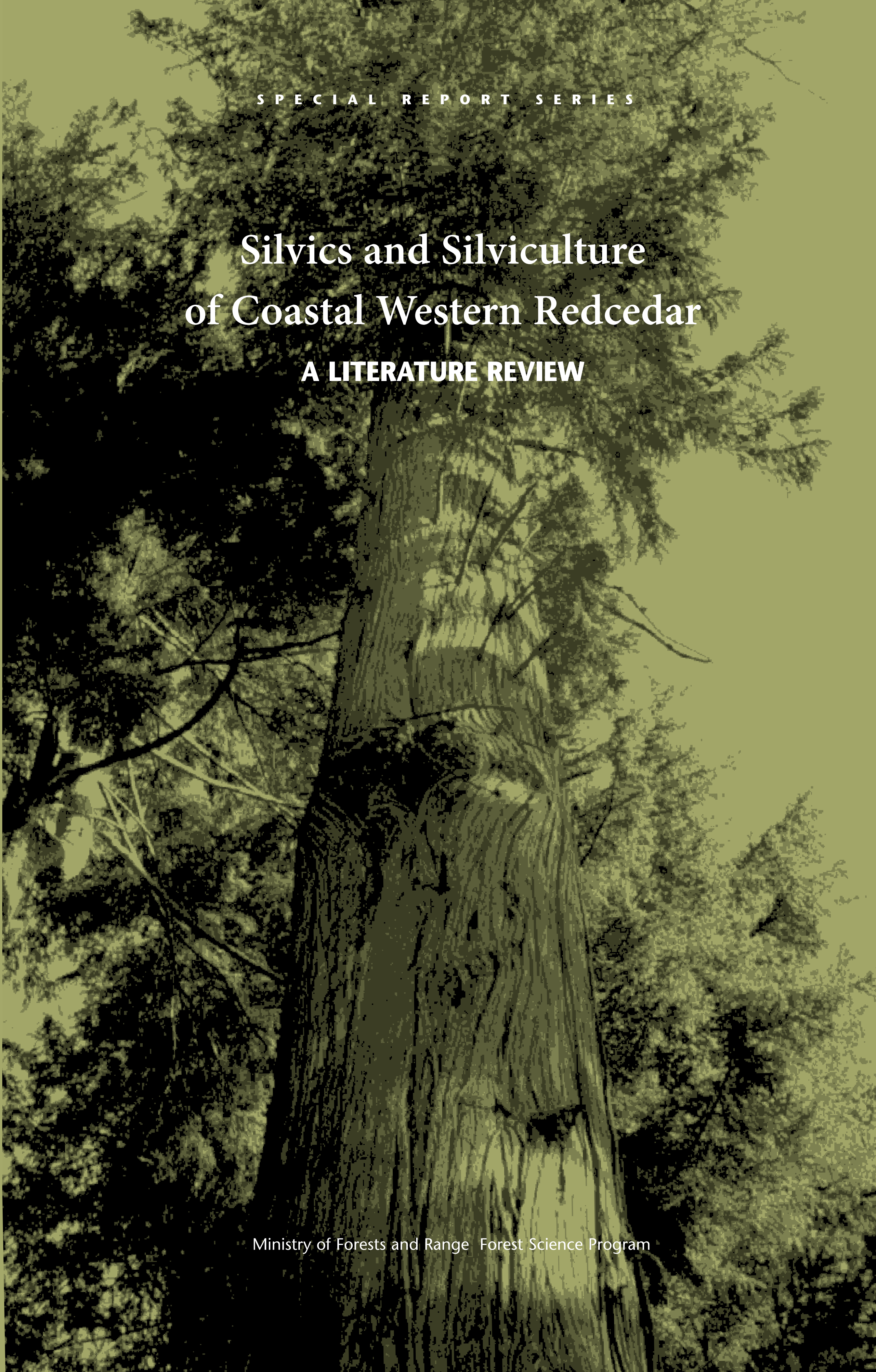

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Silvics and Silviculture of Coastal Western Redcedar

A LITERATURE REVIEW

2009

Ministry of Forests and Range Forest Science Program

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Silvics and Silviculture of Coastal Western Redcedar

A LITERATURE REVIEW

Karel Klinka and David Brisco

BRITISH COLUMBIA

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EXECUTIVE SUMMARY

This report has been produced at the request of B.C. Forest Service staff interested in the future of western redcedar on the coast of British Columbia, and provides a summary of current knowledge regarding this species. In response to their concerns, we have brought together all pertinent information related to the establishment and growth of redcedar scattered in various publications and journals, supplemented with visuals to express the statements and support the inferences made in this report.

The first three sections introduce our approach to the report and summarize well-known information about the redcedar resource and the uses of redcedar products. The fourth, silvics section describes morphological and reproduction characteristics, tolerance, damaging agents, growth development patterns, and genetics. In this section, we include summaries of several studies investigating redcedar stem form and root characteristics. Survival and growth of redcedar in relation to light availability has a direct connection to its growth development patterns.

The ecology section describes climatic amplitude of redcedar, its occurrence within biogeoclimatic units, edaphic amplitude, and associated tree species. A review of vegetation and site classification of redcedar ecosystems is presented in a tabular format. The subsequent discussion describes the ecological role of redcedar, which includes the possible modification of soil properties, increase of community diversity, self-pruning of overstorey crop tree species, and suppression of understorey vegetation. We also attempt to elucidate the origin and perpetuation of old-growth redcedar stands, and conclude that in the CWH zone the species may have a polyclimax role. General succession trends after disturbance of old-growth redcedar stands by clearcutting and windthrow are described, and the origin of many of these stands in southern coastal British Columbia is attributed to fire disturbance. Site selection recommendations for coastal redcedar are given in consideration of possible changing climatic conditions, as well as details regarding the first study on redcedar dieback on eastern Vancouver Island.

The silviculture section includes management-related topics such as growth and yield, regeneration strategies, and intensive silviculture options. When the decision to establish redcedar has been made, we propose several principles to guide management strategies. This subsection is followed by growth and yield information indicating potential productivity of redcedar. Considering the impact of climate change, we updated the list of coastal site series by including only those sites that are thought to provide for a reliable growth as a timber crop. Suitable methods of cutting to promote the regeneration of redcedar, including site preparation, potential for natural regeneration, and aspects of planting are described. The stand management subsection discusses spacing options, pruning, and thinning, and introduces the stand density management diagram. The fertilization subsection is based primarily upon the results achieved in the Salal–Cedar–Hemlock Integration Research Program (SCHIRP).

Three prominent and ongoing redcedar research initiatives are summarized in the last chapter of this document: Imajo studies funded through the University of British Columbia Forest Program, the SCHIRP Program funded co-operatively through the Ministry of Forests and Range and Western Forest Products, and the HyP^3 Project funded through the Ministry of Forests and Range Forest Science Program. For this first initiative we provide only a list of recent studies supported by the Imajo fund. However, the other two research programs merit additional attention and discussion because they convey applicable information about salal-dominated and low-productivity sites found throughout the northern portion of the redcedar range of coastal British Columbia.

PREFACE

The intent of this report is to present the most current and available information concerning establishment and growth of redcedar in the coastal region of British Columbia. The report represents a synthesis of selected information from several major sources, such as Minore (1983, 1990), Smith, N.J. (1988), Wiggins (1999), and Klinka et al. (2000), and from several recent research studies carried out at the Forest Sciences Department, University of British Columbia. The report is not a comprehensive review because we have focused on the information pertinent to regeneration and growth of redcedar, and have limited the information related to other topics. We have aimed to present the available knowledge in a manner comprehensible to those determined to restore redcedar to the role it deserves in the coastal forests of British Columbia. We hope that those users will find this report a practical and useful tool, facilitating their promotion of redcedar as a key component of our future forests.

It should be noted that any mention of particular manufacturers or brands are solely intended for simplicity for the reader. No products described within this document are explicitly endorsed by the authors to the exclusion of other suitable products.

NOTES ON TAXONOMY AND NOMENCLATURE

Thuja is a small genus limited to six species worldwide, with only two species native to North America: eastern white cedar (*T. occidentalis*) and western redcedar (*T. plicata*). Following Little (1979), the common name of western redcedar (just two words, abbreviated to **redcedar** in the text) is preferred to western red cedar, and the full scientific citation is *Thuja plicata* (Donn ex D.Don in Lamb.).

ACKNOWLEDGEMENTS

The authors thank Louise de Montigny, Hal Reveley, and Alan Banner of the B.C. Ministry of Forests and Range for their interest and support of this project. Additional credit must go to Christine Chourmouzis, who significantly improved early drafts of this report with her thorough editing, suggestions, and comments. The contributions and suggestions from Gordon Weetman and Jaroslav Dobry are noted and appreciated. Thanks are also due to Katrine Evans of the Dean's office, Faculty of Forestry, University of British Columbia, for preparing the list of Imajo-supported studies, and to all Forest Service personal who reviewed earlier drafts of this report. Unless otherwise noted, all photographic images were provided by Karel Klinka.

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1 INTRODUCTION

Western redcedar is an important species that has become dominant in our provincial coastal forests relatively recently, in contrast to its many coniferous associates as they re-colonized the coastal regions following the last glaciation. Redcedar, a western North American species, grows in the Pacific as well as the Cordilleran regions, with the larger coastal population separated from the smaller interior population (Figure 1) (Klinka et al. 2000). The current natural range of western redcedar extends along the Pacific coast from California (40° N) to southeastern Alaska (56° N) and along the interior wet belt from McGregor River, B.C. (54° N) to western Montana and northern Idaho (45° N) (Boyd 1965; Little 1979; Minore 1983, 1990). The region of optimal growth is near Washington's Olympic Peninsula (Burns and Honkala 1990).

FIGURE 1 *The range of redcedar in British Columbia (Klinka et al. 2000).*

Redcedar is the only Thuja species native to western North America. Hebda (1999) notes the fossil evidence of redcedar existing in the Pacific Northwest over 30 000 years ago, and proposes the possibility that redcedar populations may have survived the severe conditions found along the margins of the ice sheets in refugia on Brooks Peninsula on the west coast of Vancouver Island, allowing the re-establishment and expansion of redcedar populations approximately 6000 years ago. However, recent genetic evidence (O'Connell et al. 2008) suggests that the current distribution of redcedar (both coastal and interior) is the result of northward migration and colonization from a single population located south of the maximum glacial extent. It is one of the major tree species in old-growth and second-growth forests of the Pacific Northwest. It grows on a wide range of sites, and under certain stand conditions it can be a very productive and valuable timber species owing to the unique colour, texture, durability, and longevity of its wood.

Redcedar trees can grow to enormous proportions. The Big Tree Registry of British Columbia (housed at the B.C. Conservation Data Centre in Victoria, B.C. [www.env.gov.bc.ca/bigtree/docs/BigTreeRegistry.pdf]) lists a redcedar as Canada's largest tree. This individual, known as the "Cheewhat Lake Cedar," towers more than 55 m in height, has a breast height diameter of over 4.8 m, and is estimated to be over 450 m^3 in volume. At one time, high-volume, old-growth redcedar stands occurred across much of the Lower Mainland, mainland coast (except the outer central and northern coast where lower-productivity redcedar-dominated stands are widespread), Vancouver Island, and eastern Queen

Charlotte Islands (Haida Gwaii). Today, productive old-growth stands are rare and largely confined to ecological reserves, parks, and protected areas (Figure 2). The most notable and accessible example is Vancouver's Stanley Park, which is enjoyed by thousands of people from Vancouver and abroad. Along the north and central outer coast there are still large tracts of undisturbed old-growth forests of redcedar, western and mountain hemlock, yellow-cedar, and lodgepole pine. However, on the nutrient-poor soils of this hypermaritime environment (CWHvh subzone), productivity levels are often below operability thresholds, and these forests have generally not been harvested (Figure 3).

Large old-growth redcedar trees have been highly sought after throughout coastal history, as wood from these trees is used for premium products (Figure 4). In consequence, such trees have been harvested over much of their natural range, resulting in considerable depletion and often an inadequate replacement of the resource (Figure 2) (Schmidt 1955). With the current economic pressures found in coastal British Columbia (and throughout the British Columbia forest industry), the targeted harvesting of this species, often at the individual tree level, has been leading towards an unsustainable removal of the

FIGURE 2 *Second-growth, western hemlock in the Malcolm Knapp Research Forest. Large, often hollow yet remaining sound, scattered redcedar stumps are long-lasting remnants of the previous, old-growth, redcedar-dominated stands cut in the 1930s.*

FIGURE 3 *An undisturbed forest on upland rocky sites in the CWHvh subzone consisting of western hemlock, mountain hemlock, lodgepole pine, redcedar, and yellow-cedar.*

FIGURE 4 *As with Douglas-fir, large, sound, clear, old-growth redcedar trees have been most sought after in harvesting the coastal forest.*

largest and highest-quality stems. Essentially, the practice of "high grading" has been occurring at greater levels, as coastal companies attempt to keep their operations active in spite of many negative economic conditions (remote locations, high harvesting costs, relatively high Canadian dollar value, low international market demands). The targeted removal of high-value redcedar stems, known as "high retention harvesting," has become such an issue for the long-term economic value of the managed coastal stands that the provincial Forest Practices Board has recently issued a special investigation report on the subject (FPB 2008). This topic is described in further detail in section 5.4 (Cutting and Regeneration of Redcedar Stands).

Due to the targeted harvesting of this valuable species and perceived risks to its re-establishment (such as deer browse), redcedar has not been replaced in the regenerating stands at the levels it has been historically removed (Nelson 2004). Banner and LePage (2008) have documented the decreasing redcedar composition in second-growth stands, and suggest that without substantially more active management of redcedar (including both improved establishment and maintenance) this important tree species will be reduced to only a minor component of our future coastal forests. The reduced presence of redcedar has been a consistent (and historical) trend, but policies within the coastal Forest Districts have been developed in an attempt to improve the situation. Policies on the Queen Charlotte Islands now require more explicit stocking levels for this species, reversing the trend away from redcedar. In the early 1990s, less than 30% of planted seedlings were redcedar. By the mid-1990s, redcedar made up 37% of seedlings sown on the Queen Charlotte Islands (Reveley 1996), and this proportion continues to increase within the North Coast Timber Supply Area (Winter 2008). However, due to the severe browsing damage to new plantations, redcedar remains a relatively low-frequency species selected for regeneration (minor component of new plantations), and is almost never established with the intention of producing a pure stand. Due to the inherent value (both cultural and economic) of coastal western redcedar, the selective establishment of pure stands on appropriate sites should become a higher-priority consideration for silviculturists.

Most of the provincial redcedar volume is located in the coastal region. Quenet and Magdanz (1988) report that 81% of the total mature volume of 824 million m^3 is in the coastal region and the remaining 19% is found in the interior. Losses associated with decay, waste, and breakage increase with increasing age and diameter, and range from < 6% for older immature to > 50% for old-growth trees. The total volume of redcedar in coastal Alaska, Washington, and Oregon is only 153 million m^3, with 47% of that located in western Washington (Gedney and Oswald 1988).

Currently, > 20% of the harvested Annual Allowable Cut (AAC) of the provincial coastal regions is redcedar (Reveley 1996). These inventory data, however, may be outdated, and there is a call for a review and implementation of the British Columbia forest inventory (Moss et al. 2006). One of the recommendations is to determine the specific location of stand types, defined by species, stand structure, height, density, and other stand data.

Pure second-growth redcedar stands are relatively rare in unmanaged forests. However, there are stands of this type scattered throughout the mid and central coast, likely the result of burning by aboriginals (A. Banner, pers. comm., 2008). A few extensive and easily located examples of young, pure, naturally regenerated stands can be found in the Lower Mainland, predominantly in the Greater Vancouver Regional District watersheds (Capilano, Seymour, and Coquitlam), Malcolm Knapp Research Forest, and Mission Tree Farm (Figure 5).

Redcedar is often grown inside and outside its natural range either as an ornamental in arboretums and parks and as a hedge tree in northeastern United States and Europe, or as a minor timber crop species in western Europe (Minore 1983; Hermann 1987). Redcedar was introduced to Great Britain from Oregon about 150 years ago. Due to its many desirable qualities, the extent of (industrial) redcedar in Britain has increased from 300 ha of plantations prior to 1950, to over 5000 ha of plantations established by 1995 (Rollinson 1988) (Figure 6). The best-performing provenances originated from the northern slopes of the Olympic Mountains, Shuswap Lake, Sooke, and Ladysmith; the poorest-performing provenances were from the Queen Charlotte Islands and near Terrace (Lines 1987).

We have included the following information about redcedar: its range, abundance, uses, silvics, ecology, dendrochronology, and silviculture, and an extensive list of references. Many of these topics can be found in general reference texts such as *Silvics of North America*, by Burns and Honkala (1990). However, we have focussed on the most recent and relevant knowledge and research, particularly in the context of coastal issues, organizing this report in three main sections: Silvics, Ecology, and Silviculture. To facilitate the comprehension of this report, we have supplemented the text with many visuals to illustrate key points.

Although redcedar will always be part of the timber harvest, and despite its relatively rapid radial growth rate and shorter rotation to obtain sawlog values (Gedney and Oswald 1988), management practices in the Pacific Northwest tend to favour other species. This report is written primarily for field silviculturists who wish to

FIGURE 5 *A dense, immature, naturally regenerated stand of redcedar in the Malcolm Knapp Research Forest. Note the development of clear, low-taper boles.*

FIGURE 6 *One of the managed, older-immature, experimental stands of redcedar in Great Britain. Note the low cover of the understorey vegetation.*

increase the component of redcedar in second-growth stands in response to concerns about its natural regeneration, survival, growth, browsing, stand management, and health issues in view of predicted climate change. We have made a reserved attempt to accommodate the impacts of climate change by selecting reliable sites for future growth of redcedar. This can be viewed as a contribution to the Future Forest Ecosystems Initiative, focussing on one of the key tree species.

Reviewing silvics, pest susceptibility, growth and yield, and value aspects of redcedar in relation to alternative coastal tree species including Douglas-fir, yellow-cedar, western hemlock, Sitka spruce, and amabilis fir, Handley (1988) predicts redcedar to be the "future star" in coastal forest industry considering the core of its distribution in British Columbia. He based his prediction on taking into account silvical characteristics, such as easy regeneration and shade tolerance, resistance to pests, growth and yield performance as good as its competitors, and unique wood properties. Handley believes that second-growth stands will provide satisfactory wood quality and aesthetics comparable to old-growth stands. He foresees the major contributors to price are aesthetics; much of the value might even be cultural or traditional. Adams and McKetta (1988) also predict that redcedar will remain a valuable species in the future, even as second growth.

Understanding redcedar ecosystems requires knowledge of how redcedar is established and how it grows in pure stands or in mixed-species stands in different environmental conditions. Despite incomplete silviculture experience and lacking knowledge about the silvicultural potential of redcedar in comparison to Douglas-fir and western hemlock, we believe that it is possible to increase the diminishing supply of redcedar in the coastal forests if there is the willingness and the means to do it. The retention of this cultural keystone species across the coastal landscape is essential to the conservation of historical biodiversity levels and habitat features within these fragile ecosystems.

2.1 Wood Properties

Wood properties of redcedar with respect to physical (structure and anatomy, density, seasoning, and strength) and chemical properties are reviewed in detail by Swan et al. (1988). The wood is light, soft, easy to work, relatively weak but dimensionally stable and straight-grained; it has a high insulative value, and a very characteristic odour. However, much of the high market value is associated with its resistance to decay (DeBell et al. 1999). Redcedar is a preferred wood for nearly all purposes where attractive appearance or resistance to weather is important. Compounds found in the heartwood, known as extractives, act as a natural preservative and fungal repellant. The principal extractives responsible for the decay resistance include tropolone compounds and water-soluble phenolics. The concentration of tropolones, which are the most effective decay-limiting extractives (β-thujiplicin, γ-thujiplicin, and β-thujiplicinol), increases with distance from the pith, making the outer regions of heartwood the most resistant to decay. This differential in concentration may be due to their degradation over time—pith wood is oldest (Hillis 1987). Significant variation in several extractives (including β-thujiplicin) has been detected between coastal and interior redcedar populations (Daniels and Russell 2007). Certain fungi found in the heartwood of redcedar have demonstrated the ability to degrade thujaplicins into less toxic compounds (Jin et al. 1987), thus providing for their own increased rates of heartwood colonization. This inherent natural resistance to decay makes redcedar wood desirable for lumber in weather-affected projects (exterior panels, trim) as well as an important natural component of coarse woody debris for streamside structure and riparian habitat (Gray 2000).

As the supply of redcedar shifts from old-growth to second-growth timber, there are questions and concerns regarding wood quality, particularly in regard to the characteristics that make it so desirable. Preliminary analysis suggests that second-growth lumber will have lower density than old-growth products; however, tropolone extractive content appears to be highest in the most vigorous trees with rapid growth (Marshall and DeBell 2002). Taylor et al. (2006) suggest that intensive silviculture treatment such as thinning and fertilization did not significantly affect the average extractives concentrations. Lower wood density would not be a significant concern for redcedar wood products that value lightness over density. If vigorous trees produce more decay-resistance–inducing extractives, silvicultural practices enhancing the growth and yield of young managed redcedar stands could improve or maintain this characteristic.

2.2 Wood Products

Because of their longevity and resistance to decay, redcedar products have been important since prehistoric times. Redcedar is widely used today for boat construction (hull planking and cabin sides), log houses, exterior siding, shingles, sashes, cabinetry, doors, window frames, interior finishing, utility poles, pilings, fence posts, chests, caskets, crates, boxes, beehives, and gutters. Redcedar is not regarded as a prime pulpwood species, but it is suitable for paper products requiring high density, air resistance, opacity, and exceptional smoothness, such as computer and medical papers (Hatton 1988). Redcedar leaf oil, extractives, and residues are used in several non-wood products (Minore 1983, 1990).

Shingles, shakes, and sawn siding constitute the most important special products of redcedar wood. Appearance, durability, lightness, and insulation qualities are responsible for its popularity as a roofing material. The heartwood of redcedar (as well as of yellow-cedar) is very robust. Redcedar has such slow decay rates that snags, downed trees, and logging residues that have lain on the ground for decades may still produce resilient, large-dimension wood, such as used for shakes and beams (Figures 7 and 8).

Using dendrochronological techniques and radiocarbon dating, Daniels et al. (1997) investigated the year of death and rates of decay for redcedar logs and snags in old-growth stands in the CWHvm subzone. They sampled 15 logs in decay classes I (recent) to IV (old) and 17 snags in decay classes III (recent) to VI (old). Aged by radiocarbon dating, analysis revealed that the oldest logs (IV) were from trees that died approximately 550–1200 years ago, and the oldest snags were still standing after 276 years. This study demonstrated that redcedar decay rates are dramatically slower than for western hemlock and Douglas-fir. The persistence of redcedar coarse woody debris is in agreement with its chemical properties (fungi-resistant extractives) and slow rate of decay. Thus, large-diameter logs can take centuries to fully decompose (Figure 9).

FIGURE 7 *A fragment of a log cut 80 years ago in the Malcolm Knapp Research Forest showing negligible decay.*

FIGURE 8 *Salvaged wood of yellow-cedar (right) and redcedar (left) from leftover logs after past cutting, stored in Sechelt and awaiting further processing.*

FIGURE 9 *Decay class III downed redcedar log in an old-growth stand, estimated to be 120 years old (year of death was 1881). Note the negligible decay even on the roots.*

2.3 First Nations Usage

There is evidence of western redcedar being used by coastal First Nations over 3000 years ago (Nelson 2004). Due to the many advantageous properties and characteristics of redcedar wood, bark, and foliage, it became a cornerstone of the cultural and spiritual identity of these peoples, and is regarded as a prime example of a "cultural keystone species" (Garibaldi and Turner 2004). It is suggested that the expansion and appearance of redcedar in coastal forests 5000 to 2500 years ago is what permitted the cultural development and rapid evolution of woodworking technology that occurred in native communities during the later Holocene (Hebda and Mathewes 1984). Both redcedar and yellow-cedar have been exceptionally useful trees to the First Nations people of the coastal region, performing fundamental roles in their culture. From these two species, the materials for shelter, clothing, tools, transportation, and other artifacts were obtained (for more detailed accounts see Stewart 1984; Pojar and McKinnon 1994; and Wiggins (1999).

FIGURE 11 *Culturally modified trees (CMTs) in varying degrees of decompostion are often found in the coastal rainforest.*

FIGURE 10 *An unfinished canoe from a redcedar log amidst advance regeneration, abandoned for unknown reasons some years ago.*

Redcedar formed the contextual underpinnings of many coastal cultures, often featuring prominently in the language, ceremonial, spiritual, and even common everyday practices of these peoples. Use of its stem wood, branches, roots, and bark in almost all aspects of First Nations existence earned redcedar the status of the "tree of life"—arborvitae (Figures 10, 11, and 12).

Often, First Nations would harvest products from redcedar trees without cutting them down, sustainably removing large planks, or strips of bark. Trees utilized in this way can still be observed alive today, bearing the marks of these historical harvests (Figure 11). These living cultural artifacts are known as "culturally modified trees" (CMTs), and are protected under current forest practices legislation.

The reduced presence of redcedar, due to historical harvesting levels and poor rates of regeneration, is a serious concern for many First Nations groups located along the provincial coastline. In particular, the reduced availability of large old-growth trees is very concerning for those peoples attempting to carry on their traditional practices. These great trees were used for the construction of traditional longhouses, totems, and large canoes that

could handle volatile, open-ocean voyages. The Haida peoples of the Queen Charlotte Islands (Haida Gwaii) have most unequivocally voiced their alarm about the current state of redcedar. In Wiggins (1999), Gitsga, Guujaaw, White, Davidson, and Churchill-Davis express a sincere frustration with the considerable and focussed depletion of the redcedar resource and its inadequate replacement.

Gitsga and Guujaaw "are against exploitation of these trees that they treasure so much" and are greatly disturbed, "seeing millions of dollars of logs going by their village." White acknowledged that "there are not many large old redcedar trees left on the Islands; if there are, they are in smaller and smaller pockets, and within 100 years there might not be anything the right size and shape that is needed for their use." He emphasized that the Haida "do not look at trees as just money; we look at them as part of our freedom and we would like this to continue." Guujaaw acknowledged the deer problem on Haida Gwaii (see Pojar 1999) but argued that "the biggest changes that have happened on the Islands and are happening now are being made by man."

FIGURE 12 *One of several totem poles in Kitwanga village, west-central British Columbia.*

The challenge now is to improve the current situation of poor redcedar establishment, by promoting and encouraging the successful, productive, and efficient regeneration of this species on appropriate sites. Only through the sustainable improvement of the proportion of valuable redcedar within the coastal forests can either the economically important forest industry or the cultural identity of First Nations survive in these regions.

2.4 Spiritual and Aesthetic Aspects

"Oh, the cedar tree! If mankind in his infancy had prayed for the perfect substance for all material and aesthetic needs, an indulgent god would have provided nothing better."

(Bill Reid, from *Out of the Silence*, 1971)

While valued for millennia by First Nations peoples, it probably was not until after Emily Carr captured its haunting dignity and splendour nearly a century ago that it became iconic in western culture. Because of the species' significance, both culturally and ecologically, redcedar was officially adopted in 1988 as the provincial tree of British Columbia. Old-growth redcedar stands such as those in found in provincial and national parks, camping grounds, and preserved areas provide for recreational and spiritual values. Today, people from around the world visit the west coast to see these majestic trees and our giant Douglas-fir and Sitka spruce (Figure 13). Raging Grannies lie across logging roads to protect old-growth forests, RVs clog the roads to Cathedral Grove, people drive treacherous roads to visit the "Three Sisters" in the Carmanah valley, or board float planes or boats to visit the "Hanging Garden Cedar" on Meares Island. The value of forests and large trees, particularly in urban areas, is clearly evidenced by the millions of dollars donated to help "restore" Stanley Park after

FIGURE 13 *This scenic drive through an old-growth redcedar stand in the Coquitlam watershed resembles the experience from a visit to MacMillan Park (Cathedral Grove) on Vancouver Island or Stanley Park in Vancouver.*

it was hit by a major windstorm in the winter of 2006/07.

Redcedars, especially old trees, are aesthetically pleasing either grown alone or in groups. The large and long crown, drooping evergreen branches, fibrous bark, and flat sprays of scale-like leaves make redcedar an attractive ornamental tree (Figure 14) for use along roadways, in golf courses and parks, and around homes, both locally and abroad. When properly and consistently trimmed, redcedar makes excellent hedges (Figure 15).

FIGURE 14 *Redcedar makes an attractive ornamental tree especially when grown alone or in small groups.*

FIGURE 15 *A redcedar hedge in Vancouver.*

3.1 Morphological Characteristics

3.1.1 Crown and stem form On productive sites, redcedar can be >60 m tall, >200 cm in diameter at breast height, and > 1000 years old. The crown is long, symmetrical, and narrowly conical. Older trees can have an irregular shape, and for unknown reasons sometimes develop a candelabra or spike-like crown (Figures 16 and 17). Redcedars main branches are spreading, drooping, and upturned at the ends. The pendent branchlets are arranged in planar sprays, with each spray representing 1–2 years of growth. In open-grown trees, live branches can extend to the ground. The shiny yellowish green scale-like leaves are 1–2 mm in length and arranged in alternating pairs. Foliar morphology differs between sun and shade foliage: shade leaves are scale-like and decurrent, whereas sprays of sun foliage are more flexible and less planar with the smallest shoots upturned. When young, redcedar has a thin, shiny, reddish brown bark. With age the bark becomes shredded and grey-brown, and forms long, flat, narrow ridges (Farrar 1995).

Stem form of redcedar can vary greatly, strongly dependent upon the development pattern of stand growth, stand density, and canopy position. In either mixed-species stands (typically with red alder, Douglas-fir, or hemlock), where redcedar is a common, slow-growing, understorey component, or in low-density pure stands, the stems appear to be highly tapered and fluted, maintaining a large number of large and long-lived branches—all leading to undesirable wood quality (Figures 18, 19, and 20). In marked contrast, pure, even-aged, high-density, second-growth redcedar stands can be fast growing and have high wood quality with little taper or fluting, and a small number of fine branches restricted to the upper crown.

Klinka et al. (1996a) examined site quality and stand conditions in 35-year-

FIGURE 16 *Forked or candelabra crowns in an old-growth redcedar stand, often characteristic of old growth.*

FIGURE 17 *Interestingly, not all trees in a stand will develop these forked crowns.*

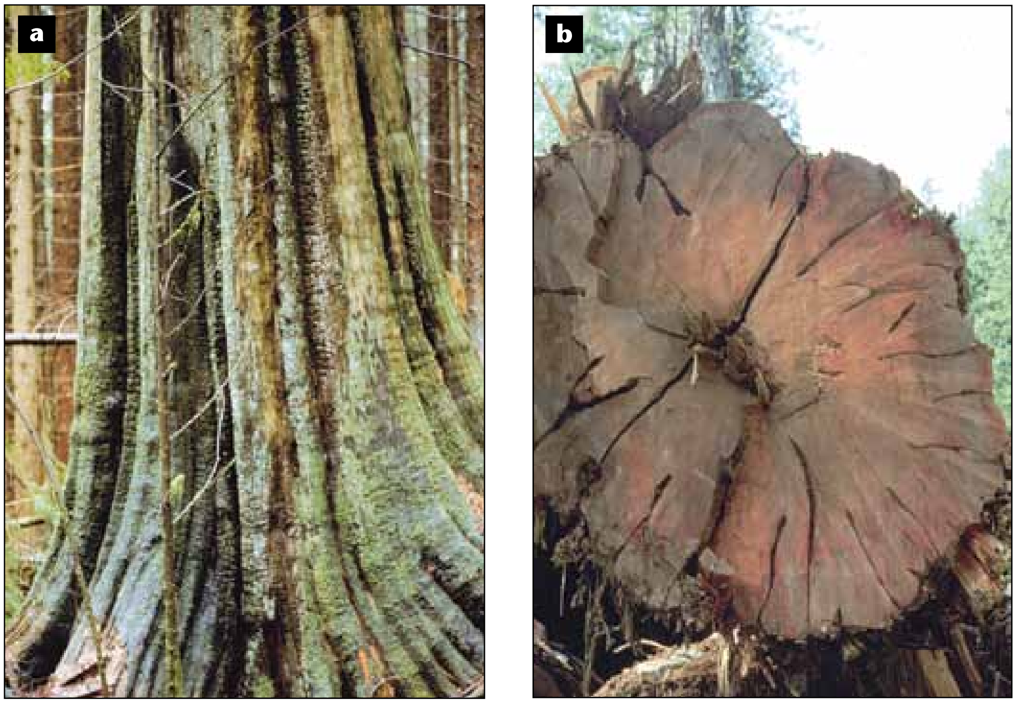


FIGURE 18 *One of the distinguishing features of redcedar can be extensive fluting at the base, as seen on a burned snag (a) and a sound log (b).*

old, experimental stands of grand fir, Pacific silver fir, redcedar, western hemlock, Douglas-fir, Port-Orford cedar, and Sitka spruce located within the Hypermaritime and Very Wet Maritime CWH subzones on Vancouver Island. The pure redcedar stands were found to have consistently open canopies, a history of initial and continued mortality (deer browsing), and slower initial growth (competing vegetation). The mean canopy cover was only 40%, and live-crown length was 85% of the total tree height. The trees had poor stem form and/or undesirable branching characteristics, reducing their future merchantable value. The live crowns were long and conical, and showed continued growth of lower lateral branches. The conspicuous and unusual features were many large, long (up to 5 m), sparsely foliated, upward-sweeping live-branches on the lower stem (Figures 19 and 20). The stems featured fluted boles, and high taper. Klinka et al. (1996a) attributed these undesirable features to low stand density (a result of low initial spacing, high mortality, and failure of early crown closure). More information regarding the development of good and poor growth forms in redcedar stands is found in section 3.6 (Growth Development Patterns).

3.1.2 Roots The root networks of redcedar are extensive. The taproots may be poorly defined or nonexistent, but fine roots develop a profuse, dense network (Figures 21 and 22). Root grafting between trees is common (Eis 1972). The root systems of understorey redcedars, even older trees, can respond dramatically in size and density when overstorey trees are removed (Koenigs 1969).

Wang et al. (2002) examined rooting 60-year-old, naturally regenerated, western

FIGURE 19 *Long, coarse, and persistent branches at the lower stem in a low-density stand.*

FIGURE 21 *The dense root system of an old redcedar established on a rock outcrop. Note the dense system of medium and coarse, lateral roots covering the outcrop.*

FIGURE 20 *An excessively high number of long, coarse, and persistent upper and middle crown branches in a low-density stand.*

FIGURE 22 *The very dense and profuse system of an old redcedar tree established in a shallow (< 40 cm) soil over bedrock.*

hemlock and redcedar in single- and mixed-species stands located on zonal sites in the Lower Mainland with a disturbance history of clearcutting and slashburning. They investigated the hypothesis that mixed-species stands may be more productive because soil resources are used more completely and in a non-competitive way.

They found that mixtures of hemlock-redcedar had the highest root density. Pure hemlock stands had intermediate root densities and pure redcedar stands had the lowest (Figure 23). In all stand types the highest concentration of fine roots was in the forest floor (particularly in the humic forest floor layer [Green et al. 1993]) and decreased with increasing depth of soil profile. In contrast with the hemlock stands, redcedar had more concentrated rooting and a higher proportion of its coarse and medium roots in the

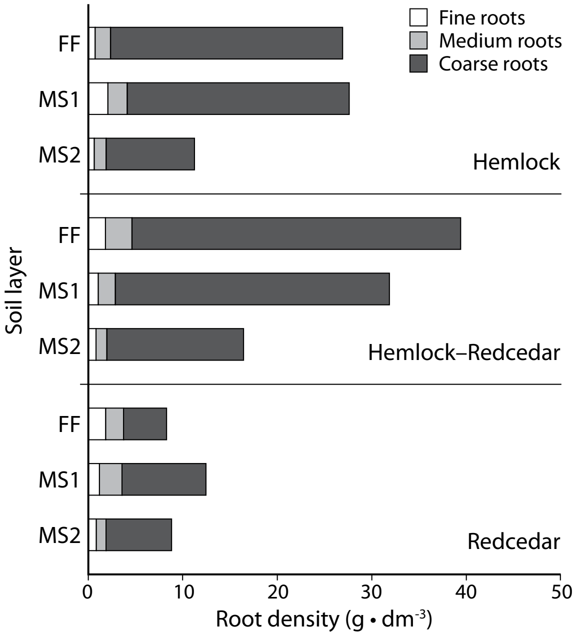


FIGURE 23 *Root density (g • dm^{-3}) of fine (< 3 mm), medium (3–10 mm), and coarse (> 10 mm) roots in the forest floor and two mineral soil layers (MS1 0–10 cm, MS2 10–20 cm) in hemlock, hemlock–redcedar, and redcedar stands (Wang et al. 2002).*

uppermost mineral (MS1) layer. Both Bennett et al. (2002) and Wang et al. (2002) have documented redcedar rooting more deeply within the soil profile than hemlock. For any given stand type and layer, coarse roots formed the highest proportion of all roots, followed by medium and fine roots. Redcedar expressed the highest proportion of fine and medium roots relative to coarse roots in relation to associated species.

Mixed hemlock-cedar stands showed root characteristics of both single-species stands (i.e., overlapping and intermingling root systems) (Figure 23). Wang et al. (2002) concluded that the higher productivity of mixed species was not due to the partitioning of underground resources. It should be noted that when thick forest floors are present (i.e., not on zonal sites as in the above study), rooting can be concentrated in the forest floor rather than in the underlying soil.

Hemlock-redcedar mixtures showed root characteristics of both hemlock and redcedar stands, as their root densities were nearly equal to the sum of those in the forest floor (FF) and MS1 layers (Figure 23). This indicates the presence of overlapping and intermingling root systems of these two species. Wang et al. (2002) concluded that hemlock and redcedar do not utilize soil resources in a selective, spatially non-competitive way. As such, the resulting competition may negatively affect the growth of one or both species.

Most species of woody plants will develop mutually beneficial relationships with mycorrhizae of various types that facilitate the absorption of soil nutrients. Redcedar have vesicular-arbuscular mycorrhizae, associated with the exterior of the fine root sheaths (Minore 1979). Beese (1987) found that redcedar nursery stock was generally not mycorrhizal until after planting. The level of mycorrhizal colonization of the seedlings and their root systems was not significantly affected by various site preparation treatments; however, trends suggest a slight increase in mycorrhizae colonization following moderate burning and possible detrimental effects after heavy burning.

3.1.3 Leader growth The height growth of redcedar is indeterminate. There is no terminal bud, and the developing topmost branches may often exist at a higher level than the terminal itself. Due to its method of indeterminate growth, redcedar lacks vegetative buds and does not exhibit shoot dormancy as observed in other bud-forming conifers (El Kassaby 1999). Shoot growth is controlled solely by temperature, with no growth or mitotic activity occurring at temperatures of 4°C or less (Grossnickle and Russell 2006).

Due to the lack of terminal buds, the measurement of the last growing-season height increment in redcedar is difficult. However, a simple, non-destructive technique for aging redcedar terminals was developed by Parker and Johnson (1987) (Figure 24).

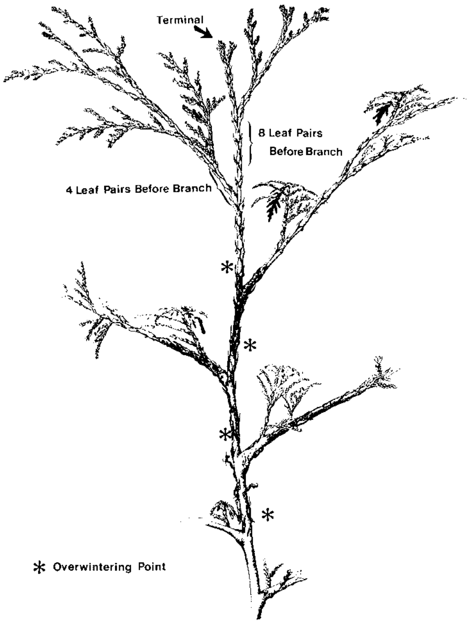


FIGURE 24 *In redcedar, a developing branch is often taller than a terminal. The main stem is distinguished by exhibiting a greater number of leaf pairs between branches than a lateral. To determine previous year's height increment, one must identify the over-wintering point (*) usually 1–2 cm above branch junction. The distinction between annual increments is made based on difference in colour and texture or presence of the stem leaves (Parker and Johnson 1987).*

3.2 Reproduction

Depending upon canopy conditions and soil moisture in the upper soil layer, redcedar can reproduce successfully by either sexual or asexual means (Habeck 1968). Sexual reproduction appears to be more prevalent on areas disturbed by wildfires and on slashburned clearcuts (Schmidt 1955; Parker 1979; Feller and Klinka 1998). In undisturbed areas, germination success and survival is low (seeds succumb to drought or to other agents), and regeneration is largely vegetative (Edwards and Leadem 1988).

3.2.1 Asexual reproduction Asexual (vegetative) reproduction involves the development of new individual stems ("veglings") directly from the parent plant, and not from a germinating seed (Figure 25). Schmidt (1955), Habeck (1968, 1978), and Dyrness et al. (1974) described three types of vegetative reproduction.

1. Rooting of attached live branches. Layering occurs when adventitious roots develop after low-hanging branches come into contact with moist soil;
2. Rooting of fallen, live branches in contact with moist soil; and
3. Rooting along the trunk of a fallen, living tree.

Low branches of a tree can touch the soil, often aided by snow or the weight of fallen trees. These will develop (adventitious) roots, turn upward, and form a new tree. Eventually, connection to the parent tree is severed through the effects of decay. Veglings then develop as independent plants, but frequently with incipient stem decay. Shaded, slower-growing trees have longer lower branches, and are more prone to produce vegetative regeneration (Parker and Johnson 1988).

Artificial rooting of stem cuttings of redcedar is easy, inexpensive, and reliable (Edwards and Leadem 1988). Vegetative propagation is routinely utilized for the production of seedlings by both the B.C. Ministry of Forests and Range and industrial suppliers. Complete redcedar plants have been also regenerated by tissue culture (Edwards and Leadem 1988).

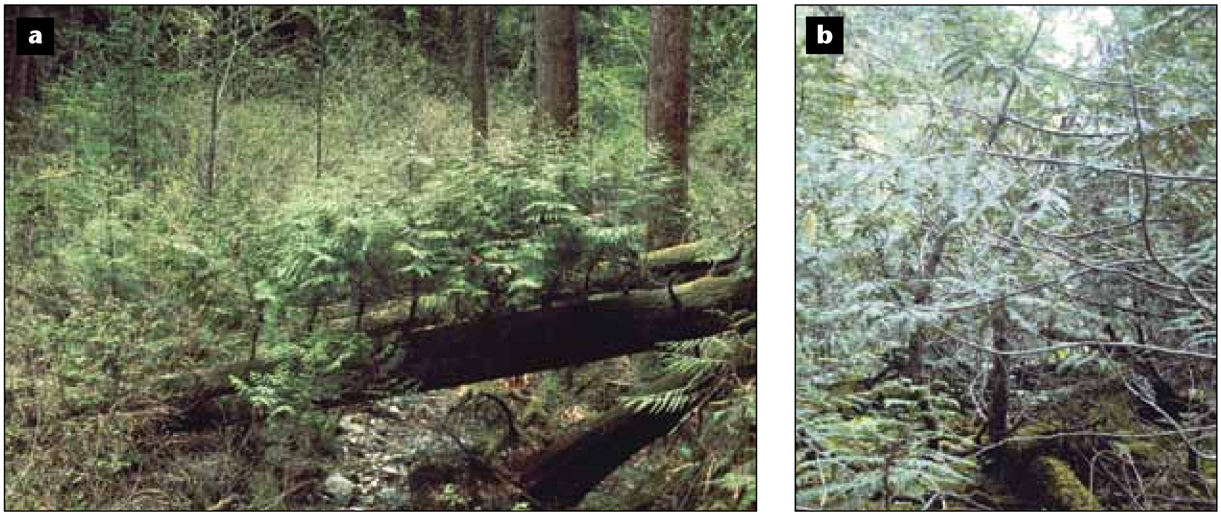


FIGURE 25 *Redcedar veglings rising from branches on a downed tree (a) and fallen branches (b).*

3.2.2 Sexual reproduction The reproductive cycle of redcedar has been described in detail by Owens and Molder (1984). Stobili are usually produced on alternate years with production beginning as early as 10 years of age on open-grown redcedar. Redcedar is monoecious; the reddish male strobili develop on the lower branches and the green female strobili form on the upper branches, typically further from the trunk (Owens and Pharis 1971). Anthesis and pollination occur during March and April on the south coast, and during May and June in coastal Alaska and the interior stands (Schopmeyer 1974).

Redcedar is a prolific seed producer (much greater than its associated species), and rarely has poor cone crops. Annual seed crops vary from 250 000 to 150 million seeds per hectare, with heavy crops every 3–4 years (Schmidt 1955; Eis and Craigdallie 1983). The small seeds are adequately dispersed within 100 m of the parent tree (Minore 1990). The rates of self-fertilization are very high relative to associated conifers, but redcedar does not suffer from inbreeding depression (O'Connell et al. 2001). For more information, see section 3.7 (Genetics).

For more detailed information on the biology of redcedar reproduction, please refer to Edwards and Leadem (1988). They cover phenology of flowering, seed maturation, cone-crop periodicity, seed-crop forecasting, cone harvesting, cone and seed processing, seed yields, seed dormancy and storage, and preparing seed for sowing in the nursery.

3.3 Tolerances

3.3.1 Low light Redcedar can be highly tolerant of low light conditions, comparable to Pacific silver fir and yellow-cedar (Krajina 1969; Minore 1979, 1983, 1990; Wang et al. 1994), but the degree of tolerance is dependent upon climatic and site conditions (see section 3.4: Survival and Growth of Redcedar Seedlings under Varying Light Conditions). Tolerance is highest in warmer and drier climates (and on warmer and drier sites in wetter climates), and relatively lower in cooler and wetter climates (and on cooler and wetter sites in warmer and drier climates) (Krajina 1965; Klinka et al. 1990). An investigation into relative mortality among eight canopy species of the Interior Cedar-Hemlock (ICH) zone in northwestern

British Columbia along a light gradient identified redcedar as the most tolerant of low light conditions (Kobe and Coates 1997).

Drever and Lertzman (2001) suggest that a minimum of 30% of above-canopy light is necessary to ensure maximal radial and height growth in redcedar saplings. In contrast, at least 60% of above-canopy light is required to achieve maximum growth rates with Douglas-fir. This low amount of full sun required to produce maximum growth in the redcedar saplings allows a relatively high degree of retention of forest structure without substantially compromising the growth rates of young trees, once established.

3.3.2 Heat and frost The tolerance of redcedar to heat and frost varies from low to medium across its range. Redcedar foliage is not protected from excessive transpiration by cutin or wax layers. It did not demonstrate drought resistance in the physiological and anatomical investigations conducted by Oppenheimer (1967). On warm, water-deficient sites in the drier and warmer mesothermal climates (i.e., CDFmm), redcedar requires protection from open-area climate by an overhead canopy. Coastal redcedar is not very frost-resistant, and is easily damaged by early and late frosts.

3.3.3 Water deficit and surplus Tolerance to water deficit is rated as medium, as redcedar likely requires protection from open-area climate on warm, water-deficient sites in the driest and warmest mesothermal climates. Its susceptibility to water deficit has been linked to the apparent dieback of redcedar on the east coast of Vancouver Island (see section 4.9: Redcedar Dieback on Eastern Vancouver Island). Its tolerance to water surplus, be it flooding or high or strongly fluctuating water table, is high, but it does not tolerate *very wet* sites well (see section 4.3: Edaphic Amplitude). Although unable to grow productively on these sites, redcedar tolerates stagnant water to a greater degree than most British Columbia conifers.

3.3.4 Nutrient deficiency and pH Tolerance to nutrient-deficient soils is high. Redcedar has been shown to survive and grow on nutrient-poor soils over much of its natural range (Krajina 1969; Minore 1979, 1990). Redcedar can tolerate a wide range of pH conditions from acid to alkaline, and in Great Britain it has grown quite well on shallow soils over chalk (Rollinson 1988). It is intolerant of ocean spray and saline soils (e.g., tidal flats) (Krajina 1969).

3.4 Survival and Growth of Redcedar Seedlings under Varying Light Conditions

Redcedar has always been considered a shade-tolerant species, but scientific evidence for interspecific and intraspecific variation in shade tolerance is poor. Contemporary rankings of tree species are based on qualitative field observations in which light was the “assumed” determinant of both its natural regeneration and resulting structure in mature stands (Klinka et al. 1990).

To better understand light–growth response relationships, Wang et al. (1994) grew redcedar seedlings on three environmentally equivalent sites, representing nearly optimum growth conditions in the CWHvm subzone in southern coastal British Columbia. On each site, the seedlings were planted on transects extending from the interior of an old-growth, redcedar-dominated stand (±5% of above-canopy light) to a clearcut (100% of above-canopy light), and protected from browse. After three growing seasons, seedling mortality, growth, and other characters were compared across five light classes and between study sites (Table 1).

Three-year seedling mortality was <27%, with most occurring during the

TABLE 1 *Mortality of planted redcedar seedlings according to study sites, growing seasons, and light classes. The five light classes indicate percent of above-canopy light received by the seedlings (I = 1–20%, II = 21–40%, III = 41–60%, IV = 61–80%, and V = 81–100%) (Wang et al. 1994).*

		Growing season mortality (%)				Light class (% total mortality)				
Site	**Planted seedlings**	**1990**	**1991**	**1992**	**3-year total**	**I**	**II**	**III**	**IV**	**V**
Eastcap Creek	490	3	22	2	27	96	1	1	1	1
Alpine Creek	497	2	14	0	16	85	10	1	2	2
Cedar Creek	494	1	15	2	18	99	0	0	0	1

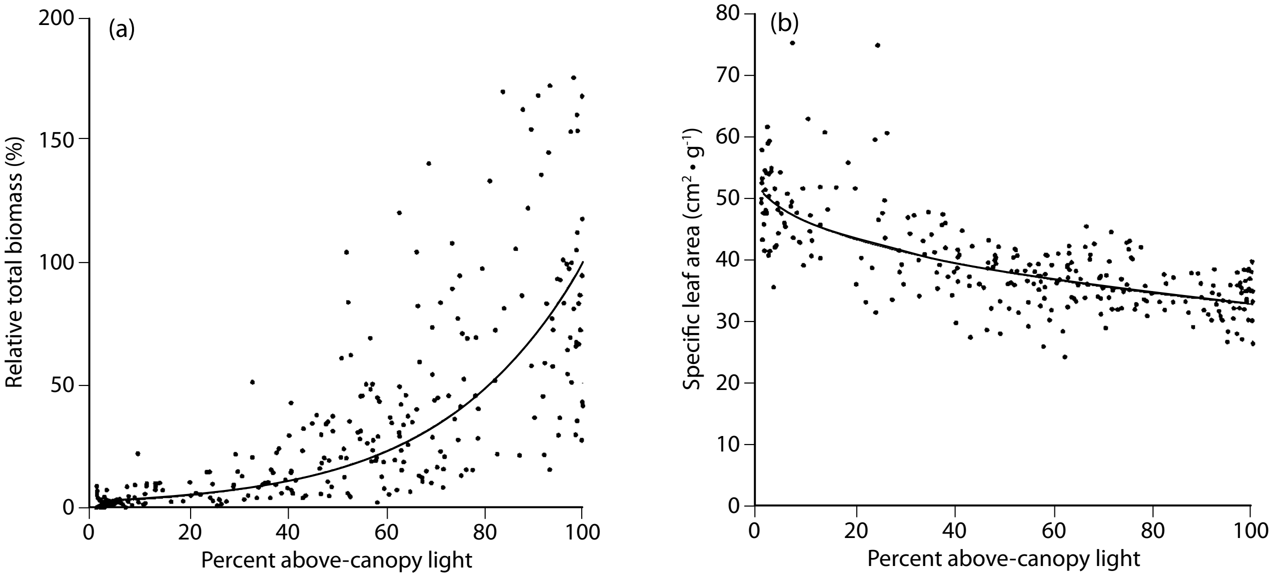


FIGURE 26 *Scattergram and regression line of total biomass (a) and specific leaf area (b) of harvested redcedar seedlings on percent of above-canopy light three growing seasons after planting (from Wang et al. 1994).*

second growing season (14–22%) and under the lowest light conditions (light class I) within the forest understorey (Figure 26a). Wang et al. (1994) suggest < 5% of above-canopy light as the likely threshold for survival of redcedar regeneration.

Seedling growth improved with increasing light; however, growth response at > 40% of above-canopy light was extremely variable (Figure 26a). This variability in growth suggests that other factors are influencing seedling survival as light availability becomes less limiting. Both aboveground and root biomass increased with increasing light, with a slightly greater response in the aboveground biomass.

After three growing seasons, seedlings demonstrated substantial reductions in specific leaf area as light increased (Figure 26b). Using a fitted regression line, specific leaf area of 55 $cm^2 \cdot g^{-1}$ in low light decreased to 35 $cm^2 \cdot g^{-1}$ (37% decrease in specific leaf area) under full light, indicating a high degree of plasticity of redcedar foliage, responsive to varying light conditions.

Seedlings were able to acclimate morphologically to changes in light conditions by three strategies: 1) specific leaf area, 2) height-to-caliper ratio, and 3) aboveground-to-root biomass ratio. These adaptations to low light are commonly associated with other shade-tolerant species. Despite these adaptations for survival when light is limiting, redcedar in the study area cannot be considered a truly shade-adapted species in this climate, as it tolerates exposure to open-area climate, achieving its most productive growth at full solar insolation.

In a similar study, seedlings of redcedar and some associated coastal species were planted within clearcut, shelterwood, or thinned Douglas-fir stands, each type expressing different light and understorey conditions. The greatest redcedar seedling growth was found in the clearcut site, which in combination with vegetation control produced the absolute greatest growth response (Harrington 2006). Light and root competition were thought to be the primary growth-limiting factors for study seedlings. Redcedar seedlings in the clearcut expressed 4–8 times greater stem volume growth rates than those found in thinned stands, without vegetation control, although deer browse on the redcedar was also highest in the clearcut. Highly visible seedlings must have preventative measures installed to protect seedlings from browse. This study also confirmed that redcedar is more tolerant of shade and root competition than is hemlock.

In a study investigating the effects of shading due to overtopping brush, redcedar seedlings were found to exhibit nearly 3 times greater height growth when overtopping vegetation was completely removed from the study site; much greater performance than when the competing vegetation was simply tied back from the redcedar (Adams and Mahoney 1991). This suggests that transpirational or nutrient/root competition plays a very significant role in determining seedling growth in these conditions, perhaps even having a greater influence than light availability.

3.5 Damaging Agents

Redcedar is less susceptible to most damaging agents than other coastal species. Most damaging agents are restricted to stressed or dying trees, or are so rare that their damage is insignificant and generally unnoticed. Young redcedar is usually healthy, making it a promising species in coastal forest systems (van der Kamp 1988).

3.5.1 Snow As a submontane and montane species, redcedar has low resistance to heavy, wet snowpack. Snow damage results in stem and branch breakage in saplings and high-density, immature stands (Scagel et al. 1989). With increasing elevation (and snowfall), the proportional stand composition of redcedar within zonal stands progressively diminishes, replaced by yellow-cedar (these two species may grow together on the same site) until in the lower limits of the MH zone where redcedar becomes absent.

3.5.2 Wind Wind-exposed sites will obviously be more windthrow-prone than other, less exposed, upland sites. On western and northern Vancouver Island and the central and northern mainland coast, wind is the major disturbance factor, and high-velocity storm events are common. In this environment, windfirmness is a very desirable characteristic in a commercial timber species.

Redcedar is considered moderately resistant to windthrow, ranking higher than western hemlock and Pacific silver fir, and expressing similar resistance as Douglas-fir (Minore 1979, 1983). In Great Britain, redcedar is also considered fairly windfirm (Savill 1991). This resistance is likely due to an extensive but less spreading root system that varies with site quality and stand conditions. On sites expressing high water tables, its wind resistance is dramatically lessened due to shallow rooting. The buttress-like fluting of the lower bole is thought to add structural stability, as there appears to be a higher incidence of fluting on exposed (wind-affected) sites. A recent study at the Malcolm Knapp Research Forest (Byrne and Mitchell 2007) indicates a similar degree of windfirmness between redcedar and western hemlock; however, the study site had a water table that restricted rooting depth to approximately 1 m. As noted in section 3.1.2 (Roots), a relatively greater proportion of redcedar roots can be found in the deeper mineral soil layers than observed with western hemlock on mesic sites (i.e., no water table constraints to rooting depth).

3.5.3 Fire The fire resistance and resilience of redcedar is low. Like western hemlock, redcedar it is severely damaged by crown and surface fire (Minore 1983). Its foliage is very flammable and trees with long live crowns are killed by crown and surface fires. The extensive fine roots in the surface organic layers and thin bark are also easily scorched by surface fires. Risk of fire varies from very low in hypermaritime and wet maritime mesothermal climates to high in dry maritime mesothermal climates.

3.5.4 Insects Redcedar is affected by few insect pests, but is a host for several economically important insect species (Furniss and Carolin 1977). The gall midge (*Mayetiola thujae*) can sometimes cause serious seed damage. Several defoliators are known but none of them causes serious damage. Similarly, several species of bark beetle (*Phloeosinus* spp.) may occur on stressed or dying trees. The ambrosia beetle (*Gnathotrichus sulcatus*) attacks the wood of recently killed trees, forming small galleries and introducing a staining fungus, degrading salvaged timber (van der Kamp 1988). The flatheaded borer (*Trachykele blondeli*) is a more serious concern, and can attack healthy trees (van der Kamp 1988). The larvae enters and invades the trunk, mining principally in the heartwood, causing considerable commercial, and possibly structural, defect.

3.5.5 Fungal disease – Roots Redcedar is less susceptible to pathological fungal attacks than other associated timber species. In the coastal region, the most important root and butt rots attacking redcedar are *Phellinus weiri*, *Armillaria obscura*, and *Poria subacida*, and the common trunk rots are *Poria asiatica* and *P. albipellucida* (Boyd 1965; Hepting 1971; van der Kamp 1988). *Armillaria obscura* girdles and kills young trees, but older trees are not so readily destroyed. *Poria subacida* can cause extensive butt rot in pole-sized trees, the damage apparently associated with thinning (van der Kamp 1988).

Following persistent attacks by *Phellinus weiri* or *Armillaria* spp., the heartwood extractives that provide decay resistance are eventually detoxified by a series of invading fungi (Jin et al. 1988). As a result, the volume of accumulated decay found in living trees can be substantial, and hollow old-growth trees are common. Relative to the coast, natural redcedar stands in the interior feature abundant advance regeneration, but the majority are veglings with incipient stem decay. This raises the question as to whether rot-free plantations can be established without the removal of vegetatively established natural regeneration (Weetman et al. 1988).

In one study, the release of overtopped and dense redcedar stands (approximately 80 years old), in combination with thinning (performed in the 1940s), caused a substantial increase in the incidence of laminated root and butt rot 20 years later (Koenigs 1969). The most common species of infection were *Armillaria obscura*, *Corticum galactinum*, *Phellinus weirii*, and *Fomes annosus*. Rots were present in the unthinned stands but restricted to very small pockets several inches in length on the roots of infected trees. Conversely, root clusters in the thinned stands were extensively decayed throughout. Koenigs (1969) postulated that the large amount of residual inoculum (in the form of stumps from the removed overstorey and understorey trees) provided the resources necessary for the large increase in fungal attack. Higher soil temperatures were also considered a factor. These were not young trees, and were healthy when attacked, countering some of the assumptions regarding root rot resilience of redcedar, which obviously can be infected and killed if enough inoculum is present.

In contrast, Nelson and Sturrock (1993) planted seedlings of many species around stumps infected with *Phellinus weirii* to determine their relative susceptibility to this fungus. After 17 years, there was no evidence that the *P. weirii* killed any redcedar seedlings (0% mortality), unlike grand fir (30%), Douglas-fir (20%), Sitka spruce (7%), or western hemlock (5%). However, deer browse was an issue compromising redcedar height growth in this study.

3.5.6 Fungal disease – Foliage and bark Redcedar germinants may be damaged by damping-off due to fungal infection, although larger seedlings are less susceptible. In addition, redcedar may be attacked by several foliar diseases, most severely by cedar leaf blight (*Didymascella thujina*), which can induce complete defoliation of young trees, or the lower crown of older trees (van der Kamp 1988). Also known as *Keithia blight*, cedar leaf blight prevalence can be most severe in dense stands where humidity is highest (Allen et al. 1996; Kope and Sutherland 1994a). The prevalence of cedar leaf blight infestation under high humidity conditions makes this disease an ongoing challenge for seedlings grown at high densities in a nursery environment. Modifying seedling densities and styroblock configuration may reduce infestation rates (Kope and Sutherland 1994b). Natural resistance to this disease can vary between different redcedar populations, with coastal, low-elevation populations exhibiting greater resistance than those found at higher elevations in the interior of the province (Russell et al. 2007).

Although relatively uncommon in redcedar, canker diseases of the bark, such as Phomopsis (*Diaporthe lokoyae*) can develop on stressed or damaged trees (Allen et al. 1996).

3.5.7 Mammals Browsing from deer and elk at the seedling and sapling stages is likely the most serious issue concerning the regeneration of redcedar (Curran and Dunsworth 1988), although bears are also known to damage stands of redcedar when alternative food supplies are low (Sullivan 1993). Low-elevation, low-snowpack, and warm-aspect sites are the most prone to browsing.

Fencing, physical barriers, and chemical repellents are the main methods of seedling protection. Barriers are the preferred method, but the costs associated with their installation and maintenance over time are quite high. The physical barriers include: 1) mesh type (degradable plastic or Stucco wire), 2) shelter types, or even 3) the complete fencing of the plantation. For a more detailed account of these barrier types, see Henigman (1999). Yerbury (1999) noted that the costs per seedling can range from slightly over one dollar to over three dollars for the installation of mesh-type protection, excluding the costs of the seedling itself. Including annual maintenance costs can increase the cost to almost six dollars per seedling over 5 years. In addition to protection by physical barriers, Henigman (1999) recommended planting with large vigorous seedlings and fertilization. Those seedlings that have been protected from browse have generally performed exceptionally well, with rapid, vigorous growth (Figure 27).

In some areas of the province, most notably on the Queen Charlotte Islands (Haida Gwaii), the regeneration of redcedar is seriously compromised by browsing. Overbrowsing by the introduced Sitka black-tailed deer on Haida Gwaii has radically altered the forests and natural vegetation communities, severely reduced shrub and herb layers, and nearly eliminated redcedar regeneration (Pojar 1999). The effects of the deer and other animal introductions are cascading through plant, animal, and insect communities (Allombert et al. 2005a, 2005b; Stockton et al. 2005), seriously threatening the survival of endemic and rare plants and animals.

Because of the major ecological damage that an extensive and uncontrolled deer population can inflict upon the resources of an island location, other more direct methods of controlling deer populations under consideration include possible culls, the introduction of predators (i.e., wolf), or even the use of contraceptives (Garrott 1995).

The recent discovery of preferential deer browsing on Haida Gwaii (Vourc'h et al. 2001, 2002a,b,c, 2003) and the subsequent redcedar breeding/selection efforts (Russell 2006) hold much promise. It was determined that deer prefer redcedar with lower foliar concentrations of monoterpenes (Figure 28). These substances make the foliage much less palatable (this is not a subtle difference—the authors easily distinguished the difference in taste). Work in this area is ongoing but it appears that monoterpene production may be related to historical browse pressures and the post-glacial re-colonization of British Columbia timberlands. Certain populations of redcedar appear to have higher concentrations of these distasteful (to deer) compounds, and the incorporation of a large proportion of seedlings from these populations that are either similarly or less palatable than the surrounding vegetation within harvested areas may make it possible to regenerate redcedar without other intensive (and expensive) measures, such as physical barriers.

In addition, it appears that there is a connection between the production of monoterpenes and troponoid (extractive) substances. Current research is exploring the identification of those clones of redcedar with higher production of these terpenoid compounds, including monoterpenes (browse resistance) and tropolones (decay resistance) (Mattsson and Russell 2007). The ability to identify and select for these important characteristics may yield future redcedar plantations that are both less palatable to deer and express greater resistance to fungal colonization.

FIGURE 27 *A healthy and vigorous redcedar seedling 2 years after planting, protected by Vexar tubing.*

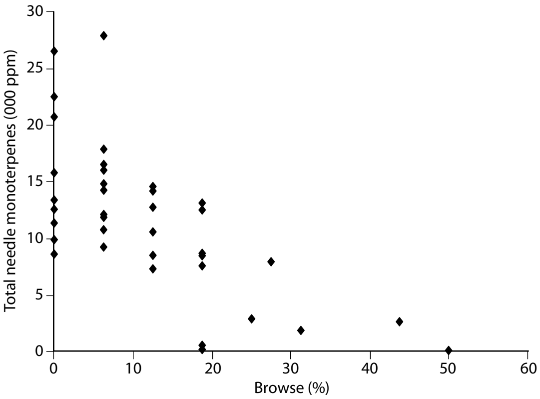


FIGURE 28 *Relationship between total needle monoterpenes and percent browsing by clone in western redcedar grown at Fairservice Main, south Vancouver Island (Russell 2006).*

3.6 Growth Development Patterns

Redcedar trees often possess a rapidly tapering stem, highly fluted lower bole, and persistent coarse branches in the lower crown. Based upon their knowledge as researchers and silviculturists, Oliver et al. (1988) discuss in detail the physiological and morphological characteristics of redcedar that lead to the development of possibly undesirable morphological characteristics. Determining the causes of these morphological traits can assist field silviculturists in management decisions that can reduce the incidence of these characteristics, and induce the development of more desirable growth forms.

Redcedar has a rapidly tapering stem, which Oliver et al. (1988) suggest is a result of the high shade tolerance of the lower crown. The longevity of lower suppressed branches on sub-canopy redcedar trees is similar to those on trees grown in the open or in low-density stands. One explanation for the taper is that the lower branches contribute photosynthate downward from the stem and allow the lower stem to grow (radially) at relatively higher rates than those species that shed their lower branches more frequently.

Redcedar can also develop a buttressed or fluted base. Fluting is the development of longitudinal grooves and ridges on the lower bole, resulting from uneven radial growth (Figure 18). For unknown reasons, radial growth stops at one or more locations around the circumference of the stem while the rest of the stem continues to grow at the same or higher rates. Oliver et al. (1988) believe that fluting may be caused by the restriction of cross-transport (lateral) in the phloem of the lower-bole due to the influence of very suppressed branches. Because a suppressed branch provides little photosynthate to the area below it, an indented flute will result in these locations where the tree grows radially very little, relative to surrounding cambium that is fed by more vigorous limbs higher in the canopy. Fluting may also result from unusual rooting conditions such as downed, decaying logs and wet sites (Figure 29). In addition, it has been noted that the incidence and severity of fluting increases with decreasing stand density (Oliver 1988) and with higher growth rates (DeBell and Gartner 1997; Singleton et al. 2003).

However, this postulated explanation of fluting and stem development has not been verified by careful observation and subsequent research. DeBell and Gartner (1997) could find no relationship between the location of dying or dead lower branches and the development of flutes. Fluting was always found to be deepest at the base of the tree, the opposite of what would be expected if flute development was influenced by dying branches. In fact, DeBell and Gartner (1997) detected minor flutes developing from the base of *all* studied trees, although most were to a very minor extent and unlikely to be noticed by casual observation. Flutes appear aligned with spaces between major roots (DeBell and Gartner 1997; Singleton et al. 2003), suggesting that fluting develops as a response to mechanical stresses acting upon the stem. Fluting appears to be more prevalent on those stems growing in locations where rooting substrates may be less structurally sound, such as on decaying logs (Figure 29), wet sites, or where exposed to frequent wind forces.

FIGURE 29 *Distinctly developed fluting in a redcedar tree that had established on a downed, above-ground log.*

Clearly, the growth of redcedar within its climatic and edaphic amplitude varies greatly depending on light conditions—its growth increases with increasing irradiance. However, redcedar will continue to survive even under low light conditions due to its high shade tolerance (Klinka et al. 2000), albeit growing slowly and with poor form (heavy branching and tapered bole).

After the release of sub-canopy redcedar through thinning, Oliver et al. (1988) suggest that much of the increased growth following release would be directed to branches in a spreading crown, and less to the stem wood. If suppressed for a significant period, the lateral branches do not appear to be controlled by the terminal any longer and begin spreading out and growing upward.

Even-aged redcedar stands growing under high-density conditions have their crowns in full light, with the terminal maintaining strong epinastic control; that is, the terminal exerts control over the length and direction of branches resulting in the development of a cone-shaped crown, with relatively short lateral branches (Oliver et al. 1988) (Figures 5 and 30). Fluting is much less pronounced and taper is less of a concern. In contrast, large, long branches and increased stem taper often develop and stay alive such as in low-density stands or suppressed (below-canopy) trees.

FIGURE 30 *Examples of dense, immature, naturally regenerated, pure redcedar stands established after clearcutting and burning. Note the desirable stem form.*

3.7 Genetics

Evidence of genetic variation in redcedar has been shown in leaf blight resistance (Soegaard 1956; Russell 2007), frost resistance (Sakai and Weiser 1973), and provenance performance (Lines 1987), but these studies did not detect the substantial variation in genetic expression between individuals commonly observed in other species.

Across its range, redcedar characteristics seem to vary less than all other northwestern conifer species, indicating that it is relatively genetically uniform (von Rudloff and Lapp 1979; Bower and Dunsworth 1988; El-Kassaby 1999; Glaubitz et al. 2000). Seedlings from different seed sources usually have remarkably similar forms and growth rates when grown in the same environment (Sakai and Weiser 1973). Bower and Dunsworth (1988) found no significant differences in survival and growth among three Vancouver Island provenances (low, mid, and high elevation) in plantations near each collection site; however, there were differences among locations. Lack of isoenzyme variation in newly germinated seedlings from British Columbia, western Oregon, and eastern and western Washington indicates that redcedar populations contain little genetic polymorphism (Copes 1981; Yeh 1988). Leaf oil terpene composition is similar in populations at both low and high elevations in British Columbia, Washington, Oregon, Idaho, and Montana; and only small differences between coastal and interior populations have been detected (von Rudloff and Lapp 1979; von Rudloff et al. 1988). Similarly, Grossnickle et al. (2005) identified minor differences in foliage carbon isotope discrimination and foliage conductance between some redcedar populations, but measures of gas exchange response and water use efficiency among redcedar populations demonstrate very little variation across a longitudinal transect/precipitation gradient—coastal to interior (in spite of large differences in environmental conditions of seed source location). Fan et al. (2008) also detected very little variation in water use efficiency across similar populations, indicating no substantial genetic adaptation to the climatic precipitation conditions of the parent populations. The apparent lack of variation across this climatic gradient is surprising, considering the absolute differences in precipitation and seasonal drought.

El-Kassaby et al. (1994) postulate that a population size bottleneck due to droughts occurring 6000–10 000 years ago may be responsible for these low levels of heterozygosity. Additional genetic research (Glaubitz et al. 2000; O'Connell et al. 2008) provides evidence that the current distribution of redcedar (from the Alexandra Archipelago in Alaska to northern California) is a result of migration and colonization from a single population that survived the most recent (Wisconsin) glacial period (80 000–18 000 years ago) in a refuge located to the south of the maximum glacial extent, possibly even south of its current range. No genetic evidence suggests populations of redcedar existing in coastal refugia within the glacial ice sheets.

Redcedar exhibits the highest level of self-fertilization reported of all coniferous species (El-Kassaby et al. 1994; O'Connell et al. 2001), with the degree of "selfing" increasing with the size of the individual tree (O'Connell et al. 2004). Typically, high rates of self-fertilization may lead to reduced levels of productivity due to the long-term impacts of inbreeding (homozygous recessive expression of lethal and sublethal genes) (Woods et al. 2002). However, in contrast to other species, redcedar seems relatively immune to the typical negative effects of self-fertilization (Wang and Russell 2006), and does not appear to suffer significant losses in productivity due to inbreeding depression. Apparently, the species is extremely plastic in its morphological development and response to site conditions (El-Kassaby 1999), offsetting the relative homogeneity of its genetic makeup. If fact, redcedar resistance to leaf blight and frost (obviously beneficial traits) has been shown to be homozygously recessive (Soegaard 1969).

Based upon the reduced genetic variability of the species, Bower and Dunsworth (1998) suggest that: 1) intensive breeding programs may not be justified, 2) greater gains may be captured from management practices, and 3) seed transfer rules can be simplified relative to other commercial species.

In spite of these comments regarding the utility (or lack thereof) of redcedar breeding programs, current genetic research has demonstrated much potential to reduce the palatability of foliage to deer (Vourc'h et al. 2002b; Russell 2006a), and possibly even to improve in the concentrations of heartwood extractives, providing more fungi-resistant redcedar wood products from second-growth timber (Mattsson and Russell 2007).

A provincial breeding program for redcedar exists, although still relatively immature in comparison to programs focussed upon other valuable conifers of the province (Russell 2006b). Using an accelerated breeding cycle experimental program, Russell and Ferguson (2008) were able to produce five generations of progeny in only 10 years. Due to the relatively low impact (negative) of self-fertilization upon subsequent stand productivity, the use of self-fertilization techniques may facilitate a continued and rapid expansion of the provincial redcedar breeding program.

With the importation of redcedar as a

potential timber crop on the British Isles, the British Forestry Commission established provenance tests in the early 1970s using 13 seed origins from British Columbia, Washington, and Oregon. Significant differences among provenances were found for height growth and for resistance to *Didymoscella thujina*. Recommended provenances for British climatic conditions are from the north slopes of the Olympic Mountains and from Ladysmith (Rollinson 1988).

4.1 Climatic Amplitude

Redcedar is adapted to climates with abundant precipitation and high humidity. It is most common in montane continental cool temperate (the interior wet belt) and cool and cold mesothermal climates (coastal), and less frequently in the maritime subalpine boreal climates (higher elevations on the coast) (Krajina 1969; Klinka et al. 2000).

The coastal population of redcedar tolerates extremes in annual precipitation, ranging from less than 800 mm on southern Vancouver Island to more than 4000 mm (mostly as winter rainfall) on western Vancouver Island (Meidinger and Pojar 1991). Interior populations receive about 700 mm to more than 1200 mm, with half falling as rain in the spring and autumn, and the remaining half falling as winter snow (Boyd 1965).

Where precipitation is sufficient, low temperatures appear to be the most limiting climatic factor. Minore (1983) estimated that the northern limits of redcedar follow the 11.5°C mean summer temperature isotherms in southeastern Alaska. Krajina (1969) estimated absolute minimum temperatures experienced by redcedar in British Columbia to be between -10° and -30°C for coastal populations, and between -14° and -47°C for interior populations. Redcedar grows from sea level to about 1200 m in southern coastal British Columbia.

4.2 Occurrence in Biogeoclimatic Units

On the coast, redcedar occurs most abundantly in the Coastal Western Hemlock (CWH) zone, and is sporadic in the Coastal Douglas-fir (CDF) and Mountain Hemlock (MH) zones (Krajina 1969; Meidinger and Pojar 1991; Klinka et al. 2000). The relative occurrence levels of redcedar within the subzones (i.e., climates) of the CWH, CDF, and MH zones are shown in Table 2.

TABLE 2 *Relative occurrence of redcedar in subzones of the Costal Douglas-fir (CDF), Coastal Western Hemlock (CWH), and Mountain Hemlock (MH) zones. Occurrence classes are: low (sporadic to infrequent), medium (common or frequent), and high (very frequent or abundant) (Banner et al. 1993; Green and Klinka 1994).*

Subzone	Occurrence	Comment
Moist Maritime CDF (CDFmm)	Low	Sporadic; restricted to non-water-deficient sites
Wet Hypermaritime CWH (CWHwh)	Medium to High	Infrequent in second-growth stands
Very Wet Hypermaritime CWH (CWHvh)	High	Abundant; infrequent in second-growth forests
Very Dry Maritime CWH (CWHxm)	Low	Absent on water-deficient sites
Dry Maritime CWH (CHWdm)	Medium	Absent on very dry sites
Moist Maritime CWH (CWHmm)	Low to Medium	Decreasing with increasing elevation (snowpack)
Wet Maritime CWH (CWHwm)	Low	Sporadic to absent
Very Wet Maritime CWH (CWHvm)	High	Decreasing with increasing elevation (snowpack)
Dry Submaritime CWH (CWHds)	Low to Medium	Decreasing with increasing continentality
Moist Submaritime CWH (CWHms)	Low	Decreasing with increasing continentality
Wet Submaritime CWH (CWHws)	Low	Rare to absent
Moist Maritime MH (MHmm)	Low	At the lowest elevation limits
Wet Hypermaritime MH (MHwh)	Low	At the low elevation limits

The climate on the coast varies along the longitudinal gradient (west to east) from hypermaritime to submaritime; and along the latitudinal gradient (south to north) as temperature and evapotranspiration decrease. Precipitation remains high throughout the whole region. In consequence, the soils in the northern coastal region are generally cooler and have growing-season water surplus compared to the southern coastal region. These climatic differences are reflected in vegetation and, therefore, in zonal (Table 2) and plant community classification (see section 4.5: Vegetation and Site Classification).

4.3 Edaphic Amplitude

Redcedar has a broad edaphic amplitude (Figure 31). It tolerates a wide range of soil moisture and nutrient conditions within its climatic range, but the most productive growth occurs on fresh to moist, nutrient-rich soils. It tolerates water surplus and flooded soils, and nutrient-deficient soils (Krajina 1969; Minore 1990; Klinka et al. 2000). Redcedar can be abundant on soil moisture regime (SMR) wet sites (Figure 32), which typically are nutrient-medium to -rich, but not on SMR very wet. It tolerates water-deficient sites to some degree, but does not tolerate the driest sites in dry and warm coastal climates (Figure 33). It can grow on sites too dry for western hemlock presumably because it has deeper root penetration (Franklin and Dyrness 1973; Klinka et al. 2000).

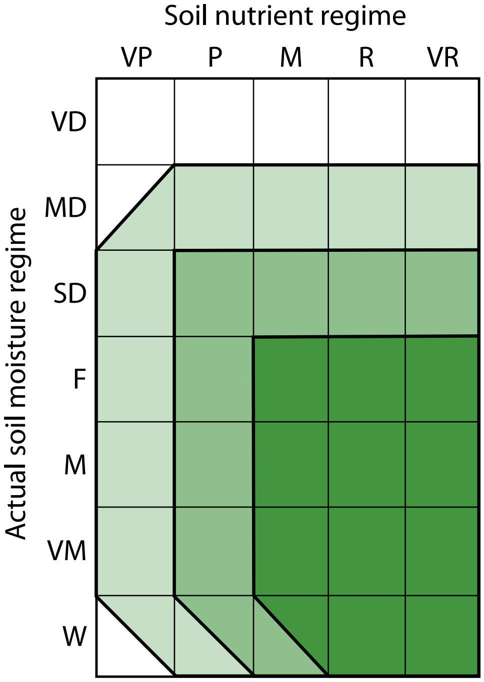


FIGURE 31 *Generalized edaphic amplitude of redcedar in the CWH zone in relation to actual soil moisture and nutrient regimes. Light green indicates absence or infrequent occurrence and marginal productivity, medium green indicates frequent occurrence and low productivity, and dark green indicates very frequent occurrence and medium to high productivity.*

Redcedar frequently occurs on nutrient-poor soils, but natural regeneration and planted seedlings often grow poorly and are chlorotic, such as those on salal-dominated sites on northern Vancouver Island (Figure 34).

Redcedar grows on soils derived from a variety of parent materials. Krajina (1969) characterized redcedar as *calciphilous*, growing best on very slightly acidic to neutral, Ca-rich soils. On Vancouver Island, productive growth of redcedar is found on limestone and limestone-derived soils. In Great Britain, redcedar grows well on chalk-derived soils but tolerates both acid and calcareous soils (Rollinson 1988). Krajina (1969) also stated that redcedar requires very high nutrient levels for optimum nutrition. However, it is not nutrient-demanding, as it commonly grows on poor sites (Weetman et al. 1988).

Krajina (1969) and Krajina et al. (1973) described soil conditions for the most productive (optimum) growth as rich in Ca, Mg, and nitrate N. Based on sand culture experiments, soil analyses, and field observations, they concluded that redcedar requires nitrate-N for its growth and cannot tolerate the complete replacement of nitrate-N by ammonium compounds.

Based on its distribution in southwestern Oregon, Imper (1981) and Imper and Zobel (1983) suggest that redcedar is tolerant of soils high in Ca, N, and Ca:Mg ratios. Krajina et al. (1973) also demonstrated that redcedar seedlings require more N for *optimum* growth than Sitka spruce, western hemlock, or Douglas-fir. Additional information regarding the foliar nutrition of redcedar can be found in section 5.5.4: Fertilization.

FIGURE 32 *Skunk cabbage – redcedar communities typically occupy margins of coastal lakes and depressions, forming a transition from non-forested wetland to upland communities.*

FIGURE 33 *A very dry, rock outcrop site on Bowen Island. Common tree species on such sites are more drought-tolerant than redcedar: Rocky Mountain juniper, Douglas-fir, and/or lodgepole pine.*

FIGURE 34 *A chlorotic redcedar plantation on an N-deficient, salal-dominated, old-growth cutover on northern Vancouver Island.*

4.4 Associated Tree Species

Redcedar is present in early, mid-, and late-succession stages in uneven- (less often in even-) aged stands. It is most common in mixed-species stands and less frequently occurs in pure stands. Mixed-species stands of shade-intolerant tree species with redcedar are typically layered, with the shade-tolerant and slower-growing redcedar relegated to below-canopy, subordinate crown positions (Figures 35 and 36). In the coastal region, redcedar commonly associates with many species: Douglas-fir, western hemlock, Sitka spruce, grand fir, Pacific silver fir, lodgepole pine, yellow-cedar, black cottonwood, red alder, and bigleaf maple (Minore 1990; Klinka et al. 2000).

Throughout its range along the coast, the presence of redcedar has been shifting in favour of western hemlock and Douglas-fir (in the south). The dominance of redcedar populations is decreasing due to poor establishment success (both natural and artificial regeneration) and to its relegation to the lower tree stratum and resulting slower growth rates in sub-canopy environments.

FIGURE 35 *A markedly stratified (two-storeyed) structure is typical for mixed-species stands of Douglas-fir and redcedar. It is not apparent whether such mixtures are even- or uneven-aged. In the absence of disturbance, redcedar will replace shade-intolerant Douglas-fir.*

FIGURE 36 *A stratified (two-storeyed) structure is typical for mixed-species stands of hardwoods (here of black cottonwood) and redcedar. In the absence of disturbance, redcedar will replace a short-lived, shade-intolerant black cottonwood.*

4.5 Vegetation and Site Classification

4.5.1 Vegetation classification Mature and old-growth stands on the coast that have or are predicted to have a significant component of redcedar at the final (climax) stage of secondary succession (see section 4.7: Succession) were classified by Krajina (1969), Nuzsdorfer and Klinka (1988), and Klinka et al. (1996b). We are aware of the elusiveness of explicitly defining the climax concept, and of the difficulties in recognizing or predicting the composition of climax stands. Moreover, the distinction between minor and major components in stand composition is arbitrary, for redcedar often occurs as a persistent component in many old-growth coastal stands, even if only in the understorey. In view of its high shade tolerance, edaphic adaptations, natural regeneration capacity, and longevity, Krajina (1969) considered redcedar an edaphic climax species on those nutrient-rich sites without a significant and prolonged soil moisture deficit. Therefore, edaphic climax stands are characterized not only by the presence of redcedar, which may be absent in early- and mid-succession stages, but also by climatic and edaphic site qualities. These environmental relationships are reflected in the site classification for the coastal region (Banner et al. 1993; Green and Klinka 1994).

At the highest categorical level, the most productive actual and potential redcedar stands are classified in the Redcedar – Salmonberry (*Thuja plicata – Rubus spectabilis*) order, which is comprised of five alliances, each consisting of two or more associations (Table 3). The sampled stands of this order are found on slightly dry to wet moisture regimes, and medium to very rich nutrient regimes within the

TABLE 3 *Vegetation units of the most productive coastal Redcedar – Salmonberry (*Thuja plicata – Rubus spectabilis*) order (simplified from Klinka et al. 1996b) and their occurrence*

Alliance *Association*	**Occurrence**
Thuja plicata – Tiarella trifoliata	**(Slightly dry), fresh to moist sites**
Alnus rubra – Rubus spectabilis	CDF, CWH; submontane sites; floodplains
Thuja plicata – Oemleria cerasiformis	CDF; floodplains, mainly on Vancouver Island
Thuja plicata – Achlys triphylla	CWH; submontane and montane sites, Vancouver Island
Thuja plicata – Polypodium glycyrrhiza	CWH, steep-rocky sites
Thuja plicata – Acer circinatum	Mainland CWH, submontane and montane sites
Thuja plicata – Rubus spectabilis	Mainland CWH, submontane and montane sites
Picea sitchensis – Tiarella trifoliata	**Fresh to moist sites (infrequent on mainland)**
Picea sitchensis – Tiarella trifoliata	Mainly hypermaritime CWH; submontane sites, floodplains
Picea sitchensis – Rubus spectabilis	Mainly hypermaritime CWH; submontane sites, floodplains
Picea sitchensis – Oplopanax horridus	Mainly hypermaritime CWH; submontane sites, floodplains
Chamaecyparis nootkatensis – Tiarella trifoliata	**Fresh to moist sites**
Chamaecyparis nootkatensis – Tiarella trifoliata	CWH; upper montane sites
Thuja plicata – Vaccinium ovatum	Hypermaritime CWH; Vancouver Island
Abies amabilis – Tiarella trifoliata	**Fresh to moist sites**
Abies amabilis – Achlys triphylla	CWH; montane sites, Vancouver Island
Abies amabilis – Streptopus amplexifolius	CWH; montane sites
Abies amabilis – Oplopanax horridus	CWH; montane sites
Thuja plicata – Lysichitum americanum	**Wet sites**
Alnus rubra – Lysichitum americanum	CDF, CWH; submontane and montane sites
Abies grandis – Lysichitum americanum	CDF; submontane sites on Vancouver Island
Picea sitchensis – Lysichitum americanum	Hypermaritime CWH, submontane sites
Thuja plicata – Sphagnum	Hypermaritime CWH; submontane and montane sites

CDF, CWH, and (marginally) MH zones. The Redcedar – Salmonberry stands are known for the majestic stature of all associated tree species, including Douglas-fir, grand fir, Pacific silver fir, and Sitka spruce.

The Redcedar – Foamflower (*Thuja plicata – Tiarella trifoliata*) alliance represents the central concept of the order (Figure 13), while other alliances represent climatic and/or edaphic variations. Communities of the Sitka spruce – Foamflower (*Picea sitchensis – Tiarella trifoliata*) alliance are confined to submontane, seepage water–receiving sites and fluvial terraces in the hypermaritime and wetter maritime CWH subzones on the Queen Charlotte Islands, Vancouver Island, and the central coast of mainland British Columbia (Figure 37). Communities of the Yellow-cedar – Foamflower (*Chamaecyparis nootkatensis – Tiarella trifoliata*) alliance are confined to submontane to montane, very moist sites in similar climates as those of the Sitka spruce – Foamflower alliance (Figure 38). Communities of the Redcedar – Skunk cabbage (*Thuja plicata – Lysichitum americanum*) alliance are observed in submontane and montane wet sites throughout the CDF and CWH zones. Communities of the Pacific silver fir – Foamflower (*Abies amabilis – Tiarella trifoliata*) alliance are confined to the distributional area of Pacific silver fir; that is, predominantly high-elevation, cool and snowy climates (Figure 39).

The floristic composition of stands in the Redcedar – Salmonberry order are

FIGURE 37 *A low-density, old-growth stand of Sitka spruce, redcedar, western hemlock, and Pacific silver fir on a lower, steep, seepage slope in the central coastal mainland.*

FIGURE 38 *A high-density, naturally regenerated, second-growth stand of western hemlock and redcedar on a zonal site in the CWHvm subzone.*

diverse and their structure is multi-layered. The tree layer of old-growth stands usually has variable proportions of western hemlock and redcedar. Depending on climate, location, history of disturbance, and succession stage, Douglas-fir or Sitka spruce may also be present. The shrub layer is well developed, and includes: *Acer circinatum* and *A. macrophyllum* (in the south), *Oplopanax horridus*, *Ribes lacustre*, *Rubus parviflorus*, *R. spectabilis*, and *Sambucus racemosa*. *Athyrium filix-femina*, *Adiantum pedatum*, *Gymnocarpium dryopteris*, *Dryopteris expansa*, and *Polystichum munitu* are common ferns. Herb species include: *Achlys triphylla* (in the south), *Galium triflorum*, *Streptopus amplexifolius*, *S. roseus*, *Tiarella trifoliata*, *T. laciniata*, and *Trillium ovatum*. The moss layer can be somewhat sparse, including notably *Kindbergia praelonga*, *Leucolepis menziesii*, and *Plagiomnium insigne*. The associated soils include Brunisols, Gleysols, Podzols, and Humisols (SCWG 1998), with Moder or Mull humus forms (Green et al. 1993).

Typically, Redcedar – Salmonberry stands occur on lower, seepage slopes (Krajina 1969; Klinka et al. 2000, 2005). When the contribution from both soil and seepage is considered together, the supply of available nutrients is high. As a result, vegetation is rich in all macronutrients and the biogeochemical cycle counteracts the processes of soil podzolization characteristic of the CWH zone.

FIGURE 39 *An unmanaged mixed-species stand of redcedar and Pacific silver fir on a moist, nutrient-rich site in the CWHvm subzone.*

4.5.2 Site classification The purpose of site classification in the system of biogeoclimatic ecosystem classification (BEC) is to organize local ecosystems according to similarities in climate, edaphic conditions and, eventually, other environmental factors that strongly influence vegetation development (see Pojar et al. 1987 and Meidinger and Pojar 1991). The resulting site units are characterized and identified using environmental features that are linked to potential vegetation.

Site units, specifically site series, circumscribing plant communities of the *Thuja plicata – Rubus spectabilis* order were framed by Banner et al. (1993) and Green and Klinka(1994) (Table 4). We consider these sites as excellent candidates for growing redcedar as the primary commercial species. Several additional site series in the CWHvh, CWHwh, and CWHvm subzones that feature a significant proportion of redcedar in old-growth stands other than nutrient-rich were also identified. Most importantly, this suggests that redcedar is likely a variable climax component on a wider range of sites within the wetter, maritime portion of the CWH zone than originally described by Krajina (1969).

4.6 Ecological Role

As a nurse species, redcedar provides several beneficial ecological effects within the ecosystems in which it grows. These benefits include: 1) potential improvement of soil quality, 2) increases of plant and structural diversity (Figure 40), 3) soil stabilization, 4) self-pruning of timber crop species, 5) suppression of understorey vegetation, and 6) wildlife habitat. These items are discussed briefly below:

FIGURE 40 *The bark of old redcedar trees is calcium-rich, often supporting corticolous fern and bryophyte communities.*

4.6.1 Soil quality amendment Relative to associated tree species, redcedar is thought to have the highest foliar requirements for N, K, Ca, and Mg to achieve optimal nutrition (Minore 1983), and yet is known to have the lowest percent composition of N in its foliage (Minore 1979). Redcedar is also known to accumulate Ca and Mg in its foliage (particularly in older branchlets), promoting the cycling of these nutrients within the forest floor (Alban 1969; Radwan and Harrington 1986; Collins et al. 2001). Radwan and Harrington (1986) considered redcedar a Ca-accumulator in excess of its nutrient requirements rather than requiring Ca-rich soils, thereby acting as a “Ca-pump” to the site (Kimmins 1997).

Redcedar litterfall can have a dramatic impact upon forest floor chemistry and nutrient cycling activity. Alban (1967, 1969) found substantial differences in the soils under western hemlock and redcedar in eastern Washington and northern Idaho. More locally, Collins et al. (2001) examined forest floors in single- and mixed-species, second-growth stands of western hemlock and redcedar on zonal sites in the CWHvm1 variant in southern

TABLE 4 *Site series in the subzones of the CDF and CWH zones where redcedar is considered a significant (major) or potential climax species (Banner et al. 1993; Green and Klinka 1994).*

Subzone	Upland sites	Floodplain sites	Fluctuating water table sites
Moist Maritime CDF (CDFmm)	05 CwFd-Kindbergia 06 CwBg-Foamflower 11 Cw-Skunk cabbage	Cw-Snowberry	12 Cw-Vanilla-leaf 13 Cw-Indian plum 14 Cw-Slough sedge
Dry Submaritime CWH (CWHds)	05 Cw-Solomon's seal 07 Cw-Devils's club 12 CwSs-Skunk cabbage	Redcedar may be a Minor species	These sites have not been found
Moist Submaritime CWH (CWHmm)	04 BaCw-Oak fern 06 BaCw-Devil's club 11 CwSs- Skunk cabbage	Redcedar may be a minor species	These sites have not been found
Wet Submaritime CWH (CWHws)	04 BaCw-Oak fern 06 BaCw-Devil's club 11 CwSs-Skunk cabbage	Redcedar is probably absent	These sites have not been found
Very Dry Maritime CWH (CWHxm)	05 Cw-Sword fern 06 HwCw-Deer fern 07 Cw-Foamflower 12 CwSs-Skunk cabbage	Redcedar may be a minor species	Cw-Salmonberry Cw-Black Twinberry Cw-Slough sedge
Dry Maritime CWH (CHWdm)	05 Cw-Foamflower 06 HwCw-Deer fern 07 Cw-Lady fern 12 Cw-Skunk cabbage		
Moist Maritime CWH (CWHmm)	04 CwHw-Sword fern 05 BaCw-Foamflower 07 CwYc-Goldthread[a] 07/08 Cw-Salmonberry[b] 10/12 CwSs-Skunk cabbage[b]	Redcedar may be a minor species	These sites have not been found
Wet Maritime CWH (CWHwm)	redcedar is not a major component in any site series	Redcedar is absent	These sites have not been found
Very Wet Maritime CWH (CWHvm)	03 HwCw-Salal[c] 04 CwHw-Sword fern[c] 05 BaCw-Foamflower[c] 07 BaCw-Salmonberry[c] 09/12 CwYc-Goldthread[c] 11/14 CwSs-Skunk cabbage[c]	No floodplain site series have been described; redcedar may be a minor species in low elevations	These sites have not been found
Wet Hypermaritime CWH (CWHwh)	02 CwHw-Salal[d] 03 CwSs-Sword fern 05/03 CwSs-Foamflower[d] 06/04 CwSs-Conocephalum[d] 10/05 CwYc-Goldthread[d] 12/06 CwSs-Skunk cabbage[d]	No floodplain site series have been described; redcedar may be a minor species in low elevations	These sites have not been found
Very Wet Hypermaritime CWH (CWHvh)	01 CwHw-Salal 03 CwYc-Salal 05 CwSs-Sword fern 06 CwSs-Foamflower 07 CwSs-Devil's club 11 CwYc-Goldthread 13 CwSs-Skunk cabbage	Redcedar may be a minor species	These sites have not been found

a In the CWHmm2 variant.
b In the CWHmm1 and CWHmm2 variants, respectively.
c Historically in both Vancouver and Prince Rupert Forest Regions; now all Coast Forest Region.
d In the CWHwh1 and CWHwh2 variants, respectively.

British Columbia with respect to soil acidity (pH), and concentrations of total C, total N, mineralizable-N, and total Ca, Mg, K, P, and S. Forest floor pH and concentrations of mineralizable-N, total Ca, and K increased, while concentrations of total C and S decreased in order from hemlock to hemlock-redcedar to redcedar stands. These results are consistent with previous studies suggesting that forest floor decomposition and nutrient availability increase with increasing presence of redcedar. Redcedar forest floors are consistently observed to have very high pH (~6.0) and Ca concentrations relative to other species (Prescott and Vesterdal 2005).

Acid, mycogenous Mor humus forms commonly develop in hemlock stands, while less-acid, more-zoogenous Mormoder, Moder, or even Mull humus forms are more often found under redcedar stands (Krajina 1969; Green et al. 1993; Collins et al. 2001). Vesterdal and Raulund-Rasmussen (1998) suggest that forest floor characteristics and nutrient availability can be modified by the selection of appropriate crop trees. Harmer and Alexander (1986) have even hypothesized that the Ca-rich litter that undergoes nitrification might give redcedar a competitive advantage in nitrogen-poor soils, possibly improving the relative vigour and growth of redcedar over time in contrast to other species on similarly nutrient-poor sites.

However, the degree to which redcedar litterfall may "improve" the inherent quality of a site is in dispute. Although there is no doubt regarding the influence of redcedar litter upon several key chemical properties of the forest floor (pH and base saturation in particular), there is some recent controversy regarding the "improvement" of soil quality and resulting stand productivity. Redcedar is not like *Alnus* species, which actually add nitrogen to the system through the actions of their associated nitrifying bacteria. By challenging some basic assumptions involving litter decomposition and nutrient availability, Prescott et al. (2004) demonstrated that redcedar litter is actually one of the slowest to decompose of the major British Columbia tree species (hardwoods and softwoods). Prescott and Versterdal (2005) suggest that the higher levels of nitrate and microbial activity found in forest floor under redcedar are merely a result of higher pH, and do not reflect an elevated level of nitrogen availability. N-mineralization rates have been found to be relatively low, and are as likely controlled by site factors as they are by species composition (Prescott et al. 2000). Prescott and Versterdal (2005) also suggest that the tendency of redcedar occurring on richer sites (in spite of its tolerance of nutrient-poor conditions) is likely more associated with its tolerance of wetter moisture regimes (often found at the base of slopes receiving nutrient-rich seepage) than its ability to improve site quality through its litterfall. Finally, Prescott and Vesterdal (2005) state that redcedar "neither prefers N-rich conditions, nor does it create them."

4.6.2 Plant and structural diversity

Including a component of redcedar can increase plant and structural diversity. Most forests do not have uniform microtopography or ground surface material composition, but rather feature mounds and depressions, with a variety of different materials on the forest floor (e.g., litter, decaying wood, exposed mineral soil, coarse fragments, and surface water). The pattern and quality of microsites is reflected in the understorey vegetation. A dominance of ericaceous plants can be found in the presence of acid Mor humus forms and/or a high cover of decaying wood. In contrast, the dominance of herbs and ferns can reflect the presence of friable Moder and Mull humus forms and higher concentrations of plant-available nutrients. Once established, redcedar litterfall may modify forest floor properties, promoting the development of less acid Mor and Mormoder humus forms. Although the presence of redcedar may not directly increase the nutrient availability of a site, it may lead to an increase in microsite complexity, and in turn, the presence and diversity of understorey vegetation (as permitted by level of available light).

Tree-size diversity has been used successfully as a proxy for structural diversity. Using tree height and diameter, Varga et al. (2005) investigated variation in tree-size diversity between single- and mixed-species stands (50–120 years old) on intermediate sites in western Canada. They found that single- and mixed-species stands of shade-tolerant species (western hemlock and redcedar) had similar structural diversity. When mixtures were composed of shade-intolerant species (lodgepole pine and western larch) or shade-intolerant and -tolerant species (lodgepole pine and black spruce), the mixed-species stands were more structurally diverse than the single-species stands. Mixing redcedar with shade-intolerant species such as Douglas-fir or with tree species with a greater height growth rate than redcedar could improve stand structural diversity (e.g., development of multi-layered stands). This could be considered as a means to provide for biodiversity and other wildlife values in future stands. The longevity of redcedar snags will add greatly to future biodiversity and habitat values of the stand.

4.6.3 Soil stabilization With its wide edaphic amplitude, tolerance to flooding, and profuse root system (Figures 21 and 22), redcedar stands can occupy rocky, seepage slopes, high-bench floodplains, and stream-edge sites. This vegetative cover provides excellent protection for sensitive sites, lessening soil erosion potential during high rainfall and flood events (Figures 41 and 42).

4.6.4 Self-pruning In stratified stands where redcedar grows uniformly in the lower canopy stratum, it will shade the lower live branches of taller, shade-intolerant crop trees in the upper stratum, thus

FIGURE 41 *Redcedar stands on rocky sites can lessen erosion of shallow soils during heavy rains.*

FIGURE 42 *Redcedar stands, along with red alder, frequently occupy stream-edge sites and help stabilize streambanks.*

hastening their foliage mortality. As a result, these branches become shorter and smaller in diameter and take less time to fall off. In these situations redcedar will accelerate the rate of self-pruning and self-thinning of other crop species (thus improving timber quality).

4.6.5 Understorey vegetation suppression Under the stand conditions as described above, a uniform layer of subcanopy (intermediate) redcedar can provide substantial interception of light reaching the forest floor, thereby limiting the development of understorey vegetation. In some situations, this may be an effective tool to limit growth of moderately shade-tolerant shrubs, reducing competition for nutrient resources on potentially limited sites. This is a particularly important factor in managing salal competition on northern Vancouver Island.

4.6.6 Wildlife features Redcedar provides many resources important to wildlife. Conifers in general offer necessary protection for birds that nest in the early spring, and many species utilize redcedar seeds as a source of food in winter. Cavity nesters also find excellent habitat in the many redcedar snags.

Several squirrel species are known to reside in stands with redcedar as a major species (Ransome and Sullivan 2002). Many bat species prefer snags for day-roosts in older redcedar stands along the coast, particularly those with high solar radiation exposure (Waldien 2000). Pileated woodpeckers (*Dryocopus pileatus*) have also been shown to prefer redcedar for roosting (diameters > 150 cm), over associated species such as Pacific silver fir and hemlock (Aubry and Raley 2002). Conversely, the endangered marbled murrelet (*Brachyramphus marmoratus*) is known to be strongly associated with coastal old-growth forests, but the frequency of nesting activity is negatively correlated with the increasing composition and density of redcedar (Burger and Bahn 2004). The marbled murrelet is known to prefer western hemlock mistletoe platforms for nesting (A. Banner, pers. comm., 2008).

Coarse woody debris from redcedar produces valuable habitat for wildlife long after the tree dies. Its coarse woody debris adds significantly to long-term fish habitat development within riparian areas, and provides excellent shading capacity to enhance conservation of stream temperatures, improving both fisheries values and structure for terrestrial species. The long-lived and durable hollowed-out cores of redcedar snags can provide a key feature for bear hibernation dens. Also, in the coastal regions, bears preferentially feed upon fresh cambium of redcedar (bark stripping), relative to other associated conifers. It can be an important early-season food source in the spring (Mason and Adams 1989).

Finally, redcedar also acts as an important source of winter browse for several ungulates. Unfortunately, one of the species most influencing the regeneration of redcedar is the Sitka black-tailed deer (*Odocoileus hemionus sitkensis*). This species arrived from the mainland to Haida Gwaii in the early 1900s, and has proliferated ever since in the absence of predators or other natural enemies (Sharpe 1999). Due to the very high population of this deer on Haida Gwaii, this forager has been negatively affecting both the regeneration potential of redcedar (high rates of selective winter and spring feeding) and the populations of rare endemic plant species (Pojar 1999). The impact of this extreme browse pressure upon rates of redcedar regeneration is discussed in section 3.5.7: Mammals.

4.7 Succession

The importance of natural disturbance in maintaining and revitalizing healthy forests is well recognized today, and people are generally more inclined to mimic disturbance regimes rather than prevent them (Geils et al. 1995). Fire, insects, and pathogens are now recognized to be performing valuable ecological functions in directing the natural successional development of a forested landscape.

Disturbances can be classified as minor or major depending on the magnitude of change they impose on ecosystems. Minor disturbances that can affect all or only certain ecosystem components are not considered to have dramatic, ecosystem-altering effects. In contrast, a major disturbance has the potential (depending on the resilience of a system) to radically alter a system, causing a shift to a different successional stage. How various disturbance types can affect the presence or regeneration of redcedar is discussed below.

4.7.1 Minor disturbance – Stand maintaining Oliver and Larson (1996) characterized the true old-growth stage in stand development as exhibiting great variation in horizontal and vertical structure. Old-growth forests were also characterized as self-replacing and as being maintained through single-tree gap dynamics. They emphasized that tree mortality and growth of understorey trees in old-growth stands is achieved when trees regenerate and grow without the influence of external disturbances. Dead overstorey trees are replaced by understorey trees from the stand re-initiation stage of development. Oliver and Larson (1996) avoided the term "climax" because of its fuzzy and elusive concept, while others have considered climax stands to be conceptually similar to true old-growth stands.

In climax stands, dead canopy trees are (assumed to be) replaced by sub-canopy individuals of the same species mixture. The mixture (i.e., tree species composition) is not expected to change dramatically, but may fluctuate over time. The maintenance of old-growth structure and character through fine-scale single-tree gap disturbance is a dynamic ecological process (Daniels 2003). One species or group of species is not necessarily expected to continually dominate the stand, but long-lived, shade-tolerant tree species are expected to maintain some presence (Oliver and Larson 1996). Redcedar has the capability to regenerate successfully (either vegetatively or from seed) on various substrates (particularly on forest floor and decaying wood) under low light conditions, and as such "should be" a consistent component of coastal climax forests. (Refer to section 5.4.2: Natural regeneration for more seedbed substrate information.)

Perhaps the most extensive, majestic, old redcedar-dominated forests in the Lower Mainland are found north of Vancouver in the Capilano, Seymour, and Coquitlam watersheds. Daniels (1994, 1996, 2003) and others (Daniels et al. 1995, 1996, 1997) intensively studied the structure and dynamics of these old redcedar-dominated forests (CWHvm subzone) (Figures 43 and 44). The stands were considered to be in the old-growth development stage, probably within the transition variation (as evident by the presence of shade-intolerant Douglas-fir, fire scars, and distinct cohorts). In spite of the relative scarcity of redcedar seedlings, saplings, and low canopy trees relative to western hemlock and Pacific silver fir, it was concluded that redcedar populations would likely not diminish due to episodic small-scale disturbance and re-establishment. The predominance of peak age classes suggested that redcedar establishment was related to past disturbances caused by fire, climate, or climate–fire interactions. The question remains whether redcedar can be replaced within a stand in the absence of large-scale disturbance (i.e., if redcedar-dominated stands are permanent features in the landscape).

Western redcedar has the potential to germinate on a variety of substrates

FIGURE 43 *A fully stocked, uniform forest with a preponderance of old redcedar on a second-order drainage in the Seymour watershed.*

FIGURE 44 *One of the many old redcedar stands in the Capilano watershed maintaining high density and uniform appearance.*

(Figure 45) and grow in low light. In these stands, Daniels (1994) found established redcedar seedlings (mostly on windthrow mounds and decaying wood), but their numbers were low compared to western hemlock (Figure 46) and Pacific silver fir. These substrates provide elevated microsites, reducing the influence of competition from tall understorey vegetation. Shade-tolerant but shorter-lived western hemlock and Pacific silver fir both exhibit greater regeneration potential under their own canopy (Franklin and Dyrness 1973; Minore 1983, 1990; Daniels 1994) and are thought to be favoured in old-growth stands with heavy accumulations of decaying wood. The low abundance of redcedar was not interpreted by Daniels as an indication of its eminent exclusion. Redcedar can withstand lengthy periods of suppression (50 years or more [unpublished data from the HyP^3 project]) in the understorey before release, and chances remain high (or high enough) that established saplings can be recruited to the canopy layer. Although not explicitly studied, it appears that redcedar has the capacity to be a persistent, albeit variable, component in old-growth stands. This situation demands a revised successional descriptive label for redcedar, such as a polyclimax species.

4.7.2 Major disturbance – Stand replacing Large-scale disturbance events in old-growth redcedar stands are discussed in the context of the four generalized stages of stand succession: initiation, stem exclusion, understorey re-initiation, and old growth (Oliver and Larson 1996). Further discussion outlines stand development and renewal in relation to redcedar following major disturbance due to clearcutting, windthrow, fire, and (to a lesser extent) landslides.

Clearcutting Clearcutting by itself does not prevent regeneration of exposure-tolerant redcedar. Clearcutting followed by planting or natural regeneration of the desired species results in the development of even-aged or single-cohort stands.

FIGURE 45 *Natural regeneration of redcedar amidst bryophytes on a well-decayed downed log near Tofino, Vancouver Island.*

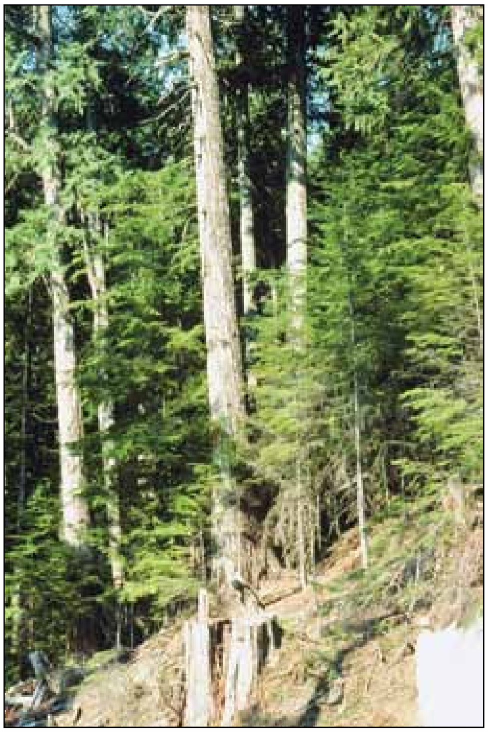


FIGURE 46 *Abundant advance regeneration of western hemlock in the shrub layer under the canopy of redcedar in the Seymour watershed.*

When species other than redcedar are established, redcedar may regenerate naturally during the initiation stage, depending on seed availability, site disturbance, site quality, and vegetation developed in response to disturbance. On salal-dominated and "high brush hazard" sites, the ingress of redcedar will likely be severely restricted due to competing vegetation. Provided the existence of an available seed source, redcedar may regenerate later during the understorey reinitiation stage, resulting in the development of stratified (uneven-aged or multi-cohort) stands (Figure 35). Redcedar may successfully regenerate naturally on some clearcut sites but it is not clear under which circumstances the greatest success occurs (i.e., with or without post-cutting site disturbance) (Figure 47).

Clearcutting on some water-surplus, nutrient-rich sites is followed by the rapid development (or re-growth after site disturbance) of understorey vegetation, notably salmonberry, which forms dense shrub thickets preventing natural regeneration of shade-tolerant conifers (Figures 48a and 48b). Easily exposed mineral soil is invaded typically by red alder, bigleaf maple, or willows. Thus, quite often, brushy, poorly stocked, open-canopy stands develop under these site conditions (Figure 49). These seral hardwood communities allow only sporadic establishment of the most shade-tolerant conifers, usually western hemlock and redcedar, which grow slowly and are visibly distinct from the canopy stratum. The possibility and benefit of growing redcedar under hardwood canopies as a management strategy is discussed in section 5.3: Site and Species Selection.

Windthrow Wind has been the primary natural disturbance agent throughout the outer coast. Wind most often creates a minor disturbance, but fierce storms can affect large areas. Apart from fine and coarse woody debris, windthrow creates mound-depression microtopography with a highly variable composition of materials across the ground surface. While depressions usually have a shallow surface organic layer, mounds can be entirely organic (either accumulation of forest floor materials or decaying wood), mineral, or a mixture of both. Windthrow by itself does not prevent regeneration of exposure-tolerant redcedar, but the rate of its ingress will depend upon seed availability, site quality, and vegetation developed in response to disturbance.

The landscape of northern Vancouver Island, particularly the Nahwiti Lowlands, features a pattern of relatively young, closed-canopy, hemlock–amabilis fir (HA) stands (Figure 50) and open-canopy, salal-dominated, old-growth, hemlock and redcedar–hemlock (CH) stands (Figure 51). Windthrow has been credited for improving forest productivity, because moss-dominated HA stands are more productive than salal-dominated CH stands. Lewis (1982, 1985) considered these stand types as two different seral stages within the same site-specific chronosequence, based upon differences in stand history. He predicted that windthrow-origin HA stands

FIGURE 47 *A dense, naturally regenerated stand of redcedar with some western hemlock and lodgepole pine on a burnt, cutover area in the CWHvh subzone (Tofino flats, Vancouver Island).*

FIGURE 48 *Salmonberry – Red alder communities effectively prevent ingress of shade-tolerant conifers; winter aspect (a) and summer aspect (b) of the same stand.*

will develop over time into CH stands.

While it is evident that HA stands can originate following windthrow events, it is not clear whether, in absence of major disturbances, they will develop into salal-dominated CH stands. First, HA stands seem to currently occupy somewhat drier and nutrient-richer sites than CH stands; therefore, technically, they cannot be two stages of the same chronosequence (McWilliams and Klinka 2005). Second, HA stands are virtually without advance regeneration of redcedar. A consistent, albeit variable, presence of redcedar in HA stands was observed only on those sites affected by fire or windthrow and always in close proximity to redcedar seed source. (Klinka 2006). Third, according to Weber et al. (unpublished): 1) in the absence of stand-replacing disturbance, both HA and CH stands are self-replacing, featuring reverse-J size distributions, and 2) the soil inoculation potential for redcedar in ectomycorrhiza-dominated stands may account for the virtual exclusion of redcedar seedlings from HA stands. Redcedar seedlings require arbuscular endomycorrhizal fungi–root relationships for successful establishment, and have difficulty establishing in arbusculae-sterile soil conditions (Minore 1979).

FIGURE 49 *Scattered saplings of redcedar and western hemlock in the understorey of a mid-seral Salmonberry – Red alder community.*

FIGURE 50 *A windthrow-origin hemlock–Pacific silver fir stand on a zonal site in the CWHvm subzone on northern Vancouver Island.*

Fire Fire has been a major disturbance factor of coastal forests since the retreat of the last glaciation, particularly in southern British Columbia. The ecological role of fire is reviewed by Oliver and Larson (1996) and Kimmins (1997). Because redcedar does not regenerate well (compared to other species) in the understorey of established stands, it has been assumed that fire has played an important role in establishing the redcedar-dominated forests on the coast. There have been relatively few studies of fire history in the CWH zone. Based on the distribution of shade-intolerant Douglas-fir, Schmidt (1970) reported extensive fires occurring nearly every century over the past 1000 years, with the most extensive fires occurring in the past 300–800 years (Green et al. 1998). Examining ages and Douglas-fir occurrence, Eis (1962) considered fire origin for many extant redcedar stands in the

Seymour and Coquitlam watersheds.

Arsenault (1995), Daniels (1995), and Green et al. (1998) have all studied and attempted to reconstruct fire history of the Vancouver watersheds. Arsenault (1995) identified fire as the most important large-scale disturbance on warm slopes in the Eastcap Creek area, which currently support extensive redcedar stands. Daniels et al. (1995) and Daniels (1996) examined the disturbance history of old-growth redcedar stands mixed with Douglas-fir. Based on the distribution of Douglas-fir and the presence of charcoal in the soil, they predicted that a large number of these stands originated following partial to complete stand-replacing fires. These fires occurred between 500 and 900 years ago, possibly related to past climatic variations. They (Daniels et al. 1995, Daniels 1996) determined the mean age of old redcedar trees in the watershed to range from 450 to 890 years. The age structure of the stands was irregular with one or more peak age classes, indicating that establishment and mortality of redcedar has been variable but episodic for over 800 years. It appears that regeneration peaks were synchronized with the major recognized fire episodes (Figure 52).

Although it is difficult to speculate as to the origin of the old-growth redcedar stands in these watersheds, it is likely that a significant portion of these stands, particularly those featuring old Douglas-fir, established following large-scale fires. In view of the long return interval of large-scale fires in these climatic zones (estimated at about 350 years), these stands are now self-replacing by small single-tree-level disturbances. Undoubtedly, catastrophic fires affected other coastal forests as well, which is consistent with the regional nature of these fires (Green et al. 1998).

The results of the recent study by Daniels and Gray (2006) provide a somewhat different story. Through an extensive dendrochronological investigation, they demonstrated that large-scale fires occur-

FIGURE 51 *An apparently truly old-growth western hemlock stand without redcedar on a near-zonal site (a), and an apparently truly old-growth redcedar–hemlock stand on a sloping zonal site (b) in the CWHvm subzone on north Vancouver Island.*

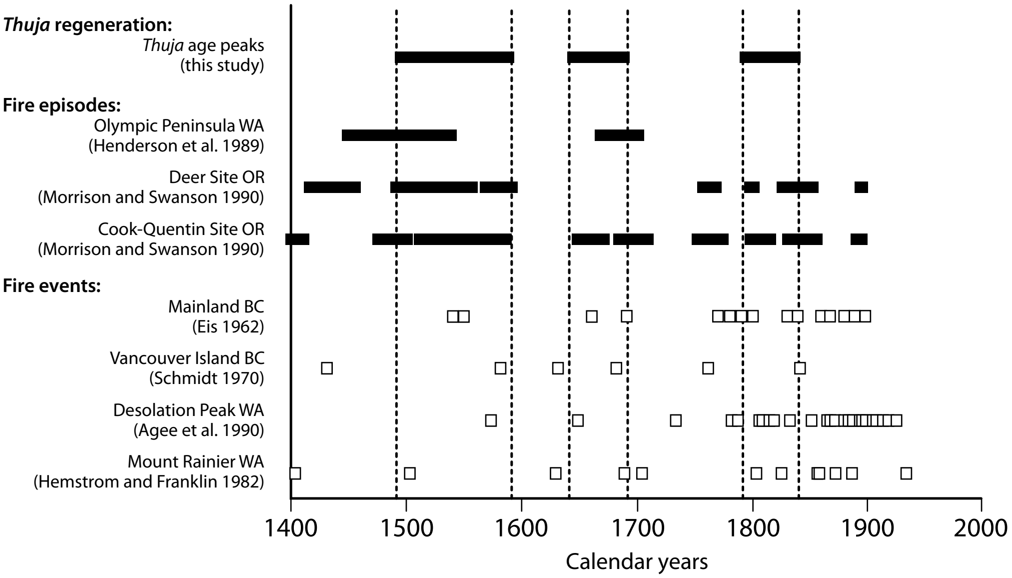


FIGURE 52 *Chronology of redcedar age peaks and fire disturbance in the Pacific Northwest. The left column identifies study areas and sources. Peak periods of redcedar regeneration are represented by solid bars bounded by the vertical broken lines. Fire episodes >1 year are represented by solid bar. Open squares show single year during which fires burned (Daniels 1995).*

ring at 250- to 350-year intervals are not the dominant disturbance force within the wet coastal temperate rainforest. Their evidence suggests that widespread stand-initiating fires were much less frequent than previously thought, and largely restricted to low- and mixed-severity events. The authors identify fine-scale gap dynamics as the dominant disturbance regime controlling the structure and successional development of most unmanaged forests in these areas. Obviously, both large- and small-scale disturbances play a role, and, in either case, redcedar has maintained its presence on the landscape. It is able to regenerate following wildfire and remain in its absence, being replaced through gap phase dynamics. Replacement levels may be greater following fire, but this remains to be determined. Two forest types observed on the central and north coast tend to substantiate the positive effect of fire on cedar regeneration (A. Banner, pers. comm., 2008): 1) redcedar stands 150–200 years old located on the central and north coast near historical First Nations Villages, which suggests that burning by aboriginals resulted in redcedar-dominated second-growth stands; and 2) redcedar-dominated stands established in the early 1980s on logged and burnt sites of the north coast. Redcedar's ability to regenerate on fire-created seedbeds is addressed in section 5.4.2: Natural regeneration.

Landslides In addition to large-scale disturbance, redcedar can also be observed playing a minor role in primary succession on colluvial materials where it may establish in the spaces between stones and boulders filled with friable organic materials (Klinka et al. 2005) (Figure 53). Other species, such as bigleaf maple and red alder, are also observed scattered across these sites. These talus communities are low-density, discontinuous, and dominated by tall shrubs such as vine maple and salmonberry, and by ericaceous shrubs.

FIGURE 53 *Redcedar occupying coarse talus deposits in the CWHvm subzone.*

4.8 Dendrochronology

Dobry et al. (1996) studied tree-ring sequences from old-growth redcedar and Pacific silver fir trees in the CWHvm subzone, near Vancouver, B.C., to improve understanding of past climatic fluctuations and climate-related events. Their study showed that ring widths of coastal redcedar on submontane and montane sites respond to variation in temperature and precipitation.

Response functions for the period from 1893 to 1990 demonstrate a stronger growth response to temperature but a weaker response to precipitation. The temperature in the previous fall and in February of the current year had a positive effect on ring growth; the late-summer precipitation of the current year had a negative effect on ring growth (Figure 54). These responses indicate that mild previous fall and winter temperatures, but not late-summer precipitation, have a favourable effect on (subsequent) redcedar radial growth.

Dobry et al. (1996) identified 1876 and 1959 as the best crossdating rings in redcedar ring-width series for dendrochronological investigations. The negative pointer (a much narrower ring than the previous one) was 1876, a year that was also observed in the redcedar cores from Bella Coola, and probably a response to the cold and dry summer of 1875 (the year of major fires in the Pacific Northwest), the very

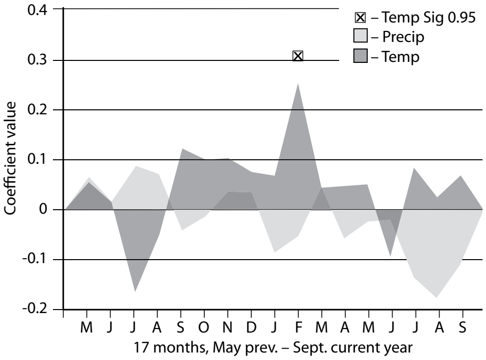


FIGURE 54 *Responses function of redcedar residual chronology of ring-width indices on 34 climatic parameters. Variation explained by climate is 42%. The February temperature of the current year is significant for diameter growth (Dobry et al. 1996).*

cold summer of 1876, and perhaps the cold winter of 1875–1876.

The negative pointer of 1959 was a response to the climatically extreme year of 1958 in which both the average temperature in July and the yearly average temperature reached the highest values in the 99 years of available climatic records (investigated prior to 1996).

These findings could mean that cold and hot summer temperatures (i.e., temperature extremes) have a negative effect on redcedar growth in the coastal region. This conclusion is in agreement with that of Seebacher (2007), who found reduced ring-width related to hot and dry summers, confirming drought as a contributing factor for observed redcedar dieback on the east coast of Vancouver Island.

4.9 Redcedar Dieback on Eastern Vancouver Island

Nearly 10 years ago, apical crown dieback of second-growth redcedar trees was observed on east Vancouver Island. Hebda (1999) linked it to climate change, suggesting that the south and central portions of eastern Vancouver Island would be outside the climatic amplitude of redcedar in the near future. This drought-changing climate hypothesis has not been tested, and drought could be either a predisposing, inciting, or contributing factor to the dieback.

4.9.1 Dieback study Seebacher (2007) studied the extent and potential causes of the dieback using dendrochronological techniques and water-balance modelling. The main objective of her study was to determine occurrence of the dieback and to explore potential causes.

Her 16 low-elevation, intermediate (near-zonal or zonal) study sites were located along the east coast of Vancouver Island from Victoria to Campbell River. The sites were located on zonal units within the CDFmm and CWHxm subzones, and CWHxm2 and CWHmm2 variants, representing a gradient of decreasing temperature and increasing precipitation (Green and Klinka 1994). All units are located within the rain shadow of the Vancouver Insular Mountains and Olympic Mountains and are relatively dry compared to other CWH subzones.

Using a transect sampling method, Seebacher (2007) detected only 27 dieback trees of the 512 trees sampled. Only four of her 16 study sites (four in each subzone) included redcedar with dieback. Study sites in the CDFmm near Qualicum Beach expressed the highest level of dieback (15 trees). Most dieback trees exhibited mild symptoms of thinning foliage. No dieback was observed in the CWHmm2 variant.

Supported by water-balance modelling, Seebacher (2007) found reduced ring-width apparently related to warm and dry summers on only a few sites. Similarly, growing-season temperature and precipitation were found to significantly influence the radial growth of redcedar on a limited number of sites. Residual ring-width of redcedar decreased with increasing June temperatures; conversely, residual ring-width increased with increasing spring and early-summer precipitation.

Seebacher (2007) concluded that climatically induced summer drought may be the primary cause of redcedar dieback; however, she considers complete loss of redcedar from Vancouver Island unlikely. She showed that the dieback is less extensive than one would assume based on observations made travelling along the Island Highway, which features recently exposed redcedar trees and altered soil moisture conditions.

However, not all her study sites appear to be zonal or near-zonal; for example, the Qualicum Beach site was associated with sandy soils; and high water table conditions were associated with Fluxnet, Shawnigan Lake, and Cowichan Lake sites. Her study also raises a number of corollary questions related to summer drought, such as: why is there no observed dieback of the more drought-sensitive western hemlock? Why is there virtually no redcedar dieback on low-elevation sites along the Sunshine Coast, where climate is similar to the CWHxm subzone? It is not surprising to find drought-induced dieback in water-deficient sites in the CDFmm subzone, where redcedar is likely requiring protection from the overhead (Douglas-fir) canopy. When exposed to open-area climates in this dry subzone, redcedar could be subjected to acute moisture stress, resulting in partial or total dieback.

4.9.2 Field investigation During the development of this manuscript, the redcedar dieback issue (Seebacher 2007) on eastern Vancouver Island became of great interest to us. To witness and explore this issue we visited areas north, west, and south of Qualicum Beach. The areas were predominantly within the CDFmm subzone and occasionally in the adjoining CWHxm1 variant to the north and west. In this section we present several of our anecdotal observations for consideration.

The dieback became immediately apparent upon leaving the Nanaimo ferry and driving north on the Island Highway. Dead-top and dead individuals and small groups of redcedar were observed scattered along the highway. Ten sites were investigated where redcedar dieback was noticed from the road. The sites ranged from drier and poorer sites (with scattered lodgepole pine, hemlock, and sub-canopy redcedar in second-growth Douglas-fir stands) to wetter and richer sites (with Sitka spruce, Douglas-fir, redcedar, red alder, and hemlock).

Several of these sites had obviously been affected by the relatively recent development of the new highway. Drainage flows had changed, and some sites were experiencing strong fluctuating water tables where (presumably) none had existed before. Once inside the stands it was noted that other species (such as Douglas-fir and hemlock) had also been killed, presumably by the raised water tables. The relatively rapid decomposition of those snags made them less obvious to observers outside the stands. It is possible that in this situation (altered moisture regime), redcedar was able to survive longer than its associates and thus became more visually obvious as vigour decreased. The redcedar snags have much less decay and are more visible from afar.

A few zonal sites were investigated. These sites commonly experience growing-season water deficit, with deep, relatively coarse soils. The stands were dominated primarily by Douglas-fir in the overstorey, with redcedar often detected in the subcanopy layers. Redcedar individuals observed growing in the canopy of these stands generally expressed symptoms of dieback, often severe (Figure 55). Understorey redcedar (sheltered) was very healthy in appearance, and helped to shade out competing salal, which was abundant in these stands (Figure 56). On some of the driest sites investigated, hemlock snags were identified even with healthy redcedar in the understorey.

One productive site was found in a depression near the Island Highway, containing redcedar, Douglas-fir, bigleaf maple, and hemlock. A cluster of three redcedar with full or partial dieback was observed. On this moist productive site, it is difficult to attribute the dieback to drought. Adjacent was a downed redcedar with obvious root rot (recent windthrow with still-green foliage) (Figure 57). With this observation, it seems that root- and butt-rot sources of mortality in relation to dieback need to be investigated further.

Dieback or mortality was not observed in every stand in the CDF. A young regenerating stand of pure redcedar was found on a fresh to moist site along the side of the Old Island Highway near Bowser. The 3- to 4-m saplings expressed no dieback, or mortality of any sort, and the stand appeared very healthy and vigorous

(Figure 58). Also, as we moved west into the CWHxm subzone, redcedar individuals on zonal sites could be seen growing well in exposed, dominant positions.

Key observations from eastern Vancouver Island

1. Redcedar dieback in the CDFmm stands was infrequent; redcedar in any stratum of the CWHxm stands showed good vigour.
2. On some driest sites, canopy hemlock snags were also observed.
3. On some wet sites where dieback was observed, there was evidence of recent disturbance and increases in water table.
4. All recently dead redcedar trees in the

FIGURE 55 *Redcedar dieback observed from highway near Qualicum Beach, Vancouver Island.*

FIGURE 57 *Root rot on redcedar, exposed by recent windthrow (still with green foliage) in association with Douglas-fir and bigleaf maple.*

FIGURE 56 *Understorey of Douglas-fir–dominated stand on a zonal site near Qualicum Beach, Vancouver Island. Note healthy redcedar in subcanopy.*

FIGURE 58 *Vigorous saplings established as a pure stand on a water-surplus site south of Bowser, Vancouver Island (CDFmm)*

All photos this page David Brisco

areas investigated appear to be in dominant crown positions, or have been left exposed to open-area climate following some recent disturbance.

5. Redcedar trees in the understorey were always healthy and vigorous with no evidence of dieback, even in those stands with dieback of dominant redcedar trees.
6. Redcedar snags last a long time. These snags become more visually apparent as the snags of other species (which may have died at the same time) rot and disintegrate. Snags of other species may be more readily attacked by fungi/insects and associated woodpecker activity.
7. Some dieback could be attributed to a vegetative mode of origin and consequential development of root rot.

4.9.3 Conclusions The CDFmm subzone of southeastern Vancouver Island is marginal for redcedar growth, as redcedar is exposure-intolerant in this climatic regime, and droughts are historically common. Under this climatic regime, redcedar cannot grow successfully in the canopy except on water-surplus sites. Due to recent summer droughts, redcedars on water-deficient (including zonal) sites, are prone to death, particularly if in an exposed situation. The redcedar stands observed in these areas of dieback were allowed to develop and exist due to fire suppression. Under natural conditions, the climatic regime would have produced fires in the understorey during extremely dry years, removing redcedar from the understorey and selecting for Douglas-fir as the dominant canopy species.

This is not to say that climate change will not influence the distribution of redcedar on the eastern side of Vancouver Island and elsewhere. We have devoted a large component of this report to the planning and selection of appropriate sites for the reliable establishment of redcedar in the context of climate change, and the associated rationale of these recommendations. However, based on our observations (albeit limited) of the "redcedar dieback" found within the CDFmm near Qualicum Beach, the situation does not appear to indicate the occurrence of events beyond the "normal" expectations for this subzone (i.e., no dieback was observed in the adjacent CWHxm). However, if widespread "dieback" of redcedar was observed on zonal sites in the CWH, that would be a much stronger indicator of possible climate change, and of much greater concern. The expressed apprehension over dieback in the particular area near Qualicum Beach appears to be due primarily to a combination of historical fire suppression, recent occurrence of periodically severe drought, high traffic, and widespread disturbance due to the construction of the 'new' Island Highway.

Will climate change decrease the prevalence of redcedar on the British Columbia coast? Possibly, but, at the same time, warming climates are expected to increase the frequency of fires (decreased interval lengths) in many of these same areas. Fire disturbance is considered one of the primary factors contributing to establishment of redcedar-dominated stands, so in certain locations a warming climate may actually benefit and promote the presence of redcedar. Alternatively, a warming and drying climate may prevent redcedar from dominating the canopy on certain sites (e.g., the zonal sites of eastern Vancouver Island). However, on water-surplus sites and in the understorey of zonal stands (Douglas-fir dominated), where redcedar is protected from exposure, it shall remain a significant component.

Some climate models (Hamman and Wang 2006) predict the CDF zone to increase in area by 300% over the next 70 years. If this occurs, then many locations that currently support healthy redcedar in a dominant and exposed crown position (CWH zone) can expect to witness major dieback, particularly in those areas currently adjacent to the CDF zone. However, our short field investigation gave us no indications of this trend yet occurring, at least not in terms of redcedar mortality. Much more work is needed to properly examine this topic, possibly establishing benchmark sites to detect any shifts in climate that would jeopardize the distribution of this valuable softwood species.

Supplementary observations from the Interior Cursory observations were also made upon the health and vigour of redcedar along the corridor from Revelstoke to Salmon Arm to Kamloops. This transect presents a transition through several zones, from the ICHmw3 variant in the east (considered climatically suitable for dominant redcedar) to the BGxw1 variant in the west (climatically unsuitable). This transition provides an opportunity to observe the possibly parallel dieback of redcedar on those sites that are marginal to its climatic tolerances. Proceeding from optimal to unsuitable climates (east to west), redcedar moves from a dominant position in the canopy to complete absence near Kamloops.

Healthy redcedars were observed in exposed and/or dominant canopy positions on zonal sites as far west as Sorrento (IDFmw2 variant), with diminishing occurrence progressing further west. In the transition to the IDFxh2 variant west of Squilax, redcedar could be seen only in the understorey and on wetter sites, and by Pritchard (PPxh2 variant), redcedar was absent as a common component of forested sites.

The only evidence of any recent redcedar dieback along the described corridor similar to that observed on Vancouver Island was located slightly northwest of Salmon Arm in the ICHmw2 variant before reaching Tappen. Several patches of redcedar showing crown dieback were observed in exposed positions near the highway. However, as these trees were on private lots, their disturbance history is unknown. Even on the steep rocky site further west, yet still east of Sorrento, where dieback would be expected (in the face of a warming and possibly drying climate), no obvious mortality was detected. The "dieback" of other species was observed in several locations along this corridor, with both hemlock and Douglas-fir snags identified in many locations, even within stands containing dominant redcedars.

In those areas where one would expect even mild drought to have an impact upon redcedar survival, no dieback situation was observed. The presence of redcedar shifted as expected between zones, but there was no explicit evidence that recent climatic changes had made previously suitable sites unsuitable (and had induced mortality).

Although most forest management practices were developed with the goal of enhanced wood production (Curtis and Carey 1996), many silvicultural practices can be readily modified to meet a broad range of multiple objectives (Curtis et al. 1998), including commodity products, wildlife habitat, and recreational values. Redcedar exhibits very little genetic variability (Bower and Dunsworth 1988), and yet is known to be an extremely "plastic" species in terms of the expression of its morphological characteristics (El-Kassaby 1999). Because of this key feature, silvicultural decisions made regarding the establishment and tending of this species will dramatically influence the quality of final crop products, perhaps more so than any other North American conifer.

The focal point of this section is on growing redcedar as a reliable crop species for future wood production; however, its other uses (such as a nurse species) may also be important silvicultural considerations (see section 4.6: Ecological Role).

5.1 Management Strategies

While the decision to establish and grow redcedar is site-specific (i.e., at the stand level), this decision should not be made without considering landscape-level management goals. Only after the geographic pattern of suitable sites is determined can redcedar regeneration plans be developed. An industrial strategy for redcedar regeneration on the Queen Charlotte Islands has been proposed by Lackey (1999).

Unlike some other coastal conifers, all available evidence suggests that redcedar will grow as a productive and valuable crop species in even-aged pure stands, even-aged cohorts in mixed-species stands, or even-aged cohorts in uneven-aged stands. These multiple options will influence the choice of reproduction cutting methods and appropriate regeneration methods. The rationale for growing redcedar in even-aged assemblages is discussed in section 3.6 (Growth Development Patterns). Oliver et al. (1998) emphasize that wood quality and growth rate of redcedar are reduced whenever it is overtopped by faster-growing species. In these situations, redcedar trees will develop long, dense crowns with large branches, and fluted, tapered stems.

In consideration of the unpredictable success of natural regeneration (including regeneration delay, which may be critical on high brush-hazard sites, irregular spacing, and potential difficulties in site preparation), planting redcedar is the most viable and reliable of regeneration methods. Even though silvicultural costs are higher (planting, and potentially vegetation or browse control), it will provide the security of stand regeneration and a more rapid arrival to free-growing status.

There are two contrasting approaches to growing redcedar as a crop species in even-aged stands: either close or wide spacing. Naturally established redcedar can be observed growing successfully at both spacing densities (section 5.5: Stand Management). The most appropriate approach will depend upon the desired nature, quality, and quantity of the wood products to be obtained from the managed stand.

In general, the management of even-aged, pure redcedar stands is considered simpler, less expensive, and more profitable than the management of mixed-species stands. Examples of young, pure, immature redcedar stands successfully established over a large area can be found in the Suquash Basin, Port McNeill, within Western Forest Products TFL 6 (Figure 59).

We have listed pertinent silvical and silvicultural characteristics of redcedar to guide its regeneration and tending (from Klinka et al. 2000):

- Reproduction capacity is high; seed-producing at an age of 10 years; heavy seed crops are frequent.
- Seed dissemination capacity is medium; adequate dissemination within 100 m from source.
- Potential for natural regeneration from seed in low light is low, but higher if vegetative reproduction is considered.
- Potential for natural regeneration in the open is high, providing the presence of exposed mineral soil or burnt forest floor.
- Potential initial growth rate (≤ 5 years) is high, may be as high as for the associated tree species commensurate to site quality.
- Response to spacing and thinning is high.
- Self-pruning capacity is high, providing a high initial stand density.
- Crown spatial requirements are low to medium.
- Windfirmness on upland sites is medium (higher than hemlock and lower than Douglas-fir).
- Light conditions beneath closed-canopy, mature stands are low and restrict the development of competing understorey vegetation.
- Potential productivity is high; site index (50 yr @ bh) up to 32 m on the most productive sites.
- Longevity is high, frequently > 1000 years.
- There is reduced susceptibility to various root and butt roots, making this a good alternative species on sites with these risk factors.

FIGURE 59 *An advanced regeneration stage of a redcedar plantation on a poor, CWHvm1/01 HwCw–Salal site in the Suquash basin.*

5.2 Growth and Yield

The available growth and yield information for coastal western redcedar is very limited in comparison to the amount existing for other associated coastal species such as Douglas-fir and western hemlock. The following information is compiled from local sources, Washington State, and Great Britain. The most current site index estimates utilized in British Columbia (Mitchell and Polsson 1988) originate from equations developed nearly three decades ago by Kurucz (1979, 1985). In spite of their age, these equations still appear to be reasonably accurate for estimating the growth of both managed and natural stands, and are still widely used (i.e., TIPSY-provincial silvicultural planning software).

Omule (1988) found early height growth in 28-year-old redcedar plantations on moist and nutrient-medium (zonal) sites in the CWHvm and CWHvh subzones on western Vancouver Island to be similar to the published height curves of Kurucz (1979) and Hamilton and Christie (1971). See Appendix 1 for the site index curves and tables produced by Mitchell and Polsson (1988) using the Kurucz equations.

To quantify relations between redcedar site index and categorical measures of site, Klinka (1994) sampled 17 immature, unmanaged, naturally regenerated, pure redcedar stands in the CWHdm and CWHvm subzones in the Malcolm Knapp Research Forest (Table 5).

Redcedar site index, years to breast height, and density in studied stands varied with site quality (soil moisture and nutrient conditions). Site index decreased from the drier CWHdm to wetter CWHvm subzone, and increased in each subzone from drier and poorer to moist and richer sites, and then decreased on wet, skunk cabbage sites (Table 5). Actual measured site index values (determined by stem analysis) were lower than predicted from the tables. The density of stands ranging from 50 to 60 years at breast height appeared comparable between the two subzones, and tended to decrease from 1200 sph on salal or flat moss and blueberry sites to 700 sph on lady fern, salmonberry, and skunk cabbage sites. Years to breast height (measured from 0.3 to 1.3 m discs) ranged from 3 to 9 years, with the actual number of years estimated at 6–10 years. The density range of 642–775 stems per hectare is similar to, albeit slightly higher than, the density of managed redcedar stands on intermediate sites in Great Britain (Hamilton and Christie 1971).

The Research Branch of the B.C. Ministry of Forests and Range provides site index estimates for crop tree species according to BEC site units. The 2006 estimates (Site Index Estimates by Site Series) are available on the Ministry of Forests and Range SIBEC website (www.for.gov.bc.ca/hre/sibec). For some species such as western hemlock and Douglas-fir, site index estimates have been developed from

TABLE 5 *Means of selected growth characteristics of 17 studied redcedar stands examined for site quality and by stem analysis. Bias was measured according to Mitchell and Polsson (1988) (from Klinka 1994).*

Stand	BH Age	Site index (m @ 50 yr bh)		Bias (m)	Years to breast height	Density (stems/ha)
		Measured	Predicted			
CWHdm/03 FdHw-Salal	51.7	24.4	24.8	-0.4	8.7	1250
CWHdm/01 Hw-Flat moss	56.5	29.0	29.4	-0.4	4.5	1144
CWHdm/07 Cw-Lady fern	59.9	30.7	31.8	-1.2	2.4	775
CWHvm1/01 HwBa-Blueberry	53.6	22.5	22.5	0.0	3.8	1225
CWHvm1/07 BaCw-Salmonberry	55.8	27.0	27.7	-0.7	2.9	642
CWHdm-vm1/12-14 CwSs-Skunk cabbage	54.1	23.8	24.7	-0.9	2.8	712

a large sample size. However, most redcedar SIBEC productivity estimates remain as the 1997 approximations, because the natural stands required for sampling are rarely found across the landscape.

Kayahara et al. (1997) investigated variation in site index with site quality in the CWHdm subzone and CWHvm1 variant, near Vancouver, studying naturally regenerated, immature, pure or mixed stands with western hemlock (Table 6). Their estimates also revealed trends of site index variation in relation to soil moisture and nutrient levels, and confirmed the validity of SIBEC productivity estimates.

The highest site index of redcedar was found on sites with no moisture deficit and high nitrogen availability (indicated by light green colour in Table 6). The mean site index was significantly lower in the warmer and drier CWHdm subzone than in the cooler and wetter CWHvm subzone. We predict a progressive decrease in site index in the CWHvm subzone from south to north. Although site index decreased outside this "green" edaphic region, slightly dry through very moist sites and poor through medium sites still support productive redcedar growth (indicated by light brown colour in Table 6).

There were no major differences observed between selected site series in site index estimates computed from Kayahara et al. (1997) and those given in SIBEC (2006) (Table 7). All the differences were < 1 m, except for the CWHvm1/07 and CWHvm1/14 site series, for which the differences were > 1 m and site index was greatly underestimated.

Kayahara et al.'s (1997) study and SIBEC estimates suggest a *wider* range of sites suitable for growing redcedar as a timber crop than indicated by the synopsis of preferred sites (Table 4), particularly within the wetter maritime and hypermaritime portions of the CWH zone, in which most sites are without a prolonged water deficit (see section 4.5: Vegetation and Site Classification and section 4.7: Succession).

TABLE 6 *Site index of redcedar in (A) CWHdm subzone and (B) CWHvm1 variant in relation to actual soil moisture and nutrient regime. Mean site index (m @ 50 years, 95% confidence interval in parentheses), and sample size are given for each edatope studied. Blank cells indicate absence of redcedar stands in the study area for those specific combinations of SMR and SNR (Kayahara et al. 1997).*

SMR/SNR	Very poor	Poor	Medium	Rich	Very rich
(A) CWHdm subzone					
Very dry	13.4 (5.4) n = 2				
Moderately dry		22.2 (7.2) n = 2			
Slightly dry		24.4 (0.6) n = 5	26.7 (1.4) n = 4		
Fresh			29.7 (0.8) n = 9		
Moist			30.3 (2.7) n = 3	32.2 (3.5) n = 3	29.0 n = 1
Very moist				29.1 (1.5) n = 3	32.0 n = 1
Wet			16.5 n = 1	25.4 n = 1	
(B) CWHvm1 variant					
Very dry					
Moderately dry					
Slightly dry		20.9 n = 1	22.0 (6.3) n = 2	24.8 (0.5) n = 3	
Fresh		23.0 (0.06) n = 5	24.7 (0.8) n = 6	26.6 (0.7) n = 7	
Moist			26.3 (0.6) n = 5	28.3 (0.5) n = 16	
Very moist		21.8 n = 1	25.2 n = 1	27.9 (1.6) n = 7	27.7 (0.6) n = 5
Wet			17.8 (1.9) n = 7	22.5 (0.5) n = 3	26.2 n = 1

TABLE 7 *Comparison of site index estimates of Kayahara et al. (1997) and SIBEC (2006) for redcedar for selected CWHdm and CWHvm site series*

Site series	Kayahara et al.(1997)	SIBEC (2006)
CWHdm/01 Hw-Flat moss	26.9	27.6
CWHdm/07 Cw-Foamflower	30.6	30.8
CWHdm/12 CwSs-Skunk cabbage	20.9	20.0
CWHvm1/01 HwBa-Blueberry	22.7	22.6
CWHvm1/07BaCw-Salmonberry	28.0	24.0
CWHvm1/14 CwSs-Skunk cabbage	22.2	19.4

Relatively little is known about the growth of redcedar, particularly in mixed-species stands. When grown in pure, even-aged stands, its site index will usually be lower than Douglas-fir, Sitka spruce, and even western hemlock. This does not necessarily mean that it has a lower volume. It can yield volumes higher than or comparable to Douglas-fir because of higher stand densities (basal area) (Hamilton and Christie 1971; Kurucz 1978; Edwards and Christie 1981; Curran and Dunsworth 1988; Oliver et al. 1988).

Oliver et al. (1988) observed the slow volume growth of redcedars in mixed-species, second-growth stands in western Washington, where redcedars were suppressed by faster-growing, shade-intolerant species. When not suppressed by faster-growing species, such as in pure, even-aged stands, redcedar grows quite rapidly. They suggested that pure, even-aged redcedar stands on upland sites in western Washington produce volumes similar to or greater than pure, even-aged Douglas-fir stands by 50 years on similar sites due to higher basal areas. Standing volumes of 379- 825 m^3 ha^{-1} were measured in 40- to 60-year-old, pure, second-growth stands on good sites in western Washington (Nystrom 1980). SIBEC studies have often reported second growth as more productive than estimates from the historical growth data of old-growth stands.

Yield tables of Edwards and Christie (1981) indicate that height growth of dominant redcedar trees is generally slower than that of other major crop species. However, both Hamilton and Christie (1971) and Edwards and Christie (1981) demonstrate that shade-tolerant tree species can grow productively at higher densities than shade-intolerant-species, compensating for shorter average heights. On medium sites, cumulative volume production at age 50 is comparable between redcedar, Douglas-fir, and western hemlock. For 80-year-old stands on medium sites, cumulative volume production of redcedar and western hemlock is similar, and greater than for Douglas-fir. A yield model on medium sites in British Columbia indicates yields of 70 m^3 ha^{-1} at age 40, 350 m^3 ha^{-1} at age 115, and 595 m^3 ha^{-1} at age 270; maximum current annual increment occurs at 82 years and maximum mean annual increment at 130 years (Nakoe 1978).

In Great Britain, the total cumulative volume produced by redcedar stands on poor sites is 50 m^3 ha^{-1} at age 20 and 953 m^3 ha^{-1} at age 80; on good sites, the cumulative volume produced is 232 m^3 ha^{-1} at age 20 and 1839 m^3 ha^{-1} at age 80 (Hamilton and Christie 1971). Interestingly, redcedar apparently grows faster than Douglas-fir in Great Britain on moist sites, and becomes increasingly more productive than Douglas-fir on higher-quality sites.

5.3 Site and Species Selection

Crown land in British Columbia is managed for many different purposes (timber, range, recreation, water, fisheries, wildlife), each requiring different management strategies. Most forest sites can support a variety of tree species, providing a range of possible options for the silviculturist. Needs, objectives, and climate will change over time; therefore, management strategies and silvicultural information must be continually updated to reflect the most current knowledge. To achieve a viable and appropriately regenerating plantation, all of these factors must be considered during the evaluation of potential site species.

Species selection and the choice of stocking level, combined with prompt and effective establishment, are crucial elements in creating a desired stand (B.C. Ministry of Forests 2000). For the purposes of producing a timber crop of redcedar, potential sites must have suitable attributes that provide for: 1) productive growth, 2) a reliable crop, and 3) feasible silvicultural management (Klinka and Feller 1984). Selected sites must be clearly within the major edaphic region of redcedar (Table 2) and reflect the recommended site classification of Banner et al. (1993) and/or Green and Klinka (1994) (Tables 4 and 8) (see section 4.5: Vegetation and Site Classification).

Although climate and species composition are known to have slowly changed over time, forest management decisions have been traditionally based upon the assumption that climate will remain relatively stable. The predicted rapidity of climate change over the next 100 years will require species compositions to shift at rates much greater than could be accommodated by natural seed dispersal and regeneration. Although climate change could lead to higher levels of forest productivity in some cases (Sohngen and Sedjo 2005), adaptation of current management strategies is necessary to conserve possibly vulnerable species and secure commercial plantations. To meet this challenge, existing forests must be assessed for their vulnerability to climate change, expectations of forest use must be revised, research and educational needs must be clarified, and forest policies to facilitate adaptation must be developed (Spittlehouse 2005).

Recent studies have explored the potential impacts of climate on British Columbia's future forests (Hamann and Wang 2006; Hebda 2006a, 2006b), basing their predictions upon ecosystem history, ecosystem response to climate changes, and climate impact models. The Royal British Columbia Museum models (Pacific Climate Impacts Consortium [online] www.pcic.org) predicts the disappearance of climate suitable for redcedar in much of the southern lowland British Columbia and an increase in northern British Columbia by 2080. In general, there is consensus that the future climate of the coastal region will be warmer, possibly with increased precipitation but with stronger summer droughts. It is not our intent to elaborate or postulate on possible outcomes of various climate-change scenarios at this time; all that can be done is to make redcedar crops reliable by rejecting drought-prone sites in all submontane and montane coastal biogeoclimatic subzones. After some deliberations, we have not considered sites within the present lower limits of the Mountain Hemlock zone for expanding the "reliable range" of redcedar, due to the inherent risk of snow damage. Keep in mind that care is needed when applying simulation-model-derived predictions of climate change at the local level. The microclimate of small-scale topographic features (e.g., frost pockets and rivers and lakes) may significantly modify larger-scale climatic trends, and local conditions will not be correctly represented into the future (Wang et al. 2006).

In view of the predicted temperature increases, sites on eastern Vancouver Island (CDFmm, CWHxm, and CWHmm subzones) and in the coast-interior transition (CWHds, CWHms, and CWHws subzones) are considered to be less reliable than those on central and west Vancouver Island (CWHvm and CWHvh subzones), the Queen Charlotte Islands (CWHvh and CWHwh subzones), and the coastal mainland (CWHdm, CWHvh, and CWHvm subzones). Due to its intolerance of ocean spray, shoreline and ocean spray–affected sites are excluded from Table 8, as are sites in the CWHwm, where redcedar is an insignificant component (Banner et al. 1993). In some of these less reliable subzones, modification of local climate due to topography (such as north-facing lower slopes) may alleviate the impacts of predicted warming to some extent, but these sites will need to be carefully assessed (local climatic as well as edaphic conditions) on an individual basis. Therefore, when evaluating suitable sites for future redcedar crops, it is imperative to consider local climatic as well as edaphic conditions.

We suggest that reliable sites would be fresh, moist, very moist, and wet sites, high-bench floodplain sites, and some fluctuating water table sites, all preferably with adequate nitrogen availability (Table 8). In view of the future potential for increased summer drought, we reject very dry, moderately dry, and slightly dry sites regardless of the contemporary presence of redcedar (Figure 60). We anticipate that fresh sites (no growing-season water deficit) will become drier, likely slightly dry, and possibly experience water deficits during the growing season. With expectations of increased precipitation, it is possible that certain wet sites may become very wet (i.e., with a water table at or above the ground surface during winter). Excess water availability may extend into the growing season due to unbalanced seasonal precipitation. Such soil moisture conditions may result in redcedar dieback (Figure 61). As a result, some skunk cab-

FIGURE 60 *A naturally regenerated, seral redcedar–hemlock stand on a water-deficient, rocky crest after cutting and fire (CWHvm2/03 HwCw–Salal) (a); old-growth (climax) redcedar–hemlock stands on rocky slope (CWHvh/03 CwYc–Salal) (b).*

FIGURE 61 *Dieback of redcedar under prolonged very wet conditions at the lake margin in the CWHvm subzone.*

bage sites could become unreliable for redcedar growth as well as for other associated tree species on these sites, such as Sitka spruce.

As with other associated species, redcedar site index is estimated to be low on moist to very moist, nutrient-poor to medium (often salal-dominated) sites, particularly in the hypermaritime subzones (Figure 62). These types of sites occupy a large area of the outer coast and are considered at or below thresholds for economic operability (see section 6.3: HyP^3 Studies). However, there is good evidence that present site index estimates derived from existing stands may not reflect the true productivity potential of redcedar on these sites (Banner et al. 2005) (refer to Table 11). Taking into account the prediction of a warming climate, we believe that new, managed stands regenerated to redcedar could be more productive than existing natural stands. On those sites with adequate plant-available nutrients, an increasingly warmer and drier climate should allow for the improving reliability of these sites for the production of valuable redcedar crops.

FIGURE 62 *An open-canopy, old-growth (climax) stand of redcedar, yellow-cedar, and western hemlock on a moist site in the CWHvh subzone.*

In contrast, selecting moist to very moist, nutrient-rich sites on upland and floodplain sites will result in regeneration difficulties and high costs associated with the management of competing vegetation. These costs would be encountered with many other crop species.

When mixed-species stands are desired, western hemlock, Pacific silver fir, or yellow-cedar with similar growth rates, or faster-growing grand fir, Douglas-fir, or Sitka spruce could be appropriate species depending on site quality. On richer, brush-hazard sites, hardwood species (e.g., black cottonwood, red alder, or bigleaf maple) could be utilized as temporary nurse species if regenerated in the spatial arrangement as proposed by McLennan and Klinka (1990) (Figure 63). Using rapidly growing black cottonwood or red alder as a nurse species to shade out

TABLE 8 *Generalized edatopic grid showing actual soil moisture regime and nutrient regime of the upland sites, floodplain, and sites with fluctuating water table that are suitable for growing redcedar as a reliable crop species. The site series names are given as numerical codes and abbreviated names. Current SIBEC estimates of site index (m @ 50 years breast height) are given in parentheses for each subzone or site series.*

SMR/SNR	Very poor–Poor	Medium	Rich–Very rich
Very dry	Not suitable	Not suitable	Not suitable
Moderately dry	Not suitable	Not suitable	Not suitable
Slightly dry	Not suitable	Not suitable	Not suitable
Fresh	CDFmm/05 Cw-Kindbergia (24.0) CWHxm/06 HwCw-Deer fern (not given) CWHdm/01 Hw-Flat moss (27.6) CWHvm1,vm2/01 HwBa-Blueberry (22.6, 20.0) CWHwh1,wh2/01 HwSs-Lanky moss (21.4, 16.0) CWHvh1,vh2/04 HwSs-Lanky moss (20.0, 22.8) CWHvh1,vh2/01 CwHw-Salal (16.0, 19.7)		CDFmm/06 CwBg-Foamflower (28.0) CWHdm/05 Cw-Tiarella (28.0) CWHvm1,vm2/05 BaCw-Foamflower (24.0, 24.0) CWHwh1/03 CwSs-Sword fern (20.0) CWHvh1,vh2/05 CwSs-Sword fern (24.0, 24.0)
Moist - Very moist	CWHds/06 Hw-Queen’s cup (24.0) CWHms1,ms2/05 HwBa-Queen’s cup (20.0, 16.0) CWHws1,ws2/05 HwBa-Queen’s cup (16.0, 16.0) CWHdm /06 HwCw-Deer fern (32.0) CWHmm1,mm2/06 HwBa-Deer fern (24.0, 20.0) CWHmm2/07 CwYc-Goldthread (16.0) CWHvm1,vm2/06 HwBa-Deer fern (23.3, 20.0) CWHvm2/09 CwYc-Goldthread (12.0) CWHwh1,wh2/04-02 CwHw-Salal (16.0, 16.0) CWHwh1,wh2/10-05 CwYc-Goldthread (12.0, 8.0) CWHvh1,vh2/11 CwYc-Goldthread (12.0, 12.0)		CWHds/07 Cw-Devil’s club (28.0) CWHms1,ms2/06 BaCw-Devil’s club(24.0, 24.0) CWHws1,ws2/06 BaCw-Devil’s club (24.0, 20.0) CWHxm/07 Cw-Foamflower (28.0) CWHdm/07 Cw-Lady fern (30.8) CWHmm1,mm2/07-08 BaCw-Salmonberry (28.0, 24.0) CWHvm1,vm2/07 BaCw-Salmonberry (24.0, 24.0) CWHvm1,vm2/08 BaSs-Devil’s club (22.1, 24.0) CWHwh1,wh2/05-03 CwSs-Foamflower (20.0, 16.0) CWHwh1,wh2/06-04 CwSs-Conocephalum (20.0, 12.0) CWHvh1,vh2/06 CwSs-Foamflower 24.0, 24.2) CWHvh1,vh2/07 CwSs-Devil’s club (24.0, 22.0)
Wet (water-collecting sites)	Not suitable	CDFmm/11 Cw-Skunk cabbage (16.0) CWHds/12 CwSs-Skunk cabbage (20.0) CWHms1,ms2/11 CwSs-Skunk cabbage (20.0, 20.0) CWHws1,ws2/11 CwSs-Skunk cabbage (16.0, 12.0) CWHxm/12 CwSs-Skunk cabbage (16.0) CWHdm/12 CwSs-Skunk cabbage (20.0) CWHmm1,mm2/10-12 CwSs-Skunk cabbage (20.0, 18.0) CWHvm1,vm2/14-11 CwSs-Skunk cabbage (19.4, 16.0 CWHwh1,wh2/12-06 CwSs-Skunk cabbage (12.0, 8.0) CWHvh1,vh2/13 CwSs-Skunk cabbage (16.0, 16.0)	
Floodplain sites			
High bench	Not suitable	CDFmm/07 Cw-Snowberry (28.0) CWHds/08 Ss-Salmonberry (28.0) CWHms/07 Ss-Salmonberry (24.0) CWHws/07 Ss-Salmonberry (20.0) CWHxm/08 Ss-Salmonberry (24.0) CWHdm/08 Ss-Salmonberry (32.0) CWHmm1,mm2/08 Ss-Salmonberry (28.0, 24.0) CWHvm1/09 Ss-Salmonberry (24.0) CWHwh1/07 Ss-Lily-of-the-valley (20.0) CWHvh1,vh2/08 Ss-Lily-of-the-valley (24.0, 24.0)	
Fluctuating water table sites			
Fresh - Very moist	Not suitable	CDFmm/13 Cw-Indian plum (28.0) CDFmm/14 Cw-Slough sedge (20.0) CWHxm,dm/13 Cw-Salmonberry (28.0) CWHxm,dm/14 Cw-Black twinberry (28.0) CWHxm,dm/15 Cw-Slough sedge (24.0)	

shade-intolerant shrubs provides marginal growth conditions for the shade-tolerant redcedar. Following the mixed planting layout design of Figure 63 with the redcedar and hardwoods spaced at 2.5 m minimizes the suppressing impact of the black cottonwood while maximizing crop tree stocking levels. The concept behind this approach is to create mixed plantations that mimic cottonwood–redcedar communities that develop in the course of succession on the high-brush sites.

Figure 64 illustrates the improved redcedar growth established in the way shown in Figure 63. The hardwood saplings could be removed at any time after 10 years or when the redcedar has reached the height of > 4 m without the risk of shrubs overtopping the crop trees. Given the relatively low level of management effort (compared to chemical or mechanical brush control) and ecologically benign nature of the nurse tree method, growing redcedar under the cottonwood or red alder understorey can be profitable if employed on appropriate sites.

Alternatively, if a mixed-species stand is desired on a site with lower brush hazard, it is possible to use redcedar as a means of shading out lower branches of Sitka spruce or Douglas-fir, thereby promoting the rate of self-pruning on the lower branches of those species. Due to its high shading capacity, once established on moderate brush hazard sites, redcedar can reduce the impact of the brush competition, and possibly reduce costs of vegetation control. To achieve this intended effect, larger stock would be essential, with seedling establishment required immediately following harvesting.

It has been demonstrated that mixed stands of western hemlock and redcedar do not exhibit aboveground productivity levels greater than single-species stands (Chen and Klinka 2003). For the best

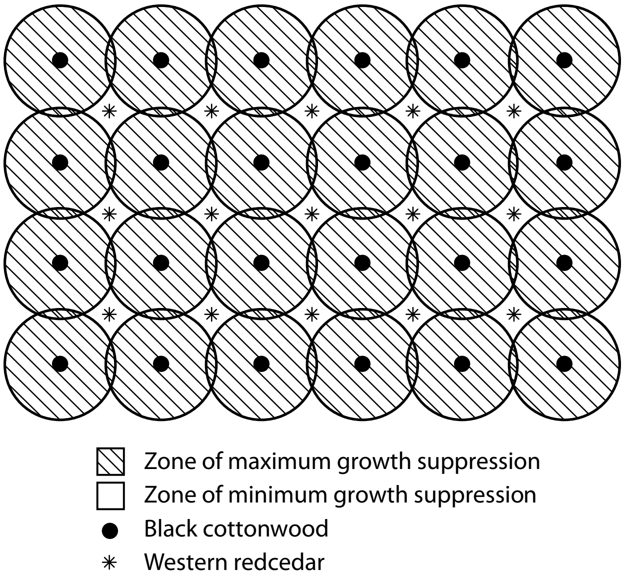


FIGURE 63 *Projection of the zone of minimum growth suppression for western redcedar under a canopy of 10-year-old black cottonwood (based upon 2.5-m spacing) for both black cottonwood and redcedar and growth rates characteristic of the CWHxm/08 (Ss – Salmonberry/coarse-skeletal) site type (McLennan and Klinka 1990).*

FIGURE 64 *Height–age relationship for redcedar saplings stratified into two growing zones at the 10-year-old cottonwood (based on 2.5-m spacing) on moist and rich sites in the CWHdm subzone (McLennan and Klinka 1990).*

results as a crop species, redcedar should be grown in even-aged, pure stands at high densities or with other species of similar shade tolerance (such as western hemlock) at relatively low spacing. In mixed-species stands, irrespective of shade tolerance of other species, arrangement of trees in the horizontal space (i.e., tree distribution pattern) should be group-random or -non-random to prevent over-topping of redcedar by faster-growing species, with the area of groups > 0.05 ha. In the end, the decision to regenerate redcedar will remain a mix of subjective but experienced judgement and objective factual evidence.

5.4 Cutting and Regeneration of Redcedar Stands

A regeneration cut is a timber harvest designed to promote the establishment of a particular tree species. Choosing an appropriate regenerating cutting method will depend on the species of choice, the site, the management objectives, and the desired products. For redcedar there are several options, although the manager must first consider if a pure redcedar stand is desired, or redcedar mixed with other species. Even when a mix with other species is desired, redcedar must be established immediately with larger stock to avoid it being overgrown by western hemlock advanced or seeded natural regeneration.

Burns (1983) suggests that clearcutting, variable retention cutting, patch-cutting, shelterwood, and selection cuttings are all appropriate for the establishment and growth of redcedar. Clearly, the choice of the harvest methodology will depend on site and management objectives, as it will influence the silvicultural feasibility, utility, productivity, and appearance of future redcedar stands. Detailed accounts of these various regeneration-cutting methods can be found in Smith (1986) and Nyland (1996).

What are the appropriate regeneration cutting methods that promote the establishment of redcedar? In consideration of the selected management strategy (section 5.1) and the relatively poor viability of natural regeneration (section 5.4.2), the appropriate cutting options are clearcutting (area > 1 ha), variable retention cutting (containing clearcut areas > 0.05 ha), patch-cutting (area 0.05–1.0 ha), and group selection (containing clear areas > 0.05 ha) (Klinka et al. 1994). These methods will facilitate planting and provide for the productive growth of redcedar in even-aged cohorts. Prior to any regeneration cut, seed trees must be clearly identified to ensure survival through harvesting operations. Leave trees must be windfirm, which should be a realistic expectation with redcedar due to its extensive root system.

If they survive, suppressed redcedars that are released during partial cuttings (shelterwood, release, and selection cuttings) will likely have developed large, long branches, spreading crowns, and tapered stem form (Oliver at al. 1988). Releasing suppressed advance regeneration may not provide acceptable levels of wood quality. Also, if evidence of root rot is observed in the area, a release could allow any resident rots to build up to high levels (using residual stumps as inoculum) and overwhelm the remaining stand structure. Even "fungi-resistant" redcedar cannot long survive a concentrated root rot attack (Koenigs 1969).

At present, redcedar stands harvested in the coastal region are generally old and often located on slopes and rugged terrain. The trees are large, and often decayed, and have large branchy tops. Wellburn and Peterson (1988) described harvesting of old-growth redcedar as difficult and expensive. Felling of large trees is dangerous, and often results in stem breakage. Large machinery is needed for yarding, loading, and sorting, and more breakage occurs during these operations. In consequence, costs of harvesting old-growth redcedar stands are high and lumber recovery is low. Such difficulties would be much reduced when harvesting second-growth stands.

It is because of these high costs that minimal investment has been historically placed upon the regeneration of redcedar, particularly in consideration of the easily regenerated but low-value hemlock, which is also considered an acceptable species for restocking most coastal redcedar sites. The combination of current poor economic conditions and the relatively high value of redcedar has led to the targeted harvesting of this species. The targeted harvesting of any high-value species at the expense of long-term economic operability and structural diversity can only be identified as high grading.

The occurrence of operational high grading (termed euphemistically as "High Retention Harvesting") has become enough of an issue within the coastal forest industry that the BC Forest Practices Board (FPB) has issued a special report detailing an investigation into the matter. (The FPB is an independent public watchdog that reports to the public about industry compliance with the *Forest and Range Practices Act*.) Their investigation (FPB 2008) describes a systematic shift (in cut profile) away from lower-value species (overmature hemlock with significant decay) towards high-value redcedar, thus shifting the residual stands to higher proportions of lower-value species. The very small openings created by this style of harvest severely limit the ability to restock the harvested areas with redcedar or other valuable species. In spite of stated intentions of replanting redcedar detailed in the approved cutting permits, the operators instead often rely on natural regeneration, which typically results in the establishment of western hemlock or amabilis fir. Alternatively, the openings may be small enough that no restocking is required.

The FPB investigation determined that only 33% (18 of 54) of the surveyed high-retention harvested stands had removed trees representative of the species (and value) profile. Unfortunately, the harvesting practices observed in the remaining 66% (n = 36) of blocks surveyed in the course of the investigation generated residual stands severely reduced in economic value and severely limited in terms of future harvest opportunity. A serious secondary consideration is that residual stands may contain a significant proportion of dwarf mistletoe infestation, rendering any potential seedling regeneration prone to continued infection and reduced value.

An additional difficulty (one of many) with the high-retention harvesting methodology is that the residual stands are often still considered fully stocked under current provincial policy, and so there are no specific replanting requirements. What little regeneration there is in these harvested locations is limited to the natural establishment of western hemlock or *Abies* species. Furthermore, the complexity of the stands resulting from retention harvesting will require the development of new tools to adequately assess productivity and predict future growth (FORCOMP 2008).

The removal of the largest stems while retaining much of the canopy substantially reduces the standing volume of the post-harvest stand, and provides no avenue for recovery of this volume. The site occupancy and high shading reduces the potential growth and vigour of any understorey saplings. Although high-retention harvesting practices may meet certain environmental and social objectives (visual, limited canopy disturbance), they do not provide for a long-term ecologically or economically viable forest industry.

5.4.1 Site preparation Site preparation for redcedar includes options for slashburning and mechanical preparation, with both decisions being site-specific (section 5.4.2: Natural regeneration). Slashburning would be undesirable on shallow, high coarse fragment, nutrient-poor soils, and mechanical site preparation would be undesirable on poorly drained, very moist or wet soils or fine-textured soils. Parker and Johnson (1988) state that disturbance is a major requirement for seed regeneration of redcedar. Fire may aid the natural regeneration of redcedar by creating burned forest floor or exposed mineral soil seedbeds (Feller and Klinka 1998) (Figure 65). Broadcast burning may not be feasible in partially cut sites or in small cleared areas. In these cases, burning piled slash would be more appropriate.

5.4.2 Natural regeneration The success of natural regeneration of redcedar is not limited by low seed production. When regeneration failures occur, they are often due to mortality during germination (Gashwiler 1967) and are related to seedbed quality and microenvironment, particularly microclimate (Minore 1983). Direct seeding in the fall may yield the greatest success (Minore 1983).

To investigate the notion of a regeneration peak after fire disturbance, and to verify seedfall, germination, and seedling growth on various substrates, Feller and Klinka (1998) carried out a 5-year study on sites in the Capilano and Coquitlam watersheds, north of Vancouver. They found high seedfall years in 1990/91 and 1994/95, and an ample supply of viable seed reaching the forest floor (200–1000 seeds/m^2). They also scattered 100 seeds in different sample plots (0.5 m^2), and after three growing seasons found that an average of only two seedlings per plot survived. It is because such large quantities of seed are required to obtain adequate stocking levels (Minore 1983) that planting seedlings is generally more strongly encouraged.

In terms of germination substrate, Minore (1990) and Haig et al. (1941) consider mineral soil to be the best seedbed (Figure 66). In old-growth stands, decaying wood is the most common (Parker and Johnson 1988), but produces the lowest survival rates. Germinant survival may be highest on mineral seedbeds, such as root mounds (Parker 1986) but subsequent seedling growth was better on decaying wood (Boyd 1959, 1965). Similarly, burned sites with exposed mineral soil favoured initial redcedar regeneration, yet unburned sites expressed better rates of long-term survival (Soos and Walter 1963). Feller and Klinka (1998) also found the highest germination success on burned plots, followed by exposed mineral soil, and then forest floor. Feller and Klinka (1998) determined that the highest growth rates occurred on burned forest floor, followed by unburnt forest floor; the lowest growth rate was observed on mineral soil seedbeds.

In terms of exposure, shaded seedbeds are associated with the best germination (Garman 1955); however, seedlings may fail due to poor root penetration (Sharpe 1974). Feller and Klinka (1998) also found higher germination success in protected understorey conditions compared to clearcuts, but growth rates were highest in clearcuts. Partial shade may protect seedlings and enable survival in moist conditions. However, once cover is removed, shallow depth of rooting may limit a seed-

FIGURE 65 *A pure, immature stand of redcedar that originated following fire on a colluvial slope in the CWHvm subzone is one of many corroborating adaptations of redcedar regeneration to fire disturbance.*

ling's ability to tolerate exposure and drought.

In undisturbed areas and in stands in which redcedar as a minor species is growing in the intermediate and suppressed canopy positions, it reproduces largely vegetatively (see section 3.2.1: Asexual reproduction). The occurrence of veglings is quite common in second-growth as well as old-growth stands, and is particularly abundant in the interior wet belt. Generally, trees that originated as veglings do not develop into desired crop trees, as fungi infect them (typically butt rot fungi) at an early growth stage.

5.4.3 Artificial regeneration When natural regeneration is not a feasible option, redcedar can be easily established by planting. Vegetative propagation from cuttings (following procedures described by Brix and Barker 1973, 1975) was routinely used by the B.C. Ministry of Forests and Range and industry as it was more cost-effective and reliable than reproduction from seed. Currently, propagation by seed has become the primary method for regenerating redcedar due to improved selection and storage methodologies. Techniques for collection, processing, testing, and storage of seed are given by Schopmeyer (1974). The seeds of redcedar are particularly prone to viability losses during long-term storage, although non-destructive methods to determine seed deterioration are being developed and implemented (Terskikh et al. 2008). A variety of containerized and bareroot seedlings is available and used for planting on the coast (Figure 67). Containerized nursery seedlings, which can be produced in 7 months, survive as well or better than bareroot stock when planted in coastal Oregon, Washington, and British Columbia (Curran and Dunsworth 1988).

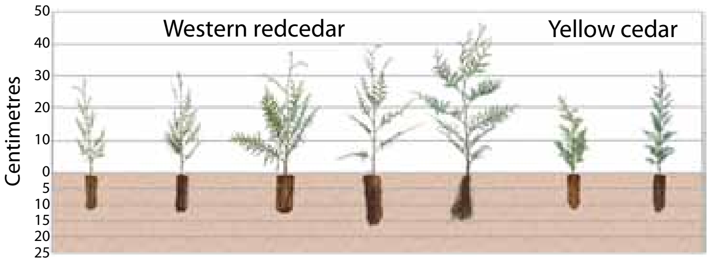
FIGURE 66 *Dense natural regeneration of redcedar on the exposed mineral soil of a roadcut.*

Typical seedling stock planted varies from 1+0 (315–615) styroblock plugs to 0.5+1.5 bareroot, ranging from 25 to 45 cm average heights. Most (~60%) planted stocktype is 410–415 PSB (Brown 1999), with the largest plugs (615 PSB) and bareroot plug transplants making up 7% of the total planted materials (3.5% each). The largest stock is planted on those sites with regeneration difficulties due to high brush competition, browse concerns, or possibly water deficits. Also, larger and sturdier stocktypes minimize the levels of Keithia fungal infection (in nurseries). A bi-weekly application of the fungicide Mancozeb through the growing season controls the spread of this disease in the nursery environment (Trotter et al. 1994).

Unless inoculated, redcedar seedling plugs directly lifted from a nursery express almost no association with mycorrhizal fungi. Within one growing season, most of these seedlings will have developed symbiotic relationships with vesicular-arbuscular mycorrhizae (VAM), primarily on newly formed (non-plug) roots (Berch et al. 1993). The degree of colonization of seedling roots by VAM was slightly influenced by the severity of burning of cutover during site preparation. The incidence of VAM inoculation was slightly reduced with greater burn severity.

It has been noted that very high rates of self-fertilization are observed in redcedar, and the genetic variability of this species is extremely low (section 3.7: Genetics). This combination of factors can lead to reductions in productivity (up to 8%) relative to out-crossed (non-selfed) stands (Wang and Russell 2006). Fortunately, many poorer performing individuals are naturally purged due to competition as crown closure is achieved. Wang and Russell (2006) recommend planting at higher initial densities to intensify the selection pressures and further reduce the negative effects of self-fertilization upon final stand productivity.

5.4.4 Establishment risks The establishment of any plantation can be a risky venture, requiring careful consideration of costs and benefits for any decisions made regarding species selection and stocking levels. The impact of these decisions must be borne for many years, during the full rotation of that stand, and possibly longer. Redcedar in particular, if established at high densities as recommended for maximum productivity (> 1600 sph) can be an (initially) expensive investment. The two greatest risks to that investment are brush and deer browse.



	CW PSB 410 112/80	CW PSB 412A 77/125	CW PSB 512A 60/220	CW PSB 615A 45/340	CW PBR 0.5+1.5	CY PSB 410 112/80	CY PSB 412A 77/112
avg. ht.	25 cm	30 cm	35 cm	40 cm	45 cm	25 cm	30 cm
avg. root collar diam.	3.0 mm	3.6 mm	4.3 mm	5.0 mm	6.0 mm	3.0 mm	3.6 mm

FIGURE 67 *Standard stocktypes available for western redcedar and yellow-cedar, with associated characteristics, coded designations, average height, and root collar diameter (Pacific Regeneration Technologies Ltd. [online] www.prtgroup.com/products/CWCY.html).*

Brush hazards On many of the most productive sites for redcedar establishment (moist and richer), brush hazard ratings are high. Redcedar has the ability to survive and slowly grow through high brush due to its shade tolerance (see section 3.3: Tolerances); however, this leads to poor growth form, heavy initial branching, and slow capture (crown closure) of a site.

Studies of planted redcedar seedling performance on Vancouver Island indicate a 3- and 5-year survival of 65% and 95%, respectively, with most of the mortality resulting from drought stress during the first growing season (Curran and Dunsworth 1988). Height growth ranged from 35 to 80 cm over five growing seasons. Two-year-old bareroot stock was found to be most effective for minimizing establishment costs; however, larger containers were more effective at achieving initial rapid height growth. Planting as early as possible has been most successful strategy. Survival is usually highest on upland sites and lower on wet sites. To ensure the maximum likelihood of establishment success in brush-hazard sites, Curran and Dunsworth (1988) suggest a five-rule protocol for planting:

1. Bareroot or container planting stock should have a shoot/root ratio < 2.5 and a caliper >3 mm (>412 PSB container stock).
2. Planting stock should not be stored for longer than 30 days.
3. Spring planting should occur as soon as possible after lifting from containers.
4. Use barriers (or chemicals) against browsing.
5. Plant immediately after harvesting operations are complete.

Shade-intolerant trees, shrubs, and tall herbs, especially on moist and nutrient-rich sites, easily overtop smaller redcedar seedlings. It has long been demonstrated that planting larger seedlings will increase survival, height, and/or volume production in numerous coastal species (Long and Carrier 1993; Newton et al. 1993; Rose and Ketchum 2003). Planting larger stock can be more effective than herbicide or mechanical treatments on high brush-hazard sites, and is often more economic. The impact of larger stocktypes on plantation growth is often long term, increasing even more over time. Larger bareroot stock was shown to attain a height of 6 m up to 8 years sooner than comparable smaller stock on the same brush-hazard site (Newton et al. 1993), thereby producing merchantable volumes more reliably, and in substantially shorter timeframes. Potential delays in plantation establishment due to the overtopping of undersized stock will increase costs by requiring either multiple replants and/or herbicide applications to release suppressed seedlings. The more quickly crown closure is achieved, the more rapidly site resources are secured for the desired crop species. This is particularly true for redcedar due to its very high shading capacity. The use of "teabag" fertilizers at time of planting has also been demonstrated to improve initial height growth, similarly reducing the need for intensive weed control measures.

Similarly, weed removal or chemical control has also demonstrated substantial increases in seedling growth response (Brisco 2004; Rose and Rosner 2005). Rosner and Rose (2006) examined the combined effects of seedling size and weeding for redcedar and some associated crop species, with the following results. The combination of larger seedling size and weed control produced the greatest volume growth rates. Redcedar growth in particular was most responsive to the initial seedling size. Rosner and Rose (2006) suggest that less competitive (more shade-tolerant) species may be more responsive to the use of larger seedling stock to keep them from being overtopped by competing vegetation. Douglas-fir did not exhibit strong growth response relative to initial seedling size. Also, larger seedling stock requiring less intensive weed controls are likely a more economically sound silvicultural decision.

Salal (*Gaultheria shallon*) is a common brush species on a wide range of sites that can compromise redcedar seedling growth throughout northern Vancouver Island. While salal does not affect redcedar to the same degree as western hemlock (Fraser et al. 1995), it has been shown to negatively affect height and root collar growth. Reduction in herbaceous competition leads to much more rapid initial height growth. Salal is an oxylophytic species, and very high application rates of nitrogen fertilizers (without phosphorus) have been shown to significantly reduce the vigour of its re-establishment (Bennett et al. 2004). Unfortunately, fertilizer applications at these levels (1000 kg N/ha) are expensive and can induce mortality in the seedling crop trees.

Browse damage Excessive deer browse can have a negative impact upon natural forest ecological systems and has been implicated in regeneration difficulties for many species (Trembley et al. 2007). Browse of redcedar seedling and saplings in plantations by deer is a major management issue throughout its range. Sitka black-tailed deer (*Odocoileus hemionus sitkensis*) was introduced to Haida Gwaii in the late 19th century, and the heavy browsing behaviour of this species has made redcedar in particular an especially difficult species to regenerate. It is almost uneconomic to replant this species in many locations.

Many deer repellents have been tested for their efficacy in reducing deer browse damage. Deer repellents work by fear, conditioned aversion, pain, and taste. Scent capsules use odours (simulated or real) derived from deer predators, either canine (wolf) or feline (cougar/tiger). BGR-P is a common scent product used by timber companies. Wolfin® capsules, a synthetic compound simulating wolf urine, was tested as a repellent against ungulate browsing (Nolte et al. 2001) but did not protect crop species from browsing. Anecdotal evidence suggests a very strong aversion to plantations inoculated with lion excrement (Pigott 2006), but this is hardly a realistic or economic alternative.

Products that affect palatability and/or induce pain often have capsicin as the active ingredient. One of these products, Hot Sauce®, was evaluated as a mammal deterrent by Wagner and Nolte (2000). A 6% Hot Sauce® solution applied to redcedar seedlings was found to be effective against black-tailed deer (*Odocoileos hemionus*) browse for 2 weeks; however, Big Game Repellent Powder® (BGR-P) was effective for the full 6 weeks of the study. BGR-P is a common product used by timber companies, promoting a fear response in the herbivores by mimicking predator scents—using putrescent egg solids (sulphur). The mountain beaver (*Aplodontia rufa*) was not deterred from food by any chemical repellent.

Garlic was evaluated and found to be a very poor repellent (Nolte et al. 1995). It lasted only for 2 days, whereas BGR-P reduced feeding damage for a period of 8 or more weeks. In a large study that compared 20 different products (Wagner and Nolte 2001), the most effective were those that included sulphurous odours and were directly applied to seedlings. Again, BGR-P was the most effective, keeping browse damage to minimum levels for over 12 weeks, although its effectiveness is dependent upon weather exposure and repeated applications.

Some recent research indicates that an alternative non-commercial product (hydrolyzed casein—a milk product) can be prepared at various concentrations for significant cost savings relative to commercial products, and may provide similar levels of seedling protection (Kimball and Nolte 2006). Also, the identification of monoterpenes as a natural agent making redcedar foliage less palatable to deer (Russell 2006) is another discovery that may facilitate the less intensive re-establishment of redcedar

Fencing or other barriers are long-term solutions to deer browse that do not typically require repeated maintenance, but are cost-prohibitive. In particular, complete fencing is extremely expensive and interferes with the natural movement patterns of resident forest-dwelling creatures. However, even with excellent fencing or other effective protective measures, it could take up to two decades for undamaged redcedar seedlings to achieve a size necessary to be immune to deer browse (Stroh et al. 2008).

In addition to ungulates, bears can cause significant damaging to juvenile stands of redcedar. Feeding bears (both black and grizzly) preferentially "barked" redcedar over western hemlock and Pacific silver fir (Sullivan 1993). Bears remove the bark and scrape their lower jaw against the exposed newly formed wood tissue, effectively girdling the tree. Barking damage mostly occurs is in the spring when the bark is easiest to remove and the vascular tissues most succulent. Redcedar trees are most frequently damaged when grown at wider spacings and/or on productive sites, where their radial growth increments are high (thicker layers of tasty new wood). The more vigorous the trees, the higher the percentage of bear attack. For example, Douglas-fir stands fertilized with urea experienced 4 times the feeding damage observed in controls (Nelson 1989). Sullivan (1993) found the greatest damage on redcedars at the widest spacing and on trees ranging from 12 to 20 cm in diameter. Up to 70% of redcedar was affected by age 33 years.

In a separate study, thinned stands were found to be 5 times more susceptible to bark stripping and sapwood feeding by bears than adjacent stands (Mason and Adams 1989). This study within the interior found that western larch and lodgepole pine were preferentially damaged, whereas redcedar and Douglas-fir were not attacked. Damaged trees were predominantly in the 10–20 cm diameter class. On the coast and in the interior, widely spaced young vigorous trees are most likely to suffer bear damage.

5.5 Stand Management

Relative to other tree species and when growing in pure stands, redcedar plantations should be regenerated at higher densities, with intermediate trees removed in a light thinning at about age 25. Stands of about 400 crop trees per hectare at time of harvest may allow maximum diameter growth without causing poor form (Hamilton and Christie 1971; Nystrom 1980). The rationale for maintaining a nearly closed canopy at all times is to encourage the development of desirable stem form (Figures 5, 38, and 68). In contrast to high-density plantations, Smith, J.H.G. (1988) suggests that faster-growing trees of acceptable quality can be grown at wide spacing if their lower boles are pruned. However, he notes that percentages of latewood will be significantly decreased.

FIGURE 68 *Canopy of a dense, naturally regenerated, fire-origin, immature stand of western hemlock and redcedar on a sloping zonal site in the CWHvm1 variant. Note the good stem form, absence of large branches, and narrow, short live-crown.*

Regarding tools for the management and prediction of redcedar growth and yield, there are very limited updated options. TIPSY® is a software product produced by the provincial government to assist in the evaluation of managed stands of known densities under different silvicultural regimes. Using TIPSY, a manager can evaluate the effects of different silvicultural treatments upon the final stand condition, and determine the most appropriate treatments to achieve desire stand product objectives. Unfortunately, TIPSY (and the TASS yield tables from which TIPSY results are interpolated) is considered fairly unreliable for redcedar (see Table 9). This unreliability stems from the poor representation (sample numbers) of redcedar stands within the provincial database and a lack of local knowledge regarding the response of redcedar to various cultural treatments.

5.5.1 Spacing and pruning A density of approximately 2400 trees per hectare (about 2-m spacing) appears to allow for unimpeded growth to 15 cm in diameter (McArdle et al. 1961; Minore 1983; Oliver at al. 1988). The trees can grow to minimal merchantable diameters before the onset of competition with adjacent redcedar

TABLE 9 *Reliability ranking of TIPSY yield output, by species (www.for.gov.bc.ca/hre/gymodels/tipsy/)*

	Species**									
	Fdc	**Hwc**	**Ss**	**Cw**	**Pl**	**Sw**	**Fdi**	**Hwi**	**Dr**	**At**
Site Index*	**Reliability*****									
High	G	G	M	P	G	M	M	P	P	M
Average	M	M	M	P	G	M	M	P	P	G
Low	P	P	P	P	M	P	P	P	P	P

* Site Index: for coastal species High =35, Average =25, Low=15; for interior species High=20, Average=15, Low=10.

** Species: Fdc (coastal Douglas-fir), Hwc (coastal western hemlock), Ss (Sitka spruce), Cw (western redcedar), Pl (lodgepole pine), Sw (white spruce), Fdi (interior Douglas-fir), Hwi (interior western hemlock), Dr (red alder), At (trembling aspen).

*** Reliability: G = Good, M = Moderate, P = Poor.

saplings for resources, allowing the first thinning to be a commercial operation. The provincial stocking standards (B.C. Ministry of Forests 2000) specify a targeted range of 800–900 well-spaced crop seedlings per hectare for the sites listed in Table 5. These are very low densities, and unlikely to produce high-quality redcedar stands. In consideration of the current "Results-Based" focus on regeneration standards, forest companies have the option to develop their own stocking standards, detailing them in their Forest Stewardship Plans. However most still rely on these Forest Practices Code Free-Growing Guidelines developed by the B.C. Forest Service in the mid 1990s. Individual growth rates may be higher at wider spacings, but crown and stem form will be negatively affected (Oliver at al. 1988; DeBell and Gartner 1997; Singleton et al. 2003).

The influence of initial spacing, site quality, and stand density on growth and yield of redcedar was studied intensively by J.H.G. Smith (1980, 1988) in stands grown near Vancouver—in the Malcolm Knapp Research Forest and in Pacific Spirit Park. He concluded that the best means of ensuring the development of high-quality timber was by pruning the lower boles of planted trees. The costs of pruning may be offset by the improvements in timber quality and a higher-value end product. N.J. Smith (1988) argues that natural pruning will be so slow that only 1 or 2% of clear lumber could be grown in a typical rotation. His projections suggest that such widely spaced redcedar stands (about 4.5 m) would produce very high yields with large piece sizes. At age 100, predictions of merchantable volume per hectare ranged from 1460 to 2651 m^3 ha^{-1} depending on initial spacing (Smith, J.H.G. 1988). Projected volumes for redcedar were lower than for Douglas-fir at the closest spacing, but greater at the widest spacing of 4.5 m (approximately 485 trees per hectare).

The establishment density of a redcedar plantation will directly influence the development of the understorey shrub and herb community. As canopy cover increases, light conditions in the understorey will deteriorate. On sites in the CWHvh and vm subzones, the cover of both salal and salmonberry was found to be inversely related to canopy cover (Figure 69), with both species shaded out when the canopy cover was approximately > 85% (Klinka et al. 1996a).

5.5.2 Stand density management diagram

Using data from natural stands and plantations, N.J. Smith (1989) constructed a stand density diagram framework that relates net standing volume to stem survival. This was updated by Farnden (1996) (Figure 70). Height and diameter isolines are overlain on the diagram, as are appropriate points of crown closure, maximum current annual increment, and mean annual increment. The diagram is entered by determining the density (stems per hectare) and quadratic mean diameter of the stand. On average, a stand will tend to follow the survival isolines, moving from the lower right to the upper left over time.

If young trees are expected to suffer

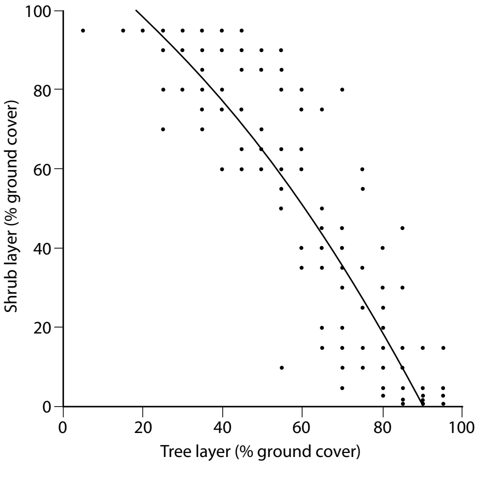
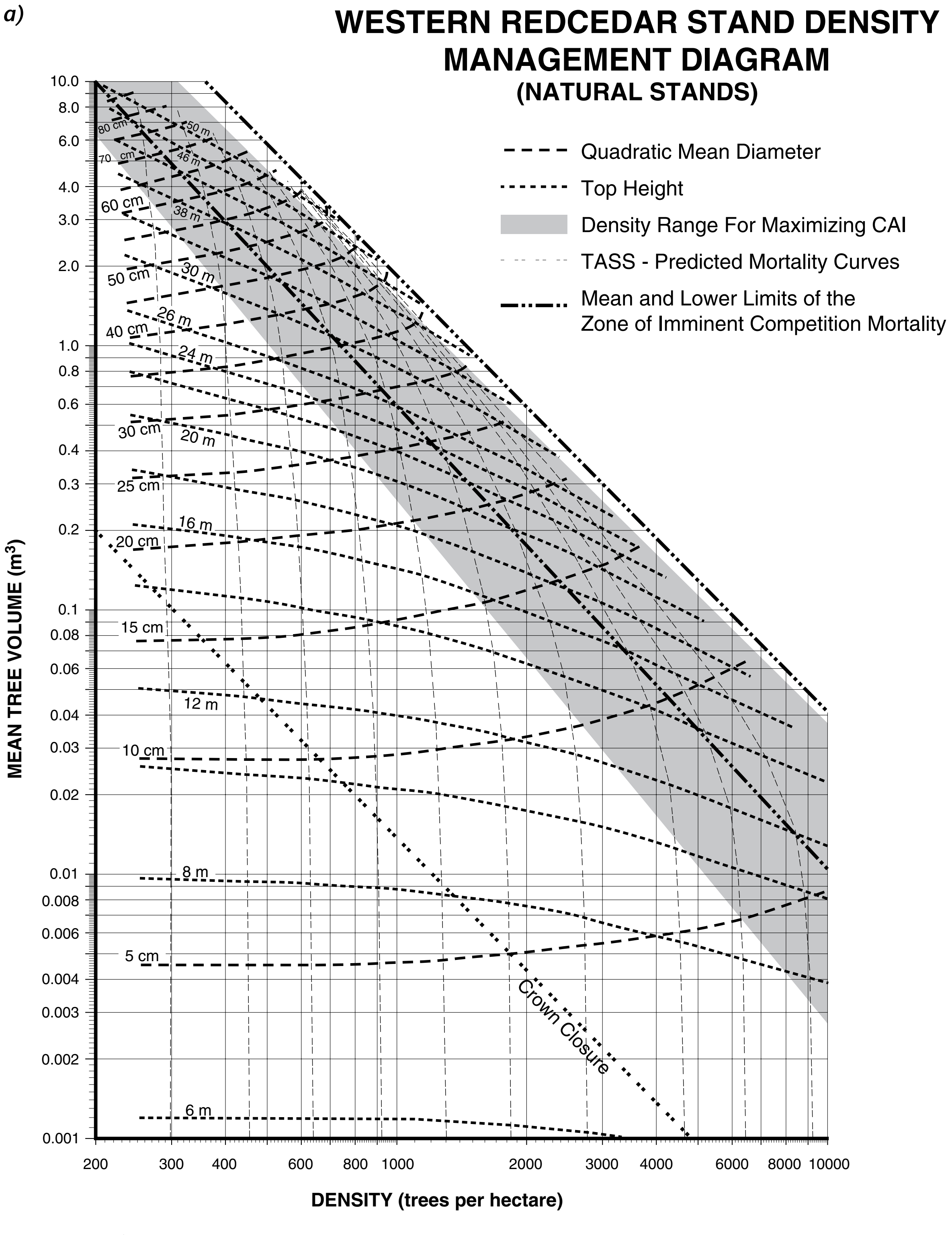


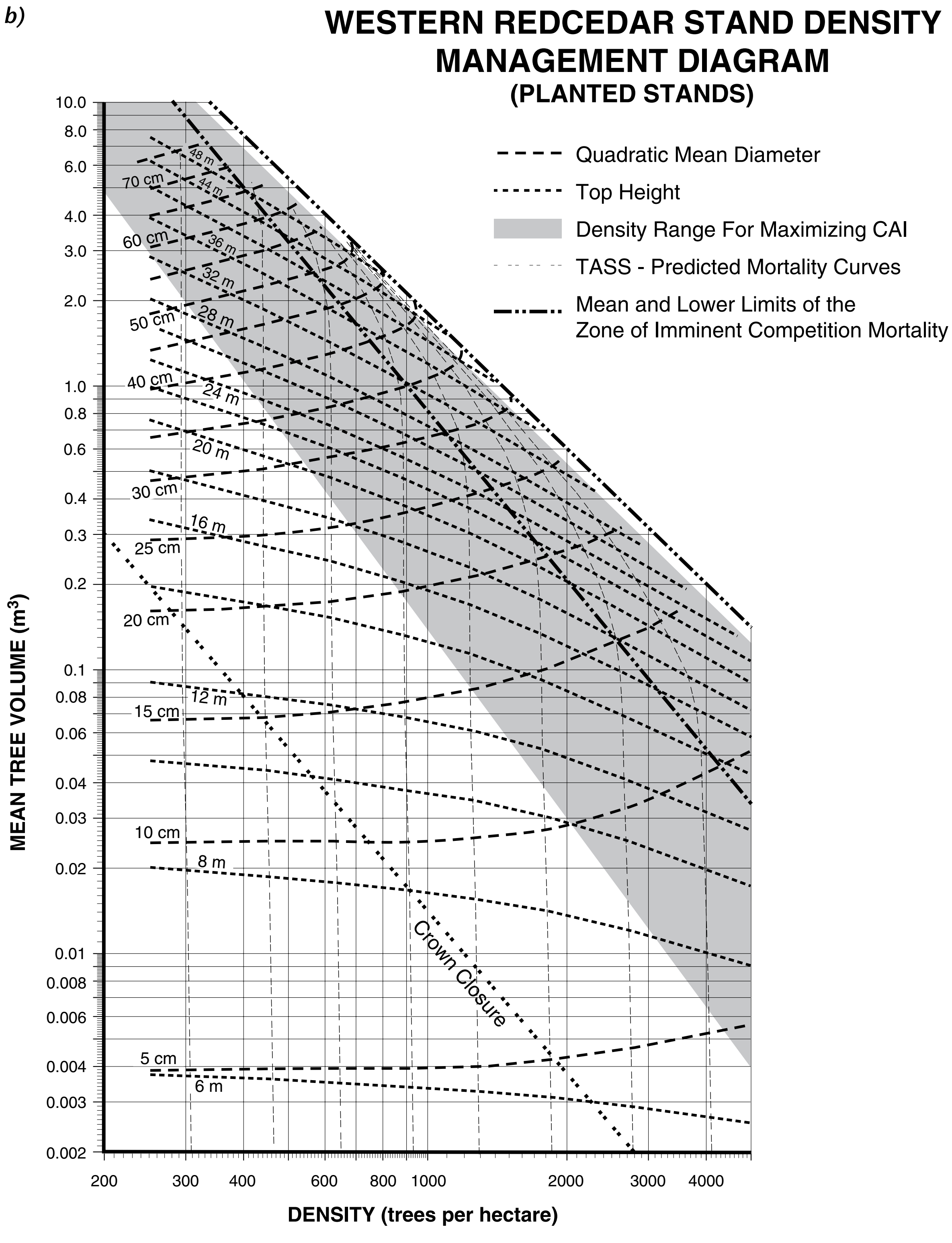
FIGURE 69 *Scattergram and fitted regression line of estimated shrub cover on estimated canopy cover (Klinka et al. 1996a).*



Produced by Craig Farnden R.P.F., May 31, 1996.
Produced for Silviculture Practices Branch, B.C. Ministry of Forests
Funding provided by Forest Renewal B.C.

Data Source: TASS generated managed stand yield tables contained in the computer program WINTIPSY version 1.3 (B.C. Ministry of Forests, Forest Productivity and Decision Support Section)

FIGURE 70 *Stand density management diagrams for both natural (a) and planted (b, next page) stands of redcedar (from Farnden 1996).*



FOREST RENEWAL BC

Produced by Craig Farnden R.P.F., May 31, 1996.
Produced for Silviculture Practices Branch, B.C. Ministry of Forests
Funding provided by Forest Renewal B.C.

Data Source: TASS generated managed stand yield tables contained in the computer program WINTIPSY version 1.3 (B.C. Ministry of Forests, Forest Productivity and Decision Support Section)

FIGURE 70 *Continued*

competition from understorey vegetation (e.g., from moderately shade-tolerant salal), it would be prudent to achieve full crown closure as soon as possible. This would be of particular importance on marginal sites, especially those prone to water deficit and/or nutrient deficiencies Full crown closure is parallel to, and slightly above, the 78% crown closure line shown in Figure 70. The slope of the line is steep, suggesting that crown closure occurs at a much lower relative density in stands with initially more stems per hectare. Dense natural regeneration or plantations would be desirable in this effect but they will require future density control to ensure maximal growth increment and high-quality timber production.

5.5.3 Thinning Selection of a thinning regime for a particular redcedar stand is a decision that will depend upon specific stand, site, and management factors, particularly on the overarching management objectives and desired end products. As it is impossible to account for all potential variations in these factors and in consideration of limited regional knowledge on growth and yield of redcedar, prescribing thinning regimes for pure or mixed-species redcedar stands must remain a local, and largely personal, decision. However, certain guidelines may be provided.

Oliver et al. (1988) recommend delaying thinning until lower branches are dead to keep lower branches from surviving. They suggest that a large portion of improved growth following release is added to large branches and not to stem wood. Depending on site quality, Hamilton and Christie (1971) and Nystrom (1980) recommend light thinning as early as 21 years and as late as 30 years with the aim of 350–750 crop trees per hectare on high- and low-productivity sites, respectively.

Thinning policies (i.e., intensity of thinning, thinning cycle, and thinning type), for redcedar are discussed by Hamilton and Christie (1971) and Edwards and Christie (1981). It is generally assumed that the method of thinning is an intermediate type that removes subordinate trees and encourages the growth of the selected, not necessarily dominant, crop trees. If the management intent is to grow clear wood for poles and high-quality sawlogs, then a higher stand density should be retained well into mid-rotation age to promote self-pruning. The effect of side-shade on branch growth and self-pruning is illustrated in Figures 71 and 72).

Harrington and Wierman (1985) determined that, in natural stands on poorly drained sites, redcedar was more responsive in height and diameter growth to fertilization than to early thinning. Combined thinning and fertilization increased growth significantly more than either treatment in isolation.

When planning for the thinning of redcedar stands, consideration should be given to the stem form of the dominants relative to the codominant trees. If many of the largest trees are expressing high degrees of taper (and possibly fluting), DeBell and Gartner (1997) suggest removing a portion of the dominants with the greatest degree of taper. Codominant individuals with better stem form and smaller-diameter branches should be left for release. A high degree of fluting results in wood waste during processing. Once the high costs associated with defects, debarking, and peeling highly fluted stems are accounted for, it may be more economic to leave the less tapered or fluted trees of smaller diameter for a future harvest of higher-quality wood.

5.5.4 Fertilization When soil moisture deficits are not a factor limiting growth, redcedar growth (like most agricultural crops) can be consistently improved by fertilization. The available literature suggests that young redcedar, even on poorly drained sites, responds in a conventional way to additions of nitrogen (Harrington and Wierman 1990). However, specific characteristics of the site will dictate the

FIGURE 71 *A half-shade crown (a) and three-quarters shaded crown (b) of immature redcedar trees showing long, coarse, and persistent branches on the unshaded portion of the stem.*

ability of a stand to respond to any nutrient amendments. Weetman et al. (1988) pointed out that only with an understanding of nutrient requirements of tree species and the interaction of site quality, foliar nutrient concentration, and species growth can one identify possible nutritional problems and prescribe appropriate silvicultural treatments.

In spite of its wide edaphic tolerances and ability to grow on nutrient-poor sites (section 4.3: Edaphic Amplitude), redcedar growth can be severely limited by deficiencies in certain macro- and micronutrients (Radwan and Harrington 1986). Stands experiencing specific nutritional deficiencies may exhibit symptoms that can be visually identified in the field (Walker et al. 1955; Ballard and Carter 1986). These visual symptoms of deficiency with their interpretations are listed in Appendix 2: Levels and symptoms of nutrient deficiency. However, diagnosis of nutrient deficiencies solely by the interpretation of visual symptoms may not be

FIGURE 72 *Excellent stem form and high, narrow live-crowns of redcedar trees that have developed in high-density (fully shaded) conditions.*

exact or reliable. For more precise nutrient diagnoses, chemical analyses should be performed upon collected foliage. Note that foliar collection requires the observation of particular protocols to ensure that data are consistent with available interpretations. The nutrient interpretations presented in Table 10 from Ballard and Carter (1986) were based upon a greenhouse seedling study performed by Walker et al. (1955), and it has been suggested that their applicability to older stands is questionable (Harrington and Wierman 1990). Concentration ranges of foliar nutrients vary between interior and coastal populations (Radwan and Harrington 1986) and were strongly correlated with productivity. As operational fertilization of forest stands is becoming more commonplace, and because foliar concentrations are so valuable for evaluating stand nutrient deficiencies, updating these 50-year-old interpretations is strongly recommended.

Nitrogen was found to be the most growth-limiting nutrient for redcedar seedlings, followed by phosphorus (Walker et al. 1955). With the application of appropriately tailored fertilizer compositions, redcedar has the ability to respond with impressive growth results. When grown in well-watered soil fertilized with nitrogen, phosphorus, and potassium, redcedar seedlings will outgrow seedlings of Douglas-fir, grand fir, Sitka spruce, ponderosa pine, and western hemlock.

Using urea as the source of nitrogen appears to be similarly effective to, or more effective than, ammonium nitrate in stimulating growth in redcedar (Harrington and Wierman 1985; Oliver et al. 1988; Weetman et al. 1988), and may produce a longer-term effect (Harrington and Wierman 1990). Urea is the most cost-effective product of the two, as it has a much higher concentration of nitrogen than ammonium nitrate, thereby decreasing the amount of product applied to achieve a desired rate of nitrogen. In addition, urea has other desirable characteristics (reduced volatility and ease of handling) in contrast to ammonium nitrate. Fall applications of fertilizers typically yield the most consistent results, and allow for easier scheduling/timing of application.

Harrington and Wierman (1985) determined that in naturally established 20-year-old stands on poorly drained sites, redcedar was more responsive in height and diameter growth to fertilization than to early thinning. Combined thinning and fertilization increased growth significantly more than either treatment in isolation. Among other treatments, thinned stands were treated with both urea and ammonium nitrate, and no differences in response were detected between the two nitrogen sources in this study. Further analysis of these same study stands (Harrington and Wierman 1990) revealed that *unthinned*, high-density redcedar responded much more strongly than expected to the fertilizer treatment, likely due to the high shade tolerance of the species and its ability to increase growth even under low light conditions. The authors suggest that this may be the best treatment to consider for the production of high-quality sawlogs.

Perhaps the most extensive fertilization efforts in redcedar plantations were car-

TABLE 10 *Interpretations of foliar macronutrient concentrations for redcedar (from Ballard and Carter 1986)*

	N	**P**	**K**	**Ca**	**Mg**
	(Concentrations in percent, dry mass basis)				
Very severely or severely deficient	<1.15	<0.10	<0.35	<0.07	<0.05
Severely or moderately-severely deficient	<1.50	<0.13	<0.40	<0.10	<0.06
Moderately to slightly deficient	<1.65	<0.16	<0.80	<0.20	<0.12
Possibly deficient, or adequate	>1.65	>0.16	>0.85	>0.25	>0.14

ried out on northern Vancouver Island under the Salal–Cedar–Hemlock Integrated Research Project (SCHIRP). The objective of these efforts was to accelerate crown closure of slowly growing (checked) redcedar plantations on salal-dominated cutovers formerly supporting old-growth cedar–hemlock (CH) stands by alleviating low nutrient availability (Figure 73). More details regarding other areas of SCHIRP research can be found in section 6.2 and online at www.forestry.ubc.ca/schirp/homepage.html.

In the early stages of SCHIRP development, Weetman et al. (1988) reported that the checked trees responded immediately to NPK (nitrogen, phosphorous, potassium) fertilizer treatment, with a 4- to 8-year temporary increase in leader length, and that repeated fertilization may be required to obtain crown closure on these salal-dominated sites. Prescott (1996a) reported positive growth responses of redcedar and hemlock on CH cutovers to both inorganic and organic fertilizers, with or without the physical removal of salal.

FIGURE 73 *A dense ericaceous shrub layer on one of the many salal- and blueberry-dominated cedar–hemlock cutovers in the CWHvh subzone.*

In the first SCHIRP research update, Prescott (1996a) reported that: 1) the growth check of conifers on CH cutovers can best be relieved by N and P fertilization or the application of fish silage and sewage sludge, 2) growth response is correlated with foliar N concentrations, 3) Sitka spruce and western hemlock are more responsive to supplemental nitrogen than is redcedar, and 4) mechanical site preparation or vegetation control are not effective at alleviating the growth check in isolation from other nutritional treatments.

In the second SCHIRP research update, including the results from 12 key silvicultural trials, Blevins and Prescott (2002) concluded that:

1. mechanical scarification and vegetation control alone have little effect on tree growth on salal-dominated CH cutovers; however, the greatest response to fertilization occurs when it is combined with some form of vegetation control,
2. redcedar is less responsive than Sitka spruce and hemlock to fertilization, but produces the most volume on unfertilized, salal-dominated CH cutovers,
3. fertilization at time of planting combined with scarification on salal-dominated CH cutovers increases the growth of redcedar and hemlock,
4. urea and ammonium nitrate fertilizers produce similar growth response in treated conifer stands/plantations,
5. growth responses to organic fertilizers are similar to growth responses to inorganic fertilizers, and
6. fertilization of salal-dominated CH cutovers with very high rates of nitrogen inhibits the growth of salal but also reduces survival and growth of seedlings.

The field guide of Prescott (1996b) addressed operational application by interpreting many SCHIRP studies and trials and proposing silvicultural strategies and possible treatments for creating closed canopies in young stands on salal-dominated CH cutovers. Recommendations for regenerating CH sites included clearcutting, site preparation, a higher planting density preferring redcedar, and fertilization with or without salal removal. Prescott (1996b) recommends nitrogen (urea) and phosphorus application for the best growth response, corroborating the findings of Walker et al. (1955).

After 11 years, Prescott and Blevins (2005) report that longer-term redcedar response continues to remain similar for both chemical fertilizers and biosolids, doubling stand volume over that time relative to controls. Hemlock is also recommended as a mixed species on fertilized sites as it may provide a long-term improvement in nitrogen availability (improving overall site quality) due to the rapid decomposition rate of its nutrient-rich foliage. Bennett et al. (2003) have also documented the long temporal response of young stands on CH sites to fertilization (> 10 years), particularly in combination with initial vegetation (salal) control. They note that hemlock in particular had excellent long-term height growth response, but do not mention diameter or volume increment (where redcedar generally demonstrates greatest relative growth) (Harrington and Wierman 1990). Fifteen years after treatment, fertilized redcedar stands continue to exhibit volumes more than double that of controls, with additional applications of phosphorus having no greater effect than nitrogen (urea) alone (Blevins et al. 2006).

In the most recent analysis of SCHIRP redcedar and western hemlock fertilized plantations, Negrave et al. (2007) make note of some specific long-term trends observed 15 years following establishment of a trial paired across both the CH and HA (hemlock–amabilis fir) site types. Overall, the fertilized hemlock stands experienced substantially greater mortality than the redcedar on both sites. The growth improvements to both species due to fertilization continued to be observed after 15 years for both the CH and (more importantly) the HA sites. On the CH sites, the hemlock is becoming chlorotic after 15 years, whereas the redcedar remains relatively productive with a greater long-term response to the fertilization treatment. On HA sites, the response of both species to fertilization is much greater and remains strong over the long term. In particular, the redcedar growth response (in terms of volume development and periodic annual increment [PAI]) is more than double that observed on the CH sites. The authors recommend that the most appropriate management strategy for these two site types is to establish moderate-density redcedar plantations on the CH sites, with fertilization investment dollars best applied to redcedar plantations established on the HA sites.

Alternatively to seedling response, recent observations of fertilized stands near Gold River suggest that pole-sized (23–36 years breast height) redcedar may not be as responsive to additions of nitrogen (Van Niejenhuis 2004) as documented in younger stands, or in the 20-year-old stands of Harrington and Wierman (1985). Testing of an application rate of 225 kg/ha nitrogen (urea sourced) upon partial to completely closed canopy stands demonstrated no strong response after 3 years. This is disappointing in light of other studies that indicate a strong fertilizer response in younger redcedar plantations. It is difficult to interpret these results conclusively as there is little information provided regarding the foliar nutrient status of the pre-treatment stands. The response of pole-sized redcedar stands to fertilizer requires further investigation for the development of appropriate management guidelines.

6.1 Imajo Studies

The Imajo Cedar Management Fund was established by Yoshihisa Imajo, President of Sanki Corporation/Panabode International in the early 1990s. For over 15 years, this fund has supported research studies intended to provide additional knowledge of the redcedar species and its ecological role in the British Columbia environment, and to promote redcedar establishment and sustainable management. The fund is administered by the Faculty of Forestry at the University of British Columbia. A list of all funded projects as compiled by Katrina Evans from the Dean's office (study details from the years prior to 1997/98 and the year 2001/02 are missing) is presented in Table 11. Results of the listed studies are either found in unpublished internal reports, as publications in non-refereed or refereed journals, or incorporated into graduate theses on file at the Faulty of Forestry. Please contact the listed recipient/researcher for details concerning the individual project.

TABLE 11 *A summary of projects funded by the Imajo Cedar Management Fund 1997/98 to 2006/07*

Year	Recipient	Project description
1997–98	K. Klinka	Two studies were conducted: (1) Relationship of site index to estimates of soil moisture and nutrients for western redcedar in southern British Columbia. In Scientia Silvica Extension Series No. 5 1997. (2) The relationship of site index to synoptic estimates of soil moisture and nutrients for western redcedar in southern coastal British Columbia. In Northwest Science 71:167–173
1997–98	K. Ritland	Study of inbreeding in western redcedar. To date, he has identified six "good" microsatellite loci using advanced molecular genetics techniques. These loci will be used to study the degree of inbreeding of natural populations of western redcedar.
1997–98	Malcolm Knapp Research Forest (MKRF)	P. Sanders reported that work was well under way on a multi-species spacing trial that included western redcedar among paper birch and red alder. The work was reported at a conference of over 20 experts from government, industry, and academia assembled in 1997 to discuss the design required to meet research objectives for this study. The trial was planted in 1997.
1998–99	Malcolm Knapp Research Forest	Funds were used to assist with the set-up of a long-term Multi-species Spacing Trial at the forest. Specifically, these funds were used to purchase several thousand western redcedar, paper birch, and red alder seedlings needed to set up this trial.
1998–99	A. Weber	Two studies were conducted: (1) Mycorrhizal relationships of western redcedar on three different substrates, and (2) The relative shade tolerance of cedar and hemlock.
1998–99	D.B. Collins	Support for study on forest floor nutrient properties in single- and mixed-species stands of western hemlock and western redcedar in southern coastal British Columbia.
1999–00	Malcolm Knapp Research Forest	Study on the use of "teabag" fertilizer to facilitate seedling growth on brush sites at the forest.
1999–00	J. Bennett	Study on the nitrogen nutrition of western redcedar, western hemlock, and salal on cedar–hemlock sites on northern Vancouver Island.
1999–00	D. MacKillop	Study on the development of old-growth stands and structural attributes in the moist Interior Cedar-Hemlock zone.
1999–00	A. Bal	Study on the endophytic bacteria found in the internal stem, foliage, and root tissue of western redcedar.

TABLE 11 *Continued*

Year	Recipient	Project description
2000–01	Malcolm Knapp Research Forest	Investigation into the regeneration of western redcedar under variable retention harvesting systems in the CWHdm subzone.
2000–01	Joanne Belik	Study on vegetation community development in riparian reserves.
2000–01	M.C. Feller	Study into the contributions of western redcedar to forest fire hazard in Coastal Western Hemlock zone forest.
2000–01	C. Chanway	Study into the possibility of whether or not plant growth–promoting or nitrogen-fixing bacterial endophytes live in redcedar.
2002–03	I. Aron and P. Lawson	Study on the use of salvaged western redcedar at the MKRF for producing signs for the Loon Lake Discovery Trail.
2002–03	A. Behennah	Study on the surveying of western hemlock looper in the MKRF.
2002–03	N.J. Sutedjo	Study on the detoxification of extractives of western redcedar wood in service. Fungal isolates on old western redcedar fences were isolated as potential white-rot fungi were confirmed.
2002–03	M. Cleary	Study on the assessment of the resistance of western redcedar in the ICH zone to *Armillaria ostoyae*. This fieldwork included comparative descriptions of resistant reactions of western redcedar, Douglas-fir and hemlock to *A. ostoyae*.
2003–04	S.Mitchell and S. Vollsinger	Study on the related variation in crown mechanical properties and drag for western redcedar.
2003–04	M. Cleary	Study on the host responses of western redcedar to infection by *Armillaria ostoyae* in the southern interior of British Columbia.
2003–04	I. Aron and P. Lawson	Extension of western red cedar research at the MKRF and development and testing of a high-density, high-value regime for management of a coastal mixedwood forest.
2003–04	G. Bull, R. Kozak, and P. Thorny	Study on the fibre supply issues of the British Columbia log home manufacturing industry.
2004–05	C. Breuil and R. Chedgy	Study on detecting fungi in standing western redcedar trees.
2004–05	I. Aron	Extension of western redcedar research at the MKRF.
2004–05	B. van der Kamp and M. Cleary	Study on reducing the impact of *Armillaria* root disease via mixed-species plantations including western redcedar.
2005–06	P. Perreault, P. Lawson, and S. Thuraismy	Study on the cedar strategy workshop to develop a value-based management planning model for western redcedar, within the CWH zone, to ensure ecological, social, and economic sustainability of redcedar over a long-term planning horizon.
2005–06	S. Gergel and A. Pearson	Study on the historical cedar inventory for Haida Gwaii to determine the original versus current extent of cedar, including monumental cedar, which will assist in land use planning, especially for traditional use.
2005–06	T. Seebacher and J.P. Kimmins	Study on western redcedar, climate change, and implications for forest management on Vancouver Island; to determine the extent and cause of top-crown dieback in western redcedar on the east coast of Vancouver Island.
2006–07	C. Chanway	Study on the visualization of western redcedar and lodgepole pine endophytic nitrogen-fixing bacteria and *nif* genes *in situ*.
2006–07	S. Gergel and N. Coops	Study investigating the possibility detecting and delineating large cedar crowns across the landscape using high-resolution remotely sensed imagery.
2006–07	Paul Wood	Study of the case for listing western redcedar in the Convention on International Trade in Endangered Species (CITES).

6.2 Salal–Cedar–Hemlock Integrated Research Program (SCHIRP)

Rarely have there been provincial research programs of such magnitude, duration, and operational significance as SCHIRP, conducted in partnership between the Faculty of Forestry, University of British Columbia and Western Forest Products Inc. The purpose of this program was: 1) to understand the cause(s) of the poor forest regeneration on cedar–salal sites featuring a dense cover of salal (Figure 74), 2) to discover the ultimate causes of the establishment/development of completely different stand types (Cedar–Hemlock [CH] and Hemlock–Amabilis fir [HA]) on apparently "similar" sites, and 3) to determine the best silvicultural practices for regenerating cedar–salal cutovers (Figures 50 and 51). The study sites for the program were located on gently undulating terrain within the CWHvm subzone in Suquash Basin, near Port McNeill on northern Vancouver Island.

The results of many SCHIRP studies are summarized in several major reports: Prescott and Weetman (1994), Prescott (1996a, 1996b), Blevins and Prescott (2002), and Prescott and van Niejenhuis (2005). Klinka (2006) reviewed 90 publications, including reports, journal articles, and graduate theses addressing the program that was initiated in TFL 6 on northern Vancouver Island in the early 1980s.

In the initial synthesis report, Prescott and Weetman (1994) proposed four general hypotheses governing the development of SCHIRP studies for determining the underlying causes of poor regeneration on CH cutovers: 1) lack of disturbance, 2) the adverse effect of salal, 3) the adverse effect of redcedar litter and coarse woody debris on nutrient availability, and 4) site differences between CH and HA sites. Nearly all research focussed on the HA and CH sites as classified by Lewis (1982, 1985). The primary operational factor distinguishing these two site types is the difficulty in regenerating productive plantations on harvested, salal-dominated CH sites.

Salal is a moderately shade-tolerant, oxylophytic species; it tolerates and is associated with acid substrates (Klinka et al. 1989). On weakly acidic sites in the CWHvm1 variant (e.g., nutrient-rich 04 [Sword fern], 05 [Foamflower], and 07 [Salmonberry] sites with Moder and Mull humus forms), salal growth is usually confined to decaying wood (old stumps and large downed coarse woody debris). The presence of salal appears to be limited by both higher nitrate concentrations (higher pH) and reduced understorey light. It appears that salal strongly competes for nutrients in the CH forest floor, greatly restricting its availability to other species. It should be noted that salal growth is not only restricted to CH sites. During their field investigations, McWilliams and Klinka (2005b) observed vigorous and

FIGURE 74 *A low-productivity, open-canopy, old-growth (climax) western hemlock–redcedar mixture on very moist, nutrient-poor sites (CWHvh2/11 CwYc-Goldthread sites). Note a well-developed, ericaceous shrub layer.*

abundant salal on cutovers and within older stands found on the HA sites.

Most salal roots are distributed in the surface organic (forest floor) horizons, with only minor proportions in the uppermost (usually Ae) mineral horizon. Bennett et al. (2002) found hemlock and salal fine roots concentrated in the upper forest floor, while redcedar fine roots were evenly distributed through the entire soil profile. Based on fine root densities, hemlock and salal probably compete for resources in the upper forest floor, whereas redcedar is able to access nutrient resources in the lower organic and mineral soil horizons. This difference in vertical root distribution may partly explain the better performance of redcedar compared to hemlock on CH sites.

Examining the SCHIRP installation plots, McWilliams and Klinka (2005a) concluded that the primary factors controlling the presence and growth of salal in these plots were: 1) light conditions—salal was absent in closed-canopy stands, and 2) forest floor quality—salal prospers in very acid (pH < 4.0), carbon-rich humus forms, such as Lignomors, Resimors, Hemimors, and Humimors, but avoids weakly acid (pH > 4.0), friable, zoogenous Moders and Mulls (Green at al. 1993).

The post-disturbance dominance of salal on CH sites appears to be due to its ability to rapidly establish and effectively compete both above and below ground (from rhizomes present before disturbance). While understorey light conditions can be manipulated through density controls, thick acidic carbon-rich forest floors in combination with a very high cover of decaying wood do not lend themselves to easy manipulation.

Prescott and van Niejenhuis (2005) reviewed the problem of poor regeneration on CH sites, various management strategies, and the results of related SCHIRP studies. In the early stages of the program, excessive salal cover, low site nutrient availability, and lack of windthrow/disturbance (protected, topographically-depressed sites) were considered the primary causes of poor regeneration. After further investigation into the effects of harvesting, age, tree species, salal cover, soil, and site characteristics, Prescott and van Niejenhuis (2005) concluded that:

1. low nutrient supply is inherent to CH ecosystems (it is not an effect of harvesting);
2. HA and CH stands are not stages of the same chronosequence;
3. redcedar litter is not contributing to the poor decomposition and N-status of the forest floor;
4. salal is not causing the predicament (as it had been previously thought);
5. soil may not be the problem as no large differences in mineral soil exist between HA and CH sites; and
6. CH sites are likely the cause of the origin of nutrient supply due to excess moisture (lower slope position) resulting in incomplete litter decomposition and N-immobilization.

Prescott and van Niejenhuis (2005) imply that the low nutrient availability likely originates in the CH forest floor. It could be argued that the low nutrient supply of the CH forest floor is the consequence of thick, compacted (poorly permeable and aerated), colloidal Hh humus horizons, which very often develop under water-surplus conditions. Furthermore, low temperature and aeration regimes of the CH mineral soils also likely affect their nutrient availability. There is converging, yet still inconclusive, evidence in support of the site-difference hypothesis; that is, CH and HA sites generally have different soil moisture, nutrient, temperature, and aeration qualities. This assertion was corroborated by McWilliams and Klinka (2005a, 2005b), who found HA sites predominantly drier and nutrient-medium (corresponding to the CWHvm1/01 HwBa-Blueberry sites), while the CH sites were predominantly wetter and nutrient-poor (corresponding to CWHvm/06 HwBa-Deer fern sites). However, the effect of the nearly ubiquitous salal, as an element of vegetation management, cannot be discounted, at least in the early stages of plantation establishment.

In examining possible application of the BEC system for use in TFL 6, McWilliams and Klinka (2005b) suggest that due to the large latitudinal range of the CWHvm subzone, the zonal classification should recognize two new variants—southern and northern—instead of the single CWHvm1 variant.

For a summary of results from SCHIRP stand and site improvement studies, refer to section 5.5.4: Fertilization.

6.3 HyP^3 Studies

The HyP^3 studies have important implications for the potential regeneration of redcedar on low-productivity sites in the CWHvh1/CWHvh2 variants.

Banner et al. (2005) present an excellent synthesis describing the patterns, processes, and productivity in the hypermaritime CWHvh2 forests that occupy much of British Columbia's outer coast. The hypermaritime forests of the central and northern coast are distinctly different from the maritime and submaritime forests in the CWHvm subzones. Much of the landscape features large tracts of undisturbed, low-productivity, old-growth forests of redcedar, western hemlock, mountain hemlock, yellow-cedar, lodgepole pine, and abundant wetlands. The predominance of the low-productivity forests (at or below operability thresholds) is due to a combination of: 1) cool, perhumid climate, 2) organic soils developed over severely glaciated, base-poor bedrock, and 3) cool, poorly aerated and poorly drained, water-surplus, nutrient-poor mineral soils (Figures 3 and 11). Banner et al. (2005) focussed on forested sites series CWHvh2/04 (HwSs-Lanky moss), CWHvh2/01 (CwHw-Salal), and CWHvh2/11 (CwYc-Goldthread) (Table 8).

The synopsis of the HyP^3 projects by Banner et al. (2005) is extensive. The focus of this report is the operationally applicable results related to disturbance (type and frequency) and productivity, operational trials, and the resulting management interpretations.

Banner et al. (2005) consider forest-floor dynamics of the hypermaritime forests the primary determinant of forest productivity and succession. Natural disturbances typically mix organic material with mineral soil, increasing the rate of organic decomposition and thereby improving forest productivity. Disturbance of this kind is rare in these forests. Without disturbance, moisture conditions facilitate the buildup of organic matter, resulting in soil paludification (lateral expansion of peatlands) and bog development, conditions very detrimental to productive tree growth.

Banner et al. (2005) constructed a simple model of ecosystem development and productivity that includes three factors: 1) bedrock geology, 2) soil drainage, and 3) disturbance history. As most soils develop from the weathering of underlying bedrock, sharp differences between soils developed between slowly weathering granodiorite (with relatively low amounts of nutrients) and easily weathered, nutrient-richer parent materials such as metamorphic rocks and limestone, producing distinct differences in forest communities and potential site productivity.

Under conditions of surplus soil water, any variation in internal soil drainage affects forest productivity. As long as soil water is free to drain, sites can support more productive forest growth, regardless of slope position. Undisturbed sites with poorly drained soils will accumulate organic matter in the surface organic layers at a high rate. As a result, thick forest floors develop, creating continually cooler, wetter, and nutrient-poorer conditions yielding lower and lower levels of productivity. In contrast, sites with a history of disturbance show evidence of higher productivity due to better drainage and higher nitrogen mineralization rates. The greater the inherent nutrient richness of the underlying parent bedrock, the greater the history of disturbance; and the better the drainage, the higher the productivity of the resulting hypermaritime forest.

Banner et al.'s (2005) study presented site index for redcedar derived from old-growth inventory estimates and from second-growth SIBEC estimates for the study area (Table 12). This comparison demonstrates that the former estimates significantly underestimated actual redcedar productivity in open-grown conditions following a disturbance. In fact, these productivity estimates derived from old-growth stands are exceedingly low, suggestive of a long-lasting condition of suppression. This comparison clearly indicates that the potential productivity of redcedar may justify managing these sites for wood production (with some special considerations) as implied earlier in section 5.3: Site and Species Selection.

Several research trials near Prince Rupert investigated the effect of site preparation, including soil mixing, soil mounding, and fertilization on seedling growth and nutrition. The preliminary results reported by Banner et al. (2005) show that survival exceeded 90% (when the seedlings were protected against browsing), and the average height growth of redcedar was marginally better on mounded microsites.

In the last chapter of the research synthesis, Banner et al. (2005) presented management interpretations focussing on the ecological and operational feasibility of sustainable practices on stands on zonal and near-zonal sites (CWHvh/01 CwHw-Salal site series). As most of these unmanaged stands have very low merchantable volumes (< 300 m^3 ha^{-1}), stands on these sites currently exist outside of the operable land base. By combining all research and operational data, Banner et al. (2005) developed a decision-making matrix to discriminate between potentially operable (suitable for redcedar crop production) and inoperable stand sites.

TABLE 12 *Redcedar site index (m @ 50 yr bh) estimates from old-growth and second-growth stands from the CWHvh2 subzone. Numbers in parentheses indicate range of site index (Banner et al. 2005).*

Site series	Old-growth stands	Second-growth stands	Estimates from
CWHvh/01 CwHw-Salal	3.9 (1.9–10.5)	17.8 (13.5–22.3)	19.7
CWHvh/04 HwSs-Lanky moss	5.2 (2.8–7.4)	22.7 (17.0–34.3)	22.8
CWHvh/11 CwYc-Goldthread	2.9 (2.0–4.5)	not given	8.0
CWHvh/12 CwSs-Skunk cabbage	3.3 (2.5–4.5)	not given	16.0

The criteria in the matrix include: depth and type of forest floor and mineral soils, bedrock type, and stand composition. The inoperable sites are those identified as having the following characteristics:

1. transitional to very moist and wet sites with the presence of Labrador tea, crowberry, lingonberry, sedges, deer-cabbage, Indian hellebore, Pacific reedgrass, and sphagnum,
2. peaty forest floor (organic surface layer) > 30 cm,
3. mineral soil < 20 cm,
4. granodiorite, quartz diorite, diorite, and gnessic diorite underlying bedrock, and
5. stand volume < 230 m^3/ha.

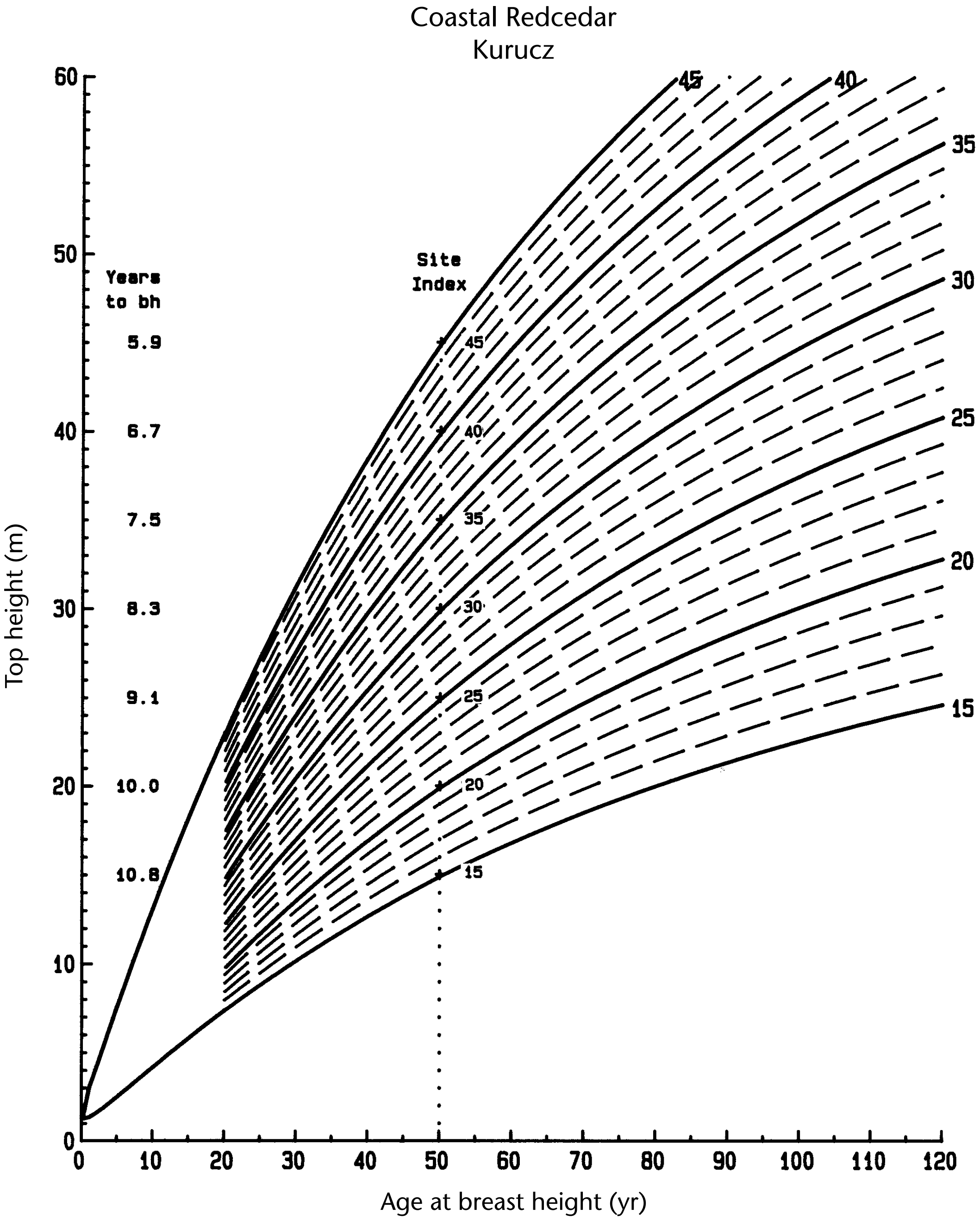
In addition, Banner et al. (2005) recommended specific terms for block layout, reproduction cuttings, harvesting methods, site preparation, and planting.

However, there still remains some uncertainty regarding the actual productivity of these sites once harvested and once a future reliable and productive crop is required. In particular, there is concern that once the original stand is removed, the water table will rise due to reduced evapotranspiration and lead to increased rates of paludification (Emili and Price 2006). By investigating the use of slope indices and topographical gradients (including ground penetrating radar) to predict forest type and productivity, Emili et al. (2006) determined that low slope index values derived from easily obtainable survey data correlated well with topographic high points. These high points had shallower organic horizons and deeper water tables. Minor topographic gradients produced large differences in site characteristics and potential productivity. Observed forest community types were a function of the extent of organic matter accumulation and water table depth as constrained by topography. Accumulations of organic matter decreased infiltration rates and drainage, resulting in higher water tables, which favours the invasion of hydrophytic species such as *Sphagnum* mosses. By using simple survey data, this methodology reduces the need for intensive hydrological investigations to determine suitability of a site for timber production.

7 RECOMMENDATIONS FOR FUTURE RESEARCH

Based upon our review of current research, and the intention of promoting the establishment of redcedar within our coastal forests, we recommend the following activities as priorities for research and policy development.

1. Review stocking standards and tree species selection guides for redcedar, giving flexibility for establishing pure, high-density, crop-reliable stands.
2. Monitor the health and vigour of coastal redcedar in the areas of marginal climatic range in relation to possible climate change. A parallel investigation in similar marginal climates in the interior of the province may also provide useful insights.
3. Investigate the relationships between climatic change, suitable climatic conditions for cedar leaf blight (including potential geographic expansion of endemic cedar leaf blight infestation), and adaptive patterns of cedar leaf blight resistance. The expanded genetic sampling of additional redcedar populations may provide further insight into the adaptive patterns of cedar leaf blight resistance.
4. Examine the susceptibility of second-growth redcedar trees found on eastern Vancouver Island to dieback instigated by root rot in relation to the mode of origin.
5. Update the foliar responsiveness and nutrient interpretation for utilization in operational fertilization decision-making.
6. Continue genetic/breeding investigations into the development of seedlings with elevated concentrations of terpenoid (deer and fungi repellency) compounds.
7. Initiate further investigation into the response of pole-sized and mature redcedar to operational fertilization. Study new stand types not currently evaluated by the ongoing SCHIRP trials, so that response across a wider range of stand types and locations can be assessed.
8. Update the yield curves for redcedar. Improve the reliability of key planning tools such as TIPSY for redcedar stand management and the application of intensive silviculture.
9. In consideration of the economic, ecological, and cultural values of this species, develop a formal redcedar strategy for coastal British Columbia to ensure a continuing and sustainable supply of old-growth and second-growth redcedar into the future.



From: Mitchell and Pollson 1988. Based upon metric equations developed by Kurucz (1985).

Age @ bh (years)	Site index: top height (m) @ breast height age 50 (Kurucz)																					Age @ bh (years)
	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	
	Top height (m)																					
20	9.9	10.3	10.8	11.3	11.8	12.3	12.8	13.3	13.8	14.4	14.9	15.4	15.9	16.5	17.0	17.5	18.1	18.6	19.2	19.7	20.3	20
21	10.3	10.8	11.3	11.8	12.3	12.8	13.4	13.9	14.4	15.0	15.5	16.0	16.6	17.1	17.7	18.2	18.8	19.4	19.9	20.5	21.1	21
22	10.7	11.2	11.7	12.3	12.8	13.3	13.9	14.4	15.0	15.5	16.1	16.7	17.2	17.8	18.4	18.9	19.5	20.1	20.7	21.3	21.9	22
23	11.1	11.6	12.2	12.7	13.3	13.8	14.4	15.0	15.5	16.1	16.7	17.3	17.8	18.4	19.0	19.6	20.2	20.8	21.4	22.0	22.6	23
24	11.4	12.0	12.6	13.2	13.7	14.3	14.9	15.5	16.1	16.7	17.3	17.9	18.5	19.1	19.7	20.3	20.9	21.5	22.2	22.8	23.4	24
25	11.8	12.4	13.0	13.6	14.2	14.8	15.4	16.0	16.6	17.2	17.8	18.5	19.1	19.7	20.3	21.0	21.6	22.2	22.9	23.5	24.2	25
26	12.2	12.8	13.4	14.0	14.7	15.3	15.9	16.5	17.1	17.8	18.4	19.0	19.7	20.3	21.0	21.6	22.3	22.9	23.6	24.2	24.9	26
27	12.6	13.2	13.8	14.5	15.1	15.7	16.4	17.0	17.7	18.3	19.0	19.6	20.3	20.9	21.6	22.3	22.9	23.6	24.3	25.0	25.6	27
28	12.9	13.6	14.2	14.9	15.5	16.2	16.9	17.5	18.2	18.9	19.5	20.2	20.9	21.5	22.2	22.9	23.6	24.3	25.0	25.7	26.4	28
29	13.3	14.0	14.6	15.3	16.0	16.7	17.3	18.0	18.7	19.4	20.1	20.8	21.5	22.1	22.8	23.5	24.2	25.0	25.7	26.4	27.1	29
30	13.7	14.4	15.0	15.7	16.4	17.1	17.8	18.5	19.2	19.9	20.6	21.3	22.0	22.7	23.4	24.2	24.9	25.6	26.3	27.1	27.8	30
31	14.0	14.7	15.4	16.1	16.8	17.6	18.3	19.0	19.7	20.4	21.1	21.9	22.6	23.3	24.0	24.8	25.5	26.3	27.0	27.7	28.5	31
32	14.4	15.1	15.8	16.5	17.3	18.0	18.7	19.5	20.2	20.9	21.7	22.4	23.1	23.9	24.6	25.4	26.1	26.9	27.6	28.4	29.2	32
33	14.7	15.5	16.2	16.9	17.7	18.4	19.2	19.9	20.7	21.4	22.2	22.9	23.7	24.5	25.2	26.0	26.7	27.5	28.3	29.1	29.8	33
34	15.1	15.8	16.6	17.3	18.1	18.8	19.6	20.4	21.1	21.9	22.7	23.5	24.2	25.0	25.8	26.6	27.4	28.1	28.9	29.7	30.5	34
35	15.4	16.2	16.9	17.7	18.5	19.3	20.1	20.8	21.6	22.4	23.2	24.0	24.8	25.6	26.4	27.1	27.9	28.7	29.5	30.4	31.2	35
36	15.7	16.5	17.3	18.1	18.9	19.7	20.5	21.3	22.1	22.9	23.7	24.5	25.3	26.1	26.9	27.7	28.5	29.3	30.2	31.0	31.8	36
37	16.1	16.9	17.7	18.5	19.3	20.1	20.9	21.7	22.5	23.4	24.2	25.0	25.8	26.6	27.5	28.3	29.1	29.9	30.8	31.6	32.4	37
38	16.4	17.2	18.0	18.9	19.7	20.5	21.3	22.2	23.0	23.8	24.7	25.5	26.3	27.2	28.0	28.8	29.7	30.5	31.4	32.2	33.1	38
39	16.7	17.5	18.4	19.2	20.1	20.9	21.7	22.6	23.4	24.3	25.1	26.0	26.8	27.7	28.5	29.4	30.3	31.1	32.0	32.8	33.7	39
40	17.0	17.9	18.7	19.6	20.4	21.3	22.2	23.0	23.9	24.7	25.6	26.5	27.3	28.2	29.1	29.9	30.8	31.7	32.6	33.4	34.3	40
41	17.3	18.2	19.1	19.9	20.8	21.7	22.6	23.4	24.3	25.2	26.1	26.9	27.8	28.7	29.6	30.5	31.4	32.2	33.1	34.0	34.9	41
42	17.6	18.5	19.4	20.3	21.2	22.1	23.0	23.9	24.7	25.6	26.5	27.4	28.3	29.2	30.1	31.0	31.9	32.8	33.7	34.6	35.5	42
43	18.0	18.9	19.8	20.7	21.6	22.5	23.4	24.3	25.2	26.1	27.0	27.9	28.8	29.7	30.6	31.5	32.4	33.3	34.3	35.2	36.1	43
44	18.3	19.2	20.1	21.0	21.9	22.8	23.8	24.7	25.6	26.5	27.4	28.3	29.3	30.2	31.1	32.0	33.0	33.9	34.8	35.7	36.7	44
45	18.6	19.5	20.4	21.3	22.3	23.2	24.1	25.1	26.0	26.9	27.9	28.8	29.7	30.7	31.6	32.5	33.5	34.4	35.4	36.3	37.2	45
46	18.9	19.8	20.7	21.7	22.6	23.6	24.5	25.5	26.4	27.4	28.3	29.3	30.2	31.2	32.1	33.1	34.0	35.0	35.9	36.9	37.8	46
47	19.1	20.1	21.1	22.0	23.0	23.9	24.9	25.9	26.8	27.8	28.7	29.7	30.7	31.6	32.6	33.5	34.5	35.5	36.4	37.4	38.4	47
48	19.4	20.4	21.4	22.4	23.3	24.3	25.3	26.2	27.2	28.2	29.2	30.1	31.1	32.1	33.1	34.0	35.0	36.0	37.0	37.9	38.9	48
49	19.7	20.7	21.7	22.7	23.7	24.7	25.6	26.6	27.6	28.6	29.6	30.6	31.6	32.5	33.5	34.5	35.5	36.5	37.5	38.5	39.5	49
50	20.0	21.0	22.0	23.0	24.0	25.0	26.0	27.0	28.0	29.0	30.0	31.0	32.0	33.0	34.0	35.0	36.0	37.0	38.0	39.0	40.0	50
51	20.3	21.3	22.3	23.3	24.3	25.3	26.3	27.4	28.4	29.4	30.4	31.4	32.4	33.4	34.4	35.5	36.5	37.5	38.5	39.5	40.5	51
52	20.5	21.6	22.6	23.6	24.6	25.7	26.7	27.7	28.7	29.8	30.8	31.8	32.8	33.9	34.9	35.9	36.9	38.0	39.0	40.0	41.0	52
53	20.8	21.8	22.9	23.9	25.0	26.0	27.0	28.1	29.1	30.1	31.2	32.2	33.2	34.3	35.3	36.4	37.4	38.4	39.5	40.5	41.5	53
54	21.1	22.1	23.2	24.2	25.3	26.3	27.4	28.4	29.5	30.5	31.6	32.6	33.7	34.7	35.7	36.8	37.8	38.9	39.9	41.0	42.0	54
55	21.3	22.4	23.4	24.5	25.6	26.6	27.7	28.8	29.8	30.9	31.9	33.0	34.0	35.1	36.2	37.2	38.3	39.3	40.4	41.4	42.5	55
56	21.6	22.6	23.7	24.8	25.9	26.9	28.0	29.1	30.2	31.2	32.3	33.4	34.4	35.5	36.6	37.6	38.7	39.8	40.8	41.9	43.0	56
57	21.8	22.9	24.0	25.1	26.2	27.3	28.3	29.4	30.5	31.6	32.7	33.8	34.8	35.9	37.0	38.1	39.1	40.2	41.3	42.4	43.4	57
58	22.1	23.2	24.3	25.4	26.5	27.6	28.7	29.8	30.8	31.9	33.0	34.1	35.2	36.3	37.4	38.5	39.6	40.7	41.7	42.8	43.9	58
59	22.3	23.4	24.5	25.6	26.8	27.9	29.0	30.1	31.2	32.3	33.4	34.5	35.6	36.7	37.8	38.9	40.0	41.1	42.2	43.3	44.4	59
60	22.5	23.7	24.8	25.9	27.0	28.2	29.3	30.4	31.5	32.6	33.7	34.9	36.0	37.1	38.2	39.3	40.4	41.5	42.6	43.7	44.8	60
61	22.8	23.9	25.1	26.2	27.3	28.5	29.6	30.7	31.8	33.0	34.1	35.2	36.3	37.5	38.6	39.7	40.8	41.9	43.0	44.2	45.3	61
62	23.0	24.2	25.3	26.5	27.6	28.7	29.9	31.0	32.2	33.3	34.4	35.6	36.7	37.8	39.0	40.1	41.2	42.3	43.5	44.6	45.7	62
63	23.3	24.4	25.6	26.7	27.9	29.0	30.2	31.3	32.5	33.6	34.8	35.9	37.1	38.2	39.3	40.5	41.6	42.7	43.9	45.0	46.1	63
64	23.5	24.7	25.8	27.0	28.2	29.3	30.5	31.6	32.8	34.0	35.1	36.3	37.4	38.6	39.7	40.9	42.0	43.1	44.3	45.4	46.6	64
65	23.7	24.9	26.1	27.2	28.4	29.6	30.8	31.9	33.1	34.3	35.4	36.6	37.8	38.9	40.1	41.2	42.4	43.5	44.7	45.8	47.0	65
66	23.9	25.1	26.3	27.5	28.7	29.9	31.1	32.2	33.4	34.6	35.8	36.9	38.1	39.3	40.4	41.6	42.8	43.9	45.1	46.3	47.4	66
67	24.2	25.4	26.6	27.8	28.9	30.1	31.3	32.5	33.7	34.9	36.1	37.3	38.5	39.6	40.8	42.0	43.2	44.3	45.5	46.7	47.8	67
68	24.4	25.6	26.8	28.0	29.2	30.4	31.6	32.8	34.0	35.2	36.4	37.6	38.8	40.0	41.2	42.3	43.5	44.7	45.9	47.1	48.2	68
69	24.6	25.8	27.0	28.2	29.5	30.7	31.9	33.1	34.3	35.5	36.7	37.9	39.1	40.3	41.5	42.7	43.9	45.1	46.3	47.5	48.6	69
70	24.8	26.0	27.3	28.5	29.7	30.9	32.2	33.4	34.6	35.8	37.0	38.2	39.4	40.7	41.9	43.1	44.3	45.5	46.7	47.8	49.0	70
71	25.0	26.3	27.5	28.7	30.0	31.2	32.4	33.7	34.9	36.1	37.3	38.6	39.8	41.0	42.2	43.4	44.6	45.8	47.0	48.2	49.4	71
72	25.2	26.5	27.7	29.0	30.2	31.5	32.7	33.9	35.2	36.4	37.6	38.9	40.1	41.3	42.5	43.8	45.0	46.2	47.4	48.6	49.8	72
73	25.4	26.7	27.9	29.2	30.5	31.7	33.0	34.2	35.5	36.7	37.9	39.2	40.4	41.6	42.9	44.1	45.3	46.5	47.8	49.0	50.2	73
74	25.6	26.9	28.2	29.4	30.7	32.0	33.2	34.5	35.7	37.0	38.2	39.5	40.7	42.0	43.2	44.4	45.7	46.9	48.1	49.4	50.6	74
75	25.8	27.1	28.4	29.7	30.9	32.2	33.5	34.7	36.0	37.3	38.5	39.8	41.0	42.3	43.5	44.8	46.0	47.2	48.5	49.7	50.9	75
76	26.0	27.3	28.6	29.9	31.2	32.5	33.7	35.0	36.3	37.6	38.8	40.1	41.3	42.6	43.9	45.1	46.3	47.6	48.8	50.1	51.3	76
77	26.2	27.5	28.8	30.1	31.4	32.7	34.0	35.3	36.6	37.8	39.1	40.4	41.6	42.9	44.2	45.4	46.7	47.9	49.2	50.4	51.7	77
78	26.4	27.7	29.0	30.3	31.6	32.9	34.2	35.5	36.8	38.1	39.4	40.7	41.9	43.2	44.5	45.7	47.0	48.3	49.5	50.8	52.0	78
79	26.6	27.9	29.2	30.6	31.9	33.2	34.5	35.8	37.1	38.4	39.7	40.9	42.2	43.5	44.8	46.1	47.3	48.6	49.9	51.1	52.4	79
80	26.8	28.1	29.5	30.8	32.1	33.4	34.7	36.0	37.3	38.6	39.9	41.2	42.5	43.8	45.1	46.4	47.7	48.9	50.2	51.5	52.7	80
81	27.0	28.3	29.7	31.0	32.3	33.6	35.0	36.3	37.6	38.9	40.2	41.5	42.8	44.1	45.4	46.7	48.0	49.3	50.5	51.8	53.1	81
82	27.2	28.5	29.9	31.2	32.5	33.9	35.2	36.5	37.8	39.2	40.5	41.8	43.1	44.4	45.7	47.0	48.3	49.6	50.9	52.1	53.4	82
83	27.4	28.7	30.1	31.4	32.8	34.1	35.4	36.8	38.1	39.4	40.7	42.1	43.4	44.7	46.0	47.3	48.6	49.9	51.2	52.5	53.8	83
84	27.5	28.9	30.3	31.6	33.0	34.3	35.7	37.0	38.3	39.7	41.0	42.3	43.7	45.0	46.3	47.6	48.9	50.2	51.5	52.8	54.1	84
85	27.7	29.1	30.5	31.8	33.2	34.5	35.9	37.2	38.6	39.9	41.3	42.6	43.9	45.3	46.6	47.9	49.2	50.5	51.8	53.1	54.4	85
Years to bh	10	10	10	10	9	9	9	9	9	9	8	8	8	8	8	8	7	7	7	7	7	Years to bh

* The broken line within the table(s) indicates the approximate age and site data used to develop the site index equations, and caution is recommended when using these curves and tables on stands 5 m site index or 20 years bha beyond this underlying data.

Age @ bh (years)	Site index: top height (m) @ breast height age 50 (Kurucz)																					Age @ bh (years)
	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	
										Top height (m)												
85	27.7	29.1	30.5	31.8	33.2	34.5	35.9	37.2	38.6	39.9	41.3	42.6	43.9	45.3	46.6	47.9	49.2	50.5	51.8	53.1	54.4	85
86	27.9	29.3	30.6	32.0	33.4	34.8	36.1	37.5	38.8	40.2	41.5	42.9	44.2	45.5	46.9	48.2	49.5	50.8	52.1	53.4	54.8	86
87	28.1	29.5	30.8	32.2	33.6	35.0	36.3	37.7	39.1	40.4	41.8	43.1	44.5	45.8	47.1	48.5	49.8	51.1	52.4	53.8	55.1	87
88	28.2	29.6	31.0	32.4	33.8	35.2	36.6	37.9	39.3	40.7	42.0	43.4	44.7	46.1	47.4	48.8	50.1	51.4	52.8	54.1	55.4	88
89	28.4	29.8	31.2	32.6	34.0	35.4	36.8	38.2	39.5	40.9	42.3	43.6	45.0	46.3	47.7	49.0	50.4	51.7	53.1	54.4	55.7	89
90	28.6	30.0	31.4	32.8	34.2	35.6	37.0	38.4	39.8	41.1	42.5	43.9	45.3	46.6	48.0	49.3	50.7	52.0	53.4	54.7	56.0	90
91	28.7	30.2	31.6	33.0	34.4	35.8	37.2	38.6	40.0	41.4	42.8	44.1	45.5	46.9	48.2	49.6	51.0	52.3	53.6	55.0	56.3	91
92	28.9	30.3	31.8	33.2	34.6	36.0	37.4	38.8	40.2	41.6	43.0	44.4	45.8	47.1	48.5	49.9	51.2	52.6	53.9	55.3	56.6	92
93	29.1	30.5	31.9	33.4	34.8	36.2	37.6	39.0	40.4	41.8	43.2	44.6	46.0	47.4	48.8	50.1	51.5	52.9	54.2	55.6	56.9	93
94	29.2	30.7	32.1	33.6	35.0	36.4	37.8	39.2	40.7	42.1	43.5	44.9	46.3	47.6	49.0	50.4	51.8	53.1	54.5	55.9	57.2	94
95	29.4	30.9	32.3	33.7	35.2	36.6	38.0	39.5	40.9	42.3	43.7	45.1	46.5	47.9	49.3	50.7	52.0	53.4	54.8	56.2	57.5	95
96	29.6	31.0	32.5	33.9	35.4	36.8	38.2	39.7	41.1	42.5	43.9	45.3	46.7	48.1	49.5	50.9	52.3	53.7	55.1	56.4	57.8	96
97	29.7	31.2	32.6	34.1	35.6	37.0	38.4	39.9	41.3	42.7	44.2	45.6	47.0	48.4	49.8	51.2	52.6	54.0	55.3	56.7	58.1	97
98	29.9	31.3	32.8	34.3	35.7	37.2	38.6	40.1	41.5	42.9	44.4	45.8	47.2	48.6	50.0	51.4	52.8	54.2	55.6	57.0	58.4	98
99	30.0	31.5	33.0	34.4	35.9	37.4	38.8	40.3	41.7	43.2	44.6	46.0	47.4	48.9	50.3	51.7	53.1	54.5	55.9	57.3	58.7	99
100	30.2	31.7	33.1	34.6	36.1	37.6	39.0	40.5	41.9	43.4	44.8	46.2	47.7	49.1	50.5	51.9	53.3	54.7	56.1	57.5	58.9	100
101	30.3	31.8	33.3	34.8	36.3	37.7	39.2	40.7	42.1	43.6	45.0	46.5	47.9	49.3	50.8	52.2	53.6	55.0	56.4	57.8	59.2	101
102	30.5	32.0	33.5	35.0	36.4	37.9	39.4	40.9	42.3	43.8	45.2	46.7	48.1	49.6	51.0	52.4	53.8	55.3	56.7	58.1	59.5	102
103	30.6	32.1	33.6	35.1	36.6	38.1	39.6	41.1	42.5	44.0	45.5	46.9	48.4	49.8	51.2	52.7	54.1	55.5	56.9	58.3	59.7	103
104	30.8	32.3	33.8	35.3	36.8	38.3	39.8	41.3	42.7	44.2	45.7	47.1	48.6	50.0	51.5	52.9	54.3	55.8	57.2	58.6	60.0	104
105	30.9	32.4	33.9	35.5	37.0	38.5	40.0	41.4	42.9	44.4	45.9	47.3	48.8	50.2	51.7	53.1	54.6	56.0	57.4	58.8	60.3	105
106	31.0	32.6	34.1	35.6	37.1	38.6	40.1	41.6	43.1	44.6	46.1	47.5	49.0	50.5	51.9	53.4	54.8	56.2	57.7	59.1	60.5	106
107	31.2	32.7	34.3	35.8	37.3	38.8	40.3	41.8	43.3	44.8	46.3	47.8	49.2	50.7	52.1	53.6	55.0	56.5	57.9	59.3	60.8	107
108	31.3	32.9	34.4	35.9	37.5	39.0	40.5	42.0	43.5	45.0	46.5	48.0	49.4	50.9	52.4	53.8	55.3	56.7	58.2	59.6	61.0	108
109	31.5	33.0	34.6	36.1	37.6	39.1	40.7	42.2	43.7	45.2	46.7	48.2	49.6	51.1	52.6	54.0	55.5	57.0	58.4	59.8	61.3	109
110	31.6	33.2	34.7	36.2	37.8	39.3	40.8	42.4	43.9	45.4	46.9	48.4	49.8	51.3	52.8	54.3	55.7	57.2	58.6	60.1	61.5	110
111	31.7	33.3	34.9	36.4	37.9	39.5	41.0	42.5	44.0	45.6	47.1	48.6	50.0	51.5	53.0	54.5	56.0	57.4	58.9	60.3	61.8	111
112	31.9	33.4	35.0	36.6	38.1	39.6	41.2	42.7	44.2	45.7	47.3	48.8	50.3	51.7	53.2	54.7	56.2	57.6	59.1	60.6	62.0	112
113	32.0	33.6	35.1	36.7	38.3	39.8	41.3	42.9	44.4	45.9	47.4	48.9	50.5	51.9	53.4	54.9	56.4	57.9	59.3	60.8	62.2	113
114	32.1	33.7	35.3	36.9	38.4	40.0	41.5	43.0	44.6	46.1	47.6	49.1	50.6	52.1	53.6	55.1	56.6	58.1	59.6	61.0	62.5	114
115	32.3	33.8	35.4	37.0	38.6	40.1	41.7	43.2	44.8	46.3	47.8	49.3	50.8	52.3	53.8	55.3	56.8	58.3	59.8	61.2	62.7	115
116	32.4	34.0	35.6	37.1	38.7	40.3	41.8	43.4	44.9	46.5	48.0	49.5	51.0	52.5	54.0	55.5	57.0	58.5	60.0	61.5	62.9	116
117	32.5	34.1	35.7	37.3	38.9	40.4	42.0	43.6	45.1	46.6	48.2	49.7	51.2	52.7	54.2	55.8	57.2	58.7	60.2	61.7	63.2	117
118	32.6	34.2	35.8	37.4	39.0	40.6	42.2	43.7	45.3	46.8	48.4	49.9	51.4	52.9	54.4	56.0	57.5	58.9	60.4	61.9	63.4	118
119	32.8	34.4	36.0	37.6	39.2	40.7	42.3	43.9	45.4	47.0	48.5	50.1	51.6	53.1	54.6	56.2	57.7	59.2	60.6	62.1	63.6	119
120	32.9	34.5	36.1	37.7	39.3	40.9	42.5	44.0	45.6	47.2	48.7	50.3	51.8	53.3	54.8	56.4	57.9	59.4	60.9	62.3	63.8	120
121	33.0	34.6	36.2	37.8	39.4	41.0	42.6	44.2	45.8	47.3	48.9	50.4	52.0	53.5	55.0	56.6	58.1	59.6	61.1	62.6	64.0	121
122	33.1	34.8	36.4	38.0	39.6	41.2	42.8	44.4	45.9	47.5	49.1	50.6	52.2	53.7	55.2	56.7	58.3	59.8	61.3	62.8	64.3	122
123	33.2	34.9	36.5	38.1	39.7	41.3	42.9	44.5	46.1	47.7	49.2	50.8	52.3	53.9	55.4	56.9	58.5	60.0	61.5	63.0	64.5	123
124	33.4	35.0	36.6	38.3	39.9	41.5	43.1	44.7	46.2	47.8	49.4	51.0	52.5	54.1	55.6	57.1	58.7	60.2	61.7	63.2	64.7	124
125	33.5	35.1	36.8	38.4	40.0	41.6	43.2	44.8	46.4	48.0	49.6	51.1	52.7	54.2	55.8	57.3	58.8	60.4	61.9	63.4	64.9	125
126	33.6	35.2	36.9	38.5	40.1	41.8	43.4	45.0	46.6	48.1	49.7	51.3	52.9	54.4	56.0	57.5	59.0	60.6	62.1	63.6	65.1	126
127	33.7	35.4	37.0	38.6	40.3	41.9	43.5	45.1	46.7	48.3	49.9	51.5	53.0	54.6	56.1	57.7	59.2	60.8	62.3	63.8	65.3	127
128	33.8	35.5	37.1	38.8	40.4	42.0	43.7	45.3	46.9	48.5	50.0	51.6	53.2	54.8	56.3	57.9	59.4	60.9	62.5	64.0	65.5	128
129	33.9	35.6	37.3	38.9	40.5	42.2	43.8	45.4	47.0	48.6	50.2	51.8	53.4	54.9	56.5	58.0	59.6	61.1	62.7	64.2	65.7	129
130	34.0	35.7	37.4	39.0	40.7	42.3	43.9	45.6	47.2	48.8	50.4	51.9	53.5	55.1	56.7	58.2	59.8	61.3	62.9	64.4	65.9	130
131	34.2	35.8	37.5	39.1	40.8	42.4	44.1	45.7	47.3	48.9	50.5	52.1	53.7	55.3	56.8	58.4	60.0	61.5	63.0	64.6	66.1	131
132	34.3	35.9	37.6	39.3	40.9	42.6	44.2	45.8	47.5	49.1	50.7	52.3	53.9	55.4	57.0	58.6	60.1	61.7	63.2	64.8	66.3	132
133	34.4	36.1	37.7	39.4	41.1	42.7	44.3	46.0	47.6	49.2	50.8	52.4	54.0	55.6	57.2	58.7	60.3	61.9	63.4	64.9	66.5	133
134	34.5	36.2	37.8	39.5	41.2	42.8	44.5	46.1	47.7	49.4	51.0	52.6	54.2	55.8	57.3	58.9	60.5	62.0	63.6	65.1	66.7	134
135	34.6	36.3	38.0	39.6	41.3	43.0	44.6	46.2	47.9	49.5	51.1	52.7	54.3	55.9	57.5	59.1	60.7	62.2	63.8	65.3	66.9	135
136	34.7	36.4	38.1	39.8	41.4	43.1	44.7	46.4	48.0	49.7	51.3	52.9	54.5	56.1	57.7	59.3	60.8	62.4	63.9	65.5	67.0	136
137	34.8	36.5	38.2	39.9	41.5	43.2	44.9	46.5	48.2	49.8	51.4	53.0	54.6	56.2	57.8	59.4	61.0	62.6	64.1	65.7	67.2	137
138	34.9	36.6	38.3	40.0	41.7	43.3	45.0	46.7	48.3	49.9	51.6	53.2	54.8	56.4	58.0	59.6	61.2	62.7	64.3	65.9	67.4	138
139	35.0	36.7	38.4	40.1	41.8	43.5	45.1	46.8	48.4	50.1	51.7	53.3	54.9	56.6	58.2	59.7	61.3	62.9	64.5	66.0	67.6	139
140	35.1	36.8	38.5	40.2	41.9	43.6	45.3	46.9	48.6	50.2	51.8	53.5	55.1	56.7	58.3	59.9	61.5	63.1	64.6	66.2	67.8	140
141	35.2	36.9	38.6	40.3	42.0	43.7	45.4	47.0	48.7	50.3	52.0	53.6	55.2	56.9	58.5	60.1	61.7	63.2	64.8	66.4	67.9	141
142	35.3	37.0	38.7	40.4	42.1	43.8	45.5	47.2	48.8	50.5	52.1	53.8	55.4	57.0	58.6	60.2	61.8	63.4	65.0	66.5	68.1	142
143	35.4	37.1	38.8	40.5	42.2	43.9	45.6	47.3	49.0	50.6	52.3	53.9	55.5	57.2	58.8	60.4	62.0	63.6	65.1	66.7	68.3	143
144	35.5	37.2	38.9	40.7	42.4	44.1	45.7	47.4	49.1	50.7	52.4	54.0	55.7	57.3	58.9	60.5	62.1	63.7	65.3	66.9	68.4	144
145	35.6	37.3	39.0	40.8	42.5	44.2	45.9	47.5	49.2	50.9	52.5	54.2	55.8	57.4	59.1	60.7	62.3	63.9	65.5	67.0	68.6	145
146	35.7	37.4	39.1	40.9	42.6	44.3	46.0	47.7	49.3	51.0	52.7	54.3	56.0	57.6	59.2	60.8	62.4	64.0	65.6	67.2	68.8	146
147	35.8	37.5	39.2	41.0	42.7	44.4	46.1	47.8	49.5	51.1	52.8	54.5	56.1	57.7	59.4	61.0	62.6	64.2	65.8	67.4	68.9	147
148	35.9	37.6	39.3	41.1	42.8	44.5	46.2	47.9	49.6	51.3	52.9	54.6	56.2	57.9	59.5	61.1	62.7	64.3	65.9	67.5	69.1	148
149	35.9	37.7	39.4	41.2	42.9	44.6	46.3	48.0	49.7	51.4	53.1	54.7	56.4	58.0	59.6	61.3	62.9	64.5	66.1	67.7	69.3	149
150	36.0	37.8	39.5	41.3	43.0	44.7	46.4	48.1	49.8	51.5	53.2	54.9	56.5	58.2	59.8	61.4	63.0	64.6	66.2	67.8	69.4	150
Years to bh	10	10	10	10	9	9	9	9	9	9	8	8	8	8	8	8	7	7	7	7	7	Years to bh

* The broken line within the table(s) indicates the approximate age and site data used to develop the site index equations, and caution is recommended when using these curves and tables on stands 5 m site index or 20 years bha beyond this underlying data.

APPENDIX 2 Levels and symptoms of nutrient deficiency

(From Walker et al. 1955; as detailed in Ballard and Carter 1986.)

Macronutrients	**Foliar concentrations (%, dry mass basis)**	**Symptoms**
Nitrogen	< 1.5	Foliage yellowish; stems reddish in young seedlings; dying of older foliage conspicuous but little shattering; roots abnormally long in solution cultures; foliage sparse.
Phosphorus	0.4	Stems and older foliage reddish or purplish during the first year, turning reddish brown and becoming necrotic in older seedlings; oldest foliage dies but does not shatter; youngest foliage retains good green colour.
Potassium	.39 – .78	Stems limber; foliage appears drooping, sparse; fourth-order branches apparently do not elongate; branch tips a good green, but older foliage necrotic or dying and any lower leaves and branches dead and brown.
Calcium	.10 – .20	Browning and drying at the tips of the leader and branch shoots; good green maintained in lower foliage; browning and dying of roots obvious in solution cultures.
Magnesium	.06 – .18	Good height growth; youngest foliage green, but older branchlets turn yellow or white then brown; a marked tendency to shatter, resulting in plants with a green tuft at the tip but bare branches below. (Other deficiencies do not seem to produce the white or yellow stage in necrosis characteristic of magnesium.)
Sulphur	.08 – .16	Foliage yellowish; older foliage paler than normal, although not so yellowish as younger portions of the plants.

Micronutrients	**Foliar concentrations (ppm, dry mass basis)**	**Symptoms**
Iron	-	Youngest foliage quite yellow, older foliage green; the difference more striking as the plants become older.
Boron	15	Elongation in growing regions much restricted, so that needles are closely bunched, approaching the “rosette” in angiosperms; stems weak, upper parts of plant lop over; older foliage near normal; younger foliage “bronzed” in advanced stages; roots short with branches somewhat bulbous on the ends.

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