 1998: 67–72). Recent changes in silvicultural practices and management policies may have effects on west-side forest health, which have as not yet been well evaluated.

The most serious diseases are the endemic root rots. Control consists in removal of infected trees followed by planting of resistant species (or removal of infected stumps). Recent interest in use of resistant species such as redcedar, red alder, and white pine to increase species diversity is consistent with control of root rots.

Extensive damage by Swiss needle cast (*Phaeocryptopus gaeumanni*), an organism formerly considered innocuous, has occurred recently on Douglas-fir plantations within or near the Sitka spruce zone. Causes are uncertain, but a plausible hypothesis is that the needle cast problem is associated with extensive planting of pure Douglas-fir (perhaps from nonlocal seed sources) on sites formerly dominated by hemlock and spruce.

In the past, the most serious insect problem has been the Douglas-fir bark beetle (*Dendroctonus pseudotsugae*). Losses to bark beetles are usually a minor factor in young vigorous stands, but large and very damaging outbreaks have occurred at intervals in the past, usually triggered by extensive blowdown or fire events (Furniss and Carolin 1977). Control is by prompt salvage of infested trees, and by appropriate thinning to maintain vigor and windfirmness. This is no longer possible on some public lands because of conflicts with reserve status and opposition by segments of the public. Hence the risk of future major outbreaks is increased.

Dwarf mistletoe (*Arceuthobium tsugense*) can be seriously damaging in hemlock. The older practices of clearcutting and broadcast slash burning were effective in controlling the problem. The shift to green-tree retention and efforts to develop multilayered stands have the potential to increase future infestations through spread from the retained trees to regeneration.

Understory development, layered stands, and increased amounts of coarse woody debris—although desirable from the standpoints of wildlife habitat and visual effects—can also increase fire risk through increased fuel loads and creation of fuel ladders that can carry fire into tree crowns. This is of particular concern in the southern and drier part of the region, where the presettlement pattern was one of relatively frequent light burns in contrast to the stand-replacing fires that occurred at long intervals farther north (Agee 1993). Appropriate thinning (followed by underburning in some situations) can reduce fuel loads and minimize the risk of intense fires.

Stand density control (initial spacing, thinning) can markedly reduce the risks of wind and snow damage (Wilson and Oliver 2000) and also enhance resistance to bark beetle attack, by lowering height/diameter ratios and increasing tree vigor.

Animal damage is often serious. With the general shift to planting rather than natural regeneration, seed consumption is no longer as critical as it once was. But browsing of seedlings by deer and elk, mountain beaver damage to seedlings and saplings, and bark stripping by bear are all serious problems. Deer and elk browsing is the principal obstacle to wider use of redcedar, otherwise silviculturally and ecologically desirable. There has been extensive research on animal repellents, physical barriers to browsing, use of large planting stock, and supplemental feeding in efforts to overcome the problems (for example, Black 1992, Newton and others 1993, Nolte and Otto 1996). Success has been limited, and animal damage remains a serious problem in many areas.

Nontimber Forest Products

Commercial harvest of nontimber forest products, although not new (Adams 1960, Isaac 1945), has become an economically important activity in recent years. These products include Christmas trees, floral greens (swordfern, salal, Oregon grape, boughs, moss), beargrass, mushrooms, huckleberries, and medicinal plants. To some extent, productivity can be influenced by silviculture, most notably through stand density control. Christmas tree and bough production can be a part of precommercial thinning. Development of understory species is influenced by stand density and by stand age.

Research is in progress on management of nontimber forest products, which necessarily involves silviculture, and which we do not review here. General discussions and extensive references are given by Duncan (2003), Kerns and others (2003), and Molina and others (1997).

Growth Trends, Rotations, and Carbon

Important research and policy questions are involved in choice of management regimes and rotations and their possible effects on carbon sequestration and climate change.

Reexamination of permanent-plot data from past experiments has shown that culmination of mean annual increment in Douglas-fir is later than commonly thought, and is probably delayed by repeated thinning. Considerable extension of commonly used rotations is possible without loss of volume production (Curtis 1995, Newton and Cole 1987), and possibly even with some increase in value production. Moderate extension of rotations combined with greater use of thinning could markedly reduce visual and environmental effects of harvest operations while increasing employment, long-term timber yields, tax revenues, carbon sequestration, wildlife values, and flexibility to respond to future unknown social and economic changes (Curtis and Carey 1996).

Carey and others (1999) simulated three alternative management strategies for an area on the Olympic Peninsula—no management with protection, maximization of net present value of timber (clearcutting on 40- to 50-year rotations, with required riparian buffers), and a "conservation of biodiversity" strategy (Carey and Curtis 1996) using a mix of treatments including extended rotations. They concluded that the "conservation of biodiversity" strategy developed a target proportion of late-seral stands much sooner than did the protection-only alternative; produced nearly as much timber as the "maximum net present value" alternative; minimized area in the stem-exclusion stage (Carey and Curtis 1996), in which development of understory vegetation is prevented and some trees become suppressed and die; and was generally more desirable from the ecological and wildlife standpoints. Although the cost in terms of reduced net present value of timber was higher for the "conservation of biodiversity" strategy than for the maximum net present value strategy, the differences were not large. Lippke and others (1996) concluded that the benefits in enhanced employment, tax revenues, and carbon sequestration were sufficient to justify some form of publicly funded incentives to compensate landowners for the added financial costs.

In recent years, there has been much public concern about climatic warming and its possible consequences, the marked increase in atmospheric CO_2 (attributed to use of fossil fuels), and the possibility that the latter is a major causal factor in climatic change and is subject to some degree of human control. Forests store large amounts of carbon, and both afforestation and modified silvicultural regimes are potential means of increasing carbon sequestration. There is also a future possibility of plantation-based biomass energy production, without the net CO_2 production inherent in the use of fossil fuels (Larson and Johanssen 2001). A goal of increasing carbon storage has at least two aspects that affect silviculture and needs for silvicultural research:

- Change in growth conditions associated with predicted warmer climate and increased atmospheric CO_2 could affect species and family adaptation and susceptibility to insects and disease. It could also require modification of growth functions and simulation programs used to predict development of forests.
- The most obvious silvicultural regime changes for the purpose of increasing carbon sequestration are an increase in rotation length with an associated increase in growing stock (Harmon and Marks 200, Haswell 2000, Peterson and others 2004), combined with minimal slash removal. Longer rotations would also benefit long-term wood production, wildlife habitat, and scenic values.

The principal difficulties in any extension of rotations are (1) temporarily reduced cash flow for those owners currently lacking older stands; (2) reduced net present (discounted) value of future timber yields, which in the absence of other incentives is an overriding consideration for those owners whose primary objective is maximum percentage return on their timber investment; and (3) recent conversion of many mills to processing small logs, with resulting loss of price premiums and markets for large logs. The potential benefits of extended rotations are primarily public benefits that do not accrue to the individual owner. Thus, extended rotations are at present primarily an option for public ownerships. This situation could change if present and predicted climatic trends lead to active public programs that encourage carbon sequestration via carbon credit trading or other forms of direct or indirect subsidy.

Riparian Silviculture

West-side stream conditions have been markedly changed since the first European settlement. Factors involved include extensive urbanization with attendant changes in runoff, stream temperatures, and stream pollution; logging; dams that obstruct the passage of fish; agricultural operations; and clearance of stream channels to facilitate transportation (including early-day log transport and fish passage). Marked declines in salmonid populations have occurred in the past several decades. The decline is at least partially attributable to the off-shore fishery. Nevertheless, the decline is widely perceived as having its origins in declining quality of freshwater habitat. Salmon recovery has been a major public concern for a couple of decades, leading to restrictions on forest operations in riparian zones. At present, such restrictions not only limit forest operations in riparian zones for either harvest or stand improvement, but also complicate efforts intended to enhance spawning and survival.

Forests are not static, and presettlement conditions included periodic large-scale disturbances (fire, windfall) and debris flows that influenced stream productivity (Reeves and others 2002). Timber harvest has in part replaced fire as a major influence, analogous to but not the same as presettlement disturbances. Low-elevation riparian zones, especially those characterized by significant terraces, are frequently occupied by red alder, a species with a limited life expectancy leading to shrub-dominated communities as overstories senesce (Newton and others 1968). The dilemma today is how to create a level of disturbance that ensures establishment of coniferous stands as characterized in the Oregon criteria for desirable future conditions (Oregon Department of Forestry 2003).

In the 1950s and 1960s, governmental programs favored removal of wood from streams in the belief that this would facilitate passage of fish (Reeves and others 2002). It was subsequently recognized that large woody debris is important in forming pools essential to spawning and survival, and current policies aim to provide such material together with streamside shading to maintain low water temperatures.

Recent research on riparian silviculture includes efforts to provide cover needed for cool streams and productive aquatic communities, to ensure production of large, durable conifer wood to enhance stream habitat (Bilby and Bisson 1998), and to enhance development of late-seral conditions. Several events, beginning with reports by Brown (1969) and Brown and Krygier (1970), led to concerns with streamside cover and water temperature interactions. This was reinforced by the Forest Ecosystem Management Assessment Team report (FEMAT 1993). The recent listing of many strains of salmon as threatened has stimulated interest in how riparian forests can be managed to ensure the future of the salmon resource.

Much of this research is concerned with determining effects of streamside buffers vs. no buffers, and occasionally with buffer characteristics; with techniques for promoting desired conditions; and with the possibilities of combining limited timber production from riparian areas with stream protection. Extremely restrictive buffer requirements have major economic impacts, and the future of stands without maintenance is uncertain. Stream-side vegetation changes over time, and some stream-side conditions present today as a result of previous disturbance are unlikely to develop desirable characteristics in the long run. Producing large conifer material for stream channel improvement has been identified as an important value of mature forests adjacent to streams (FEMAT 1993, Oregon Department of Forestry 2003). Much research in the last 20 years has been devoted to active management measures aimed at establishment and maintenance of conifers and multilayered canopies in the riparian zone. Salo and Cundy (1987) provided a major work on interaction of aquatic and terrestrial systems that led to both regulatory activity and research to resolve issues on influence of streamside forests. Walsh (1996) provided some of the first insights on how buffers and their arrangements influence aquatic insects that are a major prey base for fish. Newton and Cole (2005) expanded this to include concepts of establishing several species of conifers as long-term streamside cover following conversion from red alder.

Several major initiatives have emerged in the past decade that illustrate the cooperative nature of programs within Oregon to resolve conflicts and illuminate some unresolved questions in riparian management. The Coastal Oregon Productivity Enhancement (COPE) program brought together federal, state, and private resources in a major 10-year effort to improve understanding of the roles of terrestrial and aquatic portions of the stream environment and how these influence stream biota. Hobbs and others (2002a) summarized the findings of this program, which mostly dealt with stream processes and ecological assessment of coastal forests. Very few manipulative experiments were conducted, and the need for quantitative analysis of the specific impacts of forest practices remains.

Concurrently with COPE, several other cooperative efforts between the university and state and industrial forest landowners have led to improved understanding of the effects of harvest practices on water temperatures (Zwieniecki and Newton 1999) and of opportunities to improve streamside stand composition while maintaining stream productivity. Newton and Cole (2005), for example, discussed rehabilitation of riparian hardwood forests and the size of overstory openings needed to secure satisfactory juvenile growth of conifers. They also observed that riparian reforestation depends heavily on protection from ungulate browsing and beavers. Zwieniecki and Newton (1999) and Newton and Cole (2005) have shown that harvesting close to streams while leaving narrow buffers or strategically designed residual shade can maintain cool streamwater, while providing opportunity to establish large durable conifers close to streambanks. Their work and that of Rutherford and others (1999) also showed that stream productivity can often be increased by allowing diffuse light to reach the stream. Skaugset[4] provided evidence that timber harvest along non-fish-bearing headwater streams did not have a warming influence on downstream waters, although some unbuffered streams warmed appreciably within units. These reports reinforce the hypothesis that streamside harvests, at least in small headwaters streams, would not lead to cumulative warming.

Chan and others (2004) reported a current large-scale stand management experiment on Bureau of Land Management lands in western Oregon that includes comparisons of stream-buffer widths and within-buffer silvicultural treatments. Early results suggest that differences in residual thinning densities and buffer widths result in relatively small changes in the riparian environment, and that these effects are not associated with detectable changes in riparian-dependent organisms. Clearcutting is not a factor in this study; all streams were buffered by stands thinned to various densities. Long-term renewal of the streamside coniferous cover was not evaluated.

Integration of stream treatments with fish-biology research is now recognized as crucial. The Watershed Research Cooperative at Oregon State University and the Headwaters Research Cooperative, a consortium of landowners and agencies, has been formed to conduct research on managed watersheds and to collect and disseminate monitoring data on stream systems. One major company (Roseburg Forest Products) has contributed a 5,000-acre (2000-hectare) watershed plus considerable infrastructure in support of the Watershed Research Cooperative's Paired Watershed Study, which is a long-term initiative to evaluate the effects of intensive management on fishery resources. Two more paired watersheds on industry and state lands are currently under evaluation. Collectively, results from these studies will likely have a major effect on policies affecting streamside silviculture.

Good general discussions on riparian silviculture with extensive references are Hayes and others (1996), Hobbs and others (2002b), and Cunningham (2002).

Comparisons of Silvicultural Systems and Management Regimes

Silvicultural research in the past was typically carried out on small plots selected for uniformity and comparability of initial conditions and with close control of treatments. Given suitable experimental designs, statistical tests were easily applied. Although small-plot experiments have provided much valuable information on forest biology and on development of trees and stands, their results are often not directly applicable to the larger and more heterogeneous areas that a manager must deal with. And they cannot provide information on variables that cannot be evaluated on small areas, such as wildlife and visual effects.

A few recently established long-term studies are designed to compare results and costs of alternative management regimes that aim to combine timber production with reduced visual and ecological impacts (Arnott and Beese 1997; Maguire and Chambers 2005; McComb and others 1994; Monserud 2002, 2003). As one example, a

[4] Skaugset, A. Processes that influence the downstream propagation of stream temperatures. Manuscript submitted to *Forest Science*.

large replicated study involving the Pacific Northwest Research Station, Washington Department of Natural Resources, and the British Columbia Ministry of Forests compares costs and yields for conventional clearcutting, two-age management, repeated small-patch cutting with repeated thinning of the matrix, group selection with repeated entries, and continued thinning on an extended rotation (Curtis and others 2004, DeBell and others 1997, De Montigny 2004) (figs. 38 through 44). The treatments are expected to produce widely different stand structures with corresponding differences in visual effects, wildlife effects, and acceptability to the public. This study differs from DEMO in that it is a comparison of regimes rather than of results from a single entry. Conversion of the large units used will extend over the next half century, and a variety of intermediate growth-enhancing treatments will be applied.

Several other long-term operational-scale experimental trials of alternatives to conventional clearcutting are in progress in the United States and western Canada (Monserud 2002, Peterson and Maguire 2005). Large treatment areas are required to provide realistic evaluations of operational timber yields, costs, stand structural changes, and scenic and wildlife effects. These cannot be provided by the small-plot experiments common in the past.

Large-scale long-term experiments involve some major challenges:

- It is difficult to find large treatment areas that can be considered comparable. At best, there is much uncontrolled variation that reduces the power of statistical tests.
- Variation in soils and local climate make replication in time and space important for valid generalizations of results.
- The variety of questions and likelihood of future unforeseen questions make an interdisciplinary structure highly desirable.
- They require close cooperation and coordination between the research and land managing organizations.

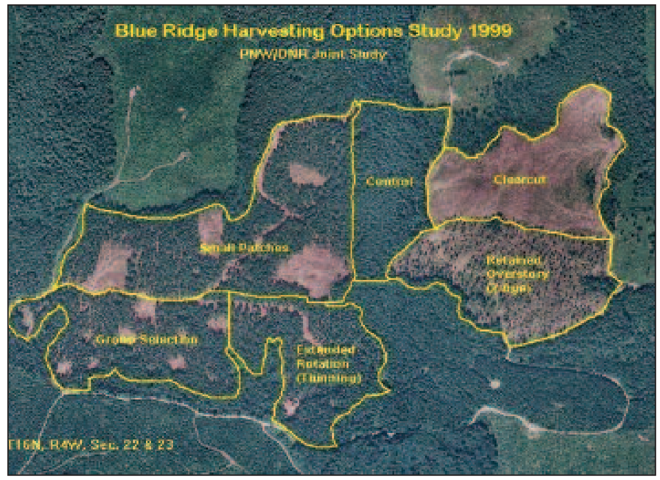

Figure 38—The Blue Ridge replication of the Silvicultural Alternatives for Young-Growth Douglas-Fir Forests study, established in 1998 in a stand of 1929 natural origin after cutting and fire. Several other experiments of similar nature are in progress in the region.

Figure 39—Control unit at Blue Ridge, with abundant understory of suppressed hemlock. It was thinned about 1970 prior to study, with no subsequent treatment.

- They must be continued over a long period if they are to answer questions about the long-term results of alternative regimes. Consistency over time in treatments and procedures is necessary and difficult to obtain.

Figure 40—Clearcut treatment at Blue Ridge at year 6 after planting: (A) planted Douglas-fir with some naturally seeded hemlock, and (B) leader growth of Douglas-fir in full light.

Figure 41—Two-age treatment at Blue Ridge, intended to develop a two-storied stand, 6 years after underplanting with Douglas-fir. Considerable natural hemlock regeneration is present. Overstory left after cut was 16 trees per acre (39 trees per hectare) with a stand basal area of 46 square feet per acre (11 square meters per hectare).

Figure 42—Patch cut treatment at Blue Ridge, six seasons after planting.

- They are expensive to establish and maintain, and are therefore in competition with activities aimed at quick answers to the question of the moment.
- They are heavily dependent on continuity in personnel and on support by both the research and administrative organizations.

Figure 43—Group selection treatment at Blue Ridge after six growing seasons.

Figure 44—Continued thinning treatment at Blue Ridge.

- Like all long-term experiments, they are liable to disruption by unplanned events (fire, pests, political changes, interrupted funding).

Nonetheless, such experiments are sorely needed to address many important questions. Lacking long-term experimental data, present estimates of long-term results of alternative silvicultural regimes are necessarily based on extrapolations and simulations that become increasingly suspect as they are extended to ages, treatment regimes, and stand conditions outside the range of existing data. And, on-the-ground demonstrations showing the feasibility of alternative regimes may be more important in a practical sense than statistical significance of small differences.

Chapter 13: Evolution of Applied Forest Management Practices[1]

Forest management practices have been and are continually evolving. Formal forestry research has been an important factor in the process, but it is only one of the factors involved. Progress in applied silviculture comes from the interaction of research results, observation and experience of managers and silviculturists, changes in harvesting and manufacturing technology, and a continually changing economic and social environment. Flora (2003) provided a good account of these changes from an economist's viewpoint.

In the following sections we briefly review the historical changes in forest management that parallel and were influenced by the development of silvicultural research.

Forest Management Changes: 1900–1925

Establishment of the U.S. Forest Service in the Department of Agriculture, by merger of the former Bureau of Forestry with the forest reserves, provided an effective organization for management of federal forest lands (Steen 1977) and for forestry research (Steen 1998). The U.S. Forest Service also played a very important role in promoting forest protection and management activities by the states and by nongovernmental organizations.

The greatest advance in this period was the introduction of effective efforts for fire control and fire prevention, stimulated by the disastrous fire years of 1902 and 1910. The states passed legislation requiring burning of slash on freshly cut areas, fire patrol of such areas, provision of spark arresters on equipment, and firefighting tools. The Washington Forest Fire Association was formed in 1908, and the Oregon Forest Fire Protective Association in 1910. The Weeks Act of 1911 included authorization for federal participation in the organization and maintenance of cooperative fire control organizations. The newly formed Western Forestry and Conservation Association, established in 1909 under leadership of E.T. Allen and George Long, became an active and effective organization promoting fire control legislation, public education, and the formation of cooperative fire control associations among landowners (Allen 1926, Martin 1945). (In later years, it also became an effective advocate of improved silviculture and of sustained yield management.) Concurrently, the national forests developed their own fire control capabilities.

The Clarke-McNary Act of 1924 expanded Forest Service authority to cooperate with and provide financial aid to states for fire protection. It also provided similar authority for aid to states in providing seed and planting stock for reforestation of denuded lands.

The great Yacolt Fire of 1902 (Felt 1977) and others of that period had left large areas of land unstocked. A large and continuing effort was mounted to replant the national forest lands involved. This necessarily included the establishment and operation of forest nurseries, beginning with the Silverton Nursery in 1909 and the Wind River Nursery in 1910 (Cameron 1979).

Timber harvesting on national forest lands was generally on a small scale, because industry controlled huge amounts of timber and had little immediate need for purchases of federal timber. Most commonly, national forest harvests used the scattered seed tree method for regeneration, with a rough standard of at least 2 seed trees per acre (5 per hectare), in line with recommendations of Munger and others. A beginning was made on working plans providing for sustained yield management.

In this period, private owners rarely made any specific provision for regeneration other than the fire protection and slash disposal required by law. However, defective trees and inaccessible groups of trees were often left and frequently approximated the seed tree method. On most areas,

[1] By R.O. Curtis and M. Newton.

Brubaker Aerial Surveys

Figure 45—Railroad logging operation some time in the 1930s. Such areas frequently reseeded naturally, but it was often a slow process and sometimes led to conversion to brush species or alder.

the only feasible logging method available at the time was the logging railroad and steam donkey, and there was therefore no feasible alternative to large clearcuts or at best leaving a few scattered seed trees (fig. 45).

Several of the more far-sighted industrial landowners acquired large timber holdings beyond their immediate needs as insurance for future supplies for long-term operation. By the 1920s, a number of large owners undertook survey and classification of their cutover lands. The largest of these efforts was that by Weyerhaeuser Timber Co., which in 1924 established a new corporation—the Weyerhaeuser Logged-Off Land Co.—to take over management of the parent company's cutover lands, with lands suitable only for timber-growing to be managed for that purpose (Brandstrom 1957).

This period also saw the beginning of a long-running controversy over proposals for federal regulation of forest practices on private lands. Legislation to this end was proposed in Congress, and supported by Pinchot (after his departure as Chief Forester) and by Graves. Graves' successor, William B. Greeley, took the position (strongly supported by E.T. Allen) that more progress could be made through cooperation between government and industry. The controversy continued and was not laid to rest until about 1950, by which time a number of states (including Washington and Oregon) had passed legislation regulating forest practices.

Forest Management Changes: 1925–1950

During this period there was a continuing increase in the effectiveness of fire prevention and control, aided by partial federal funding under the Clarke-McNary Act (1924).

The Knutson-Vandenberg Act of 1930 provided additional federal funding for nurseries and planting programs on national forest timber sale areas. The contribution of the national forests to regional timber supply was still relatively small, although steadily increasing (except for the Depression period).

During the 1920s, a number of companies (notably Crown Zellerbach and Long-Bell) undertook forest planting and seeding on a limited scale (Brandstrom 1957). Long-Bell Lumber Co. established a nursery near Ryderwood, Washington, in 1926. The company planted 13,330 acres to conifers until the Depression halted work in 1931, although about half of the planted area was subsequently lost to fire. These private reforestation efforts came to an abrupt end with the onset of the Great Depression.

The introduction of the motor truck and crawler tractor opened new possibilities for more flexible logging methods. Much of the silvicultural knowledge needed for long-term management was now available (Munger 1927). McArdle and Meyer (1930) had shown the enormous productivity of Douglas-fir and had provided a quantitative basis for management planning. It seemed that the stage was set for conversion from an industry engaged in liquidating a wasting asset to one engaged in growing timber on a permanent basis.

Then came the Great Depression. Mill capacity, which had greatly expanded in the boom years of the 1920s, was now far in excess of plummeting demand. The forest industries descended into chaos, as did many others.

One result was the rise of "selective cutting" (chapter 5). This was a silviculturally destructive practice, driven by the short-term economics of survival under conditions where only the biggest and best trees could be handled at a profit.

Congress passed the National Industrial Recovery Act (NRA) in 1933. This act provided for formation of industry associations with power to set minimum wages and prices and control production levels (Robbins 1981). The Code of Fair Competition for the Lumber and Timber Products Industries (Dana 1953: 254–257) also included a provision, Article X, requiring the industry to formulate a Forest Conservation Code, including enforceable rules of forest practice. Such a code was formulated by industry leaders in association with state and federal officials, and adopted in 1934. Then, in 1935, the Supreme Court struck down the entire NRA program.

Although no longer operative, the NRA Conservation Code had a considerable educational effect (Recknagel 1938). The West Coast Lumberman's Association and Pacific Northwest Loggers Association subsequently (1937) issued a forest practice handbook, based on the NRA Forest Conservation Code. This publication summarized existing knowledge and recommendations on fire prevention and control, called for natural reseeding of cut areas, and advocated transition to sustained yield as the eventual industry goal. It reflected changing attitudes in the industry and formed a part of the groundwork for the shift in direction of the industry during and following World War II (WWII).

In the late 1930s, a number of large timber holdings were placed under sustained yield programs, including the St. Helens Sustained Yield Unit of Weyerhaeuser Co. and the Oregon and California Railroad (O&C) land grant lands under the General Land Office of the Interior Department (which later became the Bureau of Land Management).

With the recognition that the seed tree method was frequently ineffective and that "selective cutting" had been a silvicultural fiasco, there was a general shift to the use of so-called "staggered settings"—block clearcutting in units of moderate size interspersed with blocks of uncut timber that served as a seed source (fig. 46).

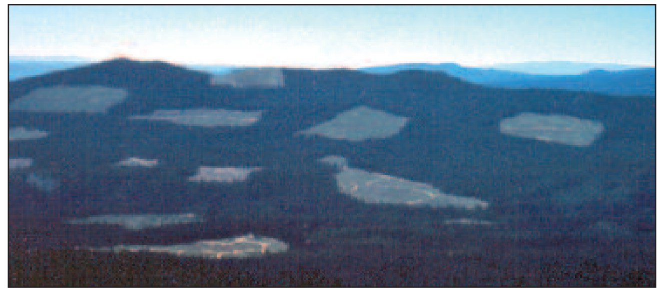

Figure 46—Unsatisfactory regeneration from the seed-tree method and from "selective cutting" led to adoption of "staggered settings" in the 1940s—moderate size clearcuts interspersed with uncut timber that served as a seed source.

By 1940, the economic upturn associated with the war in Europe and rearmament in the United States was being felt. Markets and prices improved, and the outlook for timber and other manufacturing industries brightened. Emphasis shifted to increased production to meet wartime needs. There was a corresponding shift in industry attitudes from gloom to optimism.

Nineteen-forty-one brought the birth of the industry-sponsored tree farm movement, with dedication of the Clemons Tree Farm of Weyerhaeuser Co. as the first such unit. Over subsequent years, this movement became an important vehicle for encouraging improved forest management. An industry-wide forest tree nursery was established in 1941 at Nisqually, Washington, to supply seedlings for tree farm planting, an activity that expanded rapidly.

The Oregon Forest Conservation Act of 1941 was the first in the Nation requiring regulation of cutting practices by the state. Washington passed a similar act in 1945. Although the Washington act was contested by a group of timberland owners as an infringement on private property rights, it was upheld by a 1949 Supreme Court decision.

The great Tillamook Fire of 1933, and subsequent reburns (1938, 1944, 1951) created a huge area of unstocked land in northwestern Oregon. The State of Oregon eventually acquired most of the land involved, and undertook a massive program of timber salvage followed by seeding and planting, extending through the 1950s. This effort created the present Tillamook State Forest. The reforestation problems involved provided a strong stimulus to research in artificial regeneration.

World War II was followed by a strong and continuing expansion of the general economy, and by a steady rise in demand and prices for the timber industries. Improved markets and improved transportation meant much more complete utilization of harvested timber, with reduced slash accumulations. The end of old-growth timber was visible on the horizon. Second-growth stands took on a new value. Operations such as thinning, that had previously been considered uneconomic, now seemed feasible.

In the changed economic climate and the new optimistic view of the future, most of the stronger companies undertook the transition to permanent sustained-yield management. Concurrently, there was a sharp increase in the cut from federal lands. This served both to help meet the soaring demand for timber, and to facilitate the transition to sustained yield of companies that had badly unbalanced age distributions or insufficient land base to make sustained-yield operation feasible without supplemental supplies of federal timber.

Brandstrom (1957) provided an excellent historical account of industry developments in this period.

Forest Management Changes: 1950–1985

Over the years from about 1950 to 1985, change continued in the directions foreshadowed in the immediate postwar period. Demand for timber products was high. Timber supplies, although not yet seriously limiting, clearly required foresight and planning. Old-growth timber on private lands was largely replaced by young stands. Harvests on national forest lands greatly increased and became a major supply source, and planning envisioned the gradual conversion of much of the large amount of old growth remaining on federal lands to managed young growth.

There were major and continuing improvements in wood utilization. Markets developed for much material that had previously been unusable. Harvesting equipment became more efficient and more flexible. With steadily increasing timber prices and the prospect of future supply problems, owners were ready to invest in cultural measures that promised to increase growth rates and value of young stands.

The standard regeneration practice over most of the region was now to clearcut, burn, and plant, usually to Douglas-fir. The shift to planting as the preferred regeneration method was driven by (1) the frequently unsatisfactory results of natural regeneration methods, (2) the availability of Knutson-Vandenberg funds for planting on Forest Service lands, and (3) the increasingly stringent restocking requirements under the Washington and Oregon forest practices acts. Improved nursery and planting procedures and improved vegetation control provided a steady increase in survival. With planting rather than natural seeding as the primary regeneration method, it was no longer necessary to retain seed blocks. Some owners therefore chose to use very large clearcuts to reduce logging costs.

With more complete utilization and the gradual shift to young growth—which had much less defect than old growth—less slash was left on the ground. Less slash, better fire control, and public objections to smoke led to a gradual decrease in the formerly nearly universal practice of broadcast burning.

Precommercial thinning became common practice in naturally seeded stands and in plantations, especially those with substantial additions from natural seeding.

Commercial thinning was now feasible, although there were differing opinions as to its desirability. Early trials in mid-aged stands had not shown the growth response that many people had anticipated, and some questioned the benefits of thinning on the short rotations that many owners were adopting. Others—particularly the public agencies with their somewhat longer rotations—did a considerable amount of thinning.

Nitrogen fertilization of young stands was widely adopted by industrial and state owners.

Both public agencies and the larger companies established tree improvement programs, and operational plantings used selected seed as this became available. The combination of genetic improvement with improved nursery and planting practices produced plantations that—at least in their early years—clearly outperformed natural stands.

These changes were accompanied by a general shortening of rotations used by industrial and some private owners, in some cases to as short as 40 years. Shortening of rotations was sometimes motivated by need to compensate for unbalanced age distributions, but primarily by financial considerations without much attention to other biological, social, or political effects.

Forest management on federal lands (and to a considerable extent on industrial and state lands) became more centrally planned and controlled. Forest planning became a major activity on national forests, and forest practice regulations began to affect private operations.

This was also a period of burgeoning population growth—centered in the urbanized areas around Puget Sound and the Willamette Valley—and growing affluence and mobility. The expanding road system made much formerly remote forest land readily accessible. Recreational use exploded, particularly on the national forests. Increasing areas were designated as wilderness. Conflicts between user groups intensified. It became increasingly difficult to reconcile the desires and demands of the various interest groups. The problems and policy responses on the national forests, which had a great impact on silviculture from about 1985 on, are well presented in Fedkiw (n.d.), which is also one of the best available histories of the Forest Service.

Forest Management Changes: 1985 to the Present

Several major trends are apparent in this period:

- Controversy and conflicts associated with the Endangered Species Act (and its emphasis on individual species) and the opposition of segments of the public and some influential environmental groups to any form of active management nearly halted management activities on the national forests. There was a drastic decline in harvests and associated economic damage to forest-dependent industries and communities. Federal lands ceased to be a major factor in the regional timber supply. Management emphasis shifted to recreation and perceived biodiversity issues.
- Other public ownerships were affected by the same factors although, so far, to a much lesser degree. Legal requirements that state lands be managed to provide income for educational and other institutions provided continued incentives for timber production. There was a marked increase in thinning and a willingness to consider somewhat longer rotations in management planning.
- Another result of environmental concerns was the increasing complexity of state forest practice regulations. Although these regulations have undoubtedly been beneficial on the whole, they sometimes impose considerable burdens on landowners and can have unintended negative consequences. Substantial amounts of private land were withdrawn from production to protect riparian and other areas thought to be important to wildlife and fish or other environmental considerations. Restrictions were imposed on clearcut size, leaving of "green trees" was mandated, etc. Although probably justified from the larger environmental standpoint, many of these requirements were viewed as a burden by the landowner.
- Although the adaptive management area component of the Northwest Forest Plan has been a near failure on federal lands, collaborative approaches to management of state and private forest lands have been considerably more successful. Beginning with the Timber-Fish-Wildlife Agreement of the mid-1980s and continuing through the current Forest and Fish Policy, forest practices in Washington State have been guided by consensus-building processes. Although

there has been some litigation on some aspects of the Timber-Fish-Wildlife Agreement, this has been minor compared with that associated with federal land management. Adaptive management projects are undertaken along with cooperative monitoring and evaluation. Participants include the state, tribes, large and small forest landowners, local governments, and the environmental community. Such efforts receive peer review and are used in decisionmaking and regulation by the Forest Practices Board.

Faced with a reduced and uncertain public timber supply, increasing regulatory restrictions on portions of an ownership, and increased global competition, industrial owners managed their remaining lands for maximum short-term timber production. This often included intensive site preparation, improved planting stock, control of competing vegetation, stand density control, fertilization, and short rotations. It also included extensive corporate mergers, transfer of operations to lower cost regions both within and outside the United States, sale of some lands to financial institutions (insurance firms, retirement funds, etc.), or real estate development with attendant forest fragmentation.

Thus, the current picture is a division into three broad management classes by ownership:

- On most federal lands, timber production has become a secondary objective, subordinate to recreation, wildlife, and amenity values.
- On state lands timber production remains a major objective although management practices are modified to reduce conflicts.
- On industrial and many other private lands, the primary objective is usually maximum return on the timber investment. Other objectives are likely to be pursued only in response to regulatory or public relations pressures, prospective land use changes, or possible public provision of incentives.

Chapter 14: In Conclusion[1]

The preceding pages have traced the history of silvicultural research in the Douglas-fir region and its applications in forest land management. We have made no attempt to discuss the burgeoning literature on forest ecology and tree physiology, extensive topics that form the foundation of silviculture. We have touched only lightly on the important role of silviculture in prevention and control of insect and disease problems and in reducing the risks of catastrophic windfall and fire. We have briefly sketched the concurrent evolution of management practices, which reflect the combined influence of research, operational experience and observation, and changing economic and social factors.

We have confined ourselves largely to the means of manipulating stand establishment and stand development, many of which have been developed in a somewhat empirical manner although guided by considerable knowledge of the underlying biology. Our lengthy list of citations includes most of the important research before 1950, but only a fraction of the large literature that has developed since then. Although incomplete, these citations should suffice to indicate the scope of the subject and to provide entry points to the literature for readers without detailed prior knowledge.

It should be apparent that a large part of our present knowledge has come from long-term silvicultural experiments. These are expensive; difficult to maintain through changes in personnel, budgets, and short-term political priorities; and are often unattractive to researchers because of long lead times between establishment and the publishable results that are the main criterion for advancement in the research community. But, long-term experiments provide information obtainable in no other way. Their results are far more convincing to field foresters, landowners, and managers than any amount of extrapolation from theory and short-term observations.

Looking back over the history of silviculture-related research in the coastal Pacific Northwest, one can see a number of long-term trends:

- Prior to the 1950s, forestry research was almost exclusively carried out by the U.S. Forest Service. In the early years, silvicultural research was done by a very small number of people of outstanding ability and motivation. In general, they were keen observers and far-seeing individuals with a broad outlook, who operated with a high degree of independence on very low but fairly stable funding. A number of them devoted their working lives to one area of primary interest, and developed an unparalleled knowledge of their subject. Much of their work remains valuable. Despite limited resources, these few established and maintained a number of long-term studies that have had major influences on management.
- As the Forest Service research organization expanded, it necessarily became more highly structured. The Research Station Director became primarily an administrator (although usually with a scientific background). With increased numbers of people and increased specialization, team efforts and formal research organization became more important. There was more emphasis on interdisciplinary research.
- There was a great expansion in university research after World War II (WWII). Most of this was funded by grants from various sources, including the McIntire-Stennis Act, National Science Foundation, other organizations (including the Forest Service), and (in Oregon) a harvest tax. In general, dependence on short-term grants and graduate student research assistants, conflicts with staff teaching duties, and university reward systems did not encourage continuity of effort or long-term studies (although some were undertaken, usually as cooperative efforts supported in part by federal agencies and industry).

[1] By R.O. Curtis and D.S. DeBell.

- Considerable industrial research was undertaken after WWII. Much of this was aimed at solving short-term management questions, but there were also some long-term studies. Some of these were disrupted or destroyed in the course of various reorganizations and ownership changes. Most data are not publicly available.
- From around 1970 onward, the Forest Service also had difficulties in maintaining long-term silvicultural research. Long-term research was in competition for funds with short-term studies, which were often prompted by politically "hot" questions of the moment.
- Overall, efforts and funding devoted to silvicultural research increased rapidly after WWII, peaked sometime in the 1970s, and steadily declined thereafter. Some of the decline resulted from a mistaken perception in some quarters that we already knew everything we needed to know about silviculture. More of it resulted from diversion of public agency effort and funding into the politically more popular though related fields of forest ecology, wildlife, and associated environmental questions. The decline also reflected the relatively low priority given natural resource management compared to other national concerns.
- The need for continuity combined with the limited personnel and funding resources available in individual organizations has led in the last several decades to an increased emphasis on cooperative efforts, which combine the resources of several organizations.
- There has been a revival of long-term silvicultural studies in the last few years, stimulated by the evident need for management regimes that can maintain commodity production from forest lands while simultaneously providing aesthetic, recreational, and wildlife values. Many of the questions involved can only be answered by long-term multidisciplinary studies.

It should be apparent that silviculture and silvicultural research have a much longer history than most people—both the general public and natural resource specialists in other fields—realize. There is a great amount of existing information available for those with the time, inclination, and expertise to seek it out. Because of the long-term nature of forestry and the timescales involved in forest development, public attitudes and desires may change faster than the forest can respond to changes in management, and faster than research can provide definitive answers.

Knowledge can never be complete, and information needs will continue to change with changes in the biological, economic, and social environment. There is a continuing need for silvicultural research in both traditional areas such as intensive wood production, and in alternative silvicultural systems and management regimes directed at integrated management for multiple objectives (National Research Council 1990, 2002). The latter includes the relatively new and potentially important goal of carbon sequestration.

One has only to read the media coverage of various forestry issues to realize that much of the public and the media that shape public opinion have little understanding of the long history of Northwestern forestry, the nature of forests, possible management options, or the existence of a large body of research-based information. Unfortunately, much of the existing information is only available in specialized publications that are not ordinarily seen by workers in other fields, and that are often both inaccessible and unintelligible to the general public. There is a great need for synthesis of existing information and its presentation in forms understandable by nonspecialists and by people in other natural resource-related disciplines.

We hope that this publication will contribute toward that end.

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Appendix

Table 1—Common and scientific names of European species referred to in text

Common name	Scientific name
Beech	*Fagus sylvatica* L.
Birch	*Betula pendula* Roth., and *B. pubescens* Ehrh.
Maritime pine	*Pinus pinaster* Ait.
Oak	*Quercus petraea* (Mattuschka) Liebl., and *Q. robur* L.
Scots pine	*Pinus sylvestris* L.
Silver fir	*Abies alba* Mill.
Spruce	*Picea abies* (L.) Karst.

Table 2—Common and scientific names of North American trees referred to in text

Common name	Scientific name
Alaska yellow-cedar	*Chamaecyparis nootkatensis* (D. Don) Spach
Bigleaf maple	*Acer macrophyllum* Pursh
Black cottonwood	*Populus trichocarpa* Torr. & Gray
Canyon live oak	*Quercus chrysolepis* Liebm.
Chinkapin	*Castanopsis chrysophylla* (Dougl.) A. DC.
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*
Engelmann spruce	*Picea engelmannii* Parry ex Engelm.
Grand fir	*Abies grandis* (Dougl. ex D. Don) Lindl.
Incense-cedar	*Libocedrus decurrens* Torr.
Jeffrey pine	*Pinus jeffreyi* Grev. & Balf.
Lodgepole pine	*Pinus contorta* Dougl. ex Loud.
Madrone	*Arbutus menziesii* Pursh
Mountain hemlock	*Tsuga mertensiana* (Bong.) Carr.
Noble fir	*Abies procera* Rehd.
Oak, Oregon white	*Quercus garryana* Dougl. ex Hook.
Pacific silver fir	*Abies amabilis* Dougl. ex Forbes
Ponderosa pine	*Pinus ponderosa* Dougl. ex Laws.
Red alder	*Alnus rubra* Bong.
Sitka spruce	*Picea sitchensis* (Bong.) Carr.
Sugar pine	*Pinus lambertiana* Dougl.
Tanoak	*Lithocarpus densiflorus* (Hook & Arn.) Rehd.
Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.
Western redcedar	*Thuja plicata* Donn ex D. Don
Western white pine	*Pinus monticola* Dougl. ex D. Don
White fir	*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.

Table 3—Common and scientific names of non-tree plants mentioned in text

Common name	Scientific name
Beargrass	*Xerophyllum tenax* (Pursh) Nutt.
Bitterbrush	*Purshia tridentata* (Pursh) DC.
Camas	*Camassia quamash* (Pursh) Greene
Hazelnut	*Corylus cornuta* var. *californica* (A. DC.) Sharp
Himalayan blackberry	*Rubus armeniacus* Focke
Huckleberries	*Vaccinium* (various species)
India mustard	*Brassica juncea* (L.) Czern
Oregon grape	*Berberis aquifolium* Pursh
Manzanita	*Arctostaphylos columbiana* Piper
Rhododendron	*Rhododendron macrophyllum* D. Don ex G. Don
Salal	*Gaultheria shallon* Pursh
Salmonberry	*Rubus spectabilis* Pursh
Scotch broom	*Cytisus scoparius* (L.) Link
Snowbrush	*Ceanothus velutinus* Dougl. ex Hook.
Swordfern	*Polystichum munitum* (Kaulfuss) K. Presl
Vine maple	*Acer circinatum* Pursh

Table 4—Common and scientific names of insects and diseases mentioned in text

Common name	Scientific name
Annosus root disease	*Heterobasidium annosum* (Fr.) Bref (formerly *Fomes annosus*)
Douglas-fir bark beetle	*Dendroctonus pseudotsugae* Hopkins
Dwarf mistletoe	*Arceuthobium tsugense* (Rosendahl) G.N. Jones
Laminated root rot	*Phellinus weirii* (Murr.) Gilb.
Seed chalcid	*Megastigmus spermotrophus* Wachtl
Swiss needle cast	*Phaeocryptopus gaumanni* (Rohde) Petrak
White pine blister rust	*Cronartium ribicola* Fischer

Table 5—Common and scientific names of wildlife species referred to in text

Common name	Scientific name
Bear	*Ursus americanus* Pallas, 1780
Beaver	*Castor canadensis* Kuhl, 1820
Deer	*Odocoileus hemionus* Rafinesque, 1817
Deer mouse	*Peromyscus maniculatus* Wagner, 1845
Elk	*Cervus elaphus* Linnaeus, 1758
Mountain beaver	*Aplodontia rufa* Rafinesque, 1817
Mazama gopher	*Thomomys mazama* Merriam, 1897
Northern spotted owl	*Strix occidentalis caurina* Merriam, 1898
Western gray squirrel	*Sciurus griseus* Ord 1818

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E-mail	pnw_pnwpubs@fs.fed.us
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