United States
Department of
Agriculture

Forest Service

Pacific Northwest
Forest and Range
Experiment Station

General Technical
Report
PNW-150

February 1983

Western Redcedar -- A Literature Review

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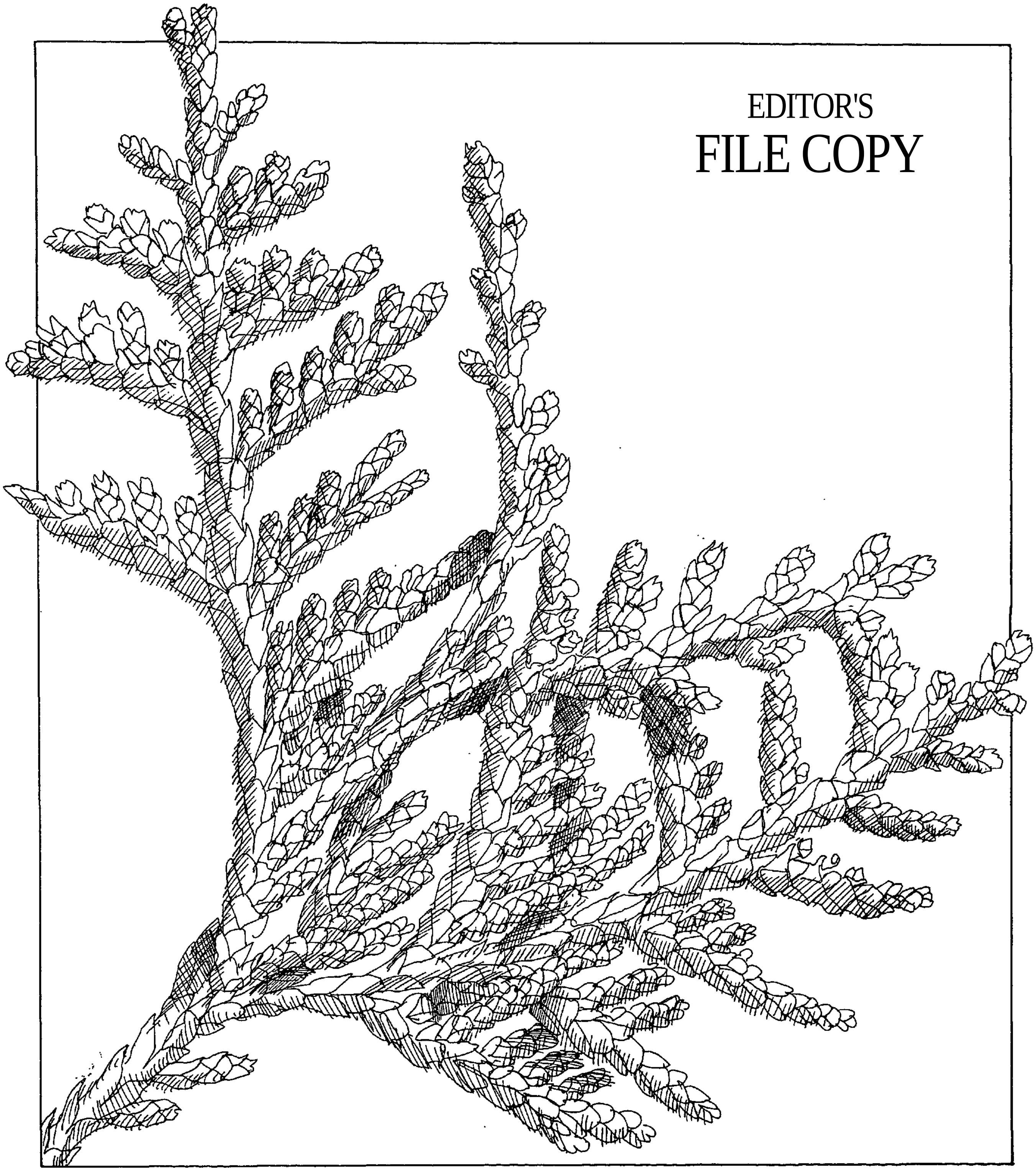

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Abstract

Minore, Don.
1983. Western redcedar: A literature review. USDA For. Serv. Gen. Tech. Rep. PNW-150, 70 p. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

This report is a comprehensive compilation of information on western redcedar (Thuja plicata Donn) — its occurrence and abundance; associated plant species; morphology and anatomy; products; medical aspects; diseases; insect, bird, and mammal. pests; genetics; horticulture; physiology; ecology; mensuration; and silviculture. Management recommendations and an extensive list of references are included.

Keywords: Western redcedar, Thuja plicata, silviculture, ecology, physiology, products.

Contents

Introduction

The western redcedar is the only ***Thuja*** species native to western North America.[1] (Northern white-cedar grows in eastern North America, and four other ***Thuja*** species occur in the Orient.) These members of the subfamily Thujoideae of the Cupressaceae are considered more highly evolved than ***Libocedrus, Cupressus, Chamaecyparis,*** or ***Juniperus*** species (see Moseley 1943).[2] Large western redcedars reach ages of 800 to 1,000 years, and some individuals in eastern Washington may be 2,000 years old (Sharpe 1974). General attributes of the species include a conical form with large and fluted base in mature trees, drooping branches, thin fibrous bark, and small scalelike leaves arranged in flat sprays (Sudworth 1908, Sharpe 1974).

Redcedar wood is valuable and used extensively. Use of redcedar products is far ahead of the management practices for replenishing the supply of high-quality timber from which most of those products are made. More efficient use of western redcedar and better management are needed; they can best be achieved by using available knowledge as a base for further advances. Considerable knowledge is available, but it is scattered in diverse publications under many subject headings and titles. This report summarizes most of the information in those publications for the scientists, administrators, and foresters who participate in western redcedar research, use, and silviculture.

[1]Nomenclature for all northwestern plant species is according to Hitchcock and Cronquist 1973. Scientific names for trees mentioned by common name throughout the text are listed on page 50.

[2]Where information was derived from a publication, but not specifically stated therein, the author's name is prefaced by "see" (e.g., see Little 1971).

Occurrence and Abundance

Range

Western redcedar grows along the Pacific coast from northern California to southeastern Alaska (fig. 1). It occurs sporadically at its southern limit in Humboldt County, California, where it is common only in the lower Mad River drainage and the wet region south of Ferndale (Griffin and Critchfield 1972). Elsewhere along the northern coast of California, western redcedar occurs only in isolated stands on boggy habitats.

North of the California-Oregon border, the natural range of western redcedar broadens to include portions of the Cascade Range. On the western slopes of the Cascades, redcedar grows from Crater Lake north (Boyd 1959, Little 1971). On the eastern slopes, it occurs north of approximately 44°30′N latitude (Franklin and Dyrness 1973). The redcedar populations of the Cascades and the coast meet occasionally in moist portions of the Willamette Valley, Oregon. Farther north, optimal growth and development are achieved near the latitudinal center of western redcedar's range — the Olympic Peninsula in Washington.

North of Vancouver Island, western redcedar is restricted to the Coast Ranges and coastal islands. The northern limits of its coastal range are the northern and western shores of Sumner Strait on Kupreanof and Kuiu Islands and the Petersburg vicinity on Mitkof Island (Harris and Farr 1974) at approximately 56°30′N latitude (see Andersen 1953). South of Petersburg, western redcedar occurs as an overstory dominant on former muskeg areas with shallow water tables (Stephens et al. 1970). It is common and important only farther south, however, near Ketchikan and Craig, in the intermediate types between bogs and upland forests (Neiland 1971).

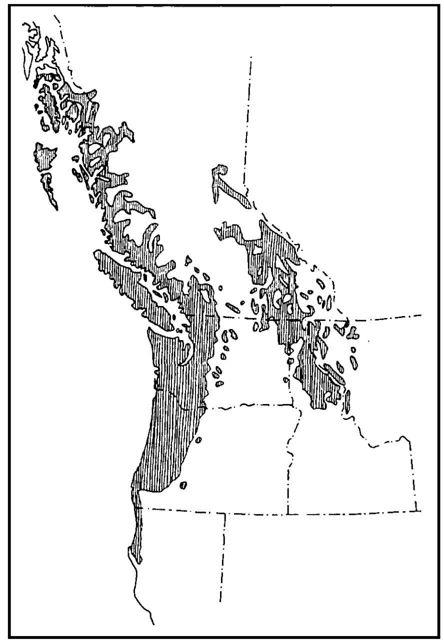

Figure 1.—The natural range of western redcedar (from Little 1971, Viereck and Little 1975).

Near the southern border of British Columbia, a few scattered populations of western redcedar occur between the Coast Ranges and Selkirk Mountains, but the coastal range is essentially isolated from the interior range of the species. The northern limit of the interior range is on the western slope of the Continental Divide at 54°30′N latitude. The interior range extends south in British Columbia through the Selkirk Mountains into western Montana and northern Idaho (Boyd 1959). The southern limit of the interior range is in western Montana's Ravalli County at 45°50′N latitude (see Little 1971). With the possible exception of a few trees east of the Continental Divide near the upper end of St. Mary's Lake, the eastern limit is near Lake McDonald in Glacier National Park (Aller 1960).

Western redcedar grows from sea level to 915 m (3,000 ft) in southeastern Alaska (Viereck and Little 1972). In British Columbia, the elevation range is higher — from sea level to 1200 m (3,900 ft) (Anderson 1961). Interior redcedar is found from 320 m (1,050 ft) near Orofino, Idaho (personal communication, Charles A. Wellner, Forestry Sciences Laboratory, Moscow, Idaho), to 2100 m (7,000 ft) (Boyd 1959). The greatest range in elevation occurs in Oregon, however, where western redcedar occurs from sea level to 2300 m (7,500 ft) at the rim of Crater Lake (Sudworth 1908, Bowers 1956).

Coastal populations of western redcedar receive from less than 89 to more than 660 cm (less than 35 to more than 260 in) of annual rainfall. Interior populations receive about 71 cm (28 in) in the north, 81 to 124 cm (32 to 49 in) of annual precipitation farther south (Boyd 1959).

Where sufficient precipitation is present, temperature apparently limits the range of western redcedar. Schmidt (1958) measured an abrupt decrease in length of the frost-free period just above the upper elevational limits of western redcedar, western hemlock, and Douglas-fir on Vancouver Island. In southeastern Alaska, the northern limits of western redcedar are not correlated with rainfall or winter temperatures, but they are between the 11.1" and 11.7°C (52" and 53°F) mean summer temperature isotherms (Andersen 1953, 1955a). Average annual temperatures in inland portions of the redcedar range are lower than those along the coast (see Boyd 1959).

Western redcedar is often grown outside its natural range. In the United States, planted trees grow as far north as Juneau, Alaska (Harris and Farr 1974), and western redcedar is occasionally cultivated as an ornamental tree in the Middle and North Atlantic States (Sargent 1933). Redcedars have been cultivated as ornamentals in the Ukraine since 1870 (Unasylva 1950, Perepadya 1971). They are also used as ornamentals and hedge trees in southern Australia (Streets 1962). Western redcedar hedges are widely used in Britain (Hubbard 1950) and in Switzerland (see Keller 1974).

For years western redcedar has been used in practical forestry in England, Ireland, Scotland, and Wales (see Keatinge 1947, Zehetmayr 1954, Ovington and Madgwick 1957, O'Carroll 1967, Aldhous and Low 1974, Priest 1974, Carey and Barry 1975). It is also well established as a useful forestry species in West Germany (see Zimmerle and Linck 1951, Borchers 1952, Degen 1965, Hesmer and Gunther 1968, Volk 1968), East Germany (see Lembcke 1970), and Austria (see Rannert 1976). Indeed, the species is almost naturalized in West Germany (Volkert 1956). Experimental redcedar stands were established in Poland in 1890 (see Gecow 1952), and the species was recommended for practical forestry in Czechoslovakia (Holubčík 1968). It has been planted in Denmark and France since the 1860's (see Søegaard 1956b, Guinier 1951). Western redcedar plantations also have been established in Italy (Ministero dell'Agricoltura e delle Foreste, Collana Verde, Roma 1965). Redcedar has been grown in western Norway (Smitt 1950), but the northernmost stands on record are in Mustila, Finland, at 60°41'N latitude (Artsȳbashev 1939).

Western redcedar has been planted extensively in New Zealand (see Perham 1938, Hocking and Mayfield 1939, Ranger 1945, Streets 1962, and Weston 1971). It has also been successfully grown at higher elevations in Tasmania, but it grows relatively slowly in Kenya (Streets 1962). The species has shown little promise in the Union of South Africa (Streets 1962) or in central Honshu, Japan (see Kawada and Yamaji 1949).

Volumes

Western redcedar is an important commercial species in much of its natural range. In North America, an estimated volume of 154 billion board feet (Scribner rule) exists in live western redcedar trees that are at least 25 percent sound (Bolsinger 1979). More than three-fourths of this volume (120 billion board feet by Bolsinger's estimate) occurs in British Columbia. Within British Columbia, 86 percent of the western redcedar volume is found in coastal areas (British Columbia Forest Service, Inventory Division 1967). The rest grows in the interior. When all trees larger than 25.4 cm (10 in) in diameter are considered, western redcedar accounts for about 11 percent of all the sound wood in

Associated Plant Species

mature, accessible commercial forests in British Columbia. In coastal areas, this proportion rises to **39** percent (Gardner **1963).** When only the north coast forests of British Columbia are considered, western redcedar makes up **52** percent of the merchantable volume (McBride **1959).** Although much of British Columbia's vast cedar resource is sawtimber, an estimated **121** million western redcedar poles also were included in 1961 (Anderson **1961).**

In the United States, most western redcedars (13 billion board feet) grow in Washington. The greatest concentration is on the Olympic Peninsula in Clallam, Grays Harbor, and Jefferson Counties, where an additional 10 percent of the present live volume probably exists as dead cedars that are at least **25** percent sound (Bolsinger **1979).** Bolsinger's compilations show that Idaho has **7.8** billion, Alaska **6.3** billion, Oregon 5 billion, Montana **1.4** billion, and California **76** million board feet of cedar volume. Three-fifths of it is in the National Forests, where most of the redcedar in Idaho, Montana, and Alaska occurs.

Bolsinger found that **66** percent of all western redcedar volume in the United States is in trees that are 53-cm (21-in) d.b.h. or larger, 44 percent is in trees larger than **74** cm **(29** in). Average size is largest in Washington and smallest in Idaho. Most of the redcedar volume in Idaho occurred in **28-** to 53-cm **(11**.O-to **20.9-in)** d.b.h. trees in **1962** (see Wilson 1962).

Trees

Pure western redcedar stands cover some small areas (Eyre **1980),** but the species usually is associated with other tree species. These species are listed by locality in table **1.**

Soil moisture conditions seem to be important in determining composition of local stands. Black cottonwood and bigleaf maple often grow with western redcedar in swamps (Sharpe **1974),** as do both Pacific silver fir and western white pine in coastal swamps of the Olympic Peninsula (Franklin and Dyrness **1973).** Dry-site associates include grand fir and lodgepole (shore) pine along the east coast of Vancouver Island (Packee **1976),** Pacific madrone on the British Columbia mainland (see Krajina **1969),** and western hemlock on the Queen Charlotte Islands (Day **1957).**

Western hemlock and black cottonwood are associated with western redcedar throughout its natural range. Douglas-fir is present in all but the Alaska range. Pacific yew occurs only in the extreme south end of southeastern Alaska (Viereck and Little **1972),** but it is often found as a redcedar associate elsewhere.

Western redcedar is a major species in two forest cover types recognized by the Society of American Foresters (Eyre **1980)** — Western Redcedar and Western Redcedar-Western Hemlock. It occurs as a minor associated species in **10** types: Western Hemlock-Sitka Spruce, Coastal True Fir-Hemlock, Douglas-Fir-Western Hemlock, Pacific Douglas-Fir, Port-Orford-Cedar, Western Larch, Western White Pine, Engelmann Spruce-Subalpine Fir, Red Alder, and Redwood.

Shrubs

Rubus parviflorus Nutt. is associated with western redcedar from Alaska to California and from coastal Washington and Oregon to Montana (table **2).** Several other shrub associates occur in both interior and coastal environments (e.g., ***Amelanchier alnifolia*** Nutt., ***Cornus stolonifera*** Michx., ***Menziesia ferruginea*** Smith, ***Oplopanax horridum*** (Smith) Miq., ***Pachistima myrsinites*** (Pursh) Raf., ***Rosa gymnocarpa*** Nutt., and ***Symphoricarpos albus*** (L.) Blake), but some associated shrubs are more limited. ***Sor**bus*, ***Lonicera,*** and ***Clematis*** species are found with redcedar only in the interior; Rubus ***spectabilis*** Pursh and ***Vaccinium parvifolium*** Smith are associated only near the coast.

Shrub associates change less with latitude than they do with longitude, but two are noteworthy. ***Rhododendron macrophyllum G.*** Don is abundant in coastal California, Oregon, and Washington; it seems to be present in only two stands in southern British Columbia, however (see Packee **1976).** In contrast, the northern limits of ***Gaultheria shallon*** Pursh are nearly the same as the northern limits of western redcedar in coastal Alaska (see Viereck and Little **1972, 1975).**

Table 1 — Tree species associated with western redcedar in 7 portions of its natural range

Alaska[1]	Coastal British Columbia[2]	Interior British Columbia[3]	Montana[4]
Abies amabilis	*Abies amabilis*	*Abies grandis*	*Abies grandis*
Alnus rubra	*Abies grandis*	*Abies lasiocarpa*	*Abies lasiocarpa*
Chamaecyparis nootkatensis	*Acer macrophyllum*	*Betula papyrifera*	*Betula papyrifera*
Picea sitchensis	*Alnus rubra*	*Larix occidentalis*	*Larix occidentalis*
Pinus contorta	*Arbutus menziesii*	*Picea engelmannii*	*Picea engelmannii*
Populus trichocarpa	*Betula papyrifera*	*Picea glauca*	*Picea glauca*
Taxus brevifolia	*Chamaecyparis nootkatensis*	*Pinus albicaulis*	*Pinus contorta*
Tsuga heterophylla	*Cornus nuttallii*	*Pinus contorta*	*Pinus monticola*
	Picea sitchensis	*Pinus monticola*	*Pinus ponderosa*
	Pinus contorta	*Populus tremuloides*	*Populus trichocarpa*
	Pinus monticola	*Populus trichocarpa*	*Pseudotsuga menziesii*
	Populus tremuloides	*Pseudotsuga menziesii*	*Taxus brevifolia*
	Populus trichocarpa	*Taxus brevifolia*	*Tsuga heterophylla*
	Pseudotsuga menziesii	*Tsuga heterophylla*	
	Quercus garryana		
	Taxus brevifolia		
	Tsuga heterophylla		
	Tsuga mertensiana		

[1]From Viereck and Little (1972).
[2]From Orloci (1961, 1965), Krajina (1969), Packee (1976).
[3]From McLean and Holland (1958), Bell (1965), Krajina (1969).
[4]From Pfister et al. (1977).
[5]From Daubenmire (1952), Daubenmire and Daubenmire (1968).
[6]From Franklin and Dyrness (1973), Dyrness et al. (1974).
[7]From Munz and Keck (1959), Axelrod (1977), Kuchler (1977), Sawyer et al. (1977), Zinke (1977).

Table 1 — Continued

Eastern Washington and northern Idaho[5]	Western Washington and Oregon[6]	California[7]
Abies grandis	*Abies amabilis*	*Abies grandis*
Abies lasiocarpa	*Abies grandis*	*Acer macrophyllum*
Betula papyrifera	*Abies procera*	*Alnus rubra*
Larix occidentalis	*Acer macrophyllum*	*Chamaecyparis lawsoniana*
Picea engelmannii	*Alnus rubra*	*Cornus nuttallii*
Pinus contorta	*Arbutus menziesii*	*Lithocarpus densiflorus*
Pinus monticola	*Calocedrus decurrens*	*Picea sitchensis*
Pinus ponderosa	*Castanopsis chrysophylla*	*Populus trichocarpa*
Populus tremuloides	*Chamaecyparis lawsoniana*	*Pseudotsuga menziesii*
Populus trichocarpa	*Chamaecyparis nootkatensis*	*Rhamnus purshiana*
Pseudotsuga menziesii	*Cornus nuttallii*	*Sequoia sempervirens*
Taxus brevifolia	*Lithocarpus densiflorus*	*Tsuga heterophylla*
Tsuga heterophylla	*Pinus contorta*	*Umbellularia californica*
	Pinus monticola	
	Picea engelmannii	
	Picea sitchensis	
	Populus tremuloides	
	Populus trichocarpa	
	Pseudotsuga menziesii	
	Taxus brevifolia	
	Tsuga heterophylla	
	Tsuga mertensiana	

Table 2 — Shrub species associated with western redcedar in 7 portions of its natural range

Alaska[1]	Coastal British Columbia[2]	interior British Columbia[3]	Montana[4]
Amelanchier alnifolia			
var. *semiintegrifolia*	*Acer circinatum*		
Alnus sinuata	*Alnus sinuata*	*Acer glabrum*	*Acer glabrum*
Cladothamnus pyroliflorus	*Amelanchier alnifolia*	*Amelanchier alnifolia*	*Alnus incana*
Cornus stolonifera	*Berberis nervosa*	*Arctostaphylos uva-ursi*	var. *occidentalis*
Gaultheria shallon	*Cladothamnus pyroliflorus*	*Ceanothus sanguineus*	*Amelanchier alnifolia*
Menziesia ferruginea	*Cornus stolonifera*	*Cladothamnus pyroliflorus*	*Arctostaphylos uva-ursi*
Oplopanax horridum	*Gaultheria shallon*	*Cornus stolonifera*	*Berberis aquifolium*
Ribes bracteosum	*Holodiscus discolor*	*Gaultheria ovatifolia*	*Berberis repens*
Ribes laxiflorum	*Menziesia ferruginea*	*Gaultheria shallon*	*Ceanothus velutinus*
Rubus parviflorus	*Myrica gale*	*Juniperus communis*	*Clematis columbiana*
Rubus spectabilis	*Oplopanax horridum*	*Lonicera ciliosa*	*Cornus stolonifera*
Salix barclayi	*Physocarpus capitatus*	*Lonicera involucrata*	*Holodiscus discolor*
Salix scouleriana	*Prunus emarginata*	*Lonicera utahensis*	*Lonicera utahensis*
Salix sitchensis	*Ribes bracteosum*	*Menziesia ferruginea*	*Menziesia ferruginea*
Sambucus racemosa ssp.	*Rosa gymnocarpa*	*Oplopanax horridum*	*Menziesia glabella*
pubens var. *arborescens.*	*Rubus parviflorus*	*Pachystima myrsinites*	*Oplopanax horridum*
Vaccinium alaskaense	*Rubus spectabilis*	*Prunus emarginata*	*Pachystima myrsinites*
Vaccinium ovalifolium	*Rubus ursinus*	*Rhododendron albiflorum*	*Ribes lacustre*
Vaccinium parvifolium	*Salix scouleriana*	*Ribes lacustre*	*Rosa gymnocarpa*
Vaccinium uliginosum	*Sambucus ovatum*	*Ribes viscosissimum*	*Rubus parviflorus*
Viburnum edule	*Sambucus racemosa*	*Rosa gymnocarpa*	*Salix* sp.
	ssp. *pubens*	*Rubus nivalis*	*Shepherdia canadensis*
	Spiraea douglasii	*Rubus parviflorus*	*Sorbus sitchensis*
	Symphoricarpos albus	*Salix scouleriana*	*Sorbus scopulina*
	Symphoricarpos mollis	*Sambucus racemosa*	*Spiraea betulifolia*
	Vaccinium alaskaense	ssp. *pubens*	var. *lucida*
	Vaccinium myrtillus	*Shepherdia canadensis*	*Symphoricarpos albus*
	Vaccinium ovalifolium	*Sorbus sitchensis*	*Symphoricarpos occidentalis*
	Vaccinium ovatum	*Spiraea betulifolia*	*Vaccinium globulare*
	Vaccinium parvifolium	var. *lucida*	*Vaccinium membranaceum*
	Vaccinium uliginosum	*Spiraea douglasii*	*Vaccinium myrtillus*
	Viburnum opulus	*Vaccinium membranaceum*	*Vaccinium scoparium*
	var. *americanum*	*Vaccinium myrtillus*	
		Vaccinium ovalifolium	
		Viburnum edule	
		Viburnum opulus	
		var. *americanum*	

[1]From Viereck and Little (1972); personal communication from Paul Alaback, Department of Forest Science, Oregon State University, Corvallis, 1980.
[2]From Orloci (1961, 1965), Krajina (1969), Packee (1976).
[3]From McLean and Holland (1958), Bell (1965), Krajina (1969).
[4]From Aller (1960), Pfister et al. (1977).
[5]From Daubenmire (1952), Daubenmire and Daubenmire (1968).
[6]From Fonda and Bliss (1969), Franklin and Dyrness (1973), Dyrness et al. (1974).
[7]From Munz and Keck (1959), Axelrod (1977), Kuchler (1977), Sawyer et al. (1977), Zinke (1977).

Table 2 — Continued

Eastern Washington and northern Idaho[5]	Western Washington and Oregon[6]	California[7]
Acer glabrum	*Acer circinatum*	*Acer circinatum*
Alnus sinuata	*Amelanchier alnifolia*	*Berberis nervosa*
Amelanchier alnifolia	*Berberis nervosa*	*Corylus cornuta*
Arctostaphylos uva-ursi	*Corylus cornuta*	*Gaultheria shallon*
Clematis columbiana	*Gaultheria shallon*	*Holodiscus discolor*
Cornus stolonifera	*Menziesia ferruginea*	*Myrica californica*
Corylus cornuta	*Oplopanax horridum*	*Rhododendron macrophyllum*
Lonicera utahensis	*Pachystima myrsinites*	*Rhododendron occidentale*
Menziesia ferruginea	*Rhododendron macrophyllum*	*Ribes bracteosum*
Oplopanax horridum	*Ribes lacustre*	*Rosa gymnocarpa*
Pachystima myrsinites	*Rosa gymnocarpa*	*Rubus parviflorus*
Ribes lacustre	*Rosa nutkana*	*Rubus spectabilis*
Ribes viscosissimum	*Rubus nivalis*	*Rubus ursinus*
Rosa gymnocarpa	*Rubus parviflorus*	*Vaccinium ovatum*
Rubus idaeus	*Rubus ursinus*	*Vaccinium parvifolium*
Rubus parviflorus	*Rubus spectabilis*	
Sambucus racemosa ssp. *pubens*	*Salix hookeriana*	
Sorbus scopulina	*Sorbus sitchensis*	
Spiraea betulifolia var. *lucida*	*Spiraea douglasii*	
Symphoricarpos albus	*Symphoricarpos albus*	
Vaccinium membranaceum	*Symphoricarpos mollis*	
Vaccinium ovalifolium	*Vaccinium alaskaense*	
	Vaccinium membranaceum	
	Vacciniurn ovalifolium	
	Vaccinium ovatum	
	Vaccinium parvifolium	

Herbs

Some of the herbs associated with western redcedar are listed in table 3. Fourteen associates are common in both coastal and interior environments: ***Athyrium filix-femina*** (L.) Roth., ***Chimaphila umbellata*** (L.) Bart., ***Clintonia uniflora*** (Schult.) Kunth., ***Cornus canadensis*** L., ***Dryopteris austriaca*** (Jacq.) Woynar, ***Galium trifidum*** L., ***Gymnocarpium dryopteris*** (L.) Newm., ***Linnaea borealis*** L., ***Polystichum munitum*** (Kaulf.) Presl, ***Pteridium aquilinum*** (L.) Kuhn., ***Rubus pedatus*** J. E. Smith, ***Streptopus amplexifolius*** (L.) DC., ***Tiarella trifoliata*** L., and ***Viola glabella*** Nutt. Two other common associates (***Carex obnupta*** Bailey and ***Oenanthe sarmentosa*** Presl) are limited to moist habitats west of the Cascades. ***Aralia nudicaulis*** L. and ***Coptis occidentalis*** (Nutt.) T. & G. occur with redcedar only in the interior.

Major Communities

Krajina (1969) described 23 British Columbia "Biogeocoenoses" that contain western redcedar as a component. The communities represented are listed in table 4. The communities of Orloci (1961, 1965) and Brooke (1965) on the southwestern British Columbia mainland also are listed in table 4. ***Thuja/Polystichum*** occurs on moist, concave lower slopes. ***Thuja/Lysichitum*** also occurs on lower slopes, but only in swampy situations and on wet outwash terraces where the ground water table is near the surface and flowing. ***Thuja/Coptis*** is found in swampy depressions where the ground water is stagnant, and ***Thuja/Oplopanax*** occurs in swampy ravines where the ground water overflows intermittently. ***Thuja-Abies amabilis/Oplopanax*** occurs along stream margins at 1067- to 1219-m (3,500- to 4,000-ft) elevations where nonstagnant ground water is near the surface. It is of limited occurrence.

Three of Bell's (1965) major plant communities for the Selkirk and Monashee Mountains of southeastern British Columbia include western redcedar. The ***Aralia/Gymnocarpium*** community occurs on slopes and alluvial flats where subsurface water is available. ***Oplopanax*** communities are found on steep lower slopes with permanent seepage at or near the surface and on alluvial flats with high water tables. The ***Lysichitum*** community is present where soil is saturated by slowly moving ground water for much of the growing season. A similar ***Thuja/Lysichitum*** community occurs in the coastal environment of Vancouver Island's Nanaimo River Valley (see McMinn 1960).

Daubenmire and Daubenmire (1968) recognized three western redcedar communities in northern Idaho. ***Thuja plicata/Pachistima myrsinites*** is an upland community where ***Athyrium*** is absent or short and ***Tsuga*** is absent. Hanley's (1976) biomass estimates indicate that this community is very productive. ***Thuja plicata/Oplopanax horridum*** and ***Thuja plicata/Athyrium filix-femina*** occur on bottomlands where ***Athyrium*** is usually abundant and tall. ***Oplopanax*** is present in the former, absent in the latter.

Three additional Idaho redcedar communities occur on the North Fork of the Clearwater River: ***Thuja plicata/Adiantum pedatum*** is common, ***Thuja plicata/Dryopteris*** spp. is uncommon, and ***Thuja plicatal Lysichitum americanum*** is rare (Steele 1971). A fourth (***Thuja plicata/Asarum caudatum***) is common in Nezperce County, Idaho (Steele et al. 1976).

Pfister et al. (1977) described two western redcedar communities in Montana that are essentially similar to the Daubenmires' communities in Idaho — ***Thuja plicata/Oplopanax horridum*** and ***Thuja plicata/Clintonia uniflora.*** The latter corresponds to the Daubenmires' ***Thuja plicatal Pachistima myrsinites*** community, but it includes a ***Menziesia ferruginea*** phase not present in Idaho. Two unnamed communities described by McLean and Holland (1958) in the upper Columbia River Valley also correspond to the Daubenmires' ***Thuja/Oplopanax*** and ***Thuja/Pachistima*** communities.

Bailey (1966) described a ***Thuja plicata/Adiantum pedatum-Athyrium filix-femina*** community in the southern Oregon Coast Ranges of eastern Coos and western Douglas Counties. ***Polystichum munitum*** and ***Oxalis oregana*** dominated the herb layer, but Bailey used the high constancy, low cover ***Adiantum*** and ***Athyrium*** as indicator species for this community. It occurred at low elevations on steep lower and middle slopes.

Franklin and Dyrness (1973) summarized the community information available from Oregon and Washington in 1973. They included two San Juan Island communities described in a 1973 report.[3] ***Thuja plicata-Abies grandis/Pachistima myrsinites*** occurs on moderately moist, north-facing slopes and level areas in the interior of Sucia Island. The moistest sites in the interior valley of Sucia Island support ***Thuja plicata-Abies grandis/Polystichum munitum.*** A report[4] is cited by Franklin and Dyrness (1973) in referring to a ***Thuja plicata-Acer circinatum/herb*** community found in moderately moist valleys of Washington's North Cascades National Park. Finally, Franklin and Dyrness (1973) described and photographed the ***Thuja plicata-Tsuga heterophylla/Oplopanax horridum/Athyrium filix-femina*** community. It occurs on very wet slopes and stream terraces in western Washington and is characterized by an extremely lush understory.

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[3]Unpublished report, "Preliminary report on the vegetation of the San Juan Islands, Washington," by R.W. Fonda and J.A. Bernardi. 1973. On file, Forestry Sciences Laboratory, Corvallis, Oregon.

[4]Unpublished report, "Phytosociological reconnaissance of western redcedar stands in four valleys of the North Cascades Park complex," by Joseph W. Miller and Margaret M. Miller. 1970. On file, Forestry Sciences Laboratory, Corvallis, Oregon.

Table 3 — Herb species associated with western redcedar in 7 portions of its natural range

Alaska[1]	Coastal British Columbia[2]	interior British Columbia[3]	Montana[4]
Athyrium filix-femina	*Achlys triphylla*	*Adenocaulon bicolor*	*Actaea rubra*
Blechnum spicant	*Adiantum pedatum*	*Adiantum pedatum*	*Adenocaulon bicolor*
Clintonia uniflora	*Anemone occidentalis*	*Angelica arguta*	*Aralia nudicaulis*
Coptis asplenifolia	*Athyrium filix-femina*	*Aralia nudicaulis*	*Athyrium filix-femina*
Cornus canadensis	*Blechnum spicant*	*Athyrium filix-femina*	*Carex disperma*
Dryopteris austriaca	*Cardamine breweri*	*Campanula rotundifolia*	*Chimaphila umbellata*
Epilobium alpinum var. *nutans*	*Carex deweyana*	*Carex disperma*	*Circaea alpina*
Gymnocarpium dryopteris	*Carex hendersonii*	*Carex laeviculmis*	*Clintonia uniflora*
Hypopitys monotropa	*Carex obnupta*	*Carex stipata*	*Coptis occidentalis*
Listera cordata	*Carex pauciflora*	*Chimaphila umbellata*	*Cornus canadensis*
Lysichitum americanum	*Chimaphila menziesii*	*Circaea alpina*	*Disporum hookeri*
Maianthemum dilatatum	*Chimaphila umbellata*	*Clintonia uniflora*	*Disporum trachycarpum*
Polypodium glycyrrhiza	*Circaea alpina*	*Corallorhiza maculata*	*Galium boreale*
Pteridium aquilinum	*Clintonia uniflora*	*Corallorhiza mertensiana*	*Galium trifidum*
Pyrola uniflora	*Coptis asplenifolia*	*Cornus canadensis*	*Goodyera oblongifolia*
Rubus pedatus	*Coptis trifolia*	*Corydalis sempervirens*	*Gymnocarpium dryopteris*
Streptopus amplexifolius	*Corallorhiza maculata*	*Dryopteris austriaca*	*Linnaea borealis*
Streptopus roseus var. *curvipes*	*Cornus canadensis*	*Equisetum palustre*	*Listera borealis*
Streptopus streptopoides	*Disporum hookeri*	*Equisetum scirpoides*	*Listera convallarioides*
Thelypteris phegopteris	*Drosera rotundifolia*	*Equisetum sylvaticum*	*Lycopodium annotinum*
Tiarella trifoliata	*Dryopteris austriaca*	*Fragaria virginiana* var. *glauca*	*Lycopodium complanatum*
	Epilobium angustifolium	*Galium boreale*	*Polystichum munitum*
	Equisetum telmateia	*Galium trifidum*	*Pteridium aquilinum*
	Eriophorum chamissonis	*Geum macrophyllum*	*Pyrola asarifolia*
	Galium trifidum	*Glycera elata*	*Pyrola chlorantha*
	Glycera elata	*Goodyera oblongifolia*	*Pyrola secunda*
	Glycera striata	*Gymnocarpium dryopteris*	*Smilacina stellata*
	Goodyera oblongifolia	*Heuchera cylindrica*	*Smilacina racemosa*
	Gymnocarpium dryopteris	*Linnaea borealis*	*Streptopus amplexifolius*
	Linnaea borealis	*Listera caurina*	*Tiarella trifoliata* var. *trifoliata*
	Listera caurina	*Listera convallarioides*	*Tiarella trifoliata* var. *unifoliata*
	Listera cordata	*Lycopodium complanatum*	*Trillium ovatum*
	Lycopodium clavatum	*Lysichitum americanum*	*Valeriana sitchensis*
	Lycopodium complanatum	*Melampyrum lineare*	*Veratrum viride*
	Lycopodium selago	*Mitella breweri*	*Viola canadensis*
	Lysichitum americanum	*Mitella pentandra*	*Viola glabella*
	Maianthemum dilatatum	*Polypodium glycyrrhiza*	*Viola orbiculata*
	Mimulus moschatus	*Polystichum andersonii*	*Xerophyllum tenax*
	Mitella ovalis	*Polystichum lonchitis*	
	Monotropa uniflora	*Pteridium aquilinum*	
	Montia sibirica	*Pyrola asarifolia*	
	Oenanthe sarmentosa	*Pyrola chlorantha*	
	Polysticum munitum	*Pyrola picta*	
	Pteridium aquilinum	*Pyrola secunda*	
	Rubus pedatus	*Rubus pedatus*	
	Scirpus microcarpus	*Scirpus microcarpus*	
	Smilacina stellata	*Smilacina stellata*	
	Stachys mexicana	*Smilacina racemosa*	
	Stellaria crispa	*Streptopus amplexifolius*	
	Streptopus amplexifolius	*Streptopus roseus* var. *curvipes*	
	Streptopus roseus var. *curvipes*	*Streptopus streptopoides*	
	Streptopus streptopoides	*Thalictrum occidentale*	
	Tiarella trifoliata var. *laciniata*	*Tiarella trifoliata* var. *laciniata*	
	Tiarella trifoliata var. *trifoliata*	*Tiarella trifoliata* var. *trifoliata*	
	Tiarella trifoliata var. *unifoliata*	*Tiarella trifoliata* var. *unifoliata*	
	Tofieldia glutinosa	*Trisetum cernuum*	
	Trillium ovatum	*Veratrum viride*	
	Trisetum cernuum	*Viola adunca*	
	Veratrum viride	*Viola glabella*	
	Viola glabella	*Viola palustris*	
	Viola orbiculata	*Woodsia scopulina*	

Table 3 — Continued

Eastern Washington and northern Idaho[5]	Western Washington and Oregon[6]	California[7]
Actaea rubra	*Achlys triphylla*	*Carex obnupta*
Adenocaulon bicolor	*Adenocaulon bicolor*	*Epilobium angustifolium*
Adiantum pedatum	*Adiantum pedatum*	*Erechtites arguta*
Anemone piperi	*Anemone deltoidea*	*Erechtites minima*
Aralia nudicaulis	*Asarum caudatum*	*Oxalis oregana*
Asarum caudatum	*Athyrium filix-femina*	*Polystichum munitum*
Athyrium filix-femina	*Blechnum spicant*	*Pteridium aquilinum*
Carex laeviculmis	*Campanula scouleri*	*Viola sempervirens*
Chimaphila menziesii	*Carex obnupta*	
Chimaphila umbellata	*Chimaphila menziesii*	
Circaea alpina	*Chimaphila umbellata*	
Clintonia uniflora	*Circaea alpina*	
Coptis occidentalis	*Clintonia uniflora*	
Corallorhiza maculata	*Coptis laciniata*	
Corallorhiza mertensiana	*Corallorhiza mertensiana*	
Corallorhiza trifida	*Cornus canadensis*	
Cornus canadensis	*Disporum hookeri*	
Disporum hookeri	*Disporum smithii*	
Dryopteris austriaca	*Dryopteris austriaca*	
Dryopteris filix-mas	*Galium oreganum*	
Epilobium angustifolium	*Galium trifidum*	
Fragaria vesca	*Goodyera oblongifolia*	
var. *bracteata*	*Gymnocarpium dryopteris*	
Galium trifidum	*Linnaea borealis*	
Goodyera oblongifolia	*Listera caurina*	
Gymnocarpium dryopteris	*Lycopodium clavatum*	
Hypopitys monotropa	*Lysichitum americanum*	
Linnaea borealis	*Maianthemum dilatatum*	
Listera caurina	*Mitella* sp.	
Listera convallarioides	*Montia sibirica*	
Lysichitum americanum	*Oenanthe sarmentosa*	
Mertensia paniculata	*Osmorhiza purpurea*	
Mitella pentandra	*Oxalis oregana*	
Mitella stauropetala	*Polystichum munitum*	
Montia sibirica	*Pteridium aquilinum*	
Polystichum munitum	*Pyrola asarifolia*	
Pteridium aquilinum	*Pyrola picta*	
Pterospora andromedea	*Pyrola secunda*	
Pyrola asarifolia	*Rubus lasiococcus*	
Pyrola chlorantha	*Rubus pedatus*	
Pyrola picta	*Smilacina stellata*	
Pyrola secunda	*Stachys mexicana*	
Pyrola uniflora	*Streptopus amplexifolius*	
Rubus pedatus	*Streptopus roseus*	
Smilacina racemosa	var. *curvipes*	
Smilacina stellata	*Synthyris reniformis*	
Stellaria crispa	*Tiarella trifoliata*	
Streptopus amplexifolius	var. *trifoliata*	
Tiarella trifoliata	*Tiarella trifoliata*	
var. *trifoliata*	var. *unifoliata*	
Tiarella trifoliata	*Tolmiea menziesii*	
var. *unifoliata*	*Trientalis latifolia*	
Trillium ovatum	*Trillium ovatum*	
Trisetum cernuum	*Vancouveria hexandra*	
Veratrum viride	*Viola glabella*	
Viola glabella	*Viola sempervirens*	
Viola orbiculata	*Whipplea modesta*	
Xerophyllum tenax	*Xerophyllum tenax*	

[1]Personal communication, Paul Alaback, Department of Forest Science, Oregon State University, Corvallis, 1980.
[2]From Orloci (1961, 1965), Krajina (1969), Packee (1976).
[3]From McLean and Holland (1958), Bell (1965), Krajina (1969).
[4]From Aller (1960), Pfister et al. (1977).
[5]From Daubenmire (1952), Daubenmire and Daubenmire (1968), Steele (1971).
[6]From Fonda and Bliss (1969), Franklin and Dyrness (1973), Dyrness et al. (1974).
[7]From Munz and Keck (1959), Axelrod (1977), Kuchler (1977), Sawyer et al. (1977), Zinke (1977).

Table 4 — Major western redcedar communltles in 5 portions of its native range[1]

Coastal British Columbia[2]	interior British Columbia[3]	Montana[4]	Eastern Washington and northern Idaho[5]	Western Washington and Oregon[6]
(1) Thpl-Abam/Opho/Gydr-Atfi	(1) ThpllLyam	(1) Thpl/Clun	(1) Thpl/Atfi	(1) Thpl/Adpe-Atfi
(2) Thpl-Abam-Psme/Vaov	(2) Thpl/Opho/Tiun	(2) Thpl/Opho	(2) Thpl/Opho	(2) Thpl-Abgr/Pamy
(3) Thpl-Abam-Psme/Vaov-Vaal/Stro-Pomu-Blsp	(3) Thpl-Potr-Pien/Cost/Pyas-Smst		(3) Thpl/Pamy	(3) Thpl-Abgr/Pomu
(4) Thpl-Abgr-Psme/Syal/Titr-Pomu	(4) Thpl-Psme/Loin/Arnu-Gydr-Clun-Tiun		(4) Thpl/Adpe	(4) Thpl-Accl/herbs
(5) Thpl-Abgr-Psme/Titr-Pomu	(5) Thpl-Tshe-Psme-Pimol Pamy/Coca		(5) Thpl/Dr	(5) Thpl-Tshe/Opho/Atfi
(6) Thpl-Abgr/Syal/Adpe	(6) Psme-Thpl-Pimo/Vaov-Pamy/Coca-Tiun		(6) ThpllLyam	
(7) Thpl-Chno-Abam-Psme/Vaov-Bene	(7) Tshe-Thpl-Psme/Lout/Arnu-Gydr-Coca-Clun-Tiun		(7) Thpl/Asca	
(8) Thpl-Pisi-Abam/Opho-Ribr-Rusp/Pomu	(8) Arnu-Gydr			
(9) Thpl-Pisi-Abam-Psme/Pomu	(9) Opho			
(10) Thpl-Pisi-Alru/Lyam/Caob	(10) Lyam			
(11) Thpl-Pisi-Pico/Spdo				
(12) Thpl-Psme/Bene				
(13) Thpl-Psme/Pomu-Actr				
(14) Thpl-Psme-Quga/Syal/Pomu				
(15) Psme-Thpl/Gash-Symo-Bene				
(16) Tshe-Thpl-Abam-Psme/Vaal/Blsp				
(17) Thpl/Pomu				
(18) Thpl/Vaal/Lyam				
(19) Thpl/Coas-Cotr-Lyam				
(20) Thpl/Opho/Adpe				
(21) Thpl-Abam/Opho				
(22) ThpllLyam				

[1]Only the first two letters of each genus and species are listed (e.g. Thuja *plicata* = Thpl).
[2]Numbers 1-16 are from Krajina (1969); 17-20 are from Orloci (1965); 21 is from Brooke (1965); 22 is from McMinn (1960).
[3]Numbers 1-7 are from Krajlna (1969); 8-10 are from Bell (1965).
[4]From Pfister (1977).
[5]Numbers 1-3 are from Daubenmire and Daubenmire (1968); 4-6 are from Steele (1971); 7 is from Steele et al. (1976).
[6]Number 1 is from Bailey (1966); 2-5 are from Franklin and Dyrness (1973).

Morphology, Anatomy, and Composition

Form

Western redcedar trees typically attain heights of 60+ m (197+ ft) and diameters of 150-300 cm (59-118 in) (Franklin and Dyrness 1973), but more massive individuals are not uncommon. Trees measuring 4.9 to 6.1 m (16 to 20 ft) in diameter and up to 76 m (250 ft) tall have been found (West Coast Lumber Trade Extension Bureau 1927). The largest western redcedar known to be alive in 1977 grew on the Olympic Peninsula. It was 592 cm (233 in) in diameter at breast height and 54 m (178 ft) tall (Pardo 1978). The largest redcedar east of the Cascades may be a tree **550** cm (216 in) in diameter and **54** m (177 ft) high, measured recently near Elk River, Idaho (personal communication, Charles A. Wellner, Forestry Sciences Laboratory, Moscow, Idaho).

Large western redcedar trees are not uncommon east of the Cascades. A preliminary survey of western redcedar in the northern Rocky Mountains[5] showed 33 groves containing redcedars larger than 152 cm (5 ft) d.b.h. Six contained trees larger than 335 cm (11 ft) d.b.h. The groves are quite evenly distributed among habitat types, but the ***Thuja plicata/Athyrium filix-femina*** type seems to be most typical. Although many groves occur on sideslopes, most of the very large western redcedars were found in stream bottoms or upper basins.

[5] Paper, "Western redcedar groves in the northern Rocky Mountains," by Frederic D. Johnson. 1980. Presented at the 53d annual meeting, Northwest Scientific Association, in Moscow, Idaho. Abstract on file, Forestry Sciences Laboratory, Corvallis, Oregon.

Wherever redcedars grow, the boles of old trees tend to be swollen or flared at the base (fig. 2). They are often conspicuously fluted, with frequent bark seams (Sudworth 1908, McBride 1959), but the fluting seems to be more common in open-grown trees than in dense stands (Nystrom 1980). Two or more leaders are frequent (Bowers 1956, Day 1957), and many old trees have hollow bases (McBride 1959, Daubenmire and Daubenmire 1968). Mature western redcedar trees tend to be larger in diameter but shorter than mature western hemlock, Sitka spruce, or Douglas-fir (Day 1957, Smith et al. 1961a).

Mature western redcedars taper more than Douglas-firs and western hemlocks. The majority of this taper **is** in the first 16 feet, and most occurs in the first 4 feet above ground (Nystrom 1980). Small western redcedar trees seem to taper less than large trees, which become nearly conical in southeastern Alaska (Andersen 1955a). Alaska redcedars growing in association with western hemlocks have much better form than those growing in pure stands (Andersen 1955b); this may be caused by the greater stand densities associated with hemlock-redcedar mixtures. Or it may be the result of mixed stands occurring on better sites than pure stands (see Gregory 1957).

Crown, Branches, and Foliage

Most western redcedar trees growing on moderately dry sites in western Oregon have rather open crowns (see Gratkowski 1956). Crown density seems to vary with age, however. Young redcedars on the Queen Charlotte Islands have dense crowns that become thinner with age until the upper portions die, leaving numerous spike tops (Day 1957). This thinning with age is accompanied by changes in the percentages of stem wood, stem bark, branches, and foliage in western redcedar trees. Branches accounted for about 14 percent of the aboveground weight of the 5- to 15-cm (2- to 6-in) d.b.h. redcedars measured by Smith and DeBell (1973), but only 11 percent of the weight of those that were 30 to 41 cm (12 to 16 in) d.b.h. Individual trees vary greatly, however; the two redcedars measured by Grier and Logan (1977) were 23 and 41 cm (9 and 16 in) d.b.h. and had about 18 percent of their weight in living branches.

The branches of young western redcedars curve upward. On older trees they swing downward near the bole, then sweep up again at the ends (Bowers 1956). Except where densely crowded, most of these branches are retained until the trees are 46- to 51-cm (18- to 20-in) d.b.h. and 15 to 24 m (**50** to 80 ft) tall (Sudworth 1908). Tiny branchlets are formed when the terminal shoot on each branch produces a lateral apex at every eighth leaf pair (see Malcolm and Caldwell 1971). These branchlets (really frondlike aggregations of leaves) die and fall off every 2 to **5** years (see Sudworth 1908, Bowers 1956).

The leaves of a mature western redcedar are small and scalelike — much smaller than the two cotyledons of a germinating seedling or the juvenile leaves produced in whorls of four soon thereafter (see Franklin 1961). They are darker green on top and lighter underneath than other cedarlike trees of the Pacific Northwest (Bowers 1956), with white markings on the lower surfaces (Dallimore and Jackson 1967).

Western redcedar leaves are numerous, and foliage comprises a higher fraction of the live-crown weight in redcedar than it does in Douglas-fir (Brown 1978). Foliage accounts for 10 percent of the above-ground weight of 5- to 15-cm (2- to 6-in) d.b.h. redcedars and 6 percent of the weight of 30- to 41 cm (12- to 16-in) d.b.h. western redcedars (Smith and DeBell 1973). A 0.6- to 0.9-m (2- to 3-ft) diameter redcedar may have 227 to 1361 kg (500 to 3,000 lb) of green foliage (Cochrane 1951), but Grier and Logan (1977) measured an average of only 15.4 kg (33.9 lb) of ovendry foliage on 0.2- and 0.4-m (0.8- and 1.3-ft) diameter trees.

Redcedar foliage seems well suited to the support of epiphytes. Four species of mosses, 1 hepatic, and 16 lichen species occur on western redcedar leaves in western British Columbia (Vitt et al. 1973). Daubenmire (1943) also found lichens on the leaves of western redcedar in northern Idaho. He described three unique attributes that may be responsible for the superiority of redcedar foliage as an epiphyte habitat: overlapping of the scalelike leaves, the surface roughness created by peglike papillae projecting from epidermal cells, and a superficial film of scurfy material. Vitt et al. (1973) proposed a fourth attribute — lack of certain inhibitory volatile compounds that are found in the foliage of other western conifers.

Figure 2.—Old-growth western redcedars. Note the fluted, flared lower boles. The striped stick is 1 m long.

Epiphyte-inhibiting compounds may not be present, but western redcedar foliage contains several other substances. The volatile foliage oil is chiefly L-thujone and d-isothujone (Von Rudloff 1962), but pinene, d-sabinene, and fenchone are also present (Cochrane 1951, Von Rudloff 1962, Banthorpe et al. 1973). Oil from young branchlets contains larger amounts of pinene and sabinene than that from older ones (Von Rudloff 1962). In addition to the above monoterpenes, diterpene hydrocarbons (Aplin and Cambie 1964), biflavonyl pigments (Rahman et al. 1972), and dilignol rhamnosides (Manners and Swan 1971, 1977) have also been found in western redcedar leaves. Some of these compounds inhibit bacterial growth (Michel 1976). Those present in the steam volatiles obtained from redcedar foliage are highly toxic to coho salmon fry (Peters 1974, Peters et al. 1976).

The dry, powdered western redcedar foliage analyzed by Chow **(1977a)** had a pH of **5.3** — equal to the pH of red alder foliage, but much higher than the pH values measured for Douglas-fir **(3.8)**, western hemlock **(4.0)**, lodgepole pine **(4.3)**, or white spruce **(4.3)** foliage. This high pH value was accompanied by a high calcium content. Ovington **(1953)** analyzed fresh leaves and also found higher pH values in redcedar than in Douglas-fir or western hemlock when all three species were measured on the same British site. He recorded great variation among sites, however, and concluded that leaf pH was related to acidity of the underlying soil.

When litter fall was analyzed near the Pacific coast, the calcium concentration in western redcedar foliage was over **2** percent — twice that of bigleaf maple foliage and **30** times that of lodgepole pine foliage (Tarrant et al. **1951).** Calcium content was also high in freshly fallen western redcedar foliage in the northern Rocky Mountains (Daubenmire **1953).** Nitrogen and phosphorus concentrations were relatively low for western redcedar foliage in both regions. Potassium concentrations were moderately high along the coast, moderately low in the northern Rocky Mountains. Packee's **(1975)** literature review showed that crude protein content of western redcedar foliage on Vancouver Island varies seasonally but is lower than that of Douglas-fir foliage. Western redcedar foliage apparently contains more fat than Douglas-fir foliage in July and December, less in March.

Redcedar does not form buds containing preformed shoots (Owens and Pharis **1971),** and no clearly visible buds or rapidly elongating succulent shoots are present (Aldhous and Low **1974).** Instead, the shoot apex is covered by numerous leaf primordia at various stages of development. Owens and Pharis found that branches are two ranked, occurring every two to four nodes. Only one branch occurs at a node, and secondary branches are more abundant on the side closest to the apex of the main branch.

Strobili and Seeds

Male and female strobili are borne on different branches of the same tree (Schopmeyer **1974).** Both occur at the tips of small lateral branches, and both are formed as a result of the transformation of previously vegetative apices (Owens and Pharis **1971).** Male and female strobili occur. at different heights, however, and they differ in color. The reddish male strobili are borne on lower branches; the green female strobili occur near the treetops (Hedlin **1964,** Søegaard **1969).** The male strobili fall off after shedding the pink pollen. Pollen grains are single and spheroidal, without bladders, apertures, ridges, or folds. They are **20** to **45** μm in diameter and have scattered, isodiametric radial projections (see McAndrews et al. **1973).** Western redcedar pollen does not preserve well, and it decays rapidly in peat bogs (Hansen **1941).**

As the female strobili ripen, they change from green to yellow and finally to a pale cinnamon-brown (Schopmeyer **1974).** Erect when young, they become reflexed when they reach their mature length of **13** mm **(1/2** in) (Dallimore and Jackson **1967).** Although immature female strobili may consist of up to **10** pairs of cone scales, only 5 or 6 develop to form the mature strobilus and, of these, only pairs **3** and **4** are fertile (Hedlin **1964).** Two or three seeds are borne under each fertile scale (Bowers **1956).**

Western redcedar seeds are chestnut brown and about **6** mm **(1/4** in) long, with lateral wings about as wide as the body (Schopmeyer **1974).** Approximately **9.65** g of cleaned seed are obtained per liter of cones (0.75 lb of seed per bushel). Schopmeyer's **1974** data summary shows **448,000** to **1,305,000** cleaned seeds per kilogram **(203,000** to **592,000** seeds per pound).

Roots

The roots of western redcedar may be recognized by their extremely thin brown outer bark, which is underlain by a thin pink to purple-red zone above the white inner bark. Young roots may have a thick, white, pulpy outer layer outside the pink zone (Gilbertson et al. **1961).** The tap roots are poorly defined or nonexistent, but a profuse fine root system is developed (Leaphart and Wicker **1966).** These small roots decay rapidly and lose most of their tensile strength within **3** to 5 years after the parent tree is felled. Larger redcedar roots may remain reasonably sound and intact for many years (O'Loughlin **1974).**

Depth of root penetration was similar for western redcedar, Douglas-fir, and western hemlock where Eis **(1974)** excavated trees on Vancouver Island, but Smith **(1964b)** found redcedar roots to be shallower than those of Douglas-fir and deeper than western hemlock roots. Boyce **(1929)** mentioned the deep root system of western redcedar in explaining its windfirmness on the Olympic Peninsula. Jackson and Knapp **(1914),** Flint **(1925),** Hepting **(1971),** and Shinn **(1971)** refer to western redcedar as a shallow-rooted species, however, and Haig **(1936)** and Haig et al. **(1941)** found the root penetration poor. Where a thick duff layer is present, most redcedar roots occur in the duff rather than underlying soil (Ross **1932).** Ross found no root hairs on these duff-inhabiting roots. Differences in local soil conditions probably are responsible for these various conclusions. Redcedar may form deep root systems on deep, moderately dry soils. Its root development is limited and shallow on wet sites (see Day **1957,** McMinn **1960).**

All authorities seem to agree that western redcedar has an extensive root system. Jackson and Knapp **(1914)** believed that bole buttresses indicated the number of principal roots, with masses of slender fibrous roots extending **3** m **(10** ft) or more in all directions from the buttresses. The ratio of rootlet length to the length of the parent lateral root was 0.960 for the redcedars examined by Leaphart (1958) in northern Idaho. It was 0.260 for grand fir and only 0.005 for lodgepole pine. Leaphart and Grismer (1974) measured the extent of roots in a mixed-species stand in northern Idaho and found that western redcedar made up only 17 percent of the basal area but accounted for 82 percent of the root length.

Root grafting is more frequent in western redcedar than in Douglas-fir or western hemlock (Eis 1972). In addition to numerous small grafts, Eis found 27 grafts greater than 1 cm (0.4 in) in diameter between two redcedar trees growing on shallow soil over bedrock.

Western redcedar mycorrhizae are of the vesicular-arbuscular type (personal communication, James M. Trappe, Forestry Sciences Laboratory, Corvallis, Oregon).

Bark

Western redcedar bark is light cinnamon-red or brown on young trunks, gray on old trees (Isenberg 1951). It is divided into wide ridges by irregular fissures that break up the surface into small plates (Dallimore and Jackson 1967). Redcedar bark is stringy (Wethern 1959) and, even on old trees, thin. It varies from 1.3 to 2.5 cm (1/2 to 1 in) thick (Sudworth 1908, Isenberg 1951, Bowers 1956, Dallimore and Jackson 1967). It is slightly heavier than the wood, weighing 0.37 to 0.39 g per cm^3 (23.1 to 24.3 lbs per ft^3) (see Smith and DeBell 1973, Brown et al. 1977).

Stem bark accounted for about 19 percent of the aboveground weight of 5- to 15-cm (2- to 6-in) d.b.h. trees measured by Smith and DeBell, 10 percent of the weight of 30- to 41-cm (12- to 16-in) d.b.h. trees. About 6 percent of the aboveground weight of 23- and 41-cm (9- and 16-in) d.b.h. redcedars measured by Grier and Logan (1977) consisted of stem bark. Smith et al. (1961a) found redcedar bark percentages to be slightly lower than those of western hemlock, much lower than the bark percentages of Douglas-fir. When Brown et al. (1977) compared bark and stem volumes in Montana and Idaho, they found the bark volume/stem volume ratio lower in western redcedar (0.15) than in ponderosa pine (0.24), white pine (0.21), Douglas-fir (0.19), western larch (0.24), or western hemlock (0.18). When they compared bark weight to stem weight, the redcedar bark proportion (0.173) was smaller than that for all other conifers except lodgepole pine (0.114).

For similar tree sizes, redcedar bark is slightly thinner than western hemlock bark at the top of the first 4.9-m (16-ft) log in southeastern Alaska. It is slightly thicker than Sitka spruce or Alaskacedar bark measured at that point (see Bones 1962). Bark thickness varies among trees, but the inner bark of western redcedar tends to be thinner than that of Sitka spruce and its outer bark tends to be thicker. Redcedar bark has less airspace, lower moisture content, and a higher specific gravity than Sitka spruce bark (see Smith and Kozak 1971).

Western redcedar has a brown first periderm and a reddish purple secondary periderm (Mullick 1971). The purple color is a property of the nonanthocyanic phlobaphene pigments found there (Mullick 1969a). One of these phlobaphenes was analyzed and described by Swan (1963a). Anthocyanidins are also present in the secondary periderm (Mullick 1969b). The inner and outer bark are similar, but outer bark has a higher lignin content (Cram et al. 1947). The lignin from the outer bark differs from that of the inner bark and from most other softwoods in that it contains fewer methoxyl groups and aromatic protons, more catechol groups, and more aliphatic protons (Swan 1966).

Compounds that have been extracted from western redcedar bark include:

arachidic acid (Fraser and Swan 1978)
aspartic acid (Swan 1963b)
campesterol (Fraser and Swan 1978)
catechin (Swan 1963b)
D-fructose (Swan 1963b)
D-glucose (Swan 1963b)
diethyl octadecanedioate (Swan 1968)
docosanoic acid (Fraser and Swan 1978)
eicosanoic acid (Fraser and Swan 1978)
epicatechin (Swan 1963b)
ethyl 18-hydroxystearate (Swan 1968
ferulic acid (Swan 1968)
isopimaric acid (Fraser and Swan 1978)
leucocyanidins B and C (Swan 1963b)
myristic acid (Fraser and Swan 1978)
19-norisopimara-8(14), 15-dien-3-one (Fraser and Swan 1973)
norditerpene alcohols (Quon and Swan 1969)
oleic acid (Fraser and Swan 1978)
palmitic acid (Fraser and Swan 1978)
phydroxyphenylpyruvic acid (Swan 1963b)
shikimic acid (Swan 1963b)
stearic acid (Fraser and Swan 1978)
sucrose (Swan 1963b)
tannins, oils, and waxes (Smith and Kurth 1953)
taxifolin glucoside (Hergert and Goldschmid (1958)
terpinen-4-ol (Fraser and Swan 1978)
tetracosanoic acid (Fraser and Swan 1978)
thujone (Fraser and Swan 1978)
xanothoperol (Fraser and Swan 1978)

When Smith and Kurth (1953) analyzed several western redcedar trees near Oakridge, Oregon, they found that extractive contents of the bark were higher in treetops than in butt logs, rangingfrom 18 to 29 percent. In contrast, calcium content of western redcedar bark Increases with distance from the treetop (Webber 1973).

Wood

Stem wood made up 57 to 73 percent of the aboveground weight of the western redcedar trees measured by Smith and DeBell (1973) and 70 percent of the two redcedars measured by Grier and Logan (1977). The wood is coarse and straight grained with a characteristic sweet odor and faint bitter taste (Brown et al. 1949, Isenberg 1951, Forest Products Laboratory 1955). The green heartwood has an average moisture content in North America of 58 percent — about the same as the moisture content in the heartwoods of western larch, western white pine, Pacific silver fir, Engelmann spruce, and Port-Orford-cedar (see Forest Products Laboratory 1955). Western redcedar heartwood grown in New Zealand is very wet in many trees, however, and heartwood moisture content up to 298 percent has been recorded there (Harris and Kripas 1959). The average moisture content of green redcedar sapwood in North America is higher than that of any other conifer — 249 percent (see Forest Products Laboratory 1955).

North American western redcedar wood weighs 0.37 to 0.38 g/cm^3 (23 to 24 lb/ft^3) when air dried, 0.31 to 0.34 g/cm^3 (19.5 to 21.0 lb/ft^3) when ovendried (Desch 1948, Isenberg 1951, Forest Products Laboratory 1955, Higgins 1957, Smith and DeBell 1973). Weight per unit volume (density) of western redcedar wood varies with its position in the tree, increasing with height and decreasing from pith to cambium (Wellwood and Jurazs 1968, Okkonen et al. 1972). Wood density also varies with geographic location and site. Western redcedar in Montana and Idaho is less dense than all other western conifer woods except that of subalpine fir (see Brown et al. 1977). Densities of commercial redcedar wood are similar in Oregon and British Columbia — 55 percent and 56 percent that of Douglas-fir. The "scrub" redcedars of British Columbia have denser wood, however — 71 percent of Douglas-fir density (Wethern 1959). A survey of densities of western woods (Maeglin and Wahlgren 1972) showed great variation, with average specific gravities of western redcedar ranging from 0.318 in western Washington to 0.357 in Montana. Western redcedar wood grown in Germany is denser (0.37 g/cm^3) than that grown in North America (see Volkert 1956). The German values decreased as annual ring widths increased — from 0.4 g/cm^3 with 2-mm rings to about 0.28 g/cm^3 with 8-mm rings.

Annual growth rings are distinct in western redcedar. Transition from springwood to summerwood within each annual ring is more or less abrupt, and the summerwood is narrow and hard (Brown et ai. 1949, Isenberg 1951, Forest Products Laboratory 1955). Resin canals are absent. Metatracheal parenchyma is present, but very variable in distribution. Rays are uniseriate and 1 to 12+ cells high, with some gummy infiltration of the ray cells (Brown et al. 1949, Johnston 1951). Ray tracheids are occasionally found on the upper and lower margins (Brown et al. 1949, Kobayashi 1956). Tracheids have one to two rows of bordered pits on the radial walls (Brown et al. 1949). The membranes of these bordered pits do not possess a torus, but consist of numerous, closely packed strands (Krahmer and Cote 1963).

Average tracheid diameter of western redcedar decreases with increased latitude, altitude, and tree age in Idaho (Crooks 1964). Redcedar tracheids in British Columbia are shortest near the stump. They reach maximum length about midheight in the tree and decrease slightly thereafter (Wellwood and Jurazs 1968). Wellwood and Jurazs found that tracheid length increased from the pith outward in redcedar wood. When the wood is macerated to make kraft pulp, western redcedar fibers average shorter (2.05 mm) than either western hemlock (2.21 mm) or Douglas-fir (2.62 mm) fibers (Graff and Isenberg 1950). Summerwood fibers of western redcedar are unique in that increasing tensile strength is associated with a decreasing Young's modulus (Jayne 1960).

Other stress limits and strength properties of western redcedar wood are listed by Newlin and Wilson (1917), the West Coast Lumber Trade Extension Bureau (1927), the Forest Products Laboratory (1955, 1963), and Bendtsen (1972). Their data show that the ends of western redcedar are harder and more difficult to crush than the ends of western white pine and sugar pine, but its sides are softer and easier to crush. Redcedar shear strength is low. Volumetric shrinkage and thermal conductivity are also low, however; western redcedar has the lowest volumetric shrinkage listed by Higgins (1957) and the lowest thermal conductivity of any softwood listed by the Forest Products Laboratory (1955). Its thermal emissivity is approximately 0.91 (Owens 1964). The low tangential shrinkage of redcedar seems to be the result of a low summerwood percentage in the annual rings, plus relatively low shrinkage of both springwood and summerwood (Erickson 1955). Its longitudinal shrinkage, though low, is greater than those of western hemlock and the true firs (Espenas 1974).

Western redcedar is a soft, stable, weak wood that splits easily and is not very tough. Toughness is increased by extracting extraneous compounds with an alcohol-benzene mixture (Raczkowski 1968, Lawniczak and Raczkowski 1970).

Toughness and strength seem to vary with redcedar wood color. Dark brown heartwood is less tough, softer, and weaker than lighter colored heartwood (Findlay and Pettifor 1941). This dark brown heartwood usually occurs near the center of the tree and is surrounded by a narrower red-stained layer inside an outer zone of straw-colored heartwood (van der Kamp 1975). Redcedar sapwood is white and narrow, generally 2.5 cm (1 in) or less wide (Lutz 1972). It is wider than western larch sapwood, narrower than the sapwoods of Engelmann spruce, Douglas-fir, lodgepole pine, or ponderosa pine (Lassen and Okkonen 1969). Krahmer and Cote (1963) found the air-permeability ratio of early sapwood to late heartwood to be 6.5 in redcedar — lower than in Douglas-fir or western hemlock. Redcedar heartwood pH (3.0 to 3.4) is lower than sapwood pH (4.1 to 4.7) (van der Kamp 1975). Although western redcedar has a lower pH than most species (see Farmer 1962), the wood acts as a pH buffer when suspended in water (Carroll et al. 1973).

The identification of heartwood and sapwood is usually relatively easy for western redcedar. Nevertheless, application of perchloric acid, Benedict's solution, Fehling's solution, or ammonium bichromate may be useful in difficult cases (Brown and Eades 1948, Eades 1958). The usual heartwood-sapwood orientation is absent in some southeastern British Columbia redcedars, where a target-shaped pattern of alternate concentric bands of light- and dark-colored wood occurs (MacLean and Gardner 1956b). The dark heartwood bands are rich in natural preservatives. Very dark oil or resin streaks are even richer in preservatives when they occasionally occur in western redcedar heartwood (Gardner 1963).

Natural preservatives comprise one of the most important and interesting characteristics of western redcedar. About 10 percent of the total heartwood consists of extractives (Gardner 1963), and up to 23 percent extractive content has been found in some portions (MacLean and Gardner 1956a). Indeed, 30 to 50 percent extractive content sometimes occurs in the resin streaks (Gardner 1963).

A complete list of the many organic compounds in redcedar wood would be long. The six most important compounds isolated from volatile oils and their approximate percentages in butt heartwood are listed below (see Anderson and Gripenberg 1948; Erdtman and Gripenberg 1948a; Rennerfelt 1948; Gardner and Barton 1958a, 1958b; Roff and Whittaker 1959; Wethern 1959; Lyr 1961; and Gardner 1963):

α-thujaplicin	0.01 percent
β-thujaplicin	0.30 percent
γ-thujaplicin	0.20 percent
β-thujaplicinol (7-hydroxy 4-isopropyltropolone)	0.07 percent
thujic acid	0.08 percent
methyl thujate	0.17 percent

Polyphenolic lignans may not be as important, but they make up the major portion of the heartwood extractives (see MacLean 1970). Eleven of these lignans have been identified and described (Gardner et al. 1960, 1966; MacDonald and Swan 1970; MacDonald and Barton 1973; Kirbach and Chow 1976): thujaplicatin, dihydroxy thujaplicatin, thujaplicatin methyl ether, hydroxy thujaplicatin methyl ether, dihydroxy thujaplicatin methyl ether, γ-thujaplicatene, plicatic acid, plicatin, plicatinaphthalene, plicatinaphthol, and β-apoplicatitoxin.

Thujaplicatin and the thujaplicatin methyl ethers are also present in much smaller concentrations within the sapwood. They build up slowly there, then increase dramatically at the sapwood-heartwood boundary (Hillis 1968, Swan et al. 1969, MacLean 1970). Treatment with enzyme inhibitors may increase the amounts of thujaplicatin, thujaplicatin methyl ethers, and β-sitosterol produced in sapwood (see Swan 1971).

Other western redcedar wood constituents include β-dolabrin (Gardner and Barton 1958a, Gardner 1963), nezukone (Hirose and Nakatsuka 1967), cumic acid (Barton and MacDonald 1971), unnamed soluble and insoluble phenols (Barton and Gardner 1954, Krueger 1968), and various hemicelluloses (Lewis 1950, Hamilton and Partlow 1958). Western redcedar hemicelluloses are similar to those of other conifers, except that the xylan contains a lower percentage of L-arabinose (Dutton and Funnell 1973). Western redcedar wood has a high lignin content (Lewis 1950) — higher than the woods of western hemlock, Douglas-fir, and Engelmann spruce (Wilson et al. 1960). More nonreducing sugars than reducing sugars are present in the sapwood (Radwan 1969).

Thujaplicin and water-soluble phenol increase in redcedar heartwood with distance from the pith, decrease with height (MacLean and Gardner 1956a, Tickle 1963). Calcium and potassium in the wood increase with height (see Webber 1973).

Soluble phenols apparently leach out of redcedar wood when fresh logs are stored in water. Kiser and Griel related the periodic absence of plankton from millponds to the presence of freshly cut western redcedar logs in those ponds.[8] Their subsequent laboratory experiments indicated that steam-distilled redcedar oil from freshly cut old-growth sawdust was more toxic to copepods and cladocerans than either formalin or chloral hydrate.

[8]Unpublished report, "The effect of red cedar oil on zooplankton organisms," by R.W. Kiser and J.V. Griel. 1956. On file, Centralia Junior College, Centralia, Washington.

Products

The thujaplicins, dolabrin, and thujaplicinol ("tropolones") are toxic to coho salmon fry (Peters 1974, Peters et al. 1976) and guppies (Erdtman and Gripenberg 1948b). They are also largely responsible for the high natural durability of western redcedar wood (Barton 1973b). Variation in tropolone content therefore leads to variation in wood durability. Some cedar roofs last 50 years, for example, but others decay in less than 10 (Roff et al. 1962). The different moisture conditions associated with steep and flat roof pitches probably also contribute to these differences. Under similar conditions, redcedar wood deteriorates more slowly than the woods of western hemlock, Pacific silver fir, Sitka spruce, or Douglas-fir (Boyce 1929, Buchanan and Englerth 1940).

Cartwright (1941) and Englerth and Scheffer (1954) found the most durable western redcedar to be that nearest the base of the tree in the outer heartwood. The wood in large western redcedar logs is often exceedingly resistant to decay, and it sometimes remains sound after hundreds of years on the ground (see West Coast Lumber Trade Extension Bureau 1927). The fire resistance of western redcedar is poor (see Hall and Dell 1970), and moist heat reduces its decay resistance (Scheffer and Eslyn 1961).

Uses and Properties

Western redcedar products have been important since prehistoric times. North American Indians, particularly tribes living along the coasts of Washington and British Columbia, used redcedar in many ways. Large logs were carved into totem poles and hollowed out to make huge ocean-going canoes. The redcedar logs were also split into wide planks used in building large timber frame structures that were often 15 m (50 ft) or more square (Vastokas 1969). Recent excavations of buried structures made by Indians have uncovered redcedar planks thought to be 6,000 to 10,000 years old (Sharpe 1974). Bark from young trees was used by the Indians to make baskets, ropes, blankets, mats, clothing, and thatch (see Sargent 1933, Bowers 1956, Dallimore and Jackson 1967, Bolsinger 1979). The flexible young branches were also used in making baskets. Thin twigs were woven into whaling ropes, and thicker ones were used for arrows (Edlin 1968). The roots were used for fishhooks (Dallimore and Jackson 1967).

Modern society also uses western redcedar in a variety of products. The wood is valued for canoe and boat construction, and redcedar is still being used to build timber frame structures — as exterior siding, shingles, sashes, doors, window frames, and interior finish (Forest Products Laboratory 1955, Wood 1959). In addition, western redcedar is used in utility poles, fenceposts, piling, paper pulp, clothes closets and chests, caskets, crates, boxes, beehives, rain gutters, and fish-trap floats (Butler 1949, Viereck and Little 1972, Sharpe 1974). A complete list would include many other products, for the wood is suitable for many uses.

Western redcedar wood is nonresinous, light, and easy to work (Forest Products Laboratory 1955, Wood 1959). It has exceptional dimensional stability and is a good thermal insulator (Forest Products Laboratory 1955, Tickle 1963). Redcedar wood glues easily, particularly with nonresin glues (Forest Products Laboratory 1955). Although naturally durable, it is difficult to impregnate with artificial preservatives — even by pressure processes (Titmuss 1965).

The ease of splitting redcedar is an advantage in the manufacture of handsplit shakes, but a disadvantage when trees are felled on rough hills and yarded with heavy machinery. Breakage, splitting, and shattering are often severe (McBride 1959). The wood is weak when used as a beam or post and low in shock resistance (Forest Products Laboratory 1955). The low density of redcedar was associated with poor fire resistance in the British standard fire-propagation test (Hall and Dell 1970). It is a soft wood that is extremely sensitive to marring (Packee 1976). The density and hardness of western redcedar can be increased threefold by using heat and pressure, without the addition of chemicals, but this is only a laboratory procedure of no commercial importance (Research News, Ottawa 1962a).

Western redcedar is one of the poorest woods for nail- and screw-holding capacity. It is also poor for bolt-holding and is one of the weakest woods for withstanding connector loads (see Forest Products Laboratory 1955, Hokhold 1965). Special ring-shanked nails improve the nail-holding capacity of redcedar (Lee and Lord 1960), and increasing the screw lengths by 0.6 cm (1/4 in) improves its screw-holding properties enough to equal those of western hemlock, Scotch pine, and Norway spruce (British Columbia Lumber Manufacturers Association, n.d.)

Dry western redcedar takes and holds stains, paints, enamels, and clear finishes very well (West Coast

Lumber Trade Extension Bureau **1927,** Wood **1959,** Jones **1966).** It ranks with redwood as the best paint substrate available in North American woods (Gardner **1963).** Lack of extreme differentiation between springwood and summerwood, plus low summerwood swelling and the resulting lack of raised grain, seem to be responsible (see Brown **1957,** MacLean **1970).** Blistering is serious where free water (not just water vapor) is present behind the paint film in western redcedar, however; more serious than in Douglas-fir, Alaska-cedar, white pine, red pine, or spruce (Veer and King **1963).** Extractive globules became concentrated on the paint surface in the 100-percent humidity maintained by Veer and King. Extractive bleedthrough can be a problem (Forest Products Laboratory **1966,** MacLean **1970).**

One of the best clear finishes for western redcedar wood is a tung oil modified, phenolformaldehyde-resin-based varnish (Oliver **1957).** The best pigmented, penetrating stain seems to be the Forest Products Laboratory natural finish **(60** percent linseed oil, 5 percent pentachlorophenol, **10** percent pigment, **0.3** percent zinc stearate, **1.0** percent wax, and **3.7** percent volatiles); the best water-soluble inorganic salt finishes contain acid copper chromate, chromated copper arsenate, or copper-pentachlorophenol (Grantham et al. **1976).** When left unfinished, western redcedar weathers gray wood **1959)** and resists decay, but erodes appreciably faster than redwood, Douglas-fir, Engelmann spruce, or ponderosa pine (Feist and Mraz **1978).** Both western redcedar and redwood weathered better than Monterey pine, alpine-ash, Brisbane boxwood, or King-William-pine in Australia (Woodhead **1969).** Redcedar wood is quite resistant to corrosion by hydrochloric acid but is less suitable than baldcypress or longleaf pine for use in contact with acids (American Wood Preservers Association **1946).**

Prices

The many uses and excellent properties of western redcedar products have increased the demand for them in recent years. This increasing demand has been accompanied by accelerating price increases. Both consumption rates and prices have increased more rapidly for western redcedar products than for products of most other west coast woods (Bolsinger **1979).** Western redcedar and Alaska-cedar commanded average round-log values higher than any other Alaska tree species in **1971** (Farr and LaBau **1971).**

In western Washington and northwestern Oregon, the average price paid for all western redcedar logs increased from **$57.30** per thousand board feet in **1965** to **$320.80** per thousand board feet in **1977** — an average annual increase of **15.4** percent compared with average annual price increases of about **12** percent for Douglas-fir and western hemlock during the same period (Bolsinger **1979).** The accelerating nature of these price increases is emphasized by Ruderman's **(1978)** calculations for **1975-77;** average annual increases in log price were **35.1** percent for western redcedar, **20.0** percent for Douglas-fir saw logs, and **13.2** percent for western hemlock. As the estimated annual harvest of western redcedar in the United States for **1975** to **1976** was **950** million board feet (Bolsinger **1979),** such price increases represent very large sums spent for redcedar products.

Accelerating price increases and an increasing demand for redcedar products may stimulate greater use of defective western redcedars like those found in the extensive stands of decadent cedar and hemlock in interior British Columbia. Dobie **(1976)** concluded that rehabilitation of these decadent stands could be profitable only at very low discount rates for short rotations on good and medium sites, but subsequent price increases may provide economic alternatives.

Lumber

Lumber was the chief western redcedar product in Oregon, Montana, and Idaho in **1976** (Bolsinger **1979).** Most redcedar logs used for lumber manufacture are acceptable in terms of eccentricity, sweep, taper, and shake (see Packee **1976).** Redcedar lumber cut from these logs is easy to kiln dry, but boards from the butt log (Desch **1948)** and thick planks (Forest Products Research Board **1950a)** sometimes collapse during drving The cell walls are distorted or obliterated, and redcedar lumber does not recover after collapsing (Tiemann **1941).** Predicting collapse from the appearance of a log is difficult or impossible, but collapse is associated with higher than normal extractive content (Meyer and Barton **1971,** Barton **1975).** Most redcedar logs subject to collapse seem to come from low or swampy ground (Guernsey **1951).** Guernsey observed that heavy boards were more likely to collapse than light ones. He recommended air drying before kiln drying or, if this is impossible, initial kiln temperatures that do not exceed **49°C (120°F).**

Kiln temperatures above **100°C (212°F)** with three to six times shorter drying times have been tested, but they resulted in nonuniform moisture content and a 5-percent loss of bending strength in western redcedar (Ladell **1953).** Less severe,' moderately accelerated drying schedules can be successfully used with lightweight boards of less 'than 45-percent moisture content (Salamon and Hejjas **1971).** Kiln drying does not destroy the heartwood extracts of redcedar, but it makes them more soluble (Sowder **1927).** Kiln corrosion should be considered when western redcedar is dried, because the thujaplicins are steam-distillable; they sometimes condense on metal kiln parts and corrode them (Barton **1972).**

Extractive-caused metal corrosion occurs even without the high temperatures associated with kiln drying. The zinc and lead used in roof gutters and valleys are sometimes corroded by rainwater extracts from western redcedar shingles or shakes (Forest Products Research Board 1950b). Iron, steel, copper, and brass fasteners (such as nails, screws, hinges) often corrode when in contact with redcedar lumber (see Campbell and Packman 1944, Farmer 1962, Titmuss 1965). The carbide-tipped saws and knives used in lumber manufacture also are corroded, dulling much sooner when used on unseasoned western redcedar than when used on other woods (Kirbach and Chow 1976). Recommended remedies include substituting another metal for the cobalt in tungsten carbide and using aluminum or stainless steel nails, screws, and fittings (Research News, Ottawa 1962b).

Where iumber is used under moist conditions, as in water-cooling towers, western redcedar seems to be less suitable than redwood (see Western Australia Forests Department 1961). Nevertheless, untreated redcedar lumber had a service life of about 18 years in Canadian cooling towers (Roff 1964). When water-repellent treatments were applied to western redcedar, waxes and wax solutions gave the most durable results (Gray and Wheeler 1959). Western redcedar responded better than eastern redcedar or baldcypress to waxing and staining treatments used in the preparation of pencil slats (Greaves and Harkom 1949).

Redcedar is the most important western species used for siding in the United States and Canada (Panshin and deZeeuw 1970), and it shows promise as a homegrown lumber species in Great Britain (Priest 1974). It is suitable for pattern making in foundries (Hale 1954). Redcedar makes excellent horticultural boxes (Moore and Bryan 1946) and is used in greenhouse construction (Syrach Larsen 1943). Western redcedar is unsuitable for apple boxes, however; the apples absorb volatiles from the wood and spoil (Ministry of Agriculture, Belfast, n.d.; Colhoun et at. 1961; Colhoun and Park 1963; Loughnane and Gallagher 1963).

Shakes and Shingles

Shakes and shingles are the chief western redcedar products in Washington, and British Columbia exported 3,294,000 squares in 1978.[7] Recent increases in shake and shingle production have been greater than the production increases in other redcedar products (Bolsinger 1979). Even before those increases, more than 95 percent of all wooden shingles manufactured in the United States were made from western redcedar (Brown and Panshin 1940). Attractive appearance, durability, lightness, and superior insulation probably are responsible for the popularity of redcedar as a roofing material. The insulating properties of 2.54 cm (1 in) of western redcedar wood are equal to 30 cm (12 in) of concrete or 19 cm (7.5 in) of brick or clay tile (O'Hea 1947).

Three types of redcedar shakes are manufactured: Straight split, taper split, and handsplit-resawn. All come in random widths of 10 to 30 cm (4 to 14 in). Lengths range from 46 to 81 cm (18 to 32 in), but the 61-cm **(24-in)** length is most common (The Lumberman 1957). Straight-split and taper-split shakes are both handsplit from redcedar blocks, but the blocks are reversed every other time for taper-split shakes. Handsplit-resawn shakes, which account for most of the shake production, have a coarse-textured split surface on one side and a smooth sawn surface on the reverse side (Munger 1970).

Only old, slow-growing, straight-grained, relatively knot-free western redcedar trees seem to be suitable for shake manufacture. Good shake material has 35 to 50 annual rings per inch (14 to 20 rings per cm). At least 245 years are required to produce a tree of suitable size for such material, and the shake industry is supported by redcedar trees that are 500 to 1,500 years old (Munger 1970). Such trees probably constitute a nonrenewable resource when considered in the scale of human time (see Munger 1970, Mitson and Holman 1975).

Younger trees may be suitable for redcedar shingles (Packee 1976). The two types of western redcedar shingles are slash grain and edge grain. Edge-grain shingles do not curl and are more durable (O'Hea 1947). Although untreated redcedar shingles may last for 25 years in Pennsylvania (Fergusson 1938) and 50 years in Washington (see Grondal 1913), they are less durable than redwood shingles in the wetter parts of Honolulu (Skolmen 1968). Leaching of the water-soluble heartwood extractives in wet conditions may be responsible (see Cserjesi 1976), but the low pitch of modern roofs also reduces durability.

Pressure impregnation with copper, chromium, and arsenic preservatives improves the durability of redcedar shingles (Smith 1964b). Impregnation with leach-resistant fire retardants makes the shingles more fire resistant (St. Clair 1969, Holmes 1971, Juneja 1972). Amino-resin-forming compounds are effective retardants (King and Juneja 1974).

[7]This statistic was obtained from the Council of Forest Industries of British Columbia, Vancouver. A "square" is the amount of shingles or shakes required to cover an area of 9.29 m² (100 ft²), exclusive of overlap.

High-temperature kiln-drying schedules can be used to bring unbundled western redcedar shingles from green to shipping weight in less than 2 hours (see Salamon 1960). Shingle durability is not appreciably affected by these high-temperature schedules (MacDonald and MacLean 1965).

Poles and Piling

Good form, large size, light shipping weight, easy climbing-spur penetration, and durability make western redcedar an excellent species for pole production, but it has a tendency to crush when used as piling (Brown and Panshin 1940). Redcedar poles taper more than southern pine or Douglas-fir poles (Bohannan et al. 1974). They are remarkably consistent in strength, however, showing no significant differences between geographic locations, elevations, or seasoning treatments (McGowan and Smith 1965).

Western redcedar poles constitute a plentiful renewable resource in British Columbia. Anderson (1961) estimated a provincial supply of about 121 million poles. Without considering annual growth, he forecast a pole supply of 300 years at the 1961 cutting rate of 400,000 poles per year. Approximately 200,000 poles were cut each year in the United States, which consumed about 400,000 redcedar poles annually (Anderson 1961).

Average-size western redcedar poles with sapwood less than 2.54 cm (1 in) thick should last about 12 to 17 years without treatment (Forest Products Laboratory 1955). More than half the untreated redcedar telephone poles on the Island of Hawaii were still serviceable after 20 years, however (Boone 1965). When in contact with the ground, they have a service life proportional to their diameter, not their cross-sectional area (Purslow 1962).

The service life of redcedar poles has been increased through several preservative treatments. Spraying freshly peeled green poles with urea minimized the checking that sometimes occurs during drying (West Coast Lumberman 1941). The dry poles were pressure treated with creosote and creosote-coal tar solutions during the 1940's (American Wood Preservers Association 1943, 1944). Hot- and cold-bath treatments with creosote and pentachlorophenol were then tried (see Colley 1946). Preservative penetration was often poor in western redcedar poles, however, and it varied with position and wood condition within a single pole (Jurazs and Wellwood 1965). Fortunately, the portions with poorest penetrability seemed to have the highest extractive content and least need for preservative treatment. Nonpressure treatment — such as butt-soaking or soaking the entire length of the pole — is common now. Pressure treatments are less used — the redcedar poles tend to become oversaturated (Randall and Sutherland 1974).

Redcedar poles are seldom retreated now, but several formerly used procedures for retreating in-service poles are of historical interest. One method was machine-shaving the sapwood and subsequently soaking the shaved pole in creosote (Lyon 1939). A somewhat similar procedure was used on redcedar bridge piling. After removing soil from around the affected portion, decayed wood was scraped off and the piling treated with a gelatinous suspension of NaF dinitrophenol and potassium dichromate (Railway Track and Structures 1955). Aboveground sap rot in redcedar poles has been treated by spraying with a 10-percent solution of pentachlorophenol (Graham and Wright 1959, Scheffer and Graham 1973).

Green or wet western redcedar power poles — particularly wet poles that have been in saltwater — may have low electrical resistances that are potentially hazardous to line workers (see Katz and Miller 1963, Breeze and Vitins 1965).

Pulp

The low density of western redcedar is the most serious handicap to its increased use in pulping (Wethern 1959). Pulp is produced and sold by weight, but the logging and lumber industries work by volume. Because a given volume of western redcedar contains only 77 percent as much wood by weight as the same volume of western hemlock and only 66 percent as much as the equivalent volume of Douglas-fir, the redcedar produces less pulp (Wethern 1959). Low lignin and ex;. active contents are highly desirable for chemical pulping processes — but western redcedar wood has relatively high contents of both (see Packee 1976).

The stringy redcedar bark is difficult to remove with standard debarking equipment. Chemical debarking with sodium arsenate has been tried successfully (DeMoisy 1952); ingrown bark is difficult to remove by any debarking technique, and it may create problems in some chemical pulping processes. Pilot-plant studies indicated that redcedar bark could be processed satisfactorily, however, and even whole-log chipping was possible (Thomas and Davis 1974).

The sulfate process is most frequently used to produce pulp from western redcedar. Yields are lower in sulfate than sulfite pulping, increasing the disadvantage of redcedar density mentioned earlier (Wethern 1959). The acidic constituents of western redcedar wood consume extra alkali, further reducing profits in a sulfate pulping operation (see Thomas and Davis 1974). Redcedar extractives corrode the steel ordinarily used in digesters and recovery equipment, sometimes reducing digester life by 50 percent compared with digesters used for western hemlock or Douglas-fir

(Wethern 1959, Thomas and Davis 1974). The life of evaporator tubes may be reduced by 80 percent (see Gardner 1963). Thujaplicins, a phenolic constituent, or both probably are responsible (British Columbia Lumberman 1953, MacLean and Gardner 1953a). Redcedar pulp drains poorly, sometimes restricting production even further (Thomas and Davis 1974). Its color constitutes a final handicap (Troxell 1954); redcedar pulp bleaches with difficulty (Isenberg 1951).

Some handicaps of redcedar pulping have been turned into advantages by skillful manipulation of the sulfate process, and redcedar has some favorable pulping characteristics. For example, adding 3 to 5 percent sodium sulfide to the cooking liquor offsets the deleterious effects of high alkalinity and improves both the yield and strength of redcedar pulp (Christiansen et al. 1957). Western redcedar requires a shorter sulfate-process cooking time than other British Columbia species (Wilson et al. 1960). It has finer fibers than western hemlock, Douglas-fir, or southern pine and makes a dense sheet with good opacity (Murray and Thomas 1961). Indeed, bleaching sulfate pulp made from western redcedar sawdust yields a product with an opacity comparable to hardwood pulps (Proctor and Chow 1976). The fine fibers tend to be shorter than those in Douglas-fir pulp (Heinig and Simmonds 1948, Graff and Isenberg 1950), but western redcedar pulp does not differ chemically from the sulfate pulps of Douglas-fir, western hemlock, black spruce, or loblolly pine (Lewis et al. 1950).

Physically, redcedar pulp has several desirable attributes. Unlike Douglas-fir, western hemlock, or Pacific silver fir, western redcedar produces very good kraft (sulfate) pulp (see Packee 1976). This pulp has high bursting, folding, and tensile strengths that offset its low tearing strength (see Bray and Martin 1947, Holzer and Booth 1950, Wethern 1959, Wilson et al. 1960, Murray and Thomas 1961). Western redcedar pulp has a high specific surface area (Browning and Baker 1950). Its cellulose characteristics are similar to those of western hemlock and loblolly pine pulps (see Clark 1950, Heuser et al. 1950). Sulfate pulp made from redcedar bark has lower bursting and tensile strengths, higher tearing strength than that made from wood (Thomas and Davis 1974).

Although sulfite pulp yields are higher than sulfate (kraft) yields for western redcedar (see Packee 1976), redcedar requires a longer cooking time and more chemicals than western hemlock in the sulfite process. The resulting low-brightness cedar pulp drains poorly (Wethern 1959). Redcedar sulfite pulp is dark and difficult to bleach (Isenberg 1951), and the use of a bisulfite cooking liquor with a high magnesium content seems necessary (see Keller and McGovern 1945). The bursting strength of western redcedar sulfite pulp is relatively high in comparison with the sulfite pulps of other species. Its tear strength is relatively low (see Holzer and Booth 1950).

Mechanical (groundwood) pulping processes are not practical for western redcedar (Wethern 1959). The resulting product has very good strength and printing qualities but poor brightness (see Packee 1976). Semichemical redcedar pulps may be useful in making paperboard (McGovern et al. 1951).

Veneer and Plywood

Western redcedar is highly suitable for decorative face veneer, but unsuitable for the inner plies of decorative veneer or for use in container material (see Packee 1976). Packee rated redcedar veneer logs as excellent when assessed for freedom from reaction wood, resin or gum, and bark pockets. Redcedar logs were rated “acceptable” when assessed for freedom from decay, knots, and wet wood.

Western redcedar plywood panels can be made by slicing the logs and cold pressing the resulting veneer (West Coast Lumberman 1946). Where hot pressing is used, high glue spreads and press temperatures of 270°F (132°C) or lower have been recommended to prevent blistering (Carstensen 1961). Although highly rated for decorative plywood (Lutz 1972), redcedar is too weak for construction grade structural plywood (Palka and Warren 1977).

Waste Utilization

Redcedar lumber, shake, and shingle manufacture produces tremendous quantities of waste material. Logging residue in some clearcut redcedar stands may average 238 m^3/ha (3,400 $ft^3/acre$) (Howard 1973). The residues produced annually from cedar sawmills in Oregon, Washington, and British Columbia were estimated to be 1 to 1.5 million ovendry tons (907 to 1361 million kilograms) in 1968 (Scroggins and Currier 1971). Annual residues from shake and shingle mills were estimated to be 700,000 ovendry tons (635 million kilograms).

The average amounts of mill residues produced in western redcedar log processing are listed in table 5. Shake manufacture produces the least amount of waste, shingle manufacture the most. In shingle manufacture only a small portion of the original tree is marketed; slash and mill residues account for most of the original standing volume.

Much of the mill residue is suitable for pulp production (Bray and Martin 1947). It can also be used in fiberboard production if treated properly. Boards made from western redcedar bark alone tend to be unacceptably weak (see Schwartz 1949, Clermont and Schwartz 1948, Stewart and Butler 1968, Maloney 1973), but ozone treatment increases the bark's internal bond strength (Chow 1977b) and the addition of 10 percent sulfite pulp or sulfite screenings makes bark boards stronger (British Columbia Lumberman 1948). Boards made from wood components of the residue were acceptably strong (King and Bender 1951, 1952). Those made from sawdust, shingle tow (a stringy waste product resulting from shingle manufacture), or both were not (see Forest Products Laboratory, Canada 1949; King and Bender 1951, 1952).

Of all west coast conifer sawdusts, that of western redcedar is the only one that can be made into high quality, opaque pulp comparable to the hardwood sulfate pulps used in high-quality papers (Proctor and Chow 1976). It can be differentiated from the sawdusts of Douglas-fir, western hemlock, true firs, and the spruces with a color test using chloroform and ferric chloride (Barton 1973a). Redcedar sawdust apparently decomposes more rapidly than Douglas-fir or western hemlock sawdust (see Bollen and Lu 1957). When not leached, it inhibits seed germination and seedling growth (Newton 1953) and damages Douglas-fir seedling roots (Krueger 1968). Redcedar sawdust makes a satisfactory rooting medium, how ever, when it is leached to remove the water-soluble extractives and mixed 3:1 with peat (Briggs 1973). Perhaps the most novel use of redcedar sawdust was as fill material where the trans-Canada highway crossed bogs and marshes (Southern Lumberman 1961).

Shingle tow has been used since about 1915 to keep tree seedlings moist during shipment. Krueger (1963, 1968) studied its effects on seedling survival and growth. He found that the thujaplicin extractives present in shingle tow were damaging to Douglas-fir seedlings but considered that the use of shingle tow was unlikely to cause heavy losses.

Table 5 — Average amounts of mill residues produced in processing of western redcedar logs[1]

Product	Coarse residues	Fine residues	Total waste
		Percent of log volume	
Lumber	18	19	37
Shakes	14	14	28
Shingles	14	47	61

[1]From McBride (1959), Gardner (1963), Scroggins and Currier (1971).

Extractives

Shingle tow, sawdust, and coarse residues are probably the best raw materials for producing most redcedar extractives (Wethern 1959). β-thujaplicin accumulates in digesters, evaporators, and kilns during redcedar processing, however, where it is readily available in commercially usable quantities (Trust and Coombs 1973). Potential uses of these extractives include insecticides, fungicides, antibiotics, chelating agents, catalysts, and perfumes (Wethern 1959).

Cedar leaf oil has been used in perfumes, insecticides, medicinal preparations, veterinary soaps, shoe polishes, and office deodorants (Forestry Abstracts 1965, Barton 1973b). It is a strongly scented, viscous liquid containing thujone, pinene, borneol, and borneol esters (Cochrane 1951, Bender 1963). Cochrane and Bender described the distillation procedure used to obtain this product. Steam extraction of freshly cut western redcedar leaves yielded 2.5 percent oil, based on dry leaf weight (Cochrane 1951).

Extractives probably were important in the successful production of fuel logs from wet redcedar sawdust (Gardner 1963). They were used to make a boiler-water additive that removed boiler scale and controlled foaming (British Columbia Lumberman 1951, McBride 1959). Water-soluble redcedar extractives have also been used in the electrolytic refining of lead (British Columbia Lumberman 1959). Even the lignin residue of ***Poria asiatica*** butt rot in western redcedar has been used — as a filler and extender in plywood glues (MacLean and Gardner 1953b).

Most of the extractives in western redcedar heartwood are formed from precursors at the sapwood/heartwood boundary (Swan et al. 1969). For example, nezukone is converted to thujaplicin at this boundary by hydroxylation of the tropone ring (Swan and Jiang 1970). The formation of different amounts of each extractive in older heartwood may be the result of changes in metabolism (more hydroxylation, less methylation) with aging (Hillis 1968).

Medical Aspects

Although less potent than sodium-penicillin G and tetracycline hydrochloride, a-thujaplicin has been shown to inhibit the growth of a wide variety of bacterial species (Trust and Coombs 1973). It loses its antibacterial potency after irradiation by laboratory lighting (Coombs and Trust 1973).

Other western redcedar extractives seem to be more stable than β-thujaplicin. Southam (1946) found that water extract of redcedar heartwood inhibited the growth of bacteria and fungi even after the extract was boiled. It was inactivated by blood, serum, and cysteine. Large doses of redcedar extract did not cause death or illness in mice, and no *in vivo* activity against infection was demonstrated (Southam 1946). Both β- and γ-thujaplicins exert a combination of stimulant and depressant actions on the mammalian central nervous system, but the depressant component appears to be more predominant in β-thujaplicin (Halliday 1959).

Western redcedar allergies are frequently mentioned in the literature. Woods workers who handle redcedar sometimes develop dermatitis, conjunctivitis, or both (Ishizaki et al. 1971a, 1971b; Mitchell and Chan-Yeung 1974). Most of the dermatitis seems to result from contact with lichens and liverworts on the logs, however, and contact dermatitis from the redcedar itself is rare (Mitchell and Chan-Yeung 1974). Where dermatitis was caused by exposure to redcedar heartwood in a mill, γ-thujaplicin and 7-hydroxyisopropyltropolone appeared to be allergenic (Bleumink et al. 1973).

Allergic millworkers, carpenters, cabinet workers, construction workers, and wood carvers develop asthma or rhinitis after being exposed to western redcedar dust (Mitchell and Chan-Yeung 1974, Chan-Yeung and Grzybowski 1976). The allergy seems quite common (Gandevia 1970; Ishizaki et al. 1971a, 1971b; Shida et al. 1971; Mue et al. 1975; Chan-Yeung 1977). Symptoms are delayed, but persistent — nocturnal coughing and asthma for days or weeks after exposure (see Milne and Gandevia 1969, Gandevia and Milne 1970, Mitchell 1970, Chan-Yeung et al. 1971). Plicatic acid probably causes these symptoms (Chan-Yeung 1973, Chan-Yeung et al. 1973, Barton 1975).

Insects

Western redcedars suffer little insect damage (Boyd 1959). Nevertheless, a considerable number of insects use redcedar as a host.

Bark Beetles

The western cedar bark beetle *(Phloeosinus punctatus* LeConte) is widespread in the native range of western redcedar (see Boyd 1959, Canada Department of Agriculture 1959, Canada Department of Forestry 1960). Generally of little importance, it has been reported to kill trees sometimes (Furniss and Carolin 1977), but it usually occurs in felled or weakened trees (Isenberg 1951).

The redwood bark beetle *(P. sequoiae* Hopkins) is present on redcedars in coastal Oregon, Washington, British Columbia, and southeastern Alaska. In southeastern Alaska it is aggressive, attacking and killing western redcedar on poor sites (see Hard 1974, Furniss and Carolin 1977). *P. thujae* Perris attacks redcedars planted in the Netherlands (Doom 1964) and Germany (Kamp 1951).

Wood Borers

The most damaging redcedar wood borer seems to be *Trachykele blondeli* Marseul, a flat-headed borer whose larvae mine the heartwood, causing degrade and cull in trees cut for products that require sound wood (Keen 1952, Boyd 1959, Furniss and Carolin 1977). Another flat-headed borer, *T. opulenta* Fall, also may occur in western redcedar (see Keen 1952).

Three round-headed borers mine the sapwood of native western redcedar: *Atimia confusa* Say (Furniss and Carolin 1977), *Semanotus amethystinus* LeConte (Boyd 1959, Furniss and Carolin 1977), and *S. ligneus* F. (Furniss and Carolin 1977). Ambrosia beetles *(Gnathotrichus sulcatus* LeConte, ***Trypodendron cavifrons*** Mannerheim, and other ***Trypodendron*** species) also work in western redcedar sapwood — but they seem to prefer Douglas-fir, western hemlock, or grand fir wood (see Johnson **1958).**

The sapwood weevil ***Hexarthrum thujae*** Brown attacks overmature redcedar in British Columbia (Canada Department of Forestry **1960,** Brown **1966,** Furniss and Carolin **1977).** Another sapwood weevil, ***Rhyncolus brunneus*** Mannerheim, breeds in dead redcedar wood (see Keen **1952,** Canada Department of Forestry **1960,** Furniss and Carolin **1977.)** Insects of a third sapwood weevil genus ***(Cossonus*** spp.) live in decaying western redcedar, causing little or no economic damage (Keen **1952).**

Other native western redcedar borers include a horntail, ***Urocerus albicornis*** F. (Furniss and Carolin **1977)** and ***Syntexis libocedrii*** Rohwer, a wood-boring sawfly (Westcott **1971,** Middlekauff **1974).** European wood borers also attack western redcedar. ***Xyloborus dispar*** F. (an ambrosia beetle) is found on western redcedars growing in Germany (von Hennig **1954),** and ***Hylotrupes bajulus*** L. (the oldhouse borer) can develop in redcedar wood grown in Poland (Dominik **1966).** Redcedar siding on several British schools was riddled with the prepupal burrow: of ***Ametastegia glabrata*** Fallen (a sawfly) after the wet summer of **1958** (Benson **1959).**

Defoliators

Seven loopers feed on western redcedar foliage:

Lambdina fiscellaria lugubrosa Hulst (Boyd **1959,** Canada Department of Fisheries and Forestry **1969,** Canada Department of the Environment **1974)**

Melanolophia imitata Walker (Evans **1962,** Dawson **1970)**

Ectropis crepuscularia Denis & Schiffermuller (Canada Department of Fisheries and Forestry **1968,** Furniss and Carolin **1977)**

Caripeta diwisata Walker (Furniss and Carolin **1977)**

Neoalcis californiaria Packard (Furniss and Carolin **1977)**

Nepytia phantasmaria Strecker (Furniss and Carolin **1977)**

Nepytia umbrosaria nigrovenaria Packard (Furniss and Carolin **1977)**

Lambdina fiscellaria lugubrosa, the western hemlock looper, is periodically destructive in coastal forests (Furniss and Carolin **1977).** Its preferred host is western hemlock, but western redcedar is damaged when the loopers attack associated trees. ***Melanolophia imitata,*** the green striped forest looper, prefers humid areas (Furniss and Carolin **1977),** where infestations sometimes cause serious defoliation of western redcedar and western hemlock (Dawson **1970).** The saddleback looper, ***Ectropis crepuscularia,*** damaged redcedar trees in Alaska and British Columbia during **1951, 1953, 1960, 1961,** and **1969.** The other loopers listed above do not damage western redcedar significantly (see Furniss and Carolin **1977).**

Nine nonlooper lepidopteran species occur on western redcedar foliage:

Argyresthia cupressella Walsingham (Keen **1952,** Pettinger and Dolph **1967)**

A. thuiella Packard (Van Frankenhuyzen **1974)**

Halisidota argentata Packard (Sellars-St. Clare **1968,** Furniss and Carolin **1977)**

Protoboarmia porcelaria Gn. ***indicataria*** Walker (McGuffin **1943)**

Callophrys acuminata Johnson (Johnson **1976)**

C. barryi Johnson (Johnson **1976)**

C. byrnei Johnson (Johnson **1976)**

C. plicataria Johnson (Johnson **1976)**

C. rosneri Johnson (Johnson **1976)**

Argyresthia cupressella, the cypress tip moth, caused moderate redcedar defoliation on the Olympic Peninsula in **1966** (Pettinger and Dolph **1967).** ***A. thuiella*** damaged western redcedar hedges in Holland during the winter of **1971-72** (Van Frankenhuyzen **1974).** An outbreak of silver-spotted tiger moth ***(Halisidota argentata)*** occurred on southern Vancouver Island in **1954-55** (Furniss and Carolin **1977).** The other species listed are not economically important.

Seed and Cone Insects

Keen (1958) and Hedlin (1959) identified several insects of minor importance in western redcedar cones:

Ptinus fur L.

Microgramme arga Reitt.

Eurytoma sp.

Torymus sp.

Amblymerus sp.

Tetrastichus sp.

Lestodiplosis taxiconis Foote

The only major seed-damaging insect on redcedar seems to be a gall midge — *Mayetiola (Phytophaga) thujae* Hedlin (Hedlin 1959, 1964, 1974; Furniss and Carolin 1977). *Mayetiola* is a common pest, sometimes infesting 100 percent of the cones (Keen 1958, Hedlin 1964) and seriously damaging western redcedar seeds in Oregon, Washington, and British Columbia (Furniss and Carolin 1977).

Miscellaneous Insects

Newly planted redcedar seedlings are sometimes damaged by the seedling weevil *Steremnius carinatus* Mannerheim) on cutover areas in British Columbia (Koot 1972), and another weevil *(Hylobius abietis* L.), attacks western redcedars in Poland (Ilmurzyhski 1968). A cicada *(Melampsalta cingulata* Fabricius) seriously damaged the western redcedars planted in Waimiha State Forest, New Zealand (Ranger 1945).

Resistance of western redcedar wood to termites seems to vary with the termite species attacking it. Redcedar heartwood was not favored by *Reticulitermes flavipes* (Kollar) in a laboratory feeding test of 11 wood species (Carter and Smythe 1974). In feeding-choice tests of 21 commercial woods with *R. virginicus* Banks and *Coptotermes formosanus* Shiraki, however, western redcedar was among the least resistant woods tested (Mannesmann 1973). *Incisitermes minor* Hagen, the western drywood termite, preferred western redcedar heartwood to that of Douglas-fir, redwood, bald cypress, and Port-Orford-cedar (see Rust and Reierson 1977). It preferred redcedar sapwood to that of birch, Douglas-fir, oak, pine, redwood, or walnut. Another drywood termite, *Cryptotermes brevis* Walker, also preferred redcedar sapwood to the sapwood of Douglas-fir or southern yellow pine (Minnick et al. 1973). Redcedar heartwood lost much of its resistance to attack by *Reticulitermes lucifugus* Rossi after weathering in Germany (Arndt and Willeitner 1969).

Extractives and Insects

Loss of extractives probably was responsible for decreased termite resistance after weathering in the German study. Although western redcedar wood is not particularly termite resistant, a neutral fraction of the volatile oil extracted from it is very effective against termites (MacLean 1970). Arndt (1968) found *Reticulitermes lucifugus* and *R. flavipes* to be adversely affected by the neutral oil fraction, unaffected by α- and γ- thujaplicins. *Incisitermes minor* preferred the extracts of walnut, Douglas-fir, sugar pine, redwood, and red oak to those of western redcedar — in almost reverse order to its preference for the woods from which these extracts were obtained (see Rust and Reierson 1977). The termite-repellent oil in redcedar, though effective when extracted, probably is present in inadequate quantities to protect redcedar wood from attack by most termite species.

Western redcedar sap probably is somewhat repellent to *Pissodes strobi* Peck, the Sitka spruce weevil. In laboratory bioassays, weevils preferred to feed on Sitka spruce sections soaked in water rather than on sections soaked in redcedar exudate (Vandersar and Borden 1977).

Volatile extractives of western redcedar wood apparently affect the choices of scolytid beetles for logs — they choose other log species (see Chapman 1963). Another volatile derived from redcedar, the N, N, diethylamid of thujic acid, is a potent mosquito repellant that surpasses the activity of standard repellants (Hach and McDonald 1971). Methyl thujate has some toxicity to carpet beetles and clothes moths, and its presence in cedar shavings used as litter probably controls poultry mites (Gardner 1963).

Wood extracts from western redcedar demonstrated juvenile-hormonelike activity on pupae of *Galleria mellonella* L. (Mansingh et al. 1970) and *Tenebrio* sp. (Barton et al. 1972). Similar activity occurred when larvae of the western tent caterpillar *(Malacosoma californicum* Packard *pluviale* Dyar) were treated with crude ether extracts of western redcedar (Wellington 1969).

Diseases

Although Shaw (1973) lists 221 fungi that occur on western redcedar, the species is reputed to be less susceptible to pathological attacks than most of its associates (Boyd 1959). Nevertheless, most redcedars harbor pathogens. Redcedars live longer than their associates, and hollow old redcedar trees are common in the interior (see Daubenmire and Daubenmire 1968). Western redcedar is twice as defective as western hemlock and 20 times as defective as Sitka spruce in southeastern Alaska, where redcedars over 94-cm (37-in) d.b.h. average more than 50 percent cull (Klein 1951). Smaller trees also are affected. Half the coastal redcedar trees in the south-central portion of Vancouver Island have some decay by age 50; 100 percent have decay by age 450. In the interior, 80 percent of the redcedars are infected by age 150 and 100 percent have decay by age 290 (Buckland 1946).

Seedling Diseases

Western redcedar seedlings are seldom damaged by damping-off fungi (Hepting 1971). They are resistant to ***Phytophthora cactorum*** Leb. & Cohn (see Vaartaja 1957b) and often undamaged by ***Thelephora terrestris*** Ehr. growth (Hepting 1971). Where redcedar seedlings are dense enough to shade the ground, however, ***T. terrestris*** sometimes smothers them (Weir 1921). Some redcedar seedlings are killed by the brown-felt snow mold ***(Herpotrichia nigra*** Hartig) in the Rocky Mountains (Hepting 1971). Other fungi that sometimes damage western redcedar seedlings include ***Diaporthe lokoyae*** Funk, ***Seiridium cardinale*** (Wagener) Sutton & Gibson, ***Kabatina thujae*** Schneider & v. Arx, and ***Velutarina rufo-olivacea*** (Alb. & Schw. ex Fr.) Korf (Funk 1974).

The major redcedar seedling disease — ***Didymascella (Keithia) thujina*** Durand — is a leaf blight that also occurs on older trees but is only serious on seedlings. When ***Didymascella*** reaches epidemic proportions, as much as 97 percent of the redcedar reproduction may be killed in its first season (Boyd 1959). Epidemics probably are rare in North America, however, and ***Didymascella*** is not as damaging there as it is in Europe (see Peace 1955, Søegaard 1969). Infection is rarely observed on 1st-year nursery seedlings in Europe, where major damage to nursery stock occurs during the 2d and 3d years (Søegaard 1966, Forestry Commission, London 1974). British attempts to avoid seedling damage by growing western redcedar in isolated nurseries (Peace 1955, 1958; Pawsey 1962b) succeeded at first, but eventually failed when those nurseries also became infected. Fortunately, diseased nursery seedlings sometimes recover after being planted out (see Keatinge 1948, Penistan 1966).

Effective control of ***Didymascella*** has been achieved by applying cycloheximide fungicides in British nurseries (Pawsey 1962a, 1965; Phillips 1962, 1964; Burdekin and Phillips 1971). Danish workers found that western redcedar cuttings are blight resistant (Søegaard 1954, 1956a).

Foliage Fungi

The ***Didymascella*** leaf blight that attacks seedlings is the most important foliage disease of western redcedar. Blights caused by ***Coryneum thujinum*** Dearn. (Boyce 1961, Hepting 1971) and ***Lepteutypa cupressi*** (Nattrass, Booth, & Sutton) Swart (Canadian Forestry Service 1975) are much less important.

Pestalotia funerea Desm. is associated with redcedar dieback in Washington (Crops Research Division, Agricultural Research Service 1960). ***P. peregrina*** Ell. & Mart. caused a severe dieback of western redcedar in India (Sharma et al. 1973) and ***Lophodermium juniperinum*** (Fr.) DeNot. has been found on redcedar in Australia (Stahl 1966).

Chloroscypha seaveri (Rehm) Seav. has been associated with the death of western redcedar twigs (Ehrlich 1942), but the twigs probably were killed by other organisms (Gremmen 1963). Other fungi inhabiting dead or senescent redcedar foliage include ***Sphaerella canadensis,*** Ell. & Ev., ***Mycosphaerella thujae*** Petr., and ***Microthyrium thujae*** Dearn. (Hepting 1971). ***Limacinia alaskensis*** (Sacc. & Scalia emend Barr.) causes a minor surface mold in cold regions (Hepting 1971).

Root and Butt Rots

Phellinus (Poria) weirii (Murr.) Gilbertson is the principal root- and butt-rot fungus infecting western redcedar (Hepting 1971). Redcedars and Douglas-firs are the most frequent hosts of ***P. weirii*** (Smith 1978). The ***P. weirii*** hosted by western redcedar seems to be different from that hosted by Douglas-fir and other northwestern conifers, however. ***P. weirii*** sporophores are perennial on western redcedar, annual on other conifers (Buckland et al. 1954). Furthermore, nonredcedar isolates are less able to parasitize western redcedar than isolates from the redcedar race (Morrison 1969). Ectotrophic mycelia are nearly absent on redcedar roots infected with ***P. weirii*** (Wallis 1976), and western redcedar is quite resistant to the fungus (Wallis 1962, Wallis and Reynolds 1967). In northern Idaho, the resulting decay usually is restricted to the first log (Canfield 1969). ***P. weirii*** is most damaging in the interior, attacking living trees only to a limited extent on the coast (Buckland 1946).

The shoestring root and butt rot, *Armillaria mellea* Vahl., attacks most conifer species in the Western United States (Scharpf 1978), but it is less damaging to western redcedar than to other species in the western white pine type (Hepting 1971). Nevertheless, nearly half the redcedar trees released in an Idaho thinning study were infested with *A. mellea* (Intermountain Forest and Range Experiment Station 1962, Koenigs 1969). Canfield (1969) found *A. mellea* in 15 percent of the Idaho redcedars he sampled in old-growth stands but judged the resulting decay to be insignificant in merchantable wood. Some *A. mellea* occurs on western redcedars planted in New Zealand (New Zealand State Forest Service 1944).

Less common root- and butt-rot fungi hosted by western redcedar include:

Corticum galactinum (Fr.) Burt (Hepting 1971)

Fomes annosus (Fr.) Cke. (Crops Research Division, Agricultural Research Service 1960, Hepting 1971, Scharpf 1978)

Odontia bicolor (Alb. & Schw.) Bres. (Hepting 1971)

Polyporus schweinitzii Fr. (Buckland 1946, Gecow 1952, Crops Research Division, Agricultural Research Service 1960, Shaw and Harris 1960, Hepting 1971, Scharpf 1978)

P. tomentosus Fr. (Hepting 1971)

Poria subacida (Pk.) Sacc. (Buckland 1946, Shaw and Harris 1960, Hepting 1971)

P. vaillantii (DC. ex Fr.) Cke. (Crops Division, Agricultural Research Service 1960, Hepting 1971).

Poria subacida seems to be most important.

Phytophthora cryptogea Pethyb. & Laff. and *P. citricola* Sawada were isolated from roots of diseased western redcedars (Young and Strouts 1976). *P. cinnamomi* Rands also infects redcedar roots but does little damage (Evans 1978). Western redcedar seems to be resistant to *P. cinnamomi* (Robertson 1969) and *P. lateralis* Tuck. & J. A. Milb. (Milbrath and Young 1949).

Stem Diseases

Western redcedar has no major stem diseases, but several minor fungi occur on weakened or dead redcedar stems:

Aleurodiscus amorphus (pers. ex Fr.) Rab. (Hansbrough 1934, Hepting 1971)

A. amylaceus Rog. & Jacks (Hepting 1971)

A. cerussatus (Bres.) Hoehn. & Litsch. (Hepting 1971)

A. lividocoeruleus (Karst.) Lemke (Hepting 1971)

A. tsugae Yas. (Hepting 1971)

A. weirii Burt (Hepting 1971)

Chloroscypha seaveri (Hepting 1971)

Coryneum cardinale Wagen. (Grasso 1952, Sutton and Gibson 1972, Strouts 1973)

Cucurbidothis conjuncta Petr. (Hepting 1971)

Diaporthe lokoyae Funk (Funk 1973)

Hendersonia thyoides Cke. & Ell. (Hepting 1971)

Pestalotia funerea Desm. (Hepting 1971)

Valsa abietis Fr. (Hepting 1971)

V. kunzei Fr. (Hepting 1971)

V. weiriana Petr. (Hepting 1971)

Redcedar seems to be resistant to the cypress canker caused by *Monochaetia unicornis* (Cke. & Ell.) Sacc. (Fuller and Newhook 1954) but susceptible to the crown gall caused by *Agrobacterium tumefaciens* (E. F. Smith & Town.) Conn. (Hepting 1971).

Trunk Rots

Buckland's (1946) investigations of decay in British Columbia western redcedar constitute the best general assessment of redcedar trunk rots. He ranked the major fungi in order of importance, with the most damaging listed first:

Coastal British Columbia

Poria asiatica (Pil.) Overh.
Poria albipellucida Baxt.
Fomes pini (Thore) Lloyd
Merulius sp.
Poria subacida

Interior British Columbia

Poria asiatica
Phellinus weirii
Fomes pini
Polyporus balsameus Pk.
Merulius sp.
Poria subacida

Other fungi that attack the heartwood of living redcedar stems less extensively were also identified by Buckland:

Coniophora cerebella (Pers.) Pers.
Fomes nigrolimitatus (Rom.) Egeland
F. pinicola (Swartz ex Fr.) Cke.
Omphalia campanella (Batsch. ex Fr.) Quél.

He found the major fungi decaying redcedar sapwood and slash to be ***Polyporus cuneafus*** (Murr.) Zell. and ***Hymenochaefe fabacina*** ([Sow.] Fr.) Lév.

Kimmey (1956) found that ***Poria albipellucida*** accounted for about 45 percent of the western redcedar trunk rot in southeastern Alaska. ***Phellinus weirii*** accounted for about 41 percent, and ***Poria ferrugineo-fusca*** Karst. was responsible for 3 percent. Kimmey found no sporophores on living redcedar trees in Alaska, so he used sucker limbs, trunk scars, dead sections, and rotten burls as decay indicators. Similar indicators were used by Canfield (1969), but Canfield found some fungal sporophores in northern Idaho. ***Phellinus weirii*** and ***Polyporus sericeomollis*** Rom. were the most common redcedar decay fungi identified by Canfield. He encountered slightly more decay where the fern ***Gymnocarpium dryopferis*** was present than where it was absent.

Isenberg (1951) rated ***Phellinus weirii*** as the most serious western redcedar decay, with ***Polyporus anceps*** Pk. and ***Fomes pini*** important on old trees. ***P. sulphureus*** Bull. ex Fr. damages redcedar trees in Washington (Shaw and Harris 1960), and ***Echinodonfium fincforium*** (E. & E.) E. & E. is occasionally found on western redcedars in British Columbia (Etheridge 1972). Young redcedar trees seem quite resistant to ***Fomes annosus*** (Fr.) Cke. in England and Poland (see Kosturkiewicz and Meixner 1956, Greig 1974, Forestry Commission, London 1978).

Nelson (1976) found western redcedar heartwood resistant to colonization by ***Phellinus weirii.*** Similar work with ***Lenzifes frabea*** Pers. ex Fr. (Morton and French 1966) and decay tests with ***L. frabea, Fomes subroseus*** (Weir) Overh., ***Lentinus lepideus*** Fr., ***Merulius lacrymans*** (Wulf.) Fr., and ***Coniophora pufeana*** (Schum. ex Fr.) Karst. (Scheffer 1957, Jacquiot and Lapetite 1960, Lutomski and Raczkowski 1963) have shown most redcedar heartwood to be resistant to most decay fungi. Resistance to ***Poria incrassafa*** (B. & C.) Burt and ***P. monficola*** Murr. is variable, however (Scheffer 1957), and dark-colored inner heartwood is less resistant to decay than light-colored outer heartwood (see Findlay and Pettifor 1941, van der Kamp 1975).

Dead western redcedar trunks were slowly decayed by ***Polyporus cuneafus*** (Murr.) Zell. (14.4 percent of the decay), ***P. versicolor*** L. ex Fr. (2.8 percent), and ***Fomes applanafus*** (Pers. ex ***S.*** F. Gray) Gill (0.7 percent) after being windthrown on the Olympic Peninsula (see Boyce 1929, Buchanan 1940). The decay probably occurred in sapwood. Eslyn and Highley (1976) found western redcedar sapwood resistant to soft-rot attack, moderately resistant to white-rot attack, and susceptible to brown-rot attack.

Product Decay

Several fungi were associated with brown sap rot of western redcedar poles in northern Idaho (Southham and Ehrlich 1950):

Polyporus guttulatus Peck
Coniophora pufeana
C. arida (Fr.) Karst.
C. olivacea (Fr.) Karst.
C. olivascens (B. & C.) Massee
Paxillus panuoides Fr.
Poria vaillanfii (DC. ex Fr.) Cke.
Merulius pinasfri (Fr.) Burt.

Polyporus guttulatus was most important in Idaho. Elsewhere, ***Lenzifes frabea*** Pers. ex Fr. is important (Eslyn 1970). Tests of decay resistance showed the lower and middle thirds of redcedar poles to be more resistant than the upper third (Englerth and Scheffer 1954).

Extractives and Decay

Heartwood color is associated with extractive content and decay resistance. Dark-colored heartwood near the center of a redcedar tree is low in both thujaplicins and resistance; light-colored heartwood near the periphery is high in both (van der Kamp 1975). The thujaplicins are highly toxic to a great variety of wood-destroying fungi (Erdtman and Gripenberg 1948b, Roff and Atkinson 1954, Roff and Whittaker 1959, Rudman 1962, Freydl 1963). Indeed, thujaplicins are about as active as pentachlorophenol (Rennerfelt 1948) — concentrations of 0.001-0.002 percent inhibit fungus growth (Rennerfelt and Nacht 1955). They apparently inhibit oxidative phosphorylation in the affected fungi (Lyr 1961). Many fungi may have the ability to chemically change nearby thujaplicin extractives to nontoxic material, however, thus becoming able to overcome increasingly high concentrations of the toxic heartwood extracts (Southam and Ehrlich 1943). This may explain the great amount of heart rot in mature western redcedar — heart rot that progresses outward from the center of the tree and is associated with reduced thujaplicin concentrations in the older, central heartwood.

Birds and Mammals

Western redcedar seeds may be sown safely (McKeever 1942), for ground-feeding birds and small mammals prefer Douglas-fir and western hemlock to redcedar seeds in western Oregon (see Gashwiler 1967). Pregermination rodent damage is minor (Helmers 1946, Boyd 1959). Redcedar mortality is high between the beginning and end of germination, however (Gashwiler 1970), *so* birds and small mammals may be important during the germination period.

Redcedar seedlings and saplings are browsed by deer and elk. They constitute one of the most important conifer foods of black-tailed deer in the coastal forest region of southern Vancouver Island (Cowan 1945). Redcedar was more severely browsed than Douglas-fir, western hemlock, or Pacific silver fir on the Olympic Peninsula (Gockerell 1966). All small western redcedars in the lower cedar groves of the Selway-Bitterroot wilderness in Idaho may have been destroyed by wintering deer and elk (Habeck 1978). Redcedar is a major winter food for big game in the northern Rocky Mountains. Deer browse redcedars all year long in British Columbia, and elk feed on them during the fall, winter, and spring (see Packee 1975). Introduced Sitka blacktail deer have greatly reduced redcedar regeneration in large portions of the Queen Charlotte Islands.

Black bears remove redcedar bark and feed on the exposed sapwood in western Washington (Radwan 1969). Opossums limit western redcedar growth in Westland, New Zealand (Weston 1971).

Domestic animals also damage young western redcedars. Cattle browsed redcedar in preference to Douglas-fir in northwestern Oregon (see Howell 1948), and sheep damaged redcedar reproduction more than that of other trees in northern Idaho (Tisdale 1961).

Genetics

Redcedar seed orchards have been established in Denmark (Søegaard 1956b), where resistance to the leaf blight caused by ***Didymascella thujina*** has been shown to be homozygously recessive (Søegaard 1956a, 1966, 1969). Søegaard's investigations indicate that frost resistance in western redcedar is inherited in the same way as leaf-blight resistance. Both seem to vary with stage of physiological development, but the redcedar clones most damaged by leaf blight are also most damaged by frost (see Larsen 1953).

Tests of several seed sources in North America showed wide variations in frost hardiness. Trees grown from inland sources were hardier than those from coastal areas (Boyd 1959, Sakai 1972, Sakai and Weiser 1973). No significant difference in leaf-oil terpene composition was found between inland and coastal populations by Von Rudloff and Lapp (1979), however, who observed that western redcedar has one of the lowest degrees of variability found thus far in northern North American conifer species. Copes (1981) detected no isoenzyme variation among widely separated western redcedar populations in Oregon and Washington, suggesting that management of redcedar by cultural procedures may yield greater returns than genetic improvement programs. Nevertheless, plantation trials indicate that Alaska redcedar provenances are inferior to those from Oregon and Idaho when grown in Poland (Ilmurzyhski et al. 1968).

Western redcedar is well suited for the use of haploidy in tree breeding (Winton and Stettler 1974). Von Pohlheim (1970, 1971, 1972, 1977a, 1977b) studied somatic mutations and chimeras in haploid and triploid cultivars.

Horticulture

Western redcedar is often cultivated as an ornamental tree in Europe (Sargent 1933). It is an excellent hedge shrub, standing trimming well and rarely spreading too far (Edlin 1968). Redcedar hedges planted along roadsides in Switzerland deflected and partially filtered traffic-polluted air, reducing lead' contamination at offroad locations (Keller 1974).

At least three horticultural varieties of western redcedar are grown in North America (Rehder 1940). ***Thuja plicata*** var. ***atrovirens*** Sudw. has dark green leaves. The ***fastigiata*** Schneid. variety has columnar form, and variety ***pendula*** Schneid. has slender, pendulous branches. In addition, a haploid variety — ***gracilis*** Beissn. — has been studied in Germany. Von Pohlheim (1972) found this haploid variety less tolerant of irradiation and more subject to irradiation-induced mutation than the normal diploid. He selected a mutant form with pendent, filiform branches (von Pohlheim 1977a) and studied diploidization in the periclinal chimeric shoot apices of variety ***gracilis*** (von Pohlheim 1971, 1977b). Simak et al. (1974) examined male strobilus development and microsporogenesis in this haploid variety. ***Thuja plicata excelsa*** Timm. is a triploid cultivar with thicker and darker leaves than ***T. plicata*** (von Pohlheim 1970).

Physiology and Ecology

Meteorological Influences

Temperature. — Western redcedar occupies a moderate position on the temperature gradient described by Zobel et al. (1976) for the central western Cascades of Oregon. It has as few as 75 frost-free days in some portions of interior British Columbia, at least 120 to 150 frost-free days along the coast (see Krajina 1969), where the average frost-free period is commonly over 200 days (Packee 1976). Absolute minimum temperatures experienced by redcedar in British Columbia are −10" to −30°C (14" to −22°F) in coastal populations, −14" to −47°C (7" to −53°F) in the interior (Krajina 1969). Western redcedar is not very frost resistant, however; early and late frosts cause damage. Bottomland frost pockets in northern Idaho are commonly occupied by subalpine fir rather than western redcedar (Daubenmire and Daubenmire 1968).

An April frost of −9°C (16°F) that followed a mild winter destroyed almost all the young western redcedars in a Scottish plantation in 1945 (Hunter Blair 1946). An earlier April frost in England was less damaging to western redcedar than to Douglas-fir or Sitka spruce, however, and Day (1928) concluded that redcedar was more frost resistant than the other two species. Aldhous and Low (1974) observed that redcedar was also more resistant than grand fir or western hemlock to late spring frosts in Britain.

Autumn frost damage seems to vary with location and preceding weather. An unusual September frost in Ireland damaged Douglas-fir, Sitka spruce, and Scotch pine more than western redcedar in 1972 (Mooney 1973). In contrast, a November frost in Washington was more injurious to redcedar than to Douglas-fir (Duffield 1956, Daubenmire 1957) or Sitka spruce (Duffield 1956). Sitka spruce seems more resistant than redcedar to winter cold (see Phillips 1965). Nevertheless, western redcedars withstand cold winters very well in Europe (see Gecow 1952, Degen 1965, Hesmer and Gunther 1968). When bright sunny days follow a period of below-freezing temperatures, young redcedar branches and leaders often die in their native habitats (Miller 1978). Dormant twigs from the interior were much hardier than those from the coast when subjected to subfreezing temperatures in a laboratory (Sakai and Weiser 1973).

Western redcedar is susceptible to heat girdling (Haig 1936). It appears to be less tolerant of high soil-surface temperatures than Engelmann spruce, grand fir, or Douglas-fir (Larsen 1940). The exposed surfaces of upper foliage in young redcedar seedlings often "sunburn" severely, but lower, unexposed surfaces remain green (personal communication, Edmond C. Packee, MacMillan Bloedel Limited, Nanaimo, British Columbia).

Moisture. — Water content in 2-year-old western redcedar seedlings was higher than in Douglas-fir or western hemlock seedlings when all three species were grown in a greenhouse by Jablanczy (1964), but western redcedar leaves lose water rapidly when severed from the parent tree (Parker 1951). The leaves are not protected from excessive transpiration by cutin and wax, and they showed no drought resistance in the physiological and anatomical investigations conducted by Oppenheimer (1967).

Redcedar is abundant in many forested swamps. It is sometimes found on sites that are too dry for western hemlock, however — in Montana (Habeck 1968, Pfister et al. 1977), Washington and Oregon (Franklin and Dyrness 1973), British Columbia (Packee 1976), and Idaho (Daubenmire and Daubenmire 1968). Daubenmire (1966) placed western redcedar between western hemlock (cooler and wetter) and western white pine (warmer and drier) in the species series that he constructed along environmental gradients in eastern Washington and northern Idaho. Redcedar dominates wet ravines and poorly drained depressions in both Glacier National Park, Montana, and the Selway Bitterroot Wilderness, Idaho (Habeck 1968, 1978), but it is almost absent where frequent flooding occurs in Glacier Park (Kessell 1979). Adequate soil moisture during the growing season seems to be essential for redcedar growth in Italy (Sanesi and Sulli 1973).

The generally observed superiority of western redcedar over western hemlock on dry sites seems to be the result of better redcedar root penetration (Haig 1936). Root penetration probably is not responsible for western redcedar superiority on wet sites, where it often is the dominant tree (fig. 3). Native redcedars are able to tolerate stagnant water tables in winter that average less than 15 cm (6 in) below the soil surface on the Olympic Peninsula (Minore and Smith 1971). Day (1957) found redcedars to be the characteristic dominants on water-retentive or wet soils in the Queen Charlotte Islands. Western redcedar seedlings tolerated year-round water table depths of only 7.5 cm (2.9 in) and 8 weeks of summer flooding in controlled experiments (Minore 1968, 1970).

Figure 3.—Western redcedars growing on a wet site in the Washington Cascades.

Photoperiod. — Vaartaja (1957a) observed no significant response when he exposed 1-month-old seedlings to a single 10-hour dark period and to two 5-hour dark periods in each 24-hour day. Growth of the redcedars measured by Malcolm and Caldwell (1971), though erratic, indicated a critical day length of about 15 hours for the faster rates of growth. Western redcedar responds rapidly to increases in photoperiod, breaking dormancy faster than western hemlock or Douglas-fir (Jablanczy 1964).

Wind. — Western redcedar is windfirm on dry sites, where Gratkowski (1956) rated it more windfirm than Douglas-fir, western hemlock, or Pacific silver fir. Boyce (1929) also classed redcedar with Douglas-fir as resistant to windfall. Western redcedar is fairly resistant to storm damage in Germany (Volk 1968) and stands up well to wind in Britain (Streets 1962). It is not windfirm on the wet sites characterized by *Adiantum, Lysichitum,* and *Athyrium* in British Columbia (Packee 1976).

Air pollution. — Western redcedar is sensitive to atmospheric pollution in Britain (Streets 1962). In Germany's industrialized Ruhr area, however, it seems more tolerant of industrial fumes than Douglas-fir or western hemlock (Glocker and Krussman 1957). German tests showed little damage to western redcedar leaves after 57 hours exposure to 2.0 parts per million (p/m) sulfur dioxide (Enderlein and Vogl 1966). Longer exposures may be more damaging; only grand fir and subalpine fir were more susceptible than redcedar when 12 conifers were tested for damage from sulfur dioxide smelter fumes in British Columbia (Scheffer and Hedgcock 1955).

Western redcedar is less tolerant of ocean spray than Sitka spruce along the west coast of Vancouver Island, British Columbia (Cordes 1973). Redcedar also is intolerant of salt-laden winds in Southland, New Zealand. In Westland, which has more rainfall, the salt damage is **less** serious (Weston 1971).

Clay dust from a brick works in British Columbia produced a columnar form in nearby western redcedars that led Glendenning (1948) to describe a new horticultural variety. When this columnar variety was grown in the absence of clay dust, however, it reverted to normal redcedar form (Rhodes 1955).

The aromatic compounds produced by western redcedar can influence other plants. The germination of oats, wheat, and corn was retarded or inhibited by air that had been in contact with redcedar wood (Weintraub and Price 1948).

Fire

Western redcedar is very susceptible to fire injury (Lutz 1972). The shallow roots under a duff layer are often scorched when that duff layer burns (Flint 1925), and even surface fires may kill coastal western redcedar (McMinn 1960). Most low-site areas have fire-killed redcedar trees in southeastern Alaska, where western redcedar is very flammable (Gregory 1957). Relative fire resistance of species does not appear to be the same in coastal and inland forests, however (Minore 1979). In the Rocky Mountains, redcedar is more resistant to fire than Engelmann spruce and western hemlock, less resistant than Douglas-fir and ponderosa pine (Haig et al. 1941). Old redcedar trees commonly are fire scarred in northern Idaho (Daubenmire and Daubenmire 1968).

Fire-killed western redcedar timber shows little deterioration after 5 years (Wallis et al. 1974). Even the bark usually remains intact on dead trees for 5 years (Embrey 1963). Fire killing produces no immediate reduction in strength of western redcedar poles (Research News, Ottawa 1962c), and some large redcedar trees remain salvageable for almost 100 years after being killed by fire (see Smith et al. 1961b).

Soils

Physical properties. — Western redcedar seems able to tolerate a wide range of physical properties in soil in most localities. It is found on all landforms, soil textures, and parent materials on Vancouver Island (Packee 1976). Coarse sandy soils are not well suited to establishment and growth of redcedar in northern Idaho and northeastern Washington, however — they are too droughty and unstable (Helmers 1946). In contrast, rocky slopes with limited soil development support western redcedar in southeastern Alaska (Gregory 1957). The wet soils developed from muskegs also are dominated by western redcedar south of Petersburg, Alaska (Stephens et al. 1970). It grows over loams, clays, sands, and chalk downland in England (Hubbard 1950, Streets 1962, Edlin 1968). Redcedar also grows on ***Molina-Juncus*** peat there (Zehetmayr 1954).

Forristall and Gessel (1955) concluded that western redcedar roots could grow in higher bulk densities of soil than could roots of red alder, Douglas-fir, or western hemlock. Unfortunately, they compared species growing separately on soils of differing textures. Minore et al. (1969) used a soil of uniform texture in the greenhouse and found that western redcedar roots could not penetrate the compacted soil columns penetrated by Douglas-fir, red alder, lodgepole pine, and Pacific silver fir.

Forest floors under western redcedar and Sitka spruce tend to be thicker and have higher water-holding capacities than those under Douglas-fir and western hemlock in western Washington (Flannery 1940).

Chemical properties. — Total amounts of essential plant nutrients stored in the forest floor were greater under western redcedar and Sitka spruce than they were under Douglas-fir and western hemlock in the stands sampled by Flannery (1940) in western Washington. The data of Tarrant et al. (1951) and Daubenmire (1953) indicate that western redcedar litter is low in nitrogen and phosphorus, so Flannery's figures may have resulted from greater thickness rather than higher concentrations. Alban (1969) measured more exchangeable calcium, higher cation-exchange capacity, and higher base saturation in soils under redcedar than under western hemlock, however, and he found soil pH to be higher under the redcedar. Ovington and Madgwick (1957) found pH higher in soil under redcedar than under European beech, European larch, Sitka spruce, oaks, Norway spruce, Scotch pine, Japanese larch, Austrian pine, birch, grand fir, noble fir, Douglas-fir, lodgepole pine, western hemlock, and tamarack. Western redcedar seems to benefit the soil. It is one of the few species that can be grown on chalk downland in southern England (Aldhous and Low 1974).

Krajina (1969) observed that redcedar growth seems to be benefited by nitrification, and he associated the presence of ***Sambucus racemosa*** L., ***Tiarella trifoliata*** L., ***Tellima grandiflorum*** (Pursh) Dougl., ***Tolmiea menziesii*** (Pursh) T. & G., and ***Urtica dioica*** L. with favorable soil conditions.

Nutrients and Nutrition

The nutrient contents of western redcedar foliage vary with season and site. Nevertheless, relatively high concentrations of calcium and low concentrations of nitrogen are nearly always present (see Gessel et al. 1951, Tarrant et al. 1951, Daubenmire 1953, Ovington 1956, Beaton et al. 1965, Webber 1973). Phosphorus concentrations are usually low, but Smith et al. (1968) found them to be higher in western redcedar than in Douglas-fir or western hemlock. Less sulfur was found in redcedar foliage than in the foliage of other British Columbia conifers sampled by Beaton et al. (1965).

Foliage-nutrient concentrations should be used with caution when comparing species, for relative nutrient concentrations do not always reflect relative nutrient requirements. Optimum nutrition of western redcedar may require very high nutrient levels (Krajina 1969). Redcedar seedlings apparently require more nitrogen than seedlings of Sitka spruce, western hemlock, or Douglas-fir for best growth (Krajina 1959), but redcedar can survive on poor sites (Gregory 1957). Redcedar may respond to nitrogen additions by increasing root growth in comparison with shoot growth (Smith et al. 1968). Although nitrate nitrogen seems to be used more efficiently than ammonium nitrogen in sand and solution cultures (see Krajina 1971, Krajina et al. 1973), additional work is needed to relate soil nitrate and ammonium to redcedar growth in nature. Nitrogen deficiencies result in yellowish foliage, reddish seedling stems, and foliage nitrogen concentrations less than 1.5 percent (Walker et al. 1955).

Phosphorus deficiencies result in reddish or purplish stems and older foliage (Walker et al. 1955). Although phosphorus and nitrogen deficiencies were blamed for plantation check in the upland heaths of Britain (Forestry Abstracts 1964), and phosphorus additions benefited root growth of western redcedar on sod-peat bog in Ireland (Carey and Barry 1975), redcedar is more tolerant of low phosphorus levels than Douglas-fir and Sitka spruce (Krajina 1969).

Potassium deficiencies do not seem as critical as deficiencies of nitrogen or phosphorus for western redcedar growth (see Walker et al. 1955). Walker et al. measured little decrease in seedling growth under potassium-deficient conditions but noted limber stems and drooping foliage on the affected seedlings.

Seedlings affected by calcium deficiencies show browning and dying at the tips of leader and branch shoots (Walker et al. 1955). Western redcedar may be less tolerant than western hemlock, Sitka spruce, or Douglas-fir to low levels of calcium, magnesium, or both (Krajina 1959, 1969).

Only low levels of sulfur seem to be required by western redcedar. Indeed, sulfur fertilization often caused reduced height growth of the western redcedars treated by Smith et al. (1968). This response may have been the result of pH changes induced by the fertilization, however, for western redcedar is reputed to grow best on neutral to slightly acid sites (University of British Columbia Forest Club 1959). Where sulfur deficiencies do occur, young redcedar foliage becomes yellowish and older foliage is paler than normal (Walker et al. 1955).

Western redcedar seedlings survive in the absence of boron, but they develop a variety of deficiency symptoms: Stem elongation is much restricted, and needles are closely bunched (Walker et al. 1955); branches become straplike or club shaped (Blaser et al. 1967); and stems are weak.

Comparisons of western redcedar foliage-nutrient concentrations, growth responses, and site conditions are sometimes confusing. Much of this confusion may result from a failure to distinguish between responses to low nutrient levels and responses to optimal nutrient levels. Western redcedar seems able to survive and grow in low-nutrient conditions, and it probably occurs in such conditions over much of its natural range. When supplied with abundant nutrients and moisture, however, redcedar may respond more vigorously than other conifer species. For example, western redcedar seedlings outgrew seedlings of Douglas-fir, grand fir, Sitka spruce, western hemlock, and ponderosa pine when all were grown for 2 years in raised, well-watered soil beds fertilized with nitrogen, phosphorus, and potassium.[8]

Asexual Reproduction

Three types of asexual reproduction of western redcedar occur in nature: layering (Schmidt 1955; Habeck 1968, 1978), rooting of fallen branches, and branch development on fallen trees. The resulting "veglings" were more abundant than seedlings in mature stands sampled by Parker (1979) in northern Idaho. Much of the redcedar regeneration observed by Dyrness et al. (1974) in the western Cascades of Oregon consisted of individuals developed from branches of saplings that were knocked down and have since rooted.

[8] Paper, "Growth of forest tree seedlings in sewage sludge amended media," by R.J. Zasoski and C.S. Bledsoe. 1980. Presented at the 53d annual meeting, Northwest Scientific Association, in Moscow, Idaho. Abstract on file, Forestry Sciences Laboratory, Corvallis, Oregon.

Redcedar clones are easily propagated by rooting stem cuttings (Larsen 1953). Untreated cuttings will root, and Søegaard (1956a) achieved 50 to 80 percent success by using new shoots cut in July and August. Nevertheless, treatment with growth-regulating substances improves results. Verleyen (1948) found α-napthalene acetic acid more effective than β-indole-acetic acid in early rooting trials. Indole-butyric acid (I.B.A.) improves rooting speed, the number of cuttings rooted, and the total length of roots per cutting (Matthews 1951). The best I.B.A. concentrations are 3,000 p/m for a 1-minute dip and 200 to 400 p/m for a 4-hour soak (Kalmár 1973). When a talc carrier is used, 6.25 p/m is effective (Matthews 1951).

Coleman and Thorpe (1977) successfully grew western redcedar plantlets from both juvenile and mature tissues by applying distinct sequential treatments for the following developmental stages: meristemoid induction and adventitious bud determination; bud growth; and rooting of the resulting adventitious shoots and reestablishment in soil. Compositions of the nutrient media used in stem tissue cultures are listed by Harvey and Grasham (1969) and Coleman and Thorpe (1977).

Sexual Reproduction

Sexual reproduction probably is more important than asexual reproduction in open clearcut units and other disturbed areas (see Parker 1979). When grown in the open, western redcedar trees begin to produce strobili at 10 years of age and usually continue every other year thereafter (Søegaard 1956a), but large seed drops occur only every 3 to 4 years (Schopmeyer 1974).

Strobilus formation is induced by branch-girdling in western redcedar (Forestry Commission, London 1970; Longman 1976). Treatment with gibberellins also induces strobilus formation (Coutts and Bowen 1973, Longman 1976). Indeed, staminate strobili can be induced in 7- to 9-month-old redcedar seedlings by applying foliar sprays of gibberellin A under long-day conditions (Pharis and Morf 1967). Long days were used by Coleman and Thorpe (1978) to induce staminate strobilus formation in western redcedar shoot tips cultured on nutrient media in the presence of high gibberellin concentrations. Simak et al. (1974) also used long days and gibberellin to induce staminate strobili in redcedar cuttings. A short photoperiod, cold treatment, or both must be applied if strobili are to develop further, however (Pharis et al. 1969, Pharis and Morf 1972). Pharis and his coworkers combined the gibberellin treatment with a sequence of long day, short day, long day to produce both staminate 'and ovulate strobili on young redcedar seedlings. They found that cold temperatures during the short-day treatment increased the number of developing strobili and that cold alone was effective, regardless of photoperiod.

Under natural conditions on Vancouver Island, staminate strobili are initiated during the long days of early June, and ovulate strobili are initiated during the long days of early July (Owens and Pharis 1971). Meiosis begins in the fall, but it is arrested at the pachytene stage from November until late January (Owens and Molder 1971). Development resumes in February near Victoria, British Columbia, where pollination occurs in early March and fertilization is accomplished in late May (Owens and Molder 1980). Pollination is delayed until late May or early June in northern Idaho (Schopmeyer 1974). Peak pollen release occurs around noon, when relative humidities are low (Haard 1971). Self-pollination is common (Søegaard 1956a). The pollination mechanism in western redcedar does not allow an accumulation of pollen, and redcedar ovules are not all receptive at the same time, so several sources of pollen shed over a prolonged period are advantageous (Owen and Molder 1980).

Western redcedar cones mature about 5 months after pollination west of the Cascades, about 3 months after pollination in northern Idaho (Schopmeyer 1974). Seedfall begins soon thereafter, continuing throughout the following winter in most locations (see Haig et al. 1941, Fowells 1965, Gashwiler 1969). Heavy seed crops are common (see Garman 1955, Schmidt 1955, Gashwiler 1969, Harris and Farr 1974).

Western redcedar seeds retain their initial viability for at least 3 years when stored at −18°C (−0.4°F) (Barton 1954, Holmes and Buszewicz 1958). Some germination occurred after 6 years when Allen (1957) stored redcedar seeds at 0"C (32°F), but −18°C (−0.4°F) seems to be a better storage temperature. Stratification may improve the germination of some dormant seed lots (Schopmeyer 1974). In others, it may lower the germination capacity (Jablanczy 1964). Schopmeyer cites a 0.2-percent solution of potassium nitrate in the germination medium as an alternative to cold stratification.

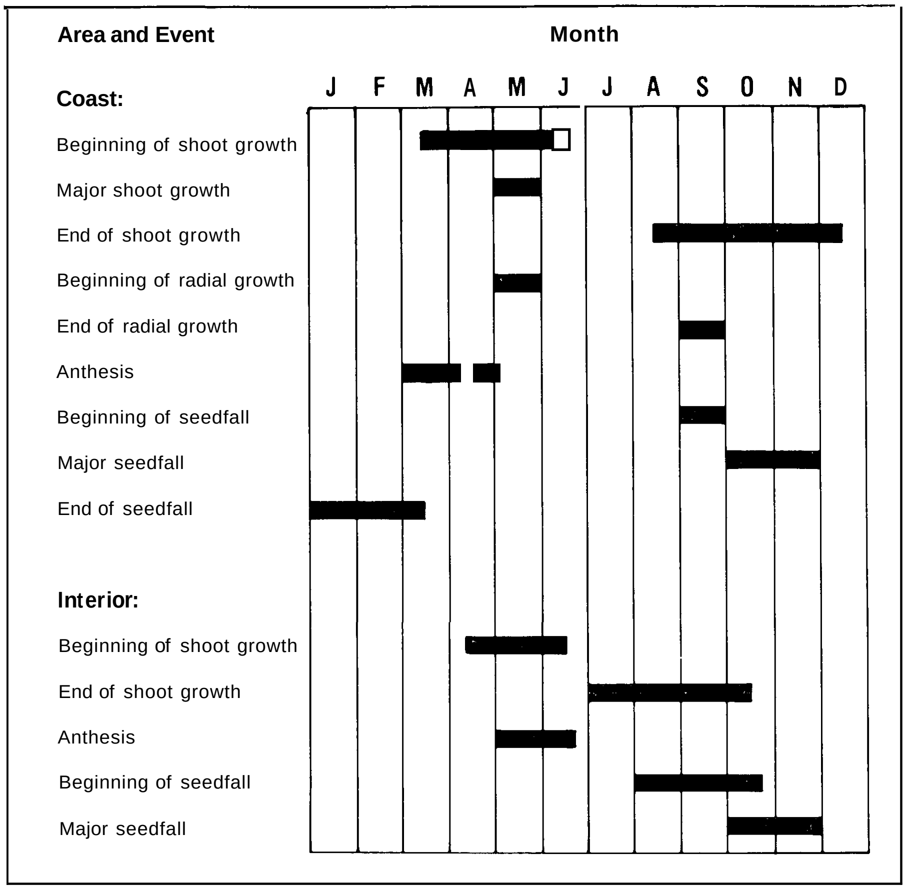

Figure 4.—Phenology of native redcedar, by area (from Haig et al. 1941, British Columbia Forest Service 1950, Garman 1955, Buckland 1956, Pacific Northwest Forest and Range Experiment Station 1957, Hedlin 1964, Hetherington 1965, Williams 1968, Owens and Pharis 1971, Schopmeyer 1974, Schmidt and Lotan 1980).

Phenology

Phenological observations vary with year and locality. Therefore, the observations summarized in figure 4 probably were influenced by the years and locations in which they were recorded.

Phenological comparisons among species may be less influenced by seasonal and spatial variations. Western redcedar had the longest height-growth season of any conifer measured by Williams (1968) in the upper slope forests of Oregon. Walters and Soos (1963) found that leader growth commenced earlier and accelerated faster in redcedar than in Douglas-fir, western hemlock, or western white pine, but then continued at a lower rate — for a longer period — than in the other species.

Radial growth phenology is not as easy to compare. It seems to vary among species from year to year (Reukema 1965). Redcedar radial growth periods are strongly influenced by altitude in the interior (see Daubenmire 1946).

Regeneration

Western redcedar regeneration probably is seldom limited by lack of seed. A fair seed crop on four trees produced over a million seeds in British Columbia (Garman 1951), and nine trees in a mature stand produced an average seedfall of over 2 million seeds during 3 crop years (Garman 1955). The average annual crop in the coastal forests of British Columbia usually ranges from 247,000 to 2,470,000 seeds per hectare (100,000 to 1,000,000 seeds/acre) in stands with up to 25 percent redcedar (Schmidt 1955), but pure stands may yield over 148 million seeds per hectare (60 million seeds/acre) (Sharpe 1974). In the interior, average seed crops range from 54,000 to 274,000 seeds per hectare per year (22,000 to 111,000 seedslacre per year) (see Fowells 1965, Clark 1970).

Western redcedar seeds tend to be sound as well as numerous. In a scrub stand in Alaska, 68 to 92 percent of the 38 million seeds per hectare (15 million seedslacre) produced in 1956 were sound (James 1959). Although he recorded great variations in size of redcedar seed crop, Gashwiler (1969) found a higher percentage of filled seeds for western redcedar than for Douglas-fir or western hemlock in west-central Oregon. Redcedar seeds fall faster and do not fly as far as the seeds of western hemlock, Sitka spruce, or Douglas-fir (see Siggins 1933).

As western redcedar seeds are usually abundant and sound, an abundance of young redcedar trees would be expected on most redcedar sites. Surprisingly, they are not present in many environments. Immature stands are uncommon in coastal British Columbia (see Packee 1976). Seedlings are either rare (Neiland 1971) or they have difficulty surviving (Gregory 1957) in southeastern Alaska. They are also rare on both well-drained undisturbed sites and cutover areas on Graham Island, British Columbia (Day 1957).

Moist redcedar sites on Graham Island regenerate if undisturbed (Day 1957), and regeneration from seed is often successful on open areas disturbed by logging, windthrow, or fire in the coastal forests of British Columbia (Schmidt 1955). Moist redcedar sites also regenerate in Montana's Glacier National Park, but the regeneration is vegetative (Habeck 1968). Western redcedar is not reproducing at all in low elevation redcedar communities within the Selway-Bitterroot wilderness of Idaho (Habeck 1978). Habeck attributed this to high populations of wildlife and a deterioration of the moist Pacific maritime influence in Idaho. Farther north, in the interior wet belt of British Columbia, 150,000 redcedar seeds were required to produce 1,000 2- to 5-year-old seedlings in a 121.5-hectare (300-acre) clearcut unit, but natural regeneration was adequate on disturbed sites within 100.6 m (330 ft) of a seed source (Clark 1970).

The failure of redcedar regeneration on some sites and the high seeds-to-established-seedling ratio on other sites are puzzling. Failures probably are not because of seed losses. Gashwiler (1967) found that a large proportion of his redcedar seeds survived until germination, which began later and finished sooner than the germination of western hemlock seeds (Soos and Walters 1963). Almost no germination occurs after the 1st year (Isaac 1940), but enough redcedar seeds should germinate to insure success on most sites. Mortality is high during the germination period, however (see Gashwiler 1970), and seedbed quality may be critical.

Germination was greater and more uniform under sand than under grit when redcedar seeds were covered in British experiments (Forestry Commission, London, 1978). Sand was a poorer seedbed than western white pine duff in Fisher's (1935) greenhouse experiments. The artificial conditions inherent in many greenhouse experiments sometimes produce misleading results, how ever, and those results should be applied to field situations with geat care, if at all. In field experiments, Haig et al. (1941) found western redcedar germination to be 5 to 10 times better on mineral soil than on duff. Mineral soil also is a better seedbed than moss in southeastern Alaska, but western redcedar seedlings seem to survive better than those of other species on the moss (Godman 1953). Average field survival of germinated western redcedar seeds was slightly higher on rotten Sitka spruce wood than on rotten Douglas-fir wood, rotten hemlock wood, or duff on light and moderately shaded seedbeds in coastal Oregon (Minore 1972). Heavily shaded seedbeds were associated with the best redcedar germination in coastal British Columbia (Garman 1955), where germination occurs throughout fall and winter when temperatures are favorable (personal communication, Edmond C. Packee, MacMillan Bloedel Limited, Nanaimo, British Columbia).

Although Soos and Walters (1963) found that unburned mineral soil favors redcedar survival more than burned mineral soil, burning after logging may favor the natural regeneration of western redcedar (British Columbia Forest Service 1948b). It probably creates more mineral soil surfaces in cutover areas. Growth of redcedar seedlings was better on burned and denuded surfaces than on organic material in northern Idaho (Larsen 1940). Seedling survival is usually best on mineral soil and poorest on rotten wood (Boyd 1959), but growth of the survivors may be best on wood; 80 percent of the dominant redcedars examined by Nystrom (1980) grew on rotten logs, but only 36 percent of the suppressed trees were on rotten wood.

Throughout the range of western redcedar, disturbance of seedbeds seems to be beneficial. Partial shade is also beneficial. Drought and high soil surface temperatures damage seedlings in full sunlight, and poor root penetration causes drought damage in full shade (Sharpe 1974). Fungi probably cause the greatest early mortality (Boyd 1959).

Shade Tolerance

Baker (1949) listed western redcedar as very tolerant. Although Schmidt (1955) observed that redcedar did not have all the characteristics usually associated with a shade-tolerant tree, most authors seem to agree with Baker's assessment. Redcedar is slightly less tolerant than western hemlock in southeastern Alaska and the south coast region of British Columbia (Packee 1976). It is also less tolerant than Pacific silver fir in British Columbia (Krajina 1965, Packee 1976). Redcedar may be more shade tolerant than western hemlock in the interior (see Haig et al. 1941). The literature indicates that shade tolerance of western redcedar along the coast may be higher in warmer zones than it is in cool zones (Packee 1976).

Succession

Western redcedar is often present in all stages of forest succession, and Packee (1975) listed its successional positions as pioneer, seral, and climax. Multiple attributes seem to be responsible, for redcedar invades disturbed areas as widely distributed seeds but regenerates vegetatively in undisturbed areas, tolerating competition in both situations (Kessell 1979). Nevertheless, redcedar is usually considered a climax or near-climax species (see Munger 1940, Guiguet 1953, Schmidt 1955, McLean and Holland 1958, Mueggler 1965). Idaho western white pine stands are slowly replaced by a western hemlock-redcedar climax (Watt 1960). Daubenmire and Daubenmire (1968) listed redcedar as the major climax species in their ***Thuja plicata/Pachistima, Thuja plicata/Oplopanax,*** and ***Thuja plicata/Athyrium*** habitat types in Idaho. It is a minor climax species in their ***Tsuga heterophylla/Pachistima*** type. Pfister et al. (1977) listed redcedar as a major climax species in Montana's ***Thuja plicata/Clintonia uniflora*** habitat type, a minor climax species in the ***Tsuga heterophylla/Clintonia uniflora*** type. Western hemlock may eventually replace western redcedar in some decadent stands of southeastern Alaska (see Gregory 1957). Redcedar will be part of the climax forest on wet sites in the ***Tsuga heterophylla*** zone of Oregon and Washington, but it probably does not have climax status on modal or dry sites (Franklin and Dyrness 1973).

Moisture and soil conditions strongly influence the successional status of western redcedar. It is climax on wet sites in the Lake McDonald region of Glacier National Park (Habeck 1968) and on calcium-rich seepage habitats in British Columbia (Krajina 1969). Redcedar probably is an edaphic climax species rather than a climatic climax tree. Longevity should not be ignored when considering successional status, however, and very old redcedar trees are often present in climatic climax situations.

Growth

Radial growth is similar in western redcedar and western hemlock (Walters and Soos 1962), but most of the pseudotransverse cell divisions in redcedar cambium occur near the end of the growing season (Bannan 1951). Both species produce non-rigid leaders, but they differ in proportions of lateral and leader growth. Growth of lateral branches is less than half of leader growth in western hemlock and more than 80 percent of leader growth in western redcedar (see Buckland 1956). Growth rates of lateral and terminal shoots were similar in the young western redcedars measured by Walters and Soos (1963).

Growth is not always rapid. Suppressed redcedar trees that are 200 years old but only 7.6-cm (3-in) d.b.h. and 7.6-m (25-ft) tall are not unusual (Schmidt 1955). Ability to survive such long periods of suppression may result from the ability of western redcedar to produce new root growth in full shade (see Haig 1936). It may also be a result of frequent root grafting. Eis (1972) found that dominant trees usually supported growth of the root systems and lower boles of suppressed trees. However they survive, these suppressed trees often recover well when released.

Forest inventory data show western redcedar trees in Oregon and Washington to be smaller in diameter and shorter than Douglas-firs and hemlocks of the same age on most sites (Bolsinger 1979). This is also true on well-drained soils in the south coast region of British Columbia. On moist sites, however, the coastal redcedar often is as large or larger than its associates (Packee 1976). Packee cites annual radial increments of 1 or even 2 cm (0.4 to 0.8 in) on the best moist sites.

Day (1957) found that vigor of western redcedar declined more slowly than that of Sitka spruce or western hemlock as site conditions became poorer on the Queen Charlotte Islands of British Columbia. This slower decline in relative vigor with decreasing site quality was not evident in the measurements of young tree growth recorded by Walters et al. (1961) on the lower mainland. Indeed, the opposite trend was apparent — young western redcedars grew faster than young western hemlocks and Douglas-firs on good sites, slower on poor sites. Ages of the trees being compared probably were responsible for these differences. Although western redcedar may not attain its most rapid growth rate until it is 10 to 30 years old (Jackson and Knapp 1914), it grows taller than western hemlock or Douglas-fir during the first 5 years on good sites (see Smith and DeBell 1973). Smith and DeBell's data show that Douglas-fir overtakes western redcedar by age 10, and western hemlock overtakes redcedar by age 15.

Growth of western redcedar tends to be faster than that of Alaska-cedar, but it may be extremely slow on poor sites in southeastern Alaska (Harris and Farr 1974). Height growth may reach a maximum at an early age in southeastern Alaska (Andersen 1955b). Nearby, along the north coast of British Columbia, approximately 10 years are required to produce a 1.2-m-tall (4-ft-tall) redcedar on average sites. Diameters of 0.5 to 4.6 cm (0.2 to 1.8 in) are produced on better sites during the same 10-year period (see British Columbia Forest Service 1948b). Western redcedars in the United States may require 80 years to reach diameters of 25 to 46 cm (10 to 18 in) (Lutz 1972).

Redcedar growth rates seem to be impaired by a droughty soil-moisture regime or highly leached soils on Vancouver Island, British Columbia (McMinn 1960). Redcedar seems to grow slower than western hemlock but faster than Pacific silver fir on coastal Douglas-fir sites (see Walters and Haddock 1966).

Growth of redcedar is slow in the inland western white pine type, and redcedar often forms an understory after being outgrown by associated species (Haig et al. 1941). Even when released, it often cannot keep up with grand fir, western hemlock, and western white pine in northern Idaho (Deitschman and Pfister 1973). Slow growth during the first few years makes Rocky Mountain redcedar more susceptible to drought and insolation injury than its faster growing associates (Schopmeyer 1940, McKeever 1942). Diameter growth of Rocky Mountain redcedar, however, is less affected by high elevation than the diameter growth of ponderosa pine or Douglas-fir (Daubenmire 1955).

Western redcedar growth varies greatly with site quality in Britain. Redcedar grew taller than Douglas-fir or Sitka spruce in a 14-year-old British plantation, and a 20-year-old western redcedar plantation achieved a height of 16.8 m (55 ft) and a total volume of 2.1 m^3/ha (30 $ft^3/acre$) (MacDonald 1957). These plantations probably were on exceptionally favorable sites, however, for Aldhous and Low (1974) found that the early growth of western redcedar was slower than that of Douglas-fir and Sitka spruce on most British sites. Growth tends to accelerate slightly after about 25 years (Evans 1950). Redcedar eventually outproduces Sitka spruce on British lowland sites. It becomes increasingly more productive than Douglas-fir as British site quality improves (see Aldhous and Low 1974). Indeed, Packee's (1976) analyses of the paired-plot comparisons made by Aldhous and Low indicate that redcedar volume growth exceeds that of Douglas-fir on most British sites.

Growth of redcedar also varies with site quality elsewhere in Europe. Dominant ,western redcedars in France have attained average heights of 19 m (62 ft) in 39 years (Andre and Lheureux 1974). Younger western redcedars in Germany grew to an average height of 7.6 m (25 ft), with at least one tree reaching a height of 10.8 m (35 ft) in 18 years (Zimmerle and Linck 1951). Danish redcedars have reached heights of 20 to 25 m (66 to 82 ft) in 50 years (Madsen 1977). Growth in the Ukraine is slower, and the largest western redcedars there were only 22 m (72 ft) tall at age 70 (Unasylva 1950).

Productivity

Published production data for native western redcedar are rare, but three North American studies are available. In the first, Smith and DeBell (1973) assessed the productivity of short-rotation redcedar and found it poorer than that of Douglas-fir, western hemlock, or black cottonwood. In a second study, Nokoe (1978) developed a yield curve for medium-site western redcedar at Salmo, British Columbia:

Age	Net volume (m^3/ha[9])
40	70
80	210
115	350
165	490
270	595

His mathematical models indicate that the maximum current annual increment occurs at 82 years and the maximum mean annual increment at 130 years for a medium site. For a poor site, the ages are 133 and 210 years, respectively.

In the third study, Nystrom (1980) measured volumes of 379 to 824 m^3/ha (5,418 to 11, 782 $ft^3/acre$) in 40-to 60-year-old, pure, second-growth stands of redcedar in western Washington. Of the 939 to 3,657 redcedars per hectare (380 to 1,480 per acre) in these young stands, 297 to 642/ha (120 to 260/acre) were dominants with a mean annual height growth of 0.5 m (1.64 ft) per year.

[9]To obtain $ft^3/acre$, multiply m^3/ha by 14.2914.

Table 6 — Growth and yield of western redcedar in Britain[1]

Site and height	Cumulative volume production in normal stands	Basal area of fully stocked stands before thinning	Average age of maximum mean annual increment
	Cubic meters per hectare[2]	Square meters per *hectare*[3]	Years
Poor sites:			72
Age 20	50		
Age 80	953		
Good sites:			58
Age 20	232		
Age 80	1838		
Stand height:			
10 meters	100		
12 meters		49	
20 meters	600	55	
30 meters	1400	70	

[1]Adapted from Hamilton and Christie (1971).
[2]Multiply by 14.2914 for cubic feet per acre.
[3]Multiply by 4.3560 for square feet per acre.

More information on productivity is available for western redcedar grown outside its natural range. A Montana provenance of redcedar planted in Austria in 1897 produced yields and stem forms comparable to those of Norway spruce grown in the same district (Rannert 1976). Redcedar equaled or exceeded the yield of Norway spruce in northwestern Germany, but it was inferior to Douglas-fir when both North American species were grown there (Hesmer and Gunther 1968). Western redcedar also produced less than Douglas-fir during a trial of species in East Germany. Nevertheless, its mean annual increment (12.5 m³/ha or 178.6 ft³/acre) was not far below that of Douglas-fir (13.9 m³/ha or 198.6 ft³/acre), and redcedar increment exceeded the mean annual increments of Norway spruce (10.8 m³/ha or 154.3 ft³/acre), Japanese larch (10.2 m³/ha or 145.8 ft³/acre), European beech (9.6 m³/ha or 137.2 ft³/acre), and Scotch pine (8.8 m³/ha or 125.8 ft³/acre) on a good site near Eberswalde (Lembcke 1970).

The mean annual increment of a 57-year-old western redcedar plantation in the Wirty State Forest of Poland was 13.0 m³/ha (185.8 ft³/acre). When previous thinning was included, its total yield of 939.5 m³/ha (13,426.7 ft³/acre) was nearly twice that for pine of the same age and site quality (see Gecow 1952). Although redcedar also matched or exceeded the production of native European species in Poland's Krynica Forests, both grand fir and Douglas-fir produced more than western redcedar there (Jaworski and Majerczyk 1975).

Western redcedar productivity in France apparently varies greatly with stand age, stand density, and the environment in which it is grown. Turpin and Pardé (1959) found that a young redcedar stand produced 13 m³/ha per year (186 ft³/acre per year) on the Barres Estate — more than Douglas-fir (12.3 m³/ha per year or 176 ft³/acre per year) and second only to western hemlock (14.8 m³/ha per year or 212 ft³/acre per year). In contrast, Guinier (1951) observed that an 85-year-old Douglas-fir stand on the Harcourt Estate would produce about twice as much (800 m³/ha or 11,433 ft³/acre) as an 80-year-old western redcedar stand (400 m³/ha or 5,716 ft³/acre) if both had 250 trees/ha.

Mensuration

Danish redcedar plantations also vary in productivity. Two plantations in eastern Denmark maintained periodic annual increments of 21 to 35 m^3/ha (300 to 500 ft^3/acre) until age 46. One plantation then declined to a periodic annual increment of 16 to 18 m^3/ha (229 to 257 ft^3/acre), but the other maintained an increment of 24 to 29 m^3/ha (343 to 414 ft^3/acre) until age 60 (Madsen 1977).

The forest-management tables published by Hamilton and Christie (1971) seem to be the best summary of western redcedar productivity in Britain. They show that height growth of redcedar is slower than, that of Douglas-fir, western hemlock, or grand fir during the first 50 years. It is sometimes faster than that of Sitka spruce, but only on poor sites. Dominant redcedars have larger diameters than other species at any given height. The volume production shown in table 6 exceeds that of Douglas-fir, grand fir, and Sitka spruce at heights of 20 and 30 m (66 and 98 ft), but is less than that of noble fir.

Where Hamilton and Christie (1971) present yields in terms of stand age rather than stand height, their normal yield tables show that cumulative volume production on good sites is lower for redcedar than for Douglas-fir, western hemlock, Sitka spruce, or grand fir — but only until age 20. For 60- and 80-year-old stands, cumulative production of redcedar equals that of western hemlock and exceeds the cumulative production of Douglas-fir or Sitka spruce on good sites.

The average age of maximum mean annual increment is older for western redcedar than for Douglas-fir, western hemlock, Sitka spruce, or grand fir on good sites. It is younger than western hemlock on poor sites, and younger than noble fir on all sites.

An early article by Jackson and Knapp (1914) provided some site information on western redcedar in terms of "short trees," "medium trees," and "tall trees." A preliminary site-class table for mature redcedars was published 34 years later (Province of British Columbia 1948). Chambers and Wilson (1972) used total age and 100-year site-index curves in developing yield tables for conifer stands of western hemlock, Sitka spruce, and western redcedar in western Washington. Differences in the shapes of height/age curves for western hemlock and western redcedar are relatively small, but redcedars usually are shorter than hemlocks at a given age (see Smith et al. 1961a). The best available site-index curves for western redcedar appear to be the preliminary, polymorphic curves developed by Kurucz (1978) for coastal British Columbia (figs. 5 and, 6).

Height-age and diameter-age relationships for British Columbia redcedars were published by the British Columbia Forest Service (1948b). For example, a 15-cm (6-in) d.b.h. redcedar that is 40 years old may be expected to attain 44.5-cm (17.5-in) d.b.h. at 100 years and 93.5-cm (36.8-in) d.b.h. at 200 years on a good site in coastal British Columbia. North coast redcedars on average sites required 18 years to reach a height of 10 feet (3 m) (British Columbia Forest Service 1948b). The height-diameter relationship determined by Brown et al. (1977) for western redcedars in Montana is:

$$\text{Height} = -15.40 + 18.80\,(\text{diameter})^{0.6039}.$$

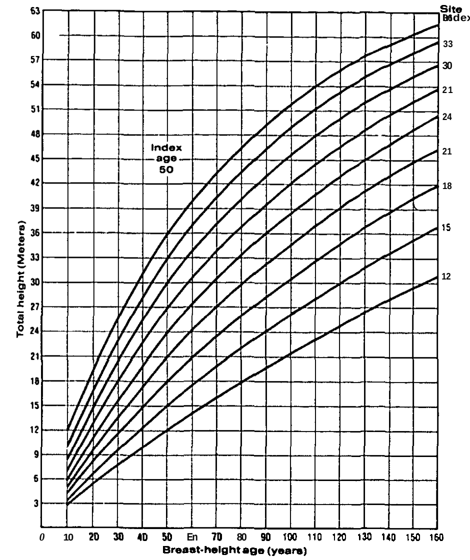

Figure 5. — Site index curves for western redcedar in coastal British Columbia (courtesy J.F. Kurucz, MacMillan Bloedel Limited).

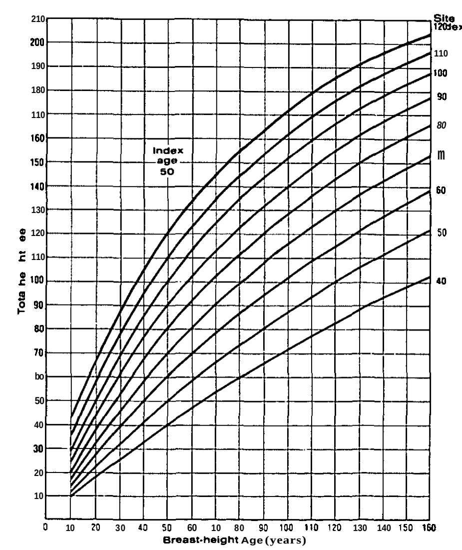

Figure 6. —Site index curves for western redcedar in coastal British Columbia (courtesy J.F. Kurucz, MacMillan Bloedel Limited).

Height growth of western redcedars in southeastern Alaska may reach its maximum at an early age, and small-diameter trees tend to have higher Girard form-classes than large-diameter trees (Andersen 1955b). Andersen's form-class measurements ranged from **55** to 76 for 9.8-m (32-ft) logs. Form-class measurements are greatly influenced by bark thickness. Bones (1962) found the average ratio of inside- to outside-bark diameters at the top of the first 4.9-m (16-ft) log of Alaska redcedar to be 0.9396. Form-class measurements have not been published as such for interior western redcedar, but butt-taper tables (Breadon 1957) are available. They permit conversion of diameters measured at 0.3, **0.5,** 0.6, 0.8, 0.9, 1.1, 1.2, 1.5, 1.8, 3.0, 3.7, or 5.2 m (1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, **5.0,** 6.0, 8.0, 10.0, 12.0, or 17.0 ft) above ground to diameter at breast height.

Western redcedar volume tables were included in Jackson and Knapp's 1914 article and in Haig's 1932 tables for the western white pine type. Several others tables have been published since. A cubic-volume table for mature western redcedar in British Columbia listed gross merchantable volume for six site classes by 2-inch (5-cm) d.b.h. intervals (Province of British Columbia 1948). The British Columbia Forest Service (1949) also published site-class volume tables. Interim tables from the Pacific Northwest Forest and Range Experiment Station (1953) were superseded by the cubic- and board-foot tables in Agriculture Handbook 92 (Johnson 1955). Those tables were based on measurements of interior western redcedar, however (table 7). The form-class volume tables published by Andersen (1955c, 1955d) for cubic- and board-foot volumes of western redcedar in southeastern Alaska are more appropriate for coastal conditions.

Constants listed by Smith and Ker (1957) for their volume equation, ($V = a + b(D^2H/100)$), included appropriate values for western redcedar in British Columbia. The British Columbia volume tables of Fligg and Breadon (1959) provided regionally applicable information by 32-foot-log position in the tree. Those of Browne (1962) included separate tables for interior and coastal redcedar in British Columbia, with the coastal volumes further segregated by mature and immature trees. Volume tables and equations for mature, old-growth redcedar were prepared by Farr and LaBau (1971) for southeastern Alaska (table 8). Immature redcedars managed for short rotations were used in deriving the volume equation published by Smith and DeBell (1973):

$$V = 0.31 + 0.234D^2H.$$

Yield data for western redcedar furnished by Jackson and Knapp (1914) for the Puget Sound area appear to be more applicable to individual redcedar trees than to stands, and relating them to modern management practices might be difficult. The preliminary redcedar growth and yield data of Smith et al. (1961b) probably would be easier to apply, because they are sorted by stand density, age, and site index. Smith et al. assumed that the growth and yield of western redcedar are generally similar to the growth and yield of western hemlock. Chambers and Wilson (1972) also seem to have made this assumption in constructing empirical yield tables for western redcedar, western hemlock, and Sitka spruce in western Washington.

Table 7 — Volumes for western redcedar in the western white pine region[1]

D.b.h.	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160
	Total height of tree (feet)															
Inches	*Cubic feet*															
1	0.02	0.05	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2	.10	.20	0.31	—	—	—	—	—	—		—	—	—	—	—	—
3	—	.47	.67	0.91	—	—	—	—	—	—	—	—	—	—	—	—
4	—	.83	1.25	1.63	2.1	2.5	—	—	—	—	—	—	—	—	—	—
5	—	1.27	1.95	2.60	3.2	3.8	—	—	—	—	—	—	—	—	—	—
6	—	—	2.8	3.6	4.5	5.3	6	7	—	—	—	—	—	—	—	—
7	—	—	4	5	6	7	8	9	—	—	—	—	—	—	—	—
8	—	—	5	6	8	9	10	12	13	14	—	—	—	—	—	—
9	—	—	6	8	9	11	13	14	16	18	—	—	—	—	—	—
10	—	—	7	9	11	14	16	18	20	22	—	—	—	—	—	—
11	—	—	—	11	14	16	19	21	23	26	29	—	—	—	—	—
12	—	—	—	13	16	19	22	25	27	30	33	36	38	—	—	—
13	—	—	—	15	18	22	25	28	32	35	38	41	44	—	—	—
14	—	—	—	—	21	25	29	33	36	40	43	47	50	—	—	—
15	—	—	—	—	24	29	33	37	41	45	49	53	56	—	—	—
16	—	—	—	—	27	32	37	41	46	50	54	58	62	—	—	—
17	—	—	—	—	30	35	40	45	50	55	60	64	69	—	—	—
18	—	—	—	—	33	39	45	50	55	60	65	70	76	—	—	—
19	—	—	—	—	36	43	49	55	61	66	71	77	83	—	—	—
20	—	—	—	—	—	—	53	60	66	72	78	84	90	—	—	—
21	—	—	—	—	—	—	58	65	72	78	84	91	98	—	—	—
22	—	—	—	—	—	—	—	—	77	84	91	98	106	114	—	—
23	—	—	—	—	—	—	—	—	83	91	99	107	115	123	—	—
24	—	—	—	—	—	—	—	—	90	98	106	115	123	131	139	146
25	—	—	—	—	—	—	—	—	96	105	114	123	132	140	149	156
26	—	—	—	—	—	—	—	—	103	113	122	131	140	149	158	167
27	—	—	—	—	—	—	—	—	110	120	130	140	149	159	168	178
28	—	—	—	—	—	—	—	—	117	128	138	148	158	168	178	188
29	—	—	—	—	—	—	—	—	125	136	146	157	167	178	188	199
30	—	—	—	—	—	—	—	—	132	143	154	165	176	187	198	209

[1]From Haig (1932), Johnson (1955). Volumes include stump, stem, and top.

Table 8 — Volumes for western redcedar in southeastern Alaska[1]

D.b.h.	Total height of tree (feet)														
	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170
Inches	*Cubic feet*														
6	2.3	2.7	3.2	3.6	4.1	—	—	—	—	—	—	—	—	—	—
8	4.9	5.7	6.6	7.4	8.2	—	—	—	—	—	—	—	—	—	
10	8.1	9.4	10.6	11.9	13.2	14.4	15.7	—	—	—	—	—	—	—	—
12	11.9	13.7	15.5	17.3	19.2	21.0	22.8	24.6	—	—	—	—	—	—	—
14	—	18.8	21.2	23.7	26.2	28.7	31.2	33.7	—	—	—	—	—	—	—
16	—	—	27.8	31.1	34.3	37.5	40.8	44.0	47.3	—	—	—	—	—	—
18	—	—	35.3	39.4	43.5	47.6	51.7	55.8	59.9	64.0	—	—	—	—	—
20	—	—	43.6	48.6	53.7	58.8	63.8	68.9	74.0	79.0	—	—	—	—	—
22	—	—	52.7	58.9	65.0	71.1	77.3	83.4	89.5	95.7	—	—	—	—	—
24	—	—	62.8	70.1	77.4	84.7	92.0	99.3	07	114	—	—	—	—	—
26	—	—	73.7	82.3	90.8	99.4	108	17	25	134	142	—	—	—	—
28	—	—	—	95.4	105	115	125	35	45	155	165	175	—	—	—
30	—	—	—	110	121	132	144	55	67	178	189	201	212	—	—
32	—	—	—	125	138	151	164	77	90	202	215	228	241	—	—
34	—	—	—	—	155	170	185	199	214	229	243	258	272	287	—
36	—	—		—	174	191	207	223	240	256	273	289	306	322	338
38	—	—	—	—	194	212	231	249	267	286	304	322	340	359	377
40	—	—	—	—	215	235	256	276	296	316	337	357	377	397	418
42	—	—	—	—	237	259	282	304	326	349	371	393	416	438	461
44	—	—	—	—	260	285	309	334	358	383	407	432	456	481	505
46	—	—	—	—	—	—	338	365	392	418	445	472	499	526	552
48	—	—	—	—	—	—	368	397	426	456	485	514	543	572	602
50	—	—	—	—	—	—	399	431	463	494	526	558	589	621	653
52	—	—	—	—	—	—	432	466	500	535	569	603	637	672	706
54	—	—	—	—	—	—	466	503	540	577	614	650	687	724	761
56	—	—	—	—	—	—	—	541	580	620	660	700	739	779	819
58	—	—	—	—	—	—	—	580	623	665	708	750	793	836	878
60	—	—	—	—	—	—	—	621	666	712	757	803	849	894	940
62	—	—	—	—	—	—	—	663	711	670	809	858	906	955	1004
64	—	—	—	—	—	—	—	706	758	810	862	914	966	1017	1069
66	—	—	—	—		—	—	751	806	861	917	972	1027	1082	1137
68	—	—	—	—	—	—	—	797	856	914	973	1032	1090	1149	1207
70	—	—	—	—	—	—	—	845	907	969	1031	1093	1155	1217	1279

[1] From Farr and LaBau (1971). Volumes are based on a 1-ft stump and 4-in-top d.i.b.

Seeding

Western redcedar regeneration occurs after clearcutting in British Columbia and Alaska (Schmidt 1955, Harris and Farr 1974). Nevertheless, natural regeneration has not been relied on to achieve immediate and complete restocking of logged areas on Vancouver Island (see Hetherington 1965). A seed and sawdust mixture was broadcast on melting snow near Cowichan Lake in an early direct-seeding trial (British Columbia Forest Service 1948a). Only 2.5 percent of the redcedar seeds survived, but 1,235 seedlingslha (500 seedlingslacre) were alive after two growing seasons. Isaac's (1939) early work indicated probable success for broadcast seeding of western redcedar at rates of 5.4 to 10.9 kglha (1 to 2 Iblacre) if it were done within 2 years of slash burning. Waiting longer than 2 years on Oregon's Tillamook burn resulted in poor stocking of redcedar when the broadcast seeding was done in the spring (see Engstrom 1955).

Trials of direct redcedar seeding in northern Idaho indicated that seed spots sown in the autumn resulted in better initial stocking than those sown in the spring (Schopmeyer 1940, Helmers 1946, Schopmeyer and Helmers 1947). Protection from rodents was unnecessary when the seeds were covered with a thin layer of soil, but insufficient soil moisture, erosion, and smothering by leaves, bark, duff, and rotten wood were serious (McKeever 1942). Excellent 5th year stocking resulted when the redcedar seeds were sown on cutovers and broadcast-burned areas with stable soils and light or moderate covers of low vegetation (Helmers 1946).

Nursery Practices

Although western redcedars amounted to only a small fraction of their total production, approximately 650,000 redcedar seedlings were produced by nurseries in Washington during 1977 (Bolsinger 1979). Redcedar has been grown in European nurseries for many years by several methods.

Redcedar seeds may be separated from the cones by kiln-drying at 32°C (90°F), shaking in a mechanical cone shaker, and fanning. They should not be dewinged (Schopmeyer 1974). Empty seeds are frequent in western redcedar cones. They may be separated from full seeds in an airstream (Schopmeyer 1974) or by immersing in petroleum ether (Lebrun 1967). Western redcedar seeds are stored at − 18°C (0°F) in many western nurseries (Schopmeyer 1974).

Seedbeds should be sown in the spring for best results (see Aldhous 1967, Schopmeyer 1974). Sowing depths of 3 to 10 mm (1/8 to 3/8 in) and seedbed densities of 377 to 1,076 seedlings/m^2 (35 to 100 seedlings/ft^2) are commonly used. Half-shaded seedbeds are recommended during the first growing season (Schopmeyer 1974). Some European nurseries had better success with seedbeds of needle or leaf litter than with mineral soil (Hutt 1956, Rohrig 1958). Organic matter in the seedbed promotes the growth of *Thelephora* terrestris, however (Weir 1921), and redcedar seedlings are usually grown in soil beds. Infrequent irrigation of nursery beds ("predroughting") had no beneficial effect on western redcedar seedlings that were subsequently subjected to dry environments (see Oppenheimer 1967). Seedlings responded best to spring transplanting in Germany (Mormann 1956).

Petroleum products have been used as nursery weedkillers. A French compound, Desherbant Carottes No. 35,[10] damaged western redcedar seedlings more than those of the firs,, spruces, or pines (Bouvarel 1951). Light petroleum was less damaging to redcedar than to Douglas-fir, Norway spruce, or the larches in Denmark (Petersen 1952). Redcedar was also resistant to the winter application of propyzamide in Britain (Brown and McKenzie 1974).

Effective control of Didymascella *thujina* has been obtained by spraying cycloheximide fungicides on the affected nursery beds. The cycloheximide itself is more damaging to western redcedar than its oxime, semicarbazone, and acetate derivatives, however (Pawsey 1962a, 1965; Phillips 1962, 1964). Concentrations of 50 to 150 plm have been recommended for these derivatives. They were most effective when applied in the spring and summer (Pawsey 1965).

Western redcedar cuttings for use in silviculture may be produced easily and cheaply (Sqegaard 1956a). Søegaard recommended July and August cuttings. Untrimmed cuttings, treatment with indolebutyric acid in talc, and a sand-peat (75 percent-25 percent) rooting medium heated to 21°C (70°F) were recommended by Matthews (1951). Misting the rooting bed with a nutrient mist fortified with 45 g/100 liters (6 oz/100 gal) soluble 23-19-17 fertilizer improved cutting growth and nutrient content (Wott and Tukey 1965).

[10] The mention of products does not imply endorsement by the U.S. Department of Agriculture to the exclusion of other products that might be suitable.

Soluble fertilizers have been added to irrigation water in the production of containerized western redcedar nursery stock. The procedures described by Owston (1974) included frequent irrigation at pH 5.0 to 5.5 in a greenhouse. Owston's redcedars were sown in mid-June in Styroblocks[11] filled with a peat-vermiculite mixture, grown all summer in the greenhouse, and hardened-off in late October to mid-November. The seedlings were ready to plant in January and February. Unfortunately, containerized western redcedar seedlings have not survived as well as bare-root stock when planted in western Oregon and western Washington (see Owston 1977). Planting has not been very successful in Idaho (Parker 1979).

Nursery stock is frequently lifted when dormant, then kept in cold storage until field sites are ready to plant in the spring. Aldhous (1964) found western redcedar to be one of the least satisfactory species tested for survival after cold storage. His results were somewhat confounded by postplanting rainfall differences, however, and Aldhous included redcedar in only one experiment.

Rapid emergence of western redcedar from dormancy may affect its survival after cold storage. In Jablanczy's (1964) experiments with responses to photoperiod, western redcedar broke dormancy in 1 week. Western hemlock took about 4 weeks, and Douglas-fir did not break dormancy until about the 7th week after the beginning of artificial illumination.

[11] Styroblocks are rectangular pieces of Styrofoam containing cavities in which tree seedlings are grown.

Stand Culture and Improvement

Natural even-aged stands of western redcedar seem to be relatively rare. Redcedar grows in even-aged stands on poor sites in southeastern Alaska, however (Gregory 1957), and even-aged redcedar plantations are occasionally established. Redcedar seedlings were planted at 0.3- by 0.3-m (1- by l-ft) spacing in the lower Fraser River Valley and studied for 15 years by Smith and DeBell (1973) to determine short-rotation yields in pure, dense stands. They were less productive than stands of Douglas-fir, western hemlock, or black cottonwood when grown this way.

The four small stands of almost pure, second-growth redcedar studied by Nystrom (1980) in western Washington were essentially even aged, and his reconstruction of their growth and development led to the following conclusions:

- Douglas-firs seem able to dominate western redcedars even if they become established 5 years later.

- Redcedars are rapidly overtopped by red alders, but they survive under an alder understory.

- On moist sites, dominant and intermediate crown classes are distinguishable by age *5* in western redcedar. Dominant and codominant classes can be identified by age 25. Stratification into crown classes occurs more slowly on dry sites.

- On moist sites where crown class differentiation occurs early, height growth of redcedar is not noticeably affected by stand density. Diameter growth varies inversely with density.

- An initial stocking level of at least 2,470 treeslha (1,000 treeslacre) will produce more volume by age 25 than lower levels. After age 25, about 1,235 treeslha (500 treeslacre) with not more than 490 dominantslha (200 dominantslacre) may provide maximum volume growth.

- When grown in fully stocked, pure stands, the stem form of western redcedar is comparable to other western conifers.

Nystrom suggested the establishment of 2,470 redcedarslha (1,000 treeslacre) on site III (McArdle et al. 1961), with a merchantable thinning to remove intermediates at age 25. The residual stand of 940 redcedar dominants and codominants per hectare (380 per acre) could be crown-thinned thereafter. The ages of first thinning recommended by Hamilton and Christie (1971) range from 21 on good sites to 30 on poor sites in Britain.

Mixed-species, uneven-aged stands with a western redcedar component are more common than pure stands. In the mixed-species stands of British Columbia, redcedar may furnish an interim pole crop that will provide financial help in carrying Douglas-fir and western hemlock to maturity (Gilmour 1945). In Idaho, well-established redcedars grow well in the understory if they have a reasonable amount of space (Watt 1960). Redcedar has been underplanted successfully in the western white pine type of Idaho (Haig 1936), in Britain (Hubbard 1950), and under Scotch pine in East Germany (see Lembcke 1970). Interplanting was successful in the Podocarp forests of New Zealand (Hocking and Mayfield 1939), where the redcedars were able to maintain their position with competing second growth and should furnish an early timber yield while the native natural regeneration is devoping to maturity (New Zealand Director of Forestry 1940). Small groups ("nests") of western redcedar and other North American species were recommended by Ilmurzyński et al. (1968) for the forests of Poland.

Several elaborate trials of larch-redcedar (Evans 1950, Jones 1964) and oak-redcedar (Keatinge 1947, Jones 1964) mixtures were carried out in Britain. The larch-redcedar stands were two-storied with larch as the overstory. Western redcedar tended to form an overstory in the oak-redcedar stands, acting as a nurse crop. Jones (1964) found that British oaks grew taller than redcedars on wet ground where competition from other vegetation was extreme, creating a redcedar understory.

Western redcedar understories seem capable of responding well to release after overstory removal (Leaphart and Grismer 1974) when the overstory is of another species. When both the overstory and understory are western redcedar, translocation through root grafts to cut stumps renders thinning from below more effective than thinning from above (see Eis 1972). The largest understory redcedars and those with least overstory competition usually respond best to overstory removal in the western white pine type (Leaphart and Foiles 1972). When that overstory is removed all at once, however, the initial increase in understory growth may be followed by redcedar chlorosis and root rot 20 years later (Intermountain Forest and Range Experiment Station 1962, Koenigs 1969). Leaphart and Foiles (1972) found that gradual removal of the overstory worked better, stimulating growth of the redcedar understory without producing chlorosis or increasing root rot. Western redcedars released in Danish thinning trials had less lower stem taper and more upper stem taper than unreleased trees (Madsen 1977). Release through herbicide use is complicated by western redcedar's susceptibility to dormant sprays of 2,4-D and 2,4,5-T iso-octyl esters in diesel oil (Packee 1976).

Taper and tree form of redcedar are profoundly influenced by stand density. From 1,976 to 2,470 treeslha (800 to 1,000 treeslacre) are needed to maintain good form and prevent "candelabra" growth of western redcedar on Vancouver Island, British Columbia (personal communication, Edmond C. Packee, MacMillan Bloedel Limited, Nanaimo, British Columbia). Unpruned western redcedars are valueless in New Zealand, but epicormic branching in open conditions makes pruning ineffective except in dense, dark stands (Weston 1971). Pruning did not cause rot or other defects in Norway, and the pruning season did not affect results (Bauger and Orlund 1962).

Fertilization with phosphorus and potassium improved western redcedar growth in Irish peat-bog plantations (Carey and Barry 1975). Small, often negative growth correlations were associated with the redcedar fertilization experiments of Smith et al. (1968) in British Columbia, ho'wever. The British Columbia fertilization had no obviously beneficial influence on production of redcedar cones.

Harvesting

As western redcedar is seldom found in pure stands within its native range, it is usually harvested with Douglas-fir, western hemlock, and other associated species (see McBride 1959). When partially cut, mixed stands in the interior wet belt of British Columbia gave the maximum economic return when western redcedar was cut to 30-cm (12-in) d.b.h., western white pine to 41 cm (16 in), and all other species to 36 cm (14 in) in 1956 (Stewart 1956). Partial cutting is seldom used, however. Western redcedars cannot be left as scattered seed trees in coastal British Columbia, where even redcedars along clearcut margins may be lost to windthrow or exposure (Garman 1955). Most redcedars are harvested by clearcutting.

Large quantities of slash are created in clearcut harvesting operations; western redcedar leaves more slash than other northwestern species (see Olson and Arnold 1959, Gockerell 1966). Tables of residues by individual tree and basal area prepared by Snell and Brown (1980) indicate that lower weights of sound slash are produced by redcedar than by Douglas-fir, grand fir, western hemlock, or ponderosa pine, however; the large quantities of slash probably result from the large amounts of cull and breakage associated with most redcedar harvesting. Breakage can be reduced by pulling large old-growth redcedars uphill (Guimier 1980). The additional directional felling costs are recovered through increases in harvested volume and improved log quality.

When slash from decadent western redcedar-western hemlock stands was burned, a greater proportion of redcedar than of hemlock slash was consumed (Muraro 1971) — a result of greater longitudinal and horizontal fracturing of the redcedar. When fracturing is not a factor, fresh western hemlock slash is at least as flammable as western redcedar slash (see Olson 1953, Fahnestock 1960). Fire spreads slower in hemlock when the slash from both species is 1 year old (Fahnestock 1960); hemlock drops its foliage, redcedar does not. The slash of both species becomes less flammable when chipped (Fahnestock 1953). The fire hazard normally associated with cutting of redcedar poles was reduced by skidding entire pole-size trees to the landing, where the slash was chipped and blown over the edges (Olson and Arnold 1959).

Chipping slash instead of burning it certainly reduces the fire hazard, but its effect on redcedar regeneration seems uncertain, and chipping is seldom practical. Although western redcedar can establish itself readily after logging with or without slash burning (Schmidt 1955), it seems to regenerate better after burning on the northern coast of British Columbia (British Columbia Forest Service 1948b). Slash burning has little effect on species composition in the hemlock-cedar type of coastal British Columbia, however, and it may retard the successful conifer regeneration that usually occurs there (Stoodley 1925). Disturbance of the forest floor seems essential for natural redcedar regeneration (Clark 1970). Slash burning probably is not.

Discussion

The various subjects included in this report have not been equally discussed. Relative length and detail included in each section were determined by the amount of information available, not by their importance. For example, the section on products is twice as long as the section on silviculture; this inequality seems particularly important. Western redcedar wood is a highly valued, intensively used product that has been studied in great detail. Unfortunately, much less time, money, and effort seem to have been invested in learning how to grow the wood. More information is needed on site evaluation, nursery culture, planting techniques, fertilization, optimum stand densities, thinning of redcedar, and management of mixed species. Trees with desirable annual ring widths, knot characteristics, and forms might even be grown to order if the silviculture of redcedar were truly understood.

A true understanding of silviculture rests on foundations of physiology, ecology, genetics, mensuration, and economics. Adequate knowledge about western redcedar is lacking in all five categories. For example, the relation of moisture to redcedar regeneration and growth should be further investigated. ***So*** should its growth on various sites — sites that are objectively described and defined. The breeding of superior redcedar planting stock has scarcely begun. Accurate local volume tables and yield information are scarce, as are comparative economic analyses of mixed- compared with pure-stand culture and redcedar rotation lengths.

Redcedar rotations do not seem to have been seriously considered apart from the rotations of associated species. Indeed, redcedar timber often has been managed like a valuable mineral that is mined when found in association with other minerals or reclaimed from old mine tailings (i.e., logging residues of former years). Utilization technology is advanced, but redcedar usually has been removed, refined, manufactured, and managed as a declining, nonrenewable resource.

Western redcedar is a renewable resource that need not decline. It can be renewed and used forever, as are several other tree species now being planted and managed intensively. More research on the culture of redcedar and a different management philosophy may be necessary, however. Western redcedar differs from Douglas-fir or western hemlock, and it should be managed differently — not as just another associated species, but as a major timber crop.

Recommendations for Management

The techniques used to manage other major timber crops are often inappropriate for western redcedar, but few techniques have been developed for redcedar. Management recommendations are based on the site, regeneration, growth, yield, tolerance, and longevity information in this report. As they have not been applied in a coordinated redcedar management program, they should be considered plausible suggestions rather than guidelines.

- Western redcedar management sites should be chosen with care. Moist, fertile conditions characterized by the presence of ***Athyrium filix-femina, Clintonia uniflora, Dryopteris austriaca, Gymnocarpium dryopteris,*** and ***Rubus parviflorus*** are best.

- Redcedar probably should be grown in pure stands when sawtimber, shingles, or shakes are the desired products. Even-aged mixtures of redcedar and other conifers will be harvested either too early for the redcedar sawtimber or too late for the other conifers when mixed-species, even-aged stands are clearcut.

- Redcedar can be grown in mixed stands when poles are to be produced under even-aged management regimes.

- Redcedar is suitable for uneven-aged management, either in pure or mixed stands. Vegetative regeneration probably will be more efficient than sexual regeneration where the selection system is practiced.

- Direct seeding with redcedar is practical and effective where a mineral soil seedbed is available. Rates of 5 to 10 kglha (1 to 2 Iblacre) seem appropriate for broadcast seeding. The seeds should be covered with a thin layer of soil when seed spots are used. Sowing should be done in the fall.

- Where mineral soil seedbeds are not available, planting may be effective. Recently lifted, bare-root stock should be used, and cold storage should be avoided.

- Redcedar plantations should be dense, with 1.2- to 1.5-m (4- to 5-ft) spacing between seedlings.

- Where pure, even-aged stand management is practiced, intermediate crown classes should be removed in a light thinning at about age 30. A nearly closed canopy should be maintained at all times, however; open-grown redcedars tend to develop poor form, excessive limbs, and multiple tops.

- Where western redcedar is managed in mixed-species or uneven-aged stands, its shade tolerance and long life should be considered. Redcedars will tolerate understory conditions in mixed-species stands. In uneven-aged stands, they should maintain acceptable growth rates over long periods. Excessive crown space should be avoided under all management regimes.

Acknowledgment

Michael E. Dubrasich, formerly forestry technician, searched much of the literature summarized here.

Common and Scientific Names of Trees

Common Name	Scientific Name
Alaska-cedar	*Chamaecyparis nootkatensis* (D. Don) Spach
Alpine-ash	*Eucalyptus delegatensis* R. T. Baker
Austrian pine	*Pinus nigra* Arnold
Baldcypress	*Taxodium distichurn* (L.) Rich.
Bigleaf maple	*Acer macrophyllum* Pursh
Birch	*Betula* L. sp.
Black cottonwood	*Populus trichocarpa* T. & G.
Brisbane boxwood	*Tristania conferta* R. Br.
California-laurel	*Umbellularia californica* (Hook. & Arn.) Nutt.
Cascara buckthorn	*Rhamnus purshiana* DC.
Chinkapin	*Castanopsis chrysophylla* (Dougl.) DC.
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
Eastern redcedar	*Juniperus virginiana* L.
Eastern white pine	*Pinus strobus* L.
Engelmann spruce	*Picea engelmannii* Parry
European beech	*Fagus sylvatica* L.
European larch	*Larix decidua* Mill.
European white birch	*Betula alba* L.
Grand fir	*Abies grandis* (Dougl.) Forbes
Incense-cedar	*Calocedrus decurrens* (Torr.) Florin
Japanese larch	*Larix kaempferi* Sarg.
King-William-pine	*Athrotaxis selaginoides* D. Don
Larches	*Larix* Mill. spp.
Lodgepole pine	*Pinus contorta* Dougl.
Longleaf pine	*Pinus palustris* Mill.
Monterey pine	*Pinus radiata* D. Don
Mountain hemlock	*Tsuga mertensiana* (Bong.) Carr.
Noble fir	*Abies procera* Rehder
Northern white-cedar	*Thuja occidentalis* L.
Norway spruce	*Picea abies* Karst
Oak	*Quercus* L. sp.
Oregon white oak	*Quercus garryana* Dougl.
Pacific dogwood	*Cornus nuttallii* Aud.
Pacific madrone	*Arbutus menziesii* Pursh
Pacific silver fir	*Abies amabilis* (Dougl.) Forbes
Pacific yew	*Taxus brevifolia* Nutt.
Paper birch	*Betula papyrifera* Marsh.
Pine	*Pinus* L. sp.
Ponderosa pine	*Pinus ponderosa* Dougl. ex Laws.
Port-or ford-cedar	*Chamaecyparis lawsoniana* (A. Murr.) Parl.
Quaking aspen	*Populus tremuloides* Michx.
Red alder	*Alnus rubra* Bong.
Red oaks	*Quercus falcata* Michx. and *Q. rubra* L.
Red pine	*Pinus resinosa* Ait.
Redwood	*Sequoia sempervirens* (D. Don) Endl.
Scotch pine	*Pinus sylvestris* L.
Shore pine	*Pinus contorta* Dougl. var. *contorta*
Sitka spruce	*Picea sitchensis* (Bong.) Carr.
Southern yellow pines	*Pinus caribaea* Morelet, *P. echinata* Mill., *P. palustris* Mill., and *P. taeda L.*
Spruce	*Picea* A. Dietr. sp.
Subalpine fir	*Abies lasiocarpa* (Hook.) Nutt.
Sugar pine	*Pinus lambertiana* Dougl.
Tamarack	*Larix laricina* (Du Roi) *l.* Koch
Tanoak	*Lithocarpus densiflorus* (Hook. & Arn.) Rehd.
Walnut	*Juglans* L. sp.
Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.
Western larch	*Larix occidentalis* Nutt.
Western redcedar	*Thuja plicata* Donn
Western white pine	*Pinus monticola* Dougl. ex D. Don
Whitebark pine	*Pinus albicaulis* Engelm.
White spruce	*Picea glauca* (Moench) *Voss*

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This report is a comprehensive compilation of information on western redcedar ***(Thuja*** plicata Donn) — its occurrence and abundance; associated plant species; morphology and anatomy; products; medical aspects; diseases; insect, bird, and mammal pests; genetics; horticulture; physiology; eeology; mensuration; and silviculture. Management recommendations and an extensive list of references are included.

Keywords: Western redcedar, ***Thuja*** plicata, silviculture, ecology, physiology, products.

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GPO 996-567