Regeneration of Montane Forests in the Coastal Western Hemlock Zone of British Columbia: A Literature Review

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Regeneration of Montane Forests in the Coastal Western Hemlock Zone of British Columbia: A Literature Review

by

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EXECUTIVE SUMMARY

Problems in the regeneration of coastal montane ecosystems centre around three factors: 1) climatic conditions, 2) species selection, and 3) harvesting methods and site preparation. Long winters and cool, short growing seasons make it critical to choose species ecologically adapted to montane environments. Harvesting disturbances and site preparation (e.g., slashburning) make these ecosystems susceptible to nutrient loss and subsequent low productivity.

The presence of abundant advance and natural regeneration as well as the availability of high-elevation species for artificial regeneration provides many silvicultural options. Stand characteristics before logging, including the number, age, and size of advance regeneration, as well as the effects of harvesting methods on site climatic and edaphic conditions, will influence management decisions.

Natural regeneration can be well suited for restocking montane stands but may not meet growth expectations as a result of site disturbance. Advance regeneration (seedlings already present in the understory before harvesting) is subject to problems associated with disturbance of the forest floor and the seedbed during stand removal. However, if disturbance is minimal, and where advance regeneration is suitable to release, the time required to reach free growth may be reduced. Delays in growth response after release (overstory removal) can also reduce expected yield for one to many years while morphological and physiological adjustments to exposure are made by the seedlings. Natural regeneration (seedlings that become established after harvesting) is prone to problems arising from its distribution in dense patches scattered over the site. Growth periodicity, indicated by decreased height growth over several years, may be related to competition above and below ground for site resources (light, water, and nutrients).

Artificial regeneration can also be used to achieve adequate stocking levels in stands where natural regeneration is poor or patchy. The availability of a variety of high-elevation species (e.g., amabilis fir, noble fir, subalpine fir, and Engelmann spruce) and stock types (styroblock plugs, plug-transplants, bare-root) has allowed greater flexibility for artificial regeneration of montane stands. Exploratory studies are under way to guide the selection of species and stock types for use on specific sites.

The selection of artificial or natural regeneration will be modified by the type and severity of environmental and biological stresses that occur after exposure. Common montane reforestation-site stresses that can reduce the survival and growth of regenerating trees include: water stress, heat stress, high light stress, winter desiccation, snowpress, and frost. Biological factors affecting regeneration include competition from non-crop vegetation (e.g., *Vaccinium* spp., fireweed, and salmonberry). Edaphic conditions, including soil water and temperature, and reductions in the rate of nutrient turnover into forms available for tree growth, can reduce site productivity.

Alternative silvicultural methods to clearcutting provide a number of options to meet these problems. Green tree retention (light conifer retention or seed-tree methods), shelterwood (heavy conifer retention), selection systems, and small patch or strip clearcuts are examples of alternatives. Suitability criteria include: presence and abundance of advance and natural regeneration, viability of ground-based harvesting systems or the availability of specialized high-lead systems, feasibility of planting and site preparation, disease and windthrow risks, operational hazards, economic return, and environmental impacts. Of prime consideration will be the requirements of shade-tolerant montane species such as amabilis fir and western hemlock. Small clearcuts (less than 8 ha) and shelterwood cutting are considered the most consistently successful systems for even-aged management of montane and subalpine true fir–hemlock forests in the Pacific Northwest.

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1 INTRODUCTION

This report provides a comprehensive review of the literature relevant to the regeneration of coastal montane forests in British Columbia. The focus is on the environmental, autecological, and physiological relationships affecting the establishment and early growth of conifer regeneration as it relates to current and past silvicultural practices.

Since the late 1960s, there has been increasing dependence on middle- and high-elevation forests in coastal British Columbia to supply more of the wood production in the coastal region. In the past, high-elevation silvicultural systems relied on reforestation practices adopted from low-elevation forestry, often with mixed or unsatisfactory results (Utzig and Herring 1975; Klinka and Pendl 1976; Reuter[1]). This is likely because high-elevation fir and hemlock forests in coastal British Columbia have regeneration requirements and climatic limitations markedly different from those of low-elevation coastal forests and that must be accommodated on a site- and species-specific basis (Klinka *et al.* 1990). A species- and site-specific approach to the regeneration of coastal montane forests is consistent with the development of ecosystem-specific silvicultural methods to sustain stand diversity and long-term site productivity (Hopwood and Island 1991).

Montane forests in the Coastal Western Hemlock biogeoclimatic zone occupy the middle to upper slopes between the submontane variants of this zone and the subalpine Mountain Hemlock zone, extending along the Vancouver Island and Coast Mountain ranges of southwestern British Columbia and continuing into Washington and Oregon states (Krajina 1969; Klinka *et al.* 1979). The elevation of montane forests in maritime climates ranges from 650 to 1000 m on western Vancouver Island and the coastal mainland (CWHmm2) and from 700 to 1100 m on eastern Vancouver Island (CWHmm2). In sub-maritime climates the range in altitude is 650 to 1200 m and 450 to 1050 m in southern (CWHms1) and central (CWHws2) British Columbia, respectively (Klinka *et al.* 1979).

Forests of the Coastal Western Hemlock zone are influenced by a humid to perhumid, cool mesothermal climate. Mean annual precipitation is high (394 cm) on windward locations (western Vancouver Island and the coastal mainland), but is reduced (189 cm) in the eastern Vancouver Island rain shadow, which is characterized by summer soil water deficits (Klinka *et al.* 1979). Precipitation accumulates as snowfall in the winter for up to 6 months at montane elevations. As a result, the growing season for montane forests is shorter than in the milder submontane climate and may not commence until mid-April (Klinka *et al.* 1979).

Montane forests in the Coastal Western Hemlock zone are typically dominated by amabilis fir (*Abies amabilis*) and western hemlock (*Tsuga heterophylla*), with a characteristic component of yellow-cedar (*Chamaecyparis nootkatensis*) and mountain hemlock (*Tsuga mertensiana*) at higher elevations. Associated species present, depending on site, stand history, and stand age, include: western redcedar (*Thuja plicata*), Douglas-fir (*Pseudotsuga menziesii*), Sitka spruce (*Picea sitchensis*), western white pine (*Pinus monticola*), and subalpine fir (*Abies lasiocarpa*). Engelmann spruce (*Picea engelmannii*), lodgepole pine (*Pinus contorta*), and grand fir (*Abies grandis*) are associates in the submaritime climates.

The understory tree component of old-growth montane forests consists of abundant suppressed advance amabilis fir, typically the dominant regeneration species, and, to a lesser extent, western hemlock, yellow-cedar, and mountain hemlock. Renewal of old-growth stands in the Coastal Western Hemlock zone is often determined by natural disturbances including: fire, on dry sites; windthrow, particularly along ridges; and senescence, which creates gaps and larger openings in the overstory, stimulating release of the suppressed understory regeneration. On wet sites, stand origin is often driven by the loss of old dead and dying trees that create small patches of young trees in the old stands. On dry sites, fire history is important and has resulted in a mosaic of stands of different ages and different successional stages (Klinka *et al.* 1979). As a result, coastal montane forests tend to be a mosaic of even- and uneven-aged stands.

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[1] Reuter, F. 1973. High elevation reforestation problems in the Vancouver Forest District. B.C. For. Serv., Res. Div. Unpublished report.

Understory vegetation is distinguished by an abundance of mosses (*Rhytidiadelphus loreus, Rhytidiopsis robusta, Plagiothecium undulatum*), the presence of ericaceous shrubs (*Vaccinium alaskaense, Vaccinium ovalifolium, Menziesia ferruginea*), and a variety of herbaceous plants (*Clintonia uniflora, Rubus pedatus*) depending upon the site association. As a result of high precipitation and relatively low temperatures, pedogenic processes in montane ecosystems are characterized by mor humus formation, leaching, gleization, and podzolization (Krajina 1969). Soils are typically Humo-Ferric Podzols with mycelial mor humus grading to Ferro-Humic Podzols with increasing precipitation.

2 MONTANE HIGH-ELEVATION REGENERATION PROBLEMS

Problems in the regeneration of coastal montane ecosystems centre around three factors: 1) climatic conditions, 2) species selection, and 3) harvesting methods and site preparation. Of these, site preparation may be the most prevalent problem. Long winters and cool, short growing seasons make it critical to choose species that are ecologically adapted to montane environments. Harvesting disturbances and site preparation (e.g., slashburning) make these ecosystems susceptible to nutrient loss and subsequent low productivity.

2.1 Climatic Conditions

Conifer establishment and growth in coastal montane ecosystems is limited by shorter growing seasons, low-productivity sites, and more severe climatic conditions than in low-elevation coastal forests. Problems have centred on site-specific species selection. From the 1960s until the mid-1970s, efforts at regeneration of coastal high-elevation forests relied on low-elevation silvicultural practices with little consideration of the inherent climatic and ecological differences between these forests. Forest management practices included large cutblocks, a fast cutting sequence, slashburning, and almost exclusive planting of Douglas-fir. Consequently, the regeneration of high-elevation sites was often unsatisfactory, with stocking levels below or barely meeting the minimum standards (Utzig and Herring 1975; Klinka and Pendl 1976; Reuter[2]).

2.2 Species Selection

Studies of coastal high-elevation regeneration in the mid-1970s predicted losses and discontinuity of wood production from improper tree species selection, growth delays, and low stocking levels (Herring and Etheridge 1976; Klinka and Pendl 1976; Reuter[3]). One contributing factor in such losses was the planting of Douglas-fir on high-elevation clearcuts. Because this species is susceptible to frost injury and stem breakage under heavy snowpack, failure of Douglas-fir plantations and marginal stocking levels were common in montane and subalpine reforestation sites in coastal British Columbia (Klinka and Pendl 1976; Reuter[4]). Many of the trees that survived exhibited form defects from frost damage and snowpack-induced breakage (Klinka and Pendl 1976; Scagel *et al.* 1989). With the advent of container stock production of high-elevation species (including amabilis fir, mountain hemlock, and yellow-cedar) in the mid-1970s, it became possible to plant species compatible with high-elevation site climatic and edaphic conditions.

2.3 Site Preparation

Slashburning was a widely used site preparation tool for Douglas-fir plantations at high elevations. This resulted in the destruction of advance regeneration, primarily amabilis fir, and the complete or partial loss of surface organic layers (Utzig and Herring 1975; Klinka and Pendl 1976). Site conditions following slashburning were often incompatible with the ecological requirements of shade-tolerant regeneration as a result of high forest floor and soil surface temperatures and lack of suitable organic substrates (Ballard

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2   Reuter, 1973.
3   Ibid.
4   Ibid.

et al. 1977; Feller 1982). Consequently, high mortality rates and delayed ingress were common on slashburned sites (Soos and Walters 1963; Minore and Dubrasich 1981). Coastal montane forests have a high risk of nutrient loss and reduced site productivity from slashburning because of the nutritionally poor mor humus forms and dependence of conifer regeneration (amabilis fir, western hemlock, mountain hemlock) on mycorrhizal associations that facilitate the cycling of nutrients from organic matter to tree roots (Klinka and Pendl 1976; Feller 1982; Kimmins *et al.*[5]). In addition, slashburning has contributed to seedling mortality from mass wasting and erosion on steep high-elevation cutovers, particularly on coarse textured, glacially derived soils with little cohesive stability when saturated (Utzig and Herring 1975; Feller 1982). As a result of the importance of an intact forest floor for the regeneration of coastal montane forests, slashburning is not now recommended on sensitive high-elevation sites (Klinka and Pendl 1976; Feller 1982).

3 NATURAL REGENERATION

Advance and post-harvest natural regeneration can be used to restock montane stands. This is done to reduce the risks and costs associated with plantation establishment on mid- and high-elevation sites, particularly where advance regeneration is abundant or can be readily supplemented by artificial regeneration. However, stocking and performance of natural regeneration is often problematic on coastal high-elevation sites (Herring and Etheridge 1976; Wagner 1980; Green and Bernardy 1991; Reuter[6]).

3.1 Stocking

Several factors contribute to low yield in naturally regenerating montane ecosystems. Dense, patchy stands composed of uneven-aged trees of variable height and growth rate tend to perform below expectations as a result of competition among trees for both above- and belowground resources.

A combination of pre-logging conditions, such as patchy distribution and large trees, and damage from logging activities, may injure up to 30% of advance regeneration (Herring and Etheridge 1976). In addition to these losses, poor post-release growth in densely stocked patches of advance amabilis fir has been attributed to mutual stem competition (Herring and Etheridge 1976; Wagner 1980). On these sites, juvenile spacing that reduces mutual stem competition and fill-planting in non-stocked openings can be used to obtain acceptable stocking levels and densities (Husted and Korelus 1982).

Variable stocking levels of advance regeneration contribute to low yield. The density of advance amabilis fir varied between 372 and 4000 stems per ha with stocking ranging from 12 to 54% on high-elevation clearcuts in the Vancouver Forest District (Herring and Etheridge 1976). Total density of advance and post-harvest natural regeneration of amabilis fir, western hemlock, and other species varied between 3720 and 8300 stems per ha. In high-elevation clearcuts in the Chilliwack Forest District, densities of advance and post-harvest natural regeneration (primarily amabilis fir) varied from 500 to 16 700 stems per ha in not sufficiently restocked (NSR) and sufficiently restocked (SR) areas, respectively (Green and Bernardy 1991). Dense (more than 1200 trees per ha) but patchy distribution of amabilis fir regeneration has also been observed in the western Cascade Mountains (Emmingham and Halverson 1982). As a result, Klinka and Carter (1991) recommended that adaquately stocked advance regeneration exceed the British Columbia Ministry of Forests target stocking standards by twofold or more to compensate for damage during harvesting and uneven distribution.

Yields below expectations were also attributed to the highly variable size and age of advance regeneration within the same stand, reflecting pre-harvest stand dynamics and understory microsite variation (Herring and Etheridge 1976; Seidel 1985). The height of amabilis fir at the time of release averaged 1.5 m or less for trees with a mean age between 30 and 50 years on several high-elevation sites in the Vancouver Forest District (Herring and Etheridge 1976). In the Washington Cascades,

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[5] Kimmins, J.P., M.C. Feller, and K.M. Tsze. 1981. Nutrient losses to the atmosphere during a slashburn in southwestern British Columbia. Unpublished manuscript.

[6] Reuter, 1973.

advance amabilis fir was predominantly less than 20 years old at the time of release (Wagner 1980). Advance hemlock regeneration is also variable on subalpine reforestation sites. On the eastern slopes of the Cascade Range in Oregon, the age of advance mountain hemlock regeneration ranged from 27 to 250 years and height ranged from 0.8 to 5.6 m (Seidel 1985).

3.2 Release

Slow growth rates after overstory removal (release) are another characteristic of regenerating montane stands. Delay in the growth response of advance amabilis fir regeneration following stand removal is common, with release not occurring for 2 to several years following clearcutting (Herring and Etheridge 1976; Wagner 1980). Thereafter, some stands respond well and rapid growth rates have been observed (Herring and Etheridge 1976; Wagner 1980; Harrington and Murray 1982). While slow initial growth is characteristic of the true firs (Harrington and Murray 1982), prolonged growth delays after release of advance amabilis fir regeneration are likely influenced by the morphological and physiological characteristics of advance regeneration associated with their growth and survival as understory trees in the old stand. For example, the legacy of low root:shoot ratios may not favour rapid aboveground growth following exposure (Herring and Etheridge 1976). In addition, shade foliage may not be suited to high light environments (Tucker et al. 1987). Photosynthesis may be reduced as a result of photo-inhibition. Poor transpirational control, particularly in high light and low-humidity environments, and soil water deficits on exposed microsites will tend to reduce both the rate and duration of growth.

Following release, shoot growth of advance amabilis fir regeneration may be slow as a result of the influences of site edaphic conditions, particularly moisture status and soil surface temperatures. Shoot growth tends to be poor on southerly aspects subject to seasonal moisture deficits and high temperatures (Herring and Etheridge 1976; Kotar 1977; Emmingham and Halverson 1982). This is consistent with the high shade tolerance of amabilis fir and its adaptation to cool moist organic microsites (Krajina 1969). The residual stand may also affect soil moisture and temperature, resulting in a gradient of growth performance extending from the stand edge into the clearcut. Post-release growth of advance amabilis fir regeneration was best under the ameliorating influence of the forest edge, although distances greater than 10 to 15 m into the clearcut were required before 100% of the advance regeneration showed some degree of release response (Wagner 1980).

Competition among species can also reduce growth after release. In true firs, advance regeneration with greater pre-release vigour (indicated by height increment, total height, or live crown ratio) tended to show the greatest growth responses after exposure and were less affected by intraspecific competition (Herring and Etheridge 1976; Ferguson and Adams 1980; Seidel 1980). Similar growth responses were observed in vigorous advance mountain hemlock after release (Seidel 1980). However, tall trees 30 years old or older may not always respond well. In grand fir (*Abies grandis*) when equally suppressed, taller and older advance regeneration did not respond to release as well as shorter, younger trees (less than 30 years old). This may result from a higher ratio of stems and branches to leaves in old trees. Large, relatively small-crowned trees may have a narrow margin between total photosynthesis in the leaves and total respiration in the stem and branches. Large trees are also more susceptible to logging damage and decay infections (Herring and Etheridge 1976; Wagner 1980) that reduce growth and therefore may be out-performed over the long term by natural regeneration. Despite the earlier establishment of advance regeneration, no significant differences were found in tree height between post-harvest natural and advance regeneration of amabilis fir 25 years after cutting (Wagner 1980).

3.3 Growth Periodicity

Growth check of natural amabilis fir regeneration has been observed following periods of good post-release growth on montane sites in eastern Vancouver Island (CWHmm2) where it appears to be a cyclic phenomenon (B.G. Dunsworth, pers. comm. 1991). Several factors may be involved. For example, cold montane soils may have slow decomposition rates and little nutrient turnover, particularly in years when snowmelt is delayed or snowfall occurs early in the fall. The resultant lack of available nutrients may induce a temporary shift in carbon allocation to the roots that is observed as a decrease in height

increment. After one or more growing seasons, when a favourable nutrient balance within the plant has been restored, shoot growth will return to a rate comparable to that found post-release. Growth check of amabilis fir has been observed in association with nitrogen (N) (and possibly phosphorus [P]) deficiency. Similar nutrient-related growth check may also be the result of aboveground competition for nutrients, particularly on poor sites (Husted 1982; G. Weetman, pers. comm. 1991). Clearcutting may increase the range of microenvironmental conditions and aggravate the problem of periodic growth check.

The incidence of growth check of amabilis fir on low-elevation sites in eastern Vancouver Island may be influenced by summer water deficits. In the short term, seasonal growth may be reduced as a result of low photosynthesis rates in dry soils. In the long term, a periodic growth check may occur if nutrient turnover is reduced sufficiently during water deficits to induce imbalances between uptake and availability that could last for several years.

3.4 Site Selection

Although post-harvest natural regeneration is frequently relied upon for reforestation of montane stands, it is a highly variable source of restocking and must often be supplemented by planting stock to achieve satisfactory stocking levels, particularly on sites employing traditional harvesting systems (Minore and Dubresich 1981; Emmingham and Halverson 1982; Green and Bernardy 1991). Characteristic ecological factors associated with areas satisfactorily restocked with post-logging natural regeneration include *Vaccinium* colonization, and undisturbed humus forms (Green and Bernardy 1991). In areas not satisfactorily restocked, sites tend to be dominated by fireweed (*Epilobium angustifolium*) on friable, disturbed, and calcium-rich humus forms.

3.5 Seed Production, Dissemination, and Germination

Low stocking may also result from poor seed production, dissemination, and germination. For example, poor and infrequent seed years, seed dispersal limitations, lack of stratification, and adverse seedbed conditions reduce the number and viability of seedlings available for regeneration, particularly for coastal shade-tolerant species such as amabilis fir and western hemlock. Seed may also be lost to insect and animal damage.

A 12-year record of cone production in Oregon and Washington states indicated that medium to heavy cone crops for amabilis fir and mountain hemlock are generally produced at 3-year intervals with few cones produced in intervening years, although local variability of periodicity can occur in response to climatic factors (Franklin *et al.* 1974). Periodicity of western hemlock cone production also followed this pattern. Large crops of yellow-cedar seed occurred at intervals of 4 or more years (Burns and Honkala 1990).

Although natural regeneration using amabilis fir is often chosen for restocking montane sites, the species is not considered a good seed producer because of its low seed cone bearing capacity, scarcity of pollen cones, and high incidence of archegonal abortion (Owens and Molder 1977). These factors contribute to the low proportion of viable seed produced in this species. The percentage of sound seed (6.7–51%) and germination percentage (20–30% on average) is the lowest and among the most variable of all the commercially important high-elevation conifers in the Pacific Northwest (Owens and Molder 1977).

Seed size is the overriding factor determining the maximum distance seeds are dispersed. Amabilis fir seed is relatively heavy and seedfall declines rapidly as distance from the stand edge increases. In a study of seed flight of amabilis fir, only 9% of the sound seeds, less than 80 000 per ha, were dispersed as far as 114 m from the stand edge (Carkin *et al.* 1978). Mountain hemlock seedfall also declines rapidly with distance from the stand edge and tends to plateau at 125 000–250 000 sound seeds per ha beyond one tree height and up to 114 m from the stand edge (Franklin and Smith 1974). These figures suggest that dispersal of seed by these species may be adequate for natural restocking of small clearcuts, given favourable conditions for germination and seedling establishment (4–8 ha), but is likely inadequate

beyond the perimeter of large clearcuts. In contrast, light seeds of western hemlock can be dispersed more than 1000 m from the source, the bulk falling within 610 m (Burns and Honkala 1990).

3.6 Microsite Requirements

Adverse microsite conditions on coastal high-elevation cutblocks often inhibit the germination and establishment of shade-tolerant species (Seidel and Couley 1974; Minore 1986). Cool moist seedbeds, high in organic matter and often with a large component of decaying wood, are good substrates for the germination and establishment of amabilis fir, western hemlock, and mountain hemlock (Krajina 1969). In clearcuts, particularly with southern aspects, the rapid drying and lethal temperatures found on the surface of exposed organic matter (Seidel and Couley 1974; Ballard et al. 1977) may make it unsuitable for seedling establishment. For species such as yellow-cedar, mineral soil may provide a more suitable seedbed on clearcuts prone to soil water deficits and intense solar radiation.

Exposure to high light levels in clearcuts may reduce the regeneration of some shade-tolerant species, particularly on mesic sites. Amabilis fir, for example, requires shade for establishment in mesic but not in hygric habitats (Krajina 1969). Western hemlock and mountain hemlock are shade tolerant, but do not require shade for establishment, except on drier sites in the Coastal Western Hemlock zone (Krajina 1969).

Stand edge effects on seedling establishment and growth were illustrated in a study of amabilis fir and western hemlock natural regeneration (Wagner 1980). Basal area, height growth, and abundance of post-harvest natural amabilis fir regeneration were greatest near the edge of a 25-year-old clearcut on the western slope of the Washington Cascades. In contrast, western hemlock regeneration increased with increasing distance from the forest edge, with the best growth occurring more than 50 m into the clearcut.

Proximity to the stand edge also influenced the success of natural regeneration. Near the forest edge, both amabilis fir and western hemlock took 2–5 years to become established, and, in the clearcut, from 5 to 15 years were required. Montane sites may be susceptible to long delays in achieving adequate stocking of post-harvest natural regeneration. On subalpine clearcuts in Oregon, mountain hemlock and associated species reached adequate stocking only after 9–12 years (Minore and Dubrasich 1981).

4 ARTIFICIAL REGENERATION

Although natural regeneration is often chosen to restock montane reforestation sites in coastal British Columbia, fill-planting with nursery stock is used, particularly on highly productive sites with brush problems and on sites that are environmentally severe or degraded (e.g., slashburned). Since the mid-1970s, large-scale production of container and bareroot stock of montane and subalpine species has allowed greater flexibility for artificial regeneration at high elevations. Little is known to guide the selection of species and stock types on montane sites (Scagel et al. 1989). In British Columbia, exploratory studies of this type are under way.

4.1 Species and Stock Type Selection

In such exploratory high-elevation (MHmm1 and CWHms1) regeneration trials in the Vancouver Forest Region, Scagel et al. (1989) reported on the survival, growth, and form of several high- and low-elevation species planted in 1976 and 1977. High-elevation species such as noble fir, amabilis fir, subalpine fir, and Engelmann spruce had the best overall performance based on consistently good survival, growth, and form. A period of slower growth in these species in the first 10 years after planting was followed by height growth increments averaging over 50 cm per year. However, natural amabilis fir generally outperformed planted stock. In low-elevation species, particularly lodgepole pine and western larch, height growth was better than in high-elevation species, though more variable. In addition, mortality and form defects were often at unacceptable levels. Yield of yellow-cedar, a mid- to high-elevation

species, was also adversely affected by layering and multiple stems. Mountain hemlock planting stock was not as productive as the other high-elevation species examined in this study and was also prone to form defects (Scagel et al. 1989).

On eastern Vancouver Island, species and stock type trials were established in the mid- to late 1970s on montane and subalpine sites.[7] Good survival and growth rates were found for native high-elevation species (amabilis fir, yellow-cedar, and mountain hemlock styroblock plug stock) 3 years after planting. Noble fir, not native to British Columbia, had much better height growth than the native amabilis fir, and was suggested as a superior substitute for the latter. Similar results were found in western Washington, where naturally regenerating noble fir outgrew amabilis fir by a substantial margin 20–30 years after establishment on clearcuts in the amabilis fir zone. Engelmann spruce, another non-native species, was also identified as having high survival rates and growth surpassing that of mountain hemlock and amabilis fir plug stock.[8] However, on another montane study site on Vancouver Island, survival of Engelmann spruce plug stock (61%) was poorer than that of amabilis fir plug stock (88%) after three growing seasons, possibly due to a large seedling height to caliper imbalance in the spruce stock.[9]

The best early growth of true firs has been obtained with plug transplant stock (Pendl and D'Anjou 1991; Arnott and Pendl[10]). Bareroot stock of amabilis fir is subject to higher mortality rates than styroblock plugs or styroblock/bareroot transplant stock and therefore may not be an appropriate stock type for regeneration of this species (Pendl and D'Anjou 1991; Reuter[11]). Better survival of noble fir and amabilis fir stock types has been obtained by spring compared to fall planting, whereas yellow-cedar survival was best in fall-planted stock.[12]

5 ENVIRONMENTAL STRESSES

Physiological and morphological responses of coastal montane species to environmental changes affecting seedling microsite conditions following harvesting may govern their stress tolerance. On clearcut sites, seedlings must endure extreme variations in temperature and moisture in which stress (except frost) is most extreme at the soil surface and decreases with distance in both directions (Emmingham and Halverson 1982). Soil moisture deficits, high and low soil temperatures, and high light intensities, can induce a suite of stresses including: desiccation, stem girdling, photo-inhibition, and sunscald (Silen 1960; Ronco 1970; Running 1976; Livingston and Black 1987; Scagel et al. 1989). Form defects may also be evident as a result of stress caused by frost and snow creep.

Stresses may also result from the condition of planting stock. Adequate hardening of planting stock is critical for survival at high elevations because of the increased risk and severity of early growing-season frost, and late-season, high soil surface temperatures and evapotranspirational stress (Koppenaal and Colombo 1988; Stathers 1989). Site preparation treatments (e.g., scalping, trenching, mounding, and inverting) can reduce exposure of planting stock to environmental stresses by modifying the seedling microsite (Spittlehouse and Stathers 1990).

5.1 Water Stress

Water stress is considered a primary limiting factor for conifer regeneration and growth in the Coastal Western Hemlock zone (Arnott 1975; Reuter[13]), particularly in the drier leeward climate of eastern Vancouver Island, which is characterized by summer soil water deficits (Klinka et al. 1979). Soil moisture

[7] Arnott, J.T. and P. Pendl. 1983. Meade Creek high elevation species and stock type trials. Unpublished report.
[8] Arnott. 1982. Species/planting season trial at Meade Creek. 1982 Summer Workshop, Coastal Silviculture Committee, Courtenay, B.C. Unpublished report.
[9] Dunsworth, B.G. 1986. Pacific silver fir and Engelmann spruce operational stock type trials. Unpublished report for MacMillan Bloedel, Woodland Services Division.
[10] Arnott and Pendl, 1983.
[11] Reuter, 1973.
[12] Arnott and Pendl, 1983.
[13] Reuter, 1973.

can be rapidly depleted in the upper decimeter of coarse textured or organic soils as a result of high evaporative demand from warm temperatures and high irradiance.

Shade-tolerant coastal conifers have had little selective pressure to develop the stomatal control characteristics and drought tolerance of species such as Douglas-fir. Low drought tolerance and poor stomatal control has been reported for western hemlock (Keller and Tregunna 1976; Brix 1979), amabilis fir (Puritch 1973; Hinkley *et al.* 1982) and mountain hemlock (Minore 1979) seedlings. In a study of amabilis fir, western hemlock, and Douglas-fir container stock planted on a south-facing high-elevation clearcut, both amabilis fir and western hemlock expended water on shoot growth to the detriment of seedling water balance during periods of soil water deficits (Livingston and Black 1988). Subsequent mortality was high in both species, but lower in the more drought-tolerant Douglas-fir (Livingston and Black 1987). Drought also induced high mortality of western hemlock compared to Douglas-fir stock types planted on a low-elevation site on Vancouver Island (Arnott 1975). Between the extremes of drought tolerance in Douglas-fir and intolerance in amabilis fir and western hemlock, yellow-cedar may be a more drought-tolerant species than its associates as a result of efficient control of water loss by rapid stomatal closure as soil water deficits increase (Grossnickle and Russell 1991).

Amabilis fir is particularly intolerant of soil water deficits. Lack of snowmelt, high summer temperatures, high evaporative demand, and seasonal water deficits at low elevations limit amabilis fir distribution to late successional conditions on high-elevation sites (Krajina 1969; Kotar 1977). In south coastal British Columbia, amabilis fir is commonly absent in areas with mean July temperatures above 16.7°C (Packee *et al.* 1982).

5.2 Heat Stress

High soil surface temperature on exposed reforestation sites in southwestern British Columbia has been identified as a serious factor affecting the survival of germinants and planted seedlings (Ballard *et al.* 1977). On clearcuts, temperatures at the soil surface often exceed lethal limits for planted and emergent natural seedlings, causing stem girdling near the soil surface and subsequent desiccation (Silen 1960; Emmingham and Halverson 1982; Minore 1986). Although very little is known about the heat tolerance of shade-tolerant montane species native to the Coastal Western Hemlock zone, lethal temperatures of other Pacific Northwest species range from 52 to 60°C (Silen 1960; Seidel 1986). Temperatures of 48°C were lethal to yellow-cedar stecklings, indicating that this species is relatively intolerant of high soil surface temperatures.[14] Western hemlock also has a low heat tolerance (Minore 1979). Even when temperatures are below lethal levels, very warm soil surfaces can cause excessive evaporative demand, indirectly leading to seedling desiccation.

Sites most at risk from high soil surface temperatures are likely to occur on southerly aspects with dark, coarse-textured litter and duff layers (Hallin 1968; Ballard *et al.* 1977). Disturbed sites will also tend to be susceptible to high surface temperatures. On a southwest-facing clearcut in southwestern British Columbia, forest floor maximum soil surface temperatures were higher on partially slashburned organic matter and lower on exposed mineral soil (Ballard *et al.* 1977) as a result of the low thermal diffusivity of organic matter, concentrating heat near the surface, whereas mineral soil tends to allow more rapid heat penetration.

5.3 High Light Intensity

Seedling exposure to high light intensities following overstory removal can result in photo-inhibition and subsequent chlorosis and loss of foliage (Ronco 1970; Keller and Tregunna 1976). Survival of understory shade-tolerant regeneration may be dependent on the extent to which foliar physiology and morphology and crown structure of the seedling can be modified upon release from the shade (Aussenac 1973). Understory amabilis fir and western hemlock have foliage with shade morphology (horizontally inclined, thin, flat needles) that is prone to photo-inhibition and accompanying needle loss upon exposure to full sunlight (Keller and Tregunna 1976; Tucker and Emmington 1977; Tucker *et al.* 1987).

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[14] Arnott, J.T. and R.S. Koppenaal. 1991. Heat tolerance of yellow cypress stecklings. Unpublished report.

A number of acclimation mechanisms to high light can act immediately after exposure. Although the capacity for alterations in leaf morphology and physiology are limited in foliage that grew in the shade, species can produce more stress-tolerant sun foliage (thick, steeply inclined needles with well-developed cuticles) in shoots emerging in open sunlight. Such morphological adjustments tend to increase transpirational resistance and thus reduce water loss (Keller and Tregunna 1976). The development of sun foliage was also found to precede increased shoot growth in amabilis fir and is probably a key factor determining the period of growth delay often observed for this species after release (Tucker *et al.* 1987).

Long-term acclimation responses to high light also occur. Changes in crown structure from a flat or umbrella-shaped crown developed in the understory to a more conical form is an example of a high light acclimation that may take several years. Shade-grown (supressed) plants tend to allocate carbon preferentially to shoots in response to low light levels. Small root:shoot ratios of understory amabilis fir may persist for a number of years after removal of the overstory (Herring and Etheridge 1976) and crown development may be delayed as supressed trees grow larger root systems to support increased demand for water and nutrients. The combination of high transpirational water loss from large crowns combined with low root volume for water uptake will tend to restrict growth and threaten the survival of these trees until relatively larger root systems are established that can withstand the water deficits and high evaporative demand of open growing conditions.

5.4 Winter Stresses

Snowpack, 1–3 m deep, blankets coastal montane forests during the winter, insulating the soil and protecting conifer regeneration from cold winds. Desiccation damage can occur when stems of established regeneration grow sufficiently to protrude above the snowpack. Heavy snowpack may also cause losses as a result of stem and branch breakage and other form defects. Low-elevation species with wider branching habits such as Douglas-fir are particularly susceptible (Scagel *et al.* 1989). In contrast, amabilis fir, with its narrower crown, is adapted to snow cover and resists stem breakage. The period immediately following exposure of the shoot after snowmelt can be critical for survival of regeneration because of the interaction of cold soils and high evaporative demand on seedling water balance. Under these conditions, seedling roots may be incapable of providing an adequate supply of water to the shoot as a result of increased viscosity of water and decreased permeability of roots at low soil temperatures (Kramer 1940). This problem is more severe in species that are not adapted to cold soils (e.g., Douglas-fir). Water uptake by roots is more severely restricted in these species at low soil temperatures (Lopushinsky and Kaufmann 1984) than for amabilis fir, which has significant water uptake at soil temperatures as low as 2.5°C (Teskey *et al.* 1984). Adaptation to cold soils is also reflected in root growth of amabilis fir at temperatures of 5°C or less (Lopushinsky and Max 1990). In contrast, yellow-cedar physiological activity at low root temperatures apparently parallels that of Douglas-fir, indicating that this species is not very functional at low soil temperatures (Grossnickle and Russell 1991).

5.5 Frost

Frost tolerance can be a major determining factor in regeneration success at mid and high elevations, particularly on slopes less than 15% , ridgetops, benches, and frost pockets (Scagel *et al.* 1989). Without the overstory to reduce radiative heat loss from the surface, the occurrence of frost is more frequent and more severe in clearcuts than in established stands. Tree species vary in their resistance to frost damage. High-elevation plantations of Douglas-fir, a species of known low frost tolerance, have been especially susceptible to frost, resulting in high rates of mortality and form defects (Klinka and Pendl 1976; Scagel *et al.* 1989; Reuter[15]). Western hemlock also has a very low frost tolerance (Minore 1979) and the shallow root system is susceptible to frost-heaving. This may explain its decreasing occurrence with increased elevation approaching the Mountain Hemlock zone.

The most frost-hardy Pacific Northwest tree species are western white pine, lodgepole pine, Engelmann spruce, and subalpine fir (Minore 1979), as these can become established even in frost

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[15] Reuter, 1973.

pockets. Relatively frost-hardy species include amabilis fir, mountain hemlock, yellow-cedar, and Sitka spruce (Minore 1979), but these are susceptible to severe frost. Frozen soils may also kill frost-tolerant species such as amabilis fir (Krajina 1969).

Results from a study examining the performance of several species planted on coastal high-elevation clearcuts in the mid-1970s showed a greater incidence of frost damage and winter-related form defects (forking, multiple leaders, stem breakage, and stem sweep) in low-elevation species (western redcedar, western hemlock, lodgepole pine, and western larch) than in high-elevation species (amabilis fir, noble fir, mountain hemlock, Engelmann spruce, yellow-cedar, and subalpine fir) (Scagel *et al.* 1989). Of the high-elevation species, noble fir was the most damaged by frost, while yellow-cedar and mountain hemlock were the most severely deformed, prone to layering and multiple stems. The risk of frost damage is greatest from late spring and early fall frosts after budbreak and before budset and can cause heavy losses to planting stock not hardy at the time of planting (Weiser 1970; Stathers 1989).

6 BIOLOGICAL FACTORS

6.1 Non-crop Vegetation

Non-crop vegetation often interferes with crop trees through allelopathy and competition for water, nutrients, and light (Hamilton and Watts 1988; Newton and Comeau 1990). Most evidence for these competitive effects comes from productive low-elevation sites (Messier and Kimmins 1990). At higher elevations in coastal British Columbia, where less productive mor humus forms and harsher winter climatic conditions prevail, the interaction between conifer performance and shrub and herb competition is poorly understood.

In coastal montane environments, *Vaccinium* spp. and fireweed are dominant pioneer species invading harvested sites. Although not normally considered an important competitor during conifer regeneration (Haeussler *et al.* 1990), densely established fireweed can reduce seedling growth as a result of decreased light penetration and increased competition for water and nutrients (Comeau 1988). Competition from *Vaccinium* spp. is likely to be more of a problem in backlog areas where delays in planting have allowed invasion of the site. On extensive cutblocks on Mount Washington, Vancouver Island, growth check and chlorosis of plantations has been observed in association with ericaceous shrubs (notably *Vaccinium* spp.), particularly on nutrient-poor sites (G. Weetman, pers. comm. 1991). In the Engelmann Spruce–Subalpine Fir zone of south-central British Columbia, survival and growth of planted Engelmann spruce and lodgepole pine increased in response to treatments reducing predominantly ericaceous vegetation cover (*Vaccinium* spp. and *Rhododendron albiflorum*) (Coates *et al.* 1991). This may be the result of cold soils and low light levels found beneath undisturbed shrub and herb cover (Coates *et al.* 1991).

Salmonberry (*Rubus spectabilis*), a nitrophytic species, is another major competitor of conifer regeneration in the Coastal Western Hemlock zone but is most abundant below 800 m on moder and mull humus forms (Klinka *et al.* 1979; Haeussler *et al.* 1990). Shade-tolerant amabilis fir can compete successfully with salmonberry (Husted and Korelus 1982), which restricts light penetration under dense thickets. On low-elevation sites, salal (*Gaultheria shallon*) can seriously inhibit conifer establishment by its almost complete invasion of the below- and aboveground environments (Messier and Kimmins 1990). However, it is not generally an important component of the vegetation colonizing coastal montane reforestation sites (Haeussler *et al.* 1990).

The presence of ericaceous shrubs and herbaceous vegetation can provide a beneficial moderating effect on the microclimate for regeneration of shade-tolerant species by reducing high soil surface temperatures and incident solar radiation (Minore 1986; Simard and Nicholson 1990). Nitrophytic species such as fireweed can capture and recycle nitrogen and other nutrients that would otherwise be lost to the ecosystem through leaching or runoff (Newton and Comeau 1990), particularly during the nutrient flush following harvesting. In addition, shrub thickets can be effective in anchoring snowpacks, thus preventing mortality and damage to conifer regeneration from snowpack movement.

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6.2 Mycorrhizae

Ectomycorrhizae are pervasive in the mor humus forms of coastal montane forests. Amabilis fir stands are highly dependent on mycorrhizae, the extent of infection in individual tree root systems seasonally varying from 56 to 98% (Vogt and Grier 1982). Possible functions of ectomycorrhizal infection of conifer seedling root systems include enhanced water uptake, drought resistance (Parke *et al.* 1983), and nutrient uptake (Vogt *et al.* 1982). On dry sites, early mycorrhizal formation can be critical to the growth and survival of conifer regeneration (Amaranthus and Perry 1987). First-year survival of non-mycorrhizal Douglas-fir seedlings on a drought-prone, high-elevation clearcut in southern Oregon increased by 50% and basal area growth by almost three times when planted in soil containing mycorrhizal inoculum from an adjoining established plantation (Amaranthus and Perry 1987).

Harvesting and site preparation practices can have both detrimental and beneficial effects on the number and types of ectomycorrhizae, depending on the level of mycorrhizal association before cutting, the presence of living hosts, warm soil temperatures, and favourable soil moisture conditions (Harvey *et al.* 1980; Pilz and Perry 1984; Amaranthus and Perry 1987). Slashburning tends to cause a temporary decrease in mycorrhizal populations, the extent of which will depend upon the intensity and duration of the burn (Feller 1982). In high-elevation amabilis fir forests, 70% of mycorrhizal roots were found in surface organic layers (Vogt and Grier 1982) and would be subject to mortality in an intense burn as a result of volatilization and sterilization of the forest floor.

7 EDAPHIC CONDITIONS

7.1 Soil Moisture

Adequate soil moisture is perhaps the most critical edaphic factor for establishment and good growth of amabilis fir, western hemlock, mountain hemlock, and yellow-cedar. These species are most productive in perhumid climates on subhygric or seepage sites (Krajina 1969) and are not tolerant of soil water deficits. While establishment on mineral soil can mitigate seedling exposure to soil surface drying and high temperatures, removal or destruction of surface organic layers during site preparation may decrease the soil moisture holding capacity (Feller 1982). Increased overland flow may then reduce the amount of water entering the soil surface layers and, as a result, growing-season water deficits may be prolonged or intensified.

7.2 Soil Nutrients

Nutrient availability may increase for a short time after harvesting. A temporary increase in decomposition rates, as a result of warmer and moister soil conditions (Binkley 1984; Edmonds *et al.* 1989), can result in the release of a flush of nutrients from the pool. Of these nutrients, nitrogen (N) may be the the major growth-limiting nutrient released in forests of the Pacific Northwest. In conjunction with the potential benefits to conifer regeneration and growth, there is the risk of substantial nutrient loss through leaching (nitrate) and erosion on coastal high-elevation sites.

Much of the site N is found in the forest floor (40%) and tree biomass (15%) (Vogt *et al.* 1989). Of the N in the forest floor, approximately 10% is in forms available to tree roots, the rest being bound in a variety of nitrogenous compounds in the litter layer. In high-elevation montane ecosystems, the forest floor litter layer can be up to twice as deep as at lower elevations (primarily because of slow decomposition rates at cooler temperatures) and represents a large reservoir of nutrients (Vogt *et al.* 1989).

The potential for nitrogen loss from these thick surface organic layers can be great, depending on the degree to which the forest floor is disturbed during harvesting and the intensity of slashburning. Hot burns that consume the forest floor have the greatest potential for volatilizing a major proportion of the site

nutrient capital. This can have long-lasting effects, decreasing site fertility (Kimmins *et al.* 1981; Feller 1982; Fyles *et al.* 1991), although there is no consensus on the significance of these losses to site productivity.

Montane species are adapted to the limited nutrient capital available in the mor humus forms on which these species grow. Nutritional requirements (including N) are relatively low for amabilis fir (Packee *et al.* 1982, Radwan *et al.* 1989) and western and mountain hemlock (Krajina 1969). However, deficient levels of N (Webster *et al.* 1976; Husted 1982; Radwan *et al.* 1989), boron, and zinc (Carter *et al.* 1986) have been reported. In natural stands of amabilis fir and western hemlock on nutrient-poor high-elevation sites, losses resulting from intensive harvesting practices may reduce the pool of available nutrients to the extent that seedling growth is reduced (Lousier 1990) and the symptoms of growth check appear. Amelioration of N deficiencies using fertilization has provided inconsistent growth responses in these shade-tolerant species (Radwan *et al.* 1991) and may not be an effective nor economical means of stimulating early growth on high-elevation reforestation sites.

8 SILVICULTURAL IMPLICATIONS

8.1 Species Selection

Selection of the appropriate species for restocking is probably the single most important management decision determining reforestation success. Appropriate species are considered those that are ecologically viable on the site in question and that fulfill management objectives. Klinka and Feller (1984) proposed that tree species be selected by three criteria: 1) crop reliability, 2) maximum sustainable productivity, and 3) silvicultural feasibility. At high elevations, crop reliability is particularly important, since climatic extremes can have a disastrous impact on the survival and productivity of species not ecologically adapted to site conditions, particularly if mortality destroys many years of accumulated production. Douglas-fir, for example, is a species with ecological characteristics inappropriate for high-elevation environments and therefore should be considered unsuitable for regeneration of those sites because of low crop reliability.

Ideally, reforestation of montane ecosystems should rely predominantly on advance and natural regeneration, with artificial regeneration filling a complementary role in achieving full site occupancy and desirable species composition (Klinka and Feller 1984; Scagel *et al.* 1989). Fill-planting with mixed species may provide more resilience and resistance to climatic and disease-related hazards. Species diversity may be a better strategy in the face of a biologically and economically uncertain future (Klinka and Feller 1984).

8.2 Species Suitability

Ecosystem-specific guidelines for tree species selection have been developed for the biogeoclimatic units of British Columbia by Klinka *et al.* (1984), enabling foresters to integrate species selection with site moisture and nutritional properties arranged on an edatopic grid. The following species are briefly discussed with reference to their potential for regenerating coastal montane forests.

8.2.1 Amabilis fir

Abundant suppressed regeneration of amabilis fir in the understory, supplemented by post-harvest natural regeneration, frequently allows this species to achieve dominance on montane reforestation sites. Advance regeneration responds well to overstory removal on cool, moist sites but is often delayed for several years following release. Amabilis fir is not well suited to establishment or growth on sites with seasonal soil water deficits or warm aspect slopes, where it requires shade. A thick surface organic layer is the preferred substrate for regeneration of this species and should be preserved, particularly at high elevations. Amabilis fir does not respond well and should not be planted on thin, friable surface layers, or on slashburned sites. Where density of advance

regeneration is high, juvenile spacing will reduce intraspecific competition and promote better release response. Older advance regeneration is prone to mechanical damage from logging activity and subsequent infection by heart rots. Suitable species for fill-planting or interplanting are mountain hemlock, western hemlock (at lower elevations), and yellow-cedar. There are indications that natural regeneration can often outperform planted stock (Scagel et al. 1989).

8.2.2 Noble fir

Noble fir is a non-native species with excellent potential for performance in habitats typically occupied by amabilis fir (Scagel et al. 1989; Arnott and Pendl[16]). Since noble fir is not shade-requiring, it can outperform amabilis fir, particularly on dry, southern-exposure sites where it should be considered as an alternative species (R.E. Carter, pers. comm. 1991). In frost pockets or on steep sites noble fir may not be suitable as it is susceptible to frost damage and may not survive well when planted on slopes greater than 15%.

8.2.3 Western hemlock

Prolific cone production and widely dispersed seed favours natural regeneration of western hemlock on suitable reforestation sites adjacent to a seed source. As a result of the low frost tolerance and poor survival of this species at high elevations (Scagel et al. 1989; Arnott and Pendl[17]), artificial regeneration of western hemlock is more appropriate on lower montane and submontane sites where it may not be as productive as Douglas-fir (Emmingham and Halverson 1982). Western hemlock is very shade tolerant and favours cool, moist undisturbed mor humus forms for germination and establishment. Sufficient rotting wood should be left on-site as favourable seedbeds for ingress of both western and mountain hemlock. Sites exposed to water deficits are not suitable for this species. Because of the very low nutritional requirements of western hemlock, natural regeneration may be preferable to that of yellow-cedar and amabilis fir on very nutrient-poor sites (Klinka et al. 1990). Release of advance regeneration is often delayed for several years (Klinka et al. 1990). There is also a high risk of decay in advance regeneration of western hemlock.

8.2.4 Mountain hemlock

Unlike amabilis fir and western hemlock, mountain hemlock can regenerate well on disturbed soils (R.E. Carter, pers. comm. 1991) but prefers a moist, organic substrate for establishment. There is evidence that mountain hemlock is not as productive as yellow-cedar or amabilis fir (Scagel et al. 1989), indicating that where artificial regeneration is desired, other species may be preferred. However, mountain hemlock may be a preferred species on nitrogen-poor sites. Both western hemlock and mountain hemlock regeneration are affected by heart rot and dwarf mistletoe, which can limit productivity.

8.2.5 Yellow-cedar

Yellow-cedar can establish and grow well on a wider range of sites than amabilis fir or hemlock. Mineral and organic material are suitable planting substrates for this species. Yellow-cedar exhibits rapid juvenile growth and should be preferred over mountain hemlock on moist, nitrogen-rich sites and over amabilis fir on colluvial and waterlogged sites (Klinka et al. 1990). Yellow-cedar is prone to form abnormalities, including forking and severe stem sweep (Scagel et al. 1989).

8.2.6 Engelmann spruce

Engelmann spruce is not native to maritime climates of the Coastal Western Hemlock zone, although it has been used operationally in reforestation of those sites since 1969 with good results. This species is highly productive on a wide range of high elevation sites but is probably most

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[16] Arnott and Pendl, 1983.
[17] Ibid.

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appropriate in the submaritime transitional climate and the east coast of Vancouver Island (Scagel *et al.* 1989). On dry or warm aspects, Engelmann spruce can be expected to outperform amabilis fir and mountain hemlock.[18] Engelmann spruce is frost-tolerant and is suited to flat sites and cold air drainages. It is moderately shade-tolerant and establishes well on mineral soil (Krajina 1969), but prefers some shade on severe or slashburned sites (Feller 1982). Nutrient-poor sites are not well suited to this species.

8.2.7 Western white pine

Western white pine (coastal provenances) is also very productive and can become established on a range of soil moisture regimes, but its suitability is limited by mortality from attack by blister rust (*Cronartium ribicola*) in the Coastal Western Hemlock zone (Krajina 1969). Its use should be restricted to rust-resistant stock on sites where it forms a component of the residual stand. This species is only moderately shade-tolerant and responds well to planting on mineral substrates, but requires calcium-rich soils (Krajina 1969). Western white pine may be effective for regenerating southern exposure and slashburned sites on eastern Vancouver Island (R.E. Carter, pers. comm. 1991). It is also one of the most frost-tolerant species and therefore suitable for planting on high-elevation flat sites and cold air drainages (Krajina 1969).

8.2.8 Douglas-fir

The susceptibility of Douglas-fir to frost injury and stem breakage under heavy snowpacks limits its suitability for regeneration of coastal montane sites and planting should be restricted to the lower elevational limits of montane forests.[19] Where snowpack and frost are minimal, this species is very productive, particularly on dry south-facing sites, where it is shade-intolerant. However, in most cases noble fir or Engelmann spruce would be more reliable on dry or warm aspects. Douglas-fir favours establishment on mineral substrates associated with moder humus forms (Krajina 1969) rather than on soils with thick organic layers.

8.2.9 Western redcedar

Although western redcedar often forms a minor component in coastal montane forests, regeneration of this species is very susceptible to frost and has poor survival and growth at high elevations (Scagel *et al.* 1989). Its use should be restricted to moist sites protected from frost. Yellow-cedar may be a more reliable alternative on montane sites.

8.2.10 Subalpine fir

In the Coastal Western Hemlock zone, subalpine fir has only limited occurrence in the submaritime and leeward maritime montane and subalpine forests. Substrate requirements are similar to those of amabilis fir, although subalpine fir is not as shade-tolerant and can be a pioneer species on moist sites. Subalpine fir is very frost-tolerant and can become established and grow in frost pockets and other frost-prone sites, but it has low commercial value (Krajina 1969).

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[18] Arnott and Pendl, 1983.
[19] Reuter, 1973.

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9 SILVICULTURAL SYSTEMS

Regeneration of montane forests in southwestern British Columbia has relied exclusively on the same progressive clearcutting systems practiced in coastal low-elevation old-growth forests. To adopt a species- and site-specific approach to the selection of regeneration methods for use in montane ecosystems, consideration of alternative silvicultural systems to clearcutting will provide a number of options to meet regeneration objectives.

A number of factors influence the selection of silvicultural methods for regenerating forest stands in the Vancouver Forest Region (Klinka and Carter 1991). Suitability criteria include:

- Presence and abundance of advance regeneration.
- Potential for competing vegetation.
- Viability and feasibility of natural regeneration.
- Feasibility of planting.
- Viability of ground-based harvesting systems.
- Feasibility of site preparation.
- Biological risks (e.g., disease).
- Operational hazards.
- Windthrow risk.
- Economic viability.
- Environmental impacts.

The shade requirements (tolerance to exposure) of candidate tree species may be the primary biological determinant for the selection of alternative silvicultural systems employing various levels of overstory retention. Growth and survival of shade-tolerant regenerating conifers may be quite variable. Site climatic and edaphic characteristics can modify shade responses such that, on dry sites, trees are more shade-tolerant and tend to grow better in the shade than in the sun (Klinka and Carter 1991).

Macroclimatic changes along the submontane to montane altitudinal gradient, and the associated changes in edaphic properties and species ecology, will also influence the selection of an appropriate silvicultural system. The dominant species in coastal montane forests, amabilis fir and western hemlock, require shade on sites that are hot and dry. It is on such severely exposed sites that silvicultural systems retaining some canopy protection can provide a more favourable microclimate for the survival and establishment of advance, natural, or artificial regeneration.

Alternative silvicultural systems are integral to principles that emphasize retaining the structural features of old-growth stands to maintain long-term site productivity and species diversity (Hopwood and Island 1991). These structural features include live standing green trees, snags, coarse woody debris, and understory trees. This approach has been termed "New Forestry."

Clearcutting, seed-tree, and shelterwood systems tend to establish even-aged second-growth stands but vary greatly in their effects on seedling microclimate and the potential for natural regeneration. In Washington and Oregon the most commonly used alternative silvicultural systems are light and medium conifer retention. These are similar to clearcuts with residuals, seed-tree, and shelterwood systems, the most notable difference being that the residual trees are not removed after regeneration is secured (Hopwood and Island 1991).

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9.1 Clearcutting Systems

Clearcutting, progressive clearcutting, or large-patch clearcutting is the traditional silvicultural system employed in coastal British Columbia and is the most efficient and economical method in terms of access and maintenance, harvesting, and site preparation. Clearcutting methods also generally provide an optimal light environment for productive growth of intolerant and moderately shade-tolerant pioneer species such as Douglas-fir and Engelmann spruce, once seedlings are established and have acclimated to the open environment (Emmingham and Waring 1973; Seidel 1985). In a study of conifer growth under different light environments in the Siskiyou Mountains of southwestern Oregon, leader elongation of Douglas-fir, Shasta red fir, white fir, and ponderosa pine increased with the amount of light received and was generally greatest in clearcuts (Emmingham and Waring 1973) where there was little competing vegetation or where seepage water was available. In contrast, shade-tolerant amabilis fir was reported to have better mean annual height growth of post-harvest natural regeneration in edge versus open environments 25 years after clearcutting (Wagner 1980).

In large cutblocks, regeneration problems encountered after clearcutting centre around the rapid exposure of planted and natural seedlings to environmental extremes, including high or low temperatures, soil surface water deficits, intense solar radiation, wind, and heavy snowpack. These conditions will likely have an adverse or delaying effect on the establishment and early performance of shade-requiring amabilis fir and western hemlock regeneration (Arnott 1975; Wagner 1980; Livingston and Black 1987), particularly on warm, dry, or frost-prone sites (Herring and Etheridge 1976; Wagner 1980). Soil disturbance and the decomposition of the root web can aggravate the problem. Particularly on steep slopes with coarse soils, regeneration may be buried by erosion.

Large cutblocks may also be unsuitable for restocking with seedling ingress. The limited dispersal distance of heavy-seeded amabilis fir (Carkin *et al.* 1978) may restrict ingress to the perimeter of large cutblocks. Seed-tree or green tree retention methods address this problem by retaining a small number of trees, usually less than 25 per ha, over the cleared area. These, however, provide little protection to germinants, or to advance or artificial regeneration. In addition, the loss of seed-trees to windthrow can be high, particularly if they are shallowly rooted (e.g., western hemlock).

Some of the problems associated with clearcutting can be mitigated by reducing the size or by altering the configuration and orientation of cutblocks. For example, on frost-prone sites, cutblocks can be laid out to ensure good cold air drainage. Modified clearcutting methods create a climatic transition between open area and stand edge environments and as such would likely benefit the germination and establishment of shade-tolerant regeneration by providing proportionally more protective cover on severe sites and thereby reducing seedbed temperatures and maintenance respiration requirements (Franklin 1963; Minore *et al.* 1977; Livingston and Black 1988). The effects of modified clearcutting systems on the natural regeneration of Douglas-fir and associated species in the Oregon Cascades were studied by comparing a conventional 40-acre clearcut (slashburned), small patchcuts (less than 1 ha), and strip clearcuts of various widths, orientations, and sizes (Franklin 1963). The east-west strip clearcuts had the best stocking followed by the patch clearcuts. North-south strip clearcuts and the large cutblock had the lowest stocking. Seed-tree (green tree) retention was also more effective for restocking small patches than the large clearcut. In southern Oregon watersheds, better stocking of natural regneration was found in small clearcut patches and shelterwood cuts than in a larger clearcut watershed (Minore *et al.* 1977).

9.2 Selection Systems

Selection systems, which promote uneven-aged stands, may not be feasible on the steep terrain characteristic of coastal montane sites (Hopwood and Island 1991). Some problems with the use of selection systems include:

- Requires multiple entries.
- Requires land-based harvesting methods.
- Soil disturbance may be severe.

- Requires harvesting the diameter distribution profile.

- High logging costs.

- Small economic return for each entry.

- High degrees of damage to remaining trees.

9.3 Shelterwood Systems

Shelterwood (Heavy Conifer Retention) silvicultural systems retain a tree canopy over all or part of the stand and do not produce an open understory environment during the regeneration period. Without examples of shelterwood methods in the coastal old-growth forests of British Columbia, it is difficult to assess their suitability. However, in other areas of the Pacific Northwest, this method has been shown to reduce mortality of conifer regeneration from excessive evaporative demand and high temperatures (Seidel and Cooley 1974; Minore *et al.* 1977; Tucker and Emmingham 1977). Shelterwood cutting is also particularly effective for reducing radiative heat loss on frost-prone sites (Emmingham and Halverson 1982).

Residual trees produce a moderating effect on the microclimate for the establishment and survival of natural regeneration. Following shelterwood cutting of a subalpine site in the Oregon Cascades, the ingress of mountain hemlock and grand fir increased exponentially with increasing basal area (0 to 23 m^3 per ha) of residual overstory trees (Seidel and Cooley 1974). This response was attributed to the mitigation of lethal surface temperatures and by residual trees. In the western Cascades, 40% basal area retention was required for understory western hemlock regeneration after clearcutting and shelterwood cutting (Tucker and Emmingham 1977). In that study, greatly reduced needle loss and mortality of hemlock saplings in the shelterwood cutting prompted a recommendation for the use of shelterwood systems that allow 3–5 years for development of sun leaf characteristics in understory hemlock before complete overstory removal. Amabilis fir may also respond favourably in shelterwood cuts. Based on results from a clearcut, Wagner (1980) suggested that east-west oriented strip shelterwood cuts approximately one tree height wide might enhance the establishment and growth of post-harvest amabilis fir regeneration. For protection- (shade-) requiring species, the residual canopy cover should be at least 40% in uniform and group shelterwood methods and not less than 20% for exposure-tolerant species (Klinka and Carter 1991).

From a biological perspective, shelterwood methods may represent a viable alternative to clearcutting on selected montane sites in coastal British Columbia. Whether shelterwood cutting is economically and technically feasible and compatible with forest management objectives is less certain, and a question beyond the scope of this review. From a management perspective, until a database is available for shelterwood methods in coastal British Columbia, modified clearcutting methods may present a more appealing alternative for providing a favourable environment for the regeneration of shade-tolerant montane species.

Although these results may not be directly transferable to British Columbia's coastal montane forests, small clearcuts (less than 8 ha) and shelterwood cuttings are considered the most consistently successful systems for even-aged management of montane and subalpine true fir–hemlock forests in the U.S. Pacific Northwest (Franklin *et al.* 1974). Particularly on severe sites and when natural regeneration is to be used, a two-stage shelterwood cut may be the most dependable regeneration method (Franklin *et al.* 1974).

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