WESTERN REDCEDAR DIEBACK: POSSIBLE LINKS TO CLIMATE CHANGE AND IMPLICATIONS FOR FOREST MANAGEMENT ON VANCOUVER ISLAND, B.C.

by

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Abstract

This thesis studied the distribution and potential causes of western redcedar (*Thuja plicata* Donn ex D. Don) dieback on the east coast of Vancouver Island, B.C. using dendrochronology and water balance modelling. Redcedar trees were cored in four of the driest and warmest biogeoclimatic (BEC) units on the island. Dieback was found in varying intensity in three of the four driest BEC units; however, it was primarily concentrated near the Qualicum Beach area (CDFmm). Ring-widths were found to be sensitive to climate on certain sites, but more complacent on other sites. Warm and dry summer climate was found to reduce radial growth of redcedar, and thus moisture stress may be the major determinant of redcedar dieback. Subsequent causes include well drained coarse textured soil conditions (predisposing), drought periods over the growing season (inciting), and contributing factors such as insects and pathogens. Water balance modelling found relationships between transpiration deficit index (TDI) and residual ring-width indices at three of the 16 study sites. The low number of significant relationships was likely caused by the low climate-sensitivity of breast-height tree ring data in redcedar growing on zonal sites. Low climate sensitivity may have been exacerbated by stand dynamics and competition, since study sites were often in mixed stands with multiple age cohorts. ForWaDy, when linked to FORECAST, could provide useful information on water stress and future growth of redcedar on the coast if linked with more climatically sensitive tree ring data. Over the next few hundred years, it is unlikely that redcedar will be lost completely from Vancouver Island due to the resilient and acclimative nature of this species; however, redcedar growing on low elevation sites vulnerable to moisture stress may experience increased dieback occurrences and eventual decline in these areas. Recommendations for future studies of redcedar dieback and considerations for forest management are provided.

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Co-Authorship Statement

Tanya Seebacher is the sole author of this Master of Science Thesis in Forestry.

Chapter 1 : Introduction to western redcedar, dendrochronology and dieback

1.1 Western Redcedar

Who can forget the sweet woody smell and long, feathery, soft foliage draped over furrowed red-brown bark of western redcedar (*Thuja plicata* Donn ex D. Don) (hereafter redcedar). I was fortunate enough to be able to study this magnificent provincial tree also known as "arbor-vitae" or the "tree of life" which has been used for centuries by North Pacific coast First Nations groups. The stringy bark was stripped in long inverted V-shaped pieces for basket weaving and clothing (Figure 1.1) while the wood was used for shelter, totem poles, tools and transportation. This tree continues to play an important role in the culture of aboriginal peoples on the west coast of Canada. Trees of all sizes were used; very large redcedar were used for canoes, house construction and totem poles, while smaller trees were used for bark stripping, medicinal and cultural purposes (Gitsga 1992). Large trees were tested by cutting a hole in the side of the tree to check for butt rot before felling. If rot was found, the tree was not used for canoes, but may have been used for other purposes.

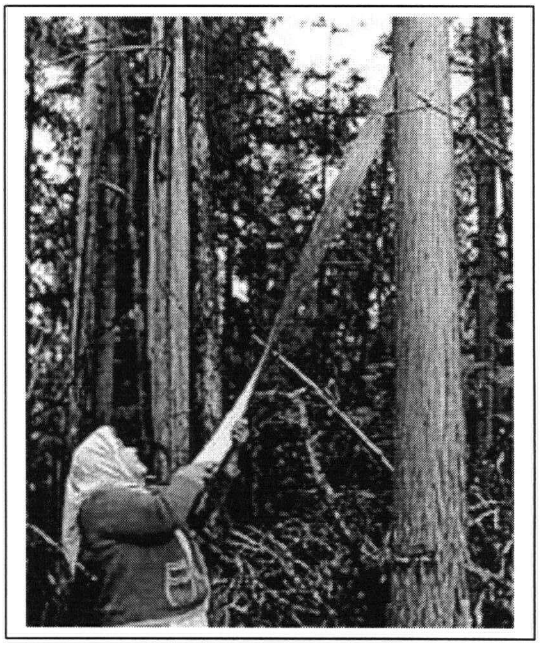


Figure 1.1: Florence Davidson stripping bark from redcedar tree, 1976. Photo: Ulli Steltzer. http://www.virtualmuseum.ca/Exhibitions/Inuit_Haida/haida/english/forest/tech2.html

Redcedar is also an extremely valuable tree species for the British Columbia (B.C.) forest industry. The wood is very light, durable and resistant to decay, has straight grain and contains very little resin, making it an excellent tree for siding, decking, fencing, and specialty products such as interior paneling, musical instruments, roofing shakes and shingles (Gonzalez 2004). Currently, there are approximately 750 million cubic meters of redcedar standing in B.C., and more than half is found on the west coast (BC Market Outreach Network 2003). The majority of redcedar on the coast is greater than 250 years old, and can be classified as old-growth; however, many second-growth redcedar stands are also currently being harvested. Coastal harvest of redcedar averages around 6.4 million cubic meters per year (Gonzalez 2004). The United States, Europe, Australia, New Zealand and Japan are major importers of redcedar products from Canada. Second only to western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), redcedar is the largest standing mature timber volume on the coast (Gonzalez 2004).

Redcedar grows along the northwest coast of North America from the northern limits of California, up to southeastern Alaska. Its interior range extends from south-central B.C. down into western Montana and northern Idaho (Figure 1.2).

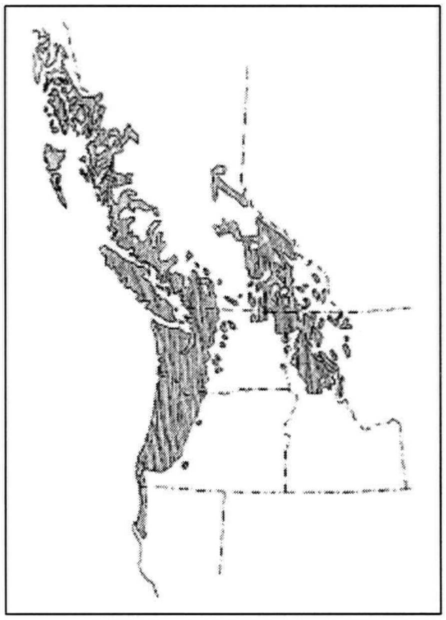


Figure 1.2: Redcedar native habitat is distributed along the western coast of North America from Alaska to California, within the southeastern portion of B.C., and south into northern Montana and Idaho (Minore 1983).

The elevation range of redcedar is highly variable depending upon the latitude; from sea level up to 915m in southern Alaska, up to 1200m on the B.C. coast, from 320-2130 m in the Interior, and up to 2300 m in Oregon, U.S.A. (Gonzalez 2004, Minore 1983). Redcedar prefers moist growing sites with mild temperatures. Hence, its southern range is limited at low elevations by insufficient precipitation and by low annual temperatures at higher elevations. Its northern range is limited primarily by low annual temperatures; precipitation is assumed not to be limiting. Tree species associated with redcedar on the coast include Douglas-fir (*Psuedotsuga menziesii* Franco), grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), bigleaf maple (*Acer macrophyllum* Pursh), and common shrubs including salal (*Gaultheria shallon* Pursh), dull Oregon grape (*Mahonia nervosa* (Pursh) Nutt.), and ocean spray (*Holodiscus discolor* (Pursh) Maxim.) (Minore 1983).

In 2001, the Intergovernmental Panel on Climate Change predicted a 1.0-7.5°C increase in North American temperatures over the next century depending on emission level changes (McCarthy *et al.* 2001). NASA climate analyses have found that the years 1998, 2002, 2003, 2004, and 2005 were the five hottest years since the 1890's (NASA 2006). Severity of summer drought is also expected to increase along with the associated incidence of drought in certain areas (Watson *et al.* 2001). These changes in climate are expected to cause changes in forest productivity, health and regeneration of forest ecosystems on the coast (Johnson *et al.* 2006).

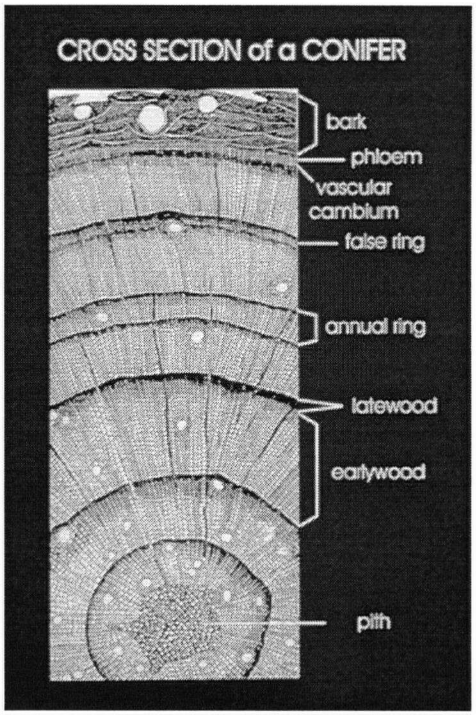
Palynological studies have shown major changes in the distributions of redcedar over time (Hebda 1995). These shifts in distribution are hypothesized to be a consequence of climate change (Overpeck *et al.* 1991; Parmesan and Yohe 2003). Between 10,000 and 6000 years BP, for example, pollen of redcedar was scarce, which corresponds to the warm and dry early Holocene xerothermic period (Hebda and Mathewes 1984). During this time, the climate did not favor redcedar growth (Hebda 1995). Pollen studies have shown that redcedar did not establish in B.C. until the mid Holocene period (6000-4000 years BP), which was known to be milder and wetter than present (Hebda 1984; Wainman 1987; Hebda 1995; Brown 2002). Redcedar pollen became abundant on Vancouver Island about 4000 years ago, and by 2000 years ago redcedar pollen was abundant on almost all coastal sites indicating healthy redcedar populations at this time (Hebda 1996). From this record we can conclude that redcedar has not been present during very warm and dry periods of the past, which supports the contention that if climate is warming and getting drier, this species may again shift its geographic distribution.

Redcedar regeneration occurs via seed dispersal, primarily in disturbed habitats, and by vegetative means primarily in undisturbed habitats (Parker 1987). Adventitious roots establish when low growing side branches or broken off shoots are in contact with moist soil. The species has been classified as shade-tolerant, but its seedlings are exposure-tolerant, and grow best at higher light levels (Daniels 1993, Daniels 2003). Thus, for proper regeneration, the species does not require shade because open grown seedlings do respond favorably to increased light levels (Daniels 1995). Nevertheless, for the first few years of growth, redcedar does best in a shaded understory. On Northern Vancouver Island, in early stages of establishment, redcedar has been found to be shade-intolerant when grown with western hemlock and amabilis fir (*Abies amabilis* (Dougl. ex Loud.) Dougl. ex Forbes), due to its needle-like primary foliage which develops before the typical scaled secondary foliage (Weber *et al.* 2003). Weber *et al.* (2003) found that redcedar most likely establishes on disturbed mineral soil in areas with little influence from the canopy, such as on the edge of a clearcut or in naturally disturbed patches.

1.2 Dendrochronology

The stem cross sections of most temperate forest tree species exhibit annual growth rings consisting of alternating light and dark bands (Baillie 1995). These bands depict the yearly growth periods of the tree, and consist of earlywood (light bands of cells that grow rapidly and are short lived), and the latewood (dark bands of cells that grow slowly and are longer lived) (Figure 1.3). Past climate is intricately linked with ring width because environmental conditions, such as temperature and precipitation, greatly affect tree growth patterns (Fritts 1976).

Figure 1.3: Cross-section of a conifer tree stem showing the varying light and dark bands corresponding to spring (earlywood) and summer (latewood) growth, respectively. The combination of early- and latewood forms an annual ring which can be counted using principles of dendrochronology. Note also the location of the bark, phloem, vascular cambium and the central pith of the tree (Fritts 1976).



Earlywood is produced during the spring, while latewood is produced during the summer. The width of each band provides clues concerning the past climate (i.e. temperature and precipitation) during the specific year of tree growth. Generally, during periods of high summer temperature and low precipitation, ring widths will be small and, conversely, when summer temperature is moderate and precipitation high, ring widths will be large (Bradley 1999). The reason for the difference in ring-width is due to the absence or abundance of water and nutrients available for cell formation. For example, during a hot dry year, limited water is available for uptake from the roots, thereby also limiting nutrient uptake since nutrients from the soil are mobilized by soil water. Water is also a medium for biochemical reactions, a participant in photosynthesis, and maintains cell turgidity for growth. Thus if water is limiting during drought years, less overall growth can occur within a tree, thereby explaining narrower growth rings during these years.

In addition to ring width, maximum ring density is also a valuable measurement for estimating long-term climatic signals and is measured using an X-ray densitometer (Bradley 1999). In order to obtain the most accurate climatic reconstruction, both ring width and density are commonly measured. However, because of time limitations, only ring width was studied in this thesis. Trees growing on wetter, nutrient rich sites with a high water table, show less evidence of climate influence and are classified as "complacent" in their ring growth (Fritts 1976). In other words, ring growth is very uniform with minor variation between years. The reasons for stable ring growth is a constant supply of water, abundant nutrient supply or protected growing location. However, trees which are more favorable for dendrochronological analysis are referred to as "sensitive" (Fritts 1976). These trees show a high degree of annual variation in ring growth because growth has been affected by slope, poor soils or limited moisture availability. Thus variations in climate are more easily seen in sensitive trees since ring growth during favorable and unfavorable growth years is more clearly observed. Trees are normally examined on environmentally stressed sites such as at high elevations near the arctic/alpine tree-line, where growth depends mainly on temperature, or in grasslands and forest transition zones, where tree growth depends mainly on precipitation (Figure 1.4).

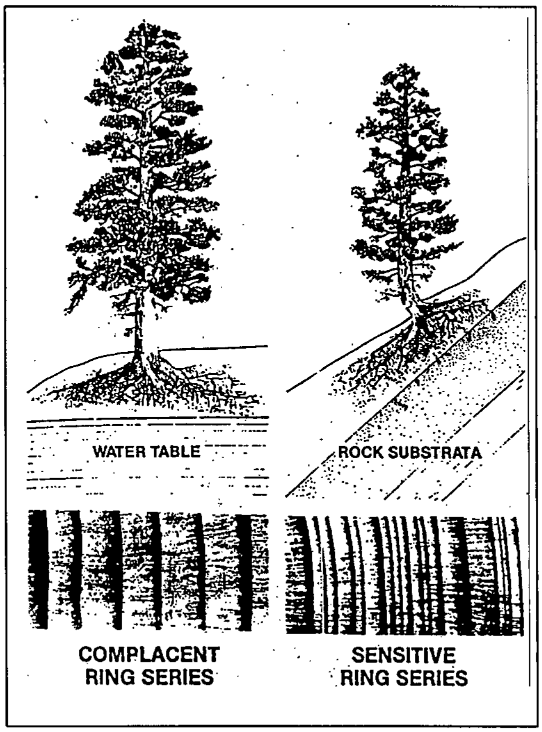


Figure 1.4: Comparison of ring patterns between complacent and sensitive trees. Climatically sensitive trees are found on slopes in upper elevation sites, or in forest transition zones, whereas complacent trees are found in low areas where the water table is close to the surface. Sensitive trees are preferred for dendroclimatic reconstructions of past climates (Bradley 1999).

In this study, trees will be sampled primarily in forest transition zones along a gradient of biogeoclimatic units, where moisture is expected to play a key role in tree growth.

1.3 Physiology and dieback

Tree stems are composed of the inner heartwood, which stores waste and supports the tree, and the outer sapwood which transmits water and minerals (Campbell *et al.* 1999). The sapwood is composed of xylem tissue which conducts water and circulates dissolved minerals. Surrounding the sapwood is the vascular cambium composed of meristematic tissues which produce new cells in the tree. The living phloem surrounds the vascular cambium and transports carbohydrates as sap around the tree. The cork cambium, the outermost layer in a cross-section, produces new layers of bark (Figure 1.5).

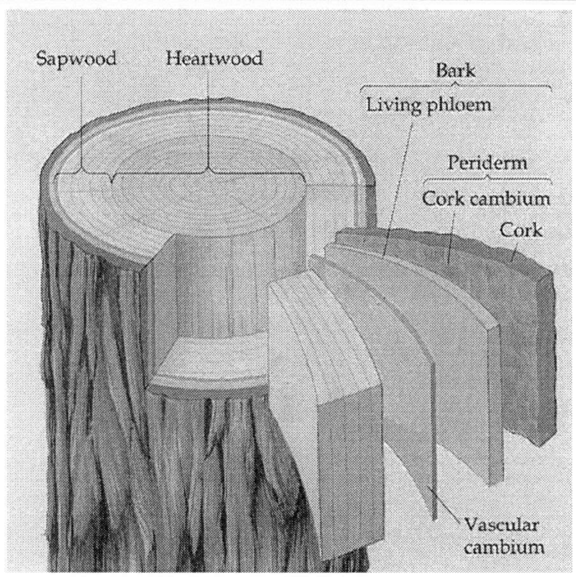


Figure 1.5: Cross-section of a typical tree stem. Note the location of the inner dark heartwood and the outer light sapwood. The cambium and phloem surround the sapwood and create new cells and move minerals and nutrients throughout the trees (www.steve.gb.com/science/plant_growth.html).

Three tissue systems are produced within a plant: the dermal, vascular, and ground (Campbell *et al.* 1999). The dermal system, or epidermis, forms the outermost "skin" of the plant tissue which protects interior tissue. Secondly, the vascular system functions in transport of water and nutrients and stem support. Finally, the ground tissue system lies in between the dermal and vascular which is involved in photosynthesis, storage and support. There are numerous types of cells which make up plant tissue. Parenchyma cells perform the majority of metabolic functions within the plant, collenchyma cells provide support, and sclerenchyma cells also provide support but are much more rigid than collenchyma cells due to the presence of lignin (Campbell *et al.* 1999). Additionally, tracheids and vessel elements are the water-conducting cells within the xylem and sieve-tube-members conduct nutrients throughout the phloem.

The secondary foliage scale leaves of redcedar are coated with a waxy epidermis layer which acts as a barrier to water loss. The only openings in the epidermis are the stomata, which are tiny pores lined by a pair of guard cells found on the underside of leaves and needles. The stomata allow water to be exchanged between the plant and the atmosphere through transpiration (Campbell *et al.* 1999). When water is lost through the stomata, a negative gradient is formed between the tree leaf and the atmosphere causing water to be pulled up through the roots, tree stem, and foliage and then transpired through the leaves. This water movement occurs from higher to lower water potentials (Simpson 1981). Depending on the tree condition, age (older trees lose more water, younger trees retain more water, depending on the past history of drought in the area), species, soil condition, and solar energy, different rates of transpiration will occur.

Depending on the length of drought experienced by a tree, different physiological responses occur to withstand the period of stress. One of the first responses to drought stress is closure of stomates (Simpson 1981). Stomatal closure allows water within the tree to be conserved, yet this conservation is at the expense of a decline in growth due to the cessation of photosynthesis occurring in the foliage. When a tree is faced with drought for a short period of time, solutes within the soil become more concentrated than solutes within the tree roots thereby causing water to move from the root to soil solution, a process called hydraulic redistribution (Caldwell *et al.* 1998). This process causes cell shrinkage and may lead to death of the cells if prolonged stress occurs. Long-term drought events can lead to death of many cells along with cavitation which occurs when air is brought into the cells causing a blockage within the root, stem or branch affected. Prolonged cavitation leads to death of the woody tissue obstructed by the blockage. Thus, leaf and branch abscission are consequences of prolonged drought periods. Additionally, long-term drought may increase root to shoot ratios by translocation of resources to roots to gain access to greater water resources (i.e. higher water use efficiency with increased root biomass and decreased shoot biomass) (Coder 1999).

Tree water balance is determined by three main resistance forces 1) water movement from soil to root, 2) water movement within the plant, and 3) plant loss of water through transpiration (Kimmins 2004). A drought stressed tree has three options to cope with water deficiency, it can either 1) increase resources by allocating more carbon to roots to access deeper water sources, 2) increase efficiency of water use within the plant (close stomata, slow growth), or 3) decrease the amount of foliage requiring water. Leaf drop is a common occurrence in many drought-stressed plants (Coder 1999). One mechanism that may trigger leaf drop is large distances of travel to the upper leaves in a tree because the top leaves do not receive sufficient moisture to remain viable and apical crown dieback often occurs before lower branches are affected.

The term "decline" is best referred to as "an episodic event characterized by premature, progressive loss of tree and stand vigor and health over a given period without obvious evidence of a single clearly identifiable causal factor such as physical disturbance or attack by an aggressive disease or insect". "Dieback", on the other hand, is defined in this thesis as a potential symptom of decline where foliage is dropped and whole branches die. This phenomenon has recently been observed on redcedar trees on the southeast coast of Vancouver Island, and will be the focus of this thesis.

There have been a number of concepts proposed attempting to explain the onset of tree decline and dieback. Houston (1992) considers a "host-stress-saprogen" model for forest dieback and decline in which the combined action of numerous stress factors followed by the attack of weakened trees by secondary organisms (saprogens) cause eventual decline and death. For example, during prolonged drought, a tree becomes stressed and unable to employ defense mechanisms as efficiently (Mattson and Haack 1987) and is thereby more likely to be attacked by insects and infected by pathogens (secondary saprogens), thus inciting further dieback and decline of the tree. Another concept developed by Manion (1991) involves "predisposing", "inciting" and "contributing" factors. "Predisposing" factors are site specific environmental variables (soil and climate) which affect the tree's ability to fight off injurious agents. "Inciting" factors are short-lived and may be physiological or biological (which cause dieback of small branches by frost or drought), and finally, "contributing" factors which further weaken and ultimately kill the tree (bark beetles or root decay fungi) (Manion 1991). Thus it is often difficult to determine specific causes of dieback and ultimately the overall decline of a stand or individual trees because long-term studies are needed to assess all three causative factors. One of the main challenges of this thesis is that there may not be a single cause for the dieback of redcedar, but potentially several factors in combination that produce the observed symptoms.

Tree dieback has been observed in different parts of the world - eastern Canada, Alaska, the Patagonian Andes, Europe, and Australia. Sudden aspen (*Populus tremuloides* Michx) dieback in northeastern Ontario and northern Alberta caused widespread interest in the decline of this species (Frey 2004). The aspen decline has been most likely linked to insect defoliation, drought and freeze-thaw events. Similarly, yellow and white birch (*Betula* spp.) have also undergone dieback over the past 50-70 years in eastern Canada and the northeastern United States (Hawboldt 1952). This decline has been linked to a combination of a warming and drying climate, the bronze birch borer, freeze-thaw events and fungal attack. Historical dieback of Alaskan yellow-cedar (*Chamaecyparis nootkatensis* D. Don), in southeastern Alaska, has also been linked with environmental stress as the primary causal factor (Shaw1985). These cedars have been observed to be dying-back for the past 75 years, and at least 200,000 hectares of forest has been affected. In the Patagonia Andes of southwestern Argentina, Cordillerian cypress (*Austrocedrus chilensis* (D. Don) Pic. Serm. & Bizzarri) decline is hypothesized to be related to changing temperatures and precipitation (Filip 1999). Recent increases in rural tree decline of *Eucalyptus gunnii* (Hook. f.) in Australia and Tasmania have also been linked with climate change due to below average rainfall over recent decades along with an increase in average temperature of 0.4°C in this region (Close and Davidson 2004). Similarly, dieback of young redcedar on the coast of B.C. may also be affected by warming and drying trends due to changing climate (Figure 1.6).

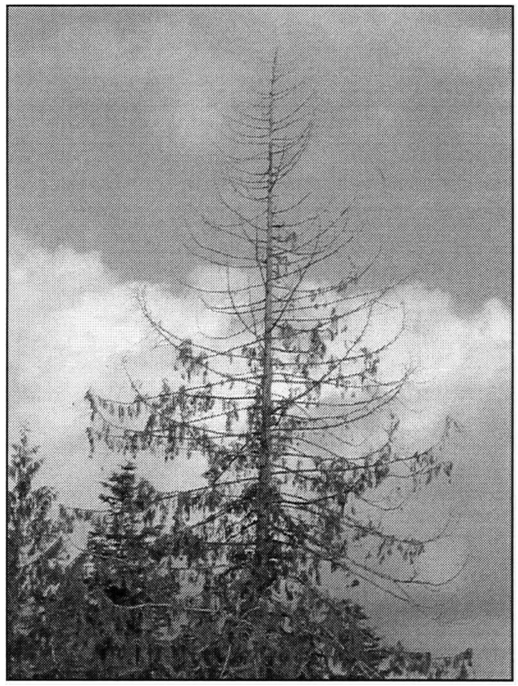


Figure 1.6: Redcedar dieback noted along upper Island highway north of Nanaimo, B.C. Note extensive drop of top foliage with foliated lower branches (Photo by Seebacher 2005).

Candelabra growth form of redcedar has been reported back into the 1960's by Vladimir Krajina and was hypothesized to be caused by calcium deficiency, especially in redcedar growing on boggy sites (Kimmins, pers. comm. February 15, 2007). Lowered concentrations of calcium can lead to lowered production of calcium pectate in cell walls, thereby weakening the cells and increasing the frequency of cell cavitation and dieback. Candelabra growth form of redcedar is typically limited to older redcedar trees greater than roughly 150 years old. It is important to note that there are also numerous dead-topped extremely old (400-1000 years) redcedar found on the wetter north and west coast of Vancouver Island. In the late 1980's dieback of older redcedar on northern Vancouver Island, near Port McNeil, was observed by Fred Nuszdorfer (former Regional Ecologist for the Vancouver Forest Region) and has been attributed to branch stripping by intense wind storms on this part of the Island (Kimmins, pers. comm. February 15, 2007). The dead-topped nature of many of these trees is likely related to intense windstripping events (Figure 1.7), but may also be related to death of major roots (due to pathogens or other causes) causing the main leader to die and new leaders to form as trees age (J.P. Kimmins, pers. comm., October 15th, 2006).

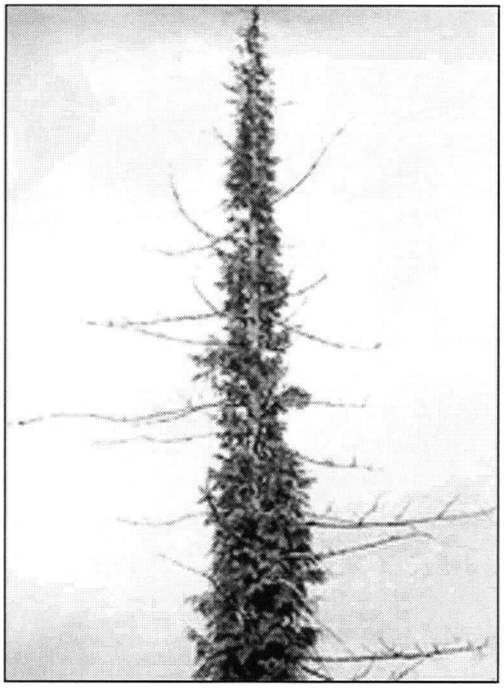


Figure 1.7: Windstripped redcedar tree with bare crown branches and newly forming epicormic shoots emerging from the main stem. It is possible that with intense windstripping, typical on western Vancouver Island, main leader stems may die and lower healthy branches may take over as the new leader during favorable growth years (Photo by Kimmins 1998).

However, around the mid-late 1990's, apical crown dieback was also noted on younger redcedar (<150 years) on the east coast of Vancouver Island, in areas less prone to such intense windstorms (Hebda pers. comm. March 21, 2007; Kimmins, pers. comm. February 15, 2007). One hypothesis for the cause of redcedar dieback is more prevalent drought with changing climate (R. Hebda, pers. comm. 2005). However, this hypothesis has not yet been proven, and drought could be either a predisposing, inciting or contributing factor to this dieback. Nutrients are not known to be limiting for redcedar on this part of Vancouver Island (Klinka pers. comm., May 6th, 2005). Subsidiary causes of redcedar dieback may be linked with insect attack (Duncan 1995; John McLean UBC, pers. comm., May 6th, 2005) or pathogens (van der Kamp 1975).

The major heart-rotting fungi of redcedar on the coast are 1) *Poria asiatica* (Pilát) Overh. (brown cubical pocket and butt rot), 2) *Poria albipellucida* Baxter (white ring rot), 3) *Fomes Pini* (Thore) Lloyd (white pitted trunk rot), 4) *Merulius* sp. (brown crumbly butt rot), and 5) *Poria subacida* (Peck) Sacc. (spongy white rot) (Buckland 1946). Other diseases affecting redcedar include: *Armillaria ostoyae* (Armillaria root disease), *Didymascella thujina* (Cedar leaf blight), and *Phellinus weirii* (Laminated Root Rot) (Canada 2003). Nevertheless, decay of redcedar is very slow due to the presence of thujaplicin, a heartwood extractive that resists decay (Jin 1988). In this study, decay organisms were assessed qualitatively and noted if present based on examination of the trunk (Heningman 2001).

There are only a few insects reported to attack redcedar which include: 1) *Trachykele blondeli* (Western cedar borer, powderworm), 2) *Phloeosinus punctatus* (Western cedar bark beetle), and 3) *Lambdina fiscellaria lugubrosa* (Hemlock looper) (Furniss 1977); signs of insect attack were also noted. Both decay organisms and insects may be prevalent on redcedar trees showing signs of extensive dieback because these organisms commonly attack stressed trees. If trees are originally stressed due to drought, the organisms would preferentially select and colonize these stressed trees due to lowered defense mechanisms.

The following thesis examines potential causes of redcedar dieback on the east coast of Vancouver Island using dendrochronological methods and water balance modelling. Ring width chronologies were compared with monthly records of temperature and precipitation to determine redcedar's sensitivity to climate in Chapter 2 section 2.3.3, along with a more detailed dieback analysis examined in Chapter 2 section 2.3.4. Secondly, in Chapter 3, a water balance model, ForWaDy, was used to try and determine the relationship between ring width and transpirational deficit index (TDI), an index which incorporates both temperature and precipitation influences. In Chapter 4, results from both the dendrochronological and modelling chapters are compiled into a discussion. Finally, conclusions are presented based on causal factors of redcedar dieback, implications for forest management, along with recommendations for future redcedar dieback studies.

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Chapter 2 : Dendrochronological Analysis of Redcedar Dieback

2.1 Introduction

[1]Redcedar is a very beautiful and valuable tree species on the Pacific Coast and has numerous uses in First Nation culture. Over the past decade, concern has been raised regarding observed apical crown dieback of this species on the east coast of Vancouver Island B.C., and what the future might hold for the distribution of the species on the coast (Hebda pers. comm. 2005; Kimmins pers. comm. 2005). Recent warming and drying over the growing season has exacerbated drought events on this portion of the island. It is hypothesized that drought may be the underlying stressor causing dieback and loss of redcedar foliage (R. Hebda pers. comm. 2005). There have been numerous studies examining dieback and decline of yellow cedar in northwestern B.C. (Shaw *et al.* 1985, Hennon *et al.* 1990, Hennon *et al.* 2002). However, there have been no published studies, to date, that have examined the extent or potential causes of young redcedar dieback on the coast.

The area of focus for this thesis is low elevation sites on the eastern side of the southern half of Vancouver Island, from Campbell River south to Victoria. Precipitation over Vancouver Island is extremely variable due to the presence of the Insular Mountain Range, bisecting the island from northwest to southeast, and the Olympic Mountain Range in Washington, U.S.A. The Olympic Range creates a rainshadow effect as warm moist air comes from the central Pacific and is pushed up and over depositing precipitation before crossing the mountain range, and causing a very warm dry climate on southeastern Vancouver Island (Green 1994) (Figure 2.1). The Insular Range creates a similar but less intense rainshadow on eastern Vancouver Island.

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[1] A version of this thesis chapter is in preparation for publication.

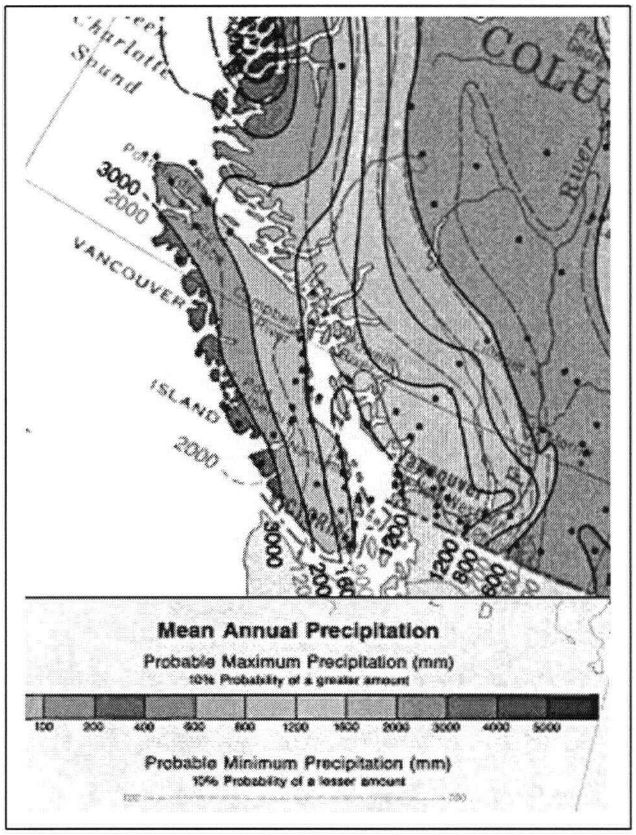

Figure 2.1: Mean annual precipitation lines (mm) of Vancouver Island and the adjacent mainland. The southeast coast of the island has much lower annual precipitation compared to the more exposed west coast. This difference is due to the Insular and Olympic Mountain Ranges which create a rainshadow effect on the east coast of the island and neighboring mainland (NRC 2005).

The majority of precipitation falls during winter months and precipitation values increase from south to north and from east to west. During the summer, extensive dry periods often leave most areas on eastern Vancouver Island with water deficits; the southeast region being most severely affected (Jungen 1985). As a consequence, redcedar apical crown dieback would most likely be observed within the drier southeastern portion of the island.

2.2 Objectives

The main objective for this thesis was to first determine where dieback is occurring, and then to explore potential causes. The primary hypothesis being tested is that observed dieback on younger redcedar (<150 years) is caused by drought due to changing climate. Dendrochronological analysis was undertaken to see whether radial growth of redcedar trees on the study sites exhibit sensitivity to climate, and which climate variables have the strongest relationship to ring-width indices. Further analysis of dieback trees was undertaken in case the climate signal was diluted by other factors when examining the entire population of redcedar trees on the study sites. The following research questions were addressed to advance our understanding of the dieback phenomenon.

Main Chapter Questions:

- Is redcedar growth more sensitive in drier coastal BEC units than in wetter units?
- Do redcedar trees on the study sites show evidence of historical interannual climatic variation?
- To which climate variables are the trees most sensitive?
- Is redcedar dieback related to documented drought years?

2.3 Study Sites and Methodology

2.3.1 Forest Composition and Structure

The east portion of Vancouver Island is comprised of the dry, low elevation Coastal Douglas Fir moist maritime subzone (CDFmm) biogeoclimatic (BEC) unit, and the Coastal Western Hemlock (CWH) zone, which grades into the Mountain Hemlock (MH) zone at higher elevations (Figure 2.2).

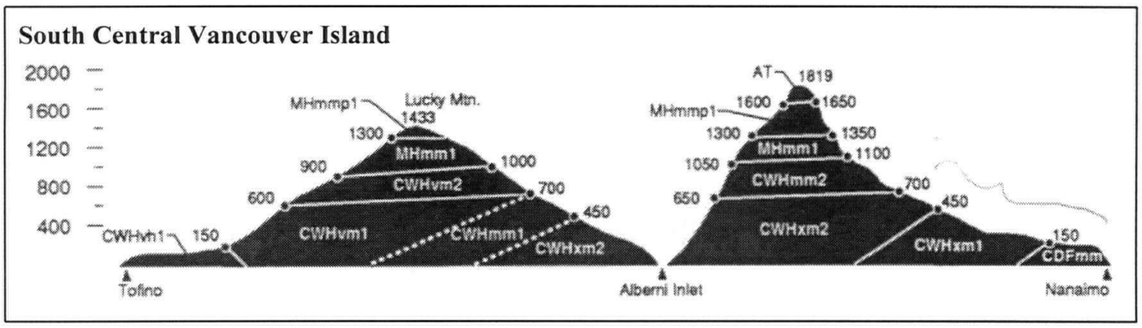

Figure 2.2: Elevational profiles of BEC units for south central Vancouver Island across from Nanaimo in the east to Tofino on the west coast. Where CDFmm is the moist maritime subzone of the Coastal Douglas-fir zone, CWHxm1 is the submontane variant very dry maritime subzone of the Coastal Western Hemlock zone, CWHxm2 is the montane variant very dry maritime subzone of the Coastal Western Hemlock zone, CWHmm1 is the Submontane variant moist maritime subzone of the Coastal Western Hemlock zone, CWHmm2 is the Montane variant moist maritime subzone of the Coastal Western Hemlock zone, MHmm1 is the windward variant moist maritime subzone of the Mountain Hemlock zone, AT is the Alpine tundra, CWHvm1 is the submontane variant very wet maritime subzone of the Coastal Western Hemlock zone, CWHvm2 is the montane variant very wet maritime subzone of the Coastal Douglas-fir zone, and CWHvh1 is the southern variant very wet hypermaritime subzone of the Coastal Western Hemlock zone (Green and Klinka 1994).

Vancouver Island comprises mainly pre-Cretaceous (>135 million years B.P.) sedimentary and volcanic rocks intruded by granitic batholiths (Jungen 1985). The landscape has been greatly affected by glacial processes throughout the Pleistocene epoch, leaving large surficial deposits covering an extensive amount of the Island. There are five main soil orders present: 1) Podsolic, 2) Brunisolic, 3) Gleysolic, 4) Regosolic, and 5) Organic. Podsolic soils are the most extensive soil order on the island, having thick organic (L-F-H) horizons, while only very thin Ae (eluviated topsoil) horizons and also have strongly developed B (subsoil) horizons (Jungen 1985). Mor humus forms predominate (low microbial activity, abundant fungi), however, some moder (transitional between mor and mull humus) and mull (microbially active, abundant bacteria) forms do occur.

Sites were selected within each of four BEC subzones and variants (hereafter units) with increasing elevation and precipitation in order to see how redcedar in different BEC units is affected by climate along a moisture gradient from the drier-low elevation units to the wetter-high elevation units (Table 2.1).

Table 2.1: Site characteristics of 16 study sites on the southeast coast of Vancouver Island showing dieback presence or absence, BEC units, position, elevation, aspect, site series and slope of each site.

Site #	Dieback?	Name	BEC Unit	Latitude	Longitude	Elevation (m)	Aspect (°)	Site Series	Slope (°)
1	No	Burnt Mt. 1	CWHmm	N 48°58.593'	W123°59.297'	706	315	1	11.3
2	No	Burnt Mt. 2	CWHmm	N 48°57.363'	W123°58.116'	689	315	1->3	7.4
3	No	Galiano Island	CDFmm	N 48°56.571'	W123°29.446'	88	90	1	1.7
4	Yes	Shawnigan Lake	CWHxm1	N 48°47.576'	W123°57.547'	136	45	1	0.6
5	Yes	Cowichan Lake	CWHxm2	N 48°47.576'	W123°57.547'	167	180	4->5	2.9
6	No	Skutz Falls 6	CWHxm1	N 48°47.576'	W123°57.547'	173	45	1	0.6
7	No	Skutz Falls 7	CWHxm2	N 48°45.612'	W123°55.204'	175	45	1	0
8	No	Royal Roads	CDFmm	N 48°25.965'	W123°28.856'	164	270	4	2.9
9	Yes	Qualicum Beach	CDFmm	N 49°20.716'	W124°27.067'	78	90	1	0
10	No	Qualicum Bay	CDFmm	N 49°25.184'	W124°40.652'	80	45	1	1.1
11	No	Horne Lake	CWHxm1	N 49°20.642'	W124°40.556'	146	180	4->5	1.7
12	No	Bacon Lake	CWHxm1	N 49°58.124'	W125°37.983'	441	45	4	0.6
13	No	Ranald Main	CWHmm	N 49°58.625'	W125°39.188'	615	45	1->3	6.3
14	Yes	Flux net	CWHxm2	N 49°52.163'	W125°20.076'	315	45	7	2.3
15	No	Gray Lake/Fry	CWHxm2	N 50°03.311'	W125°36.440'	263	45	1->3	0.6
16	No	BC Timber Sales	CWHxm1	N 49°58.541'	W125°27.271'	210	45	6	1.7

The four units, listed from driest to wettest were: 1) Moist Maritime subzone of the Coastal Douglas-fir zone (CDFmm); 2) Submontane variant of the very dry Maritime subzone of the Coastal Western Hemlock zone (CWHxm1); 3) Montane variant very dry Maritime subzone of the Coastal Western Hemlock zone (CWHxm2); and 4) the Moist Maritime subzone of the Coastal Western Hemlock zone (CWHmm). Four sites were chosen within each subzone for a total of 16 sites sampled in the late summer-fall of 2005 (Figure 2.3).

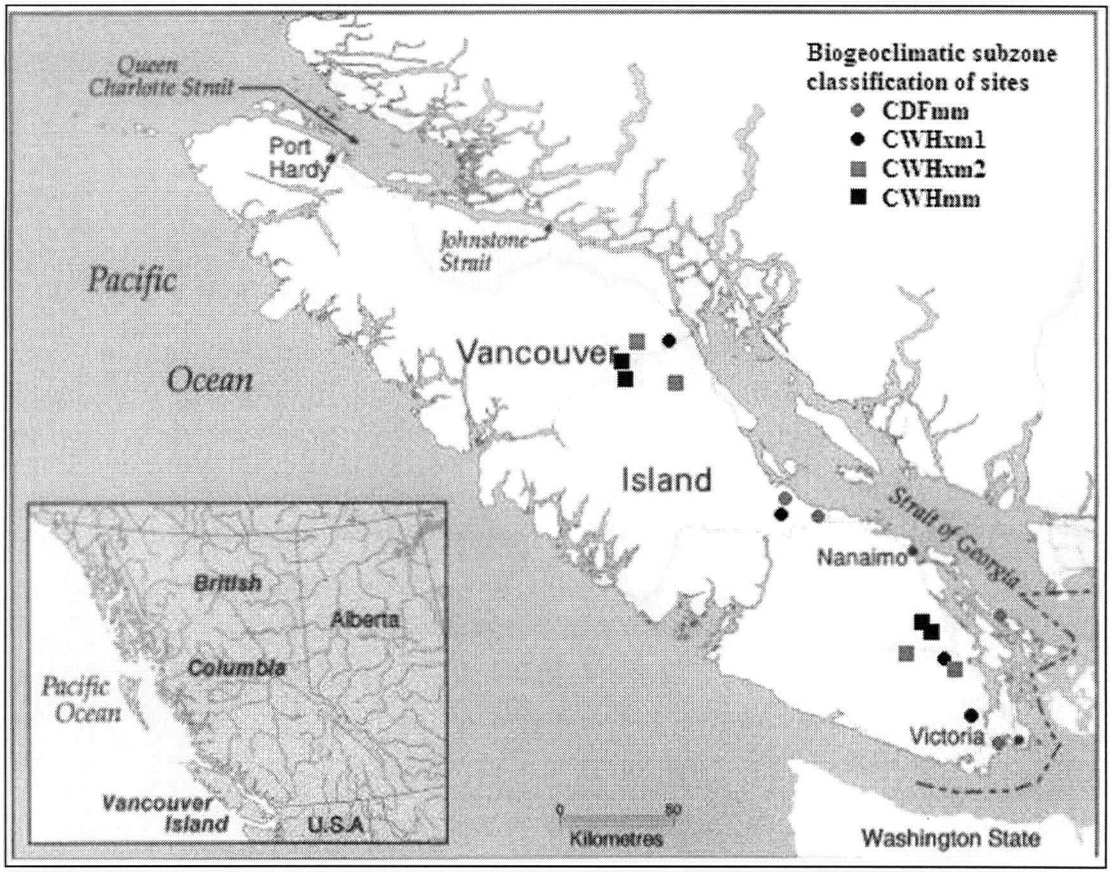

Figure 2.3: **Location of 16 study sites within each of four BEC units on the east coast of Vancouver Island (grey circles CDFmm sites, black circles CWHxm1 sites, grey squares CWHxm2 sites, and black squares CWHmm sites) (modified from Integrated Land Management Bureau 2005).**

Stratified random sampling of sites occurred within each BEC unit that satisfied four criteria as follows: (a) road access - sites had to be greater than 50m off a major road; (b) species composition - stands in which redcedar was dominant or co-dominant; (c) harvesting – sites had not been subject to recent harvesting in order to avoid confounding influences on ring growth; and (d) forest age – sampling was limited to second growth (30-150 years) forest stands. Typical old, "dead-topped" candelabra redcedar trees found on the north and west coast of the Island may also experience periods of moisture stress, however newly regenerating stands of redcedar experiencing dieback were selected for study because they represent the future harvestable volume of this species on the coast.

The first stage of the study sampled two locations, hereafter referred to as "North" (Campbell River to Nanaimo) and "South" (Nanaimo to Victoria) locations. The four

BEC units listed above were sampled in each location. General site information such as latitude, longitude, aspect, mesoslope position (crest, mid-slope, or toe), slope angle, elevation and surface topography (smooth, slightly mounded, or strongly mounded) were recorded.

Transects were established along the long-axis of polygons at each study site. Sampling employed a modification of the point-centered quarter (PCQ) method whereby a transect roughly 200 m long was created with eight systematically spaced points along the center line (Mitchell 2001). This method assumes that trees are randomly distributed within a stand. The distance between points was generally 20 m but was adjusted to avoid sampling any tree twice. At each sampling point, an imaginary line was drawn perpendicular to the center transect line, and within each segmented quarter the closest living redcedar tree with a diameter at breast height (DBH) greater than 10 cm was measured (Figure 2.4). Thirty-two redcedar trees were sampled at each site for a total of 512 redcedar from all sites. Although redcedar was the focus species of the dendrochronological analysis, stand density measurements involved sampling the diameter of all tree species (>10cm in diameter). To measure stand density, a 5.64 m plot cord was used at each of the eight transect points and DBH was measured on all trees within the circular plot. Overall, based on the PCQ data, the number of redcedar stems per hectare, redcedar basal area per hectare, redcedar proportion of all tree species on the site, the total number of stems/ hectare and the total basal area of all species present on the site were summarized. Dominant understory species were noted along the entire transect, along with the overall % cover of understory vegetation estimated visually on the site (Green and Klinka 1994).

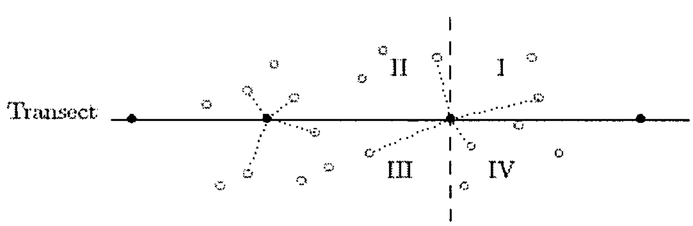

Figure 2.4: Typical layout using the point-centered quarter method in which a center transect is established, and center points are located at every 20 m. At each sampling point, a perpendicular line was imagined to divide the world into 4 quarters (I, II, III, IV). Within each quarter, the closest redcedar tree was sampled (Mitchell 2001).

Height and height-to-live-crown were measured using a vertex hypsometer; DBH (cm) and tree dominance were also recorded for each sampled redcedar. Two increment cores were taken at breast height from each redcedar on opposing sides of each sampled tree. In addition, evidence of insect or pathogen damage was noted. In regards to dieback, trees were classed using visual assessment criteria based on foliage and crown condition derived from tree health guidebooks (Innes 1990; Table 2.2).

Table 2.2: Classification criteria of dieback used to assess extent of dieback on each redcedar tree from healthy (0% dieback) to dead (100% dieback).

Classification Criteria	% Dieback	Dieback Class
Dead	100	4
Significant foliage loss to very little foliage left on tree crown	60-99	3
At least ¼ of foliage dropped with overall thinning to half of foliage dropped	30-59	2
Healthy to slight thinning of foliage and first signs of dieback	0-29	1

2.3.2 Soil Analysis

One large soil pit was dug at each site. The pit location was randomly situated along the dendrochronological transect in a position considered to be representative of the rest of the site. Each pit was dug to a minimum depth of 1 m, or until a restricting layer (such as bedrock or hardpan) was reached. The soil profile was classified based on Luttmerding *et al.* (1990). The thicknesses and colour of major soil horizons, and the size and shape of coarse fragments were noted. In addition, if mottling was present, the thickness of the mottling layer, the abundance and type of boundary present (sharp, clear or diffuse) was recorded. Tree and understory rooting depths were visually estimated. Distinctive soil characteristics were noted such as the presence of mycelium, the size of coarse fragments, and soil organism presence. Soil sampling for bulk density determination required four 10 cm x 10 cm pits to be dug at four locations around the main soil pit using the excavation method (Black *et al.* 1965). First the LF layers (litter and fermentation layers) were removed and a bag was used to fill up the removed litter space with water to determine volume (m^3). This process was repeated for the humus layer and the top 10 cm of mineral soil.

Four litter samples, four humus samples, four top-10 cm mineral soil samples (all for bulk density determination), and a small sample from each soil horizon (for soil texture determination) were taken from each soil pit. Soil moisture content was determined in the lab by weighing subsamples after drying at 100°C for 24 hours (Black *et al.* 1965). The coarse fragment (CF) content of each sample was determined by air drying, sieving through a 2 mm sieve, weighing the CF's and then calculating the % CF by weight. The % CF by volume was determined by water displacement (Lavkulich pers. comm. 2005). The coarse fragment volume was then subtracted from the total soil sample volume measured in the field. Bulk density (g/cm^3) was determined for each sample based on the following Equation 2.1 (USDA 2006):

Equation 2.1:

$$\text{Bulk density } (g/cm^3) = \frac{\text{weight of sample (g) } (<2\text{mm})}{1 + \text{moisture content } (\%)} \div (\text{Total soil vol - coarse fragment vol (ml)})$$

Samples from each horizon were hand textured (Thein 1979) and the % clay determined using the Canadian Textural Triangle online bulk density calculator (Pedosphere 2002).

Field capacity is defined as the amount of water remaining in the soil once all gravitational water has drained after a fixed period (usually 48 hours: Klute 1986). A measure of soil field capacity (% moisture content at field capacity based on the dry weight) was determined for a sub-sample of mineral soil using two different methods: a gravitational drainage method and a pressure plate method (L. Lavkulich, UBC pers. comm. October 2005; Richards 1986). The more accurate of the two methods was determined through consultation with a soil scientist (L. Lavkulich, UBC, pers. comm. October 2005) and the corresponding results used in water balance modelling (see Chapter 3 of this thesis). Details of each of these two soil methods are found in Appendix 2.

2.3.3 Dendrochronology Methodology

2.3.3.1 Dendrochronology Statistics

Cores were air dried for 24 hours and then glued to core mounts. Only one core per tree was analyzed, unless there was major rot or damage to one of the cores; in this case, both cores were mounted. Cores were sanded to improve the visibility of tree rings under a microscope. The dot method was used to date the pith of each core (Stokes and Smiley 1968). This method involves dating the outermost complete ring (2004 in this project given that trees were cored in the summer of 2005), and marking single dots on the core at each decade (e.g. 1990, 1980 etc.), two dots for each half century (e.g. 1950, 1850 etc.), and three dots at each century (e.g. 2000, 1900 etc.) until the pith or last complete inner ring was reached. In cases where the pith was not reached, the Duncan (1989) method was used to estimate the number of missing rings. The mean age of redcedar trees at each site was then calculated.

Tree rings from each core were measured to the nearest 0.01 mm on a Velmex bench connected to a stereomicroscope and computer in the UBC Geography Department Tree-Ring Lab. The computer program Measure J2X was used to record each tree ring measurement (VoorTech 2006). This program records tree ring measurements in "decadal format" which is easily transferred into other tree ring analysis programs. Following ring measurement, the program COFECHA was used to statistically crossdate the ring-width measurements and to create a master ring-width chronology for each site (Grissino-Mayer 2001). This program identifies and suggests corrections for potential dating and measurement errors in cores which might not be detected by visual crossdating. Individual cores which did not crossdate with other trees were re-examined under a microscope to look for potential dating or measurement errors. Corrections in each ring-width series were made with the Edit Ring Measurements (EDRM) program (Grissino-Mayer 2001). Once a master tree ring series was built for each site, the program ARSTAN was used to detrend and standardize the data (Holmes 1993). This program corrects for any age- or size-related decline in ring-widths as trees grow larger and removes autocorrelation in the chronology (Holmes 1993). ARSTAN undertakes three steps to create the final chronology of the tree ring series: 1) detrending of ring widths using negative exponential/straight line, cubic smoothing splines or double detrending (ex. negative exponential followed by spline) where the detrended ring-index series are averaged into a "**standard**" chronology, 2) autoregressive modeling to remove autocorrelation producing a ring-index series which is averaged into a "**residual**" chronology, and 3) the autocorrelation component is modeled back into the residual series which is then averaged into an "**arstan**" chronology (Cook 1999). Since this study analyzes tree ring data against climate data, the residual chronology was used for further analysis (L. Daniels, pers. comm. May 13th, 2006). Ring-width indices are referenced against a standardized average of 1.0; ring-width indices greater than 1.0 are wider than average rings, and those less than 1.0 are narrower than average rings. Output from ARSTAN was converted to be easily read into Excel using the FRMT program (Holmes 1994). Finally, output from FRMT was converted into columnar format using the program YUX to produce delimited columnar data which can easily be compared to yearly and monthly climate data (Holmes 1994). Ring-width chronologies were made for each individual site along with a regional chronology for the east coast of Vancouver Island.

A ranking system was created in order to list the study sites from driest to wettest and hottest to coolest using the ClimateBC model (Wang *et al.* 2006). The model was first regressed against climate data from the Comox Airport for the period of 1975-1995 to test model output. Regressions of mean, maximum and minimum temperature and total precipitation were completed with the following R^2 values: 0.99, 0.99, 0.99, and 0.82, respectively. Since model output fit very well with local climate data, this model was used to calculate climate normals for the period of 1970-2000. Mean annual temperature and mean annual precipitation were output from the model and sites were ranked based on first, the model climate output and second, latitude and elevation of each site. Specifically, sites with lowest precipitation, hottest temperatures, lowest latitude and lowest elevation were ranked closest to warmest-driest rank, and vice versa for cooler-wetter sites (Table 2.3).

Table 2.3: Site ranking from coolest-wettest and hottest-driest based on ClimateBC model output, latitude and elevation.

Climate Ranking	
Burnt Mt. 2	Coolest-wettest
Burnt Mt. 1	↓
Flux net	
Ranald Main	
Bacon Lake	
Cowichan Lake	
Gray Lake/Fry	
Horne Lake	
BC Timber Sales	
Skutz Falls 7	
Skutz Falls 6	
Shawnigan Lake	
Qualicum Bay	
Qualicum Beach	
Royal Roads	
Galiano Island	Warmest-driest

2.3.3.2 Pearson Correlation Matrix

To determine how well site residual ring width chronologies compared to each other a matrix of Pearson correlation coefficients was constructed using JMP IN 5.1 software (SAS Institute 1989-2004) calculated between each of the site residual ring-width index chronologies. This analysis was completed to assess the similarity of growth patterns amongst study sites.

2.3.3.3 Preliminary SAS Analysis

Since ring-width from pith to bark contains the natural signal of tree growth as trees get larger and older, calculation of basal area increment allows us to standardize growth rates and make comparisons among trees and between sites. Basal area increments (BAI) were calculated for each ring-width index based on Equation 2.2: (Duchesne *et al.* 2002).

Equation 2.2:
Basal area increment (BAI) = $\pi (R^2_n - R^2_{n-1})$

Where R is the tree radius and n is the year of tree ring formation. A preliminary SAS analysis was undertaken to assess how tree growth varied among the four BEC units. A two-factor (location and BEC unit) factorial split plot (because the factors were observed over several years) analysis was undertaken using SAS software. This analysis considered the two study locations (south and north), the four BEC units (CDFmm, CWHxm1, CWHxm2, and CWHmm), and average BAI over a period of 24 years (1981-2004).

2.3.3.4 Marker Ring Analysis

Marker rings (wider or narrower than average) can be used for crossdating, and determining the influence of climate on tree growth (Fritts 1976). To assess marker rings common to different sites, deviations from the mean of the residual ring-width indices were calculated. If these deviations were more than 0.1 units greater or less than the mean (% positive, % negative, respectively), these yearly ring-width indexes were highlighted over the common period of 1975-2004. In this study, a marker ring was identified if greater than 60% of the sites showed a common ring-width index.

2.3.3.5 DendroClim-2002 Analysis

DendroClim-2002 was used to analyze relationships between the site-specific residual ring-width chronologies and climate variables (Biondi and Waikul 2004). Daily climate data including maximum and minimum temperatures (°C) and total precipitation (mm) were obtained from the National Climate Data and Information Archive for five climate stations in the study area (NRC 2005) (Table 2.4).

Table 2.4: Climate stations used in DendroClim-2002 analysis showing latitude (°), longitude (°) and elevation (m) of each station along with the study sites used for analysis with each climate station.

Climate Station	Latitude (°)	Longitude (°)	Elevation (m)	Study Sites
Cowichan Lake Research Station	48.82	-124.13	176.8	Burnt #1, Burnt #2, Cowichan Lake #5, Skutz Falls #6, Skutz Falls #7
Nanaimo Airport	49.05	-123.87	28.4	Galiano Island #3, Qualicum Beach #9
Shawnigan Lake	48.65	-123.63	138	Shawnigan Lake #4
Campbell River Airport	49.95	-125.27	105.5	Fry Lake #15, BC Timber Sales #16, Bacon Lake #12, Ranald Main #13
Comox Airport	49.72	-124.9	25.6	Fluxnet #14, Qualicum Bay #10, Horne Lake #11
Victoria International Airport	48.65	-123.43	19.2	Royal Roads #8

DendroClim-2002 was run using residual ring-width index outputs from ARSTAN and four monthly climate variables (mean, maximum, minimum temperature (°C), and total precipitation (mm)) over a 19-month period from the previous year April data to the current year October data. This length of time period was chosen because coniferous trees are often influenced by climate conditions in the previous year. Bootstrap confidence intervals were calculated to assess the significance of correlation and response coefficients (Bondi and Waikul 2004). Tests were conducted for the period of 1975 to 2004. The process of bootstrapping involves using the original sample as an approximation of the sample population (Johnson 2001). This method allows a sample to be derived from our sample population (with replacement) from which repeated samples are drawn. DendroClim generates 1000 samples (selected at random) from the sample population and runs numerical computations including linear correlation, Jacobean rotations for Eigen values, singular value decomposition and solutions of linear systems along with principle component regression (Bondi and Waikul 2004).

2.3.4 Dieback Analysis Methodology

All four sites with dieback were compared to one another to see if there was a common period when growth was significantly reduced which would allow the dieback onset date to be clarified. Dieback was greatest at the Qualicum Beach site, and questionable at the other three dieback sites. An in-depth analysis of Qualicum Beach was completed using simple linear regression, threshold analysis, and a two-way analysis of variance to test a hypothesized dieback onset date.

2.3.4.1 Regression Analysis

Residual ring-widths for the Qualicum Beach site were calculated and these values were plotted against residuals of climate data calculated using the difference from a 40-year mean value for each variable. The climate variables analyzed were: June, July, spring, summer, fall, winter, and growing season mean temperature (May-September) (°C), June, July, spring, fall, winter, and growing season total precipitation (mm). For each core, ARSTAN produced a best fit equation to the data using either linear regression or a negative exponential fit to the data. Based on these recommended equations, a curve was fit which was used to calculate the residuals of the ring-width indices (Figure 2.5).

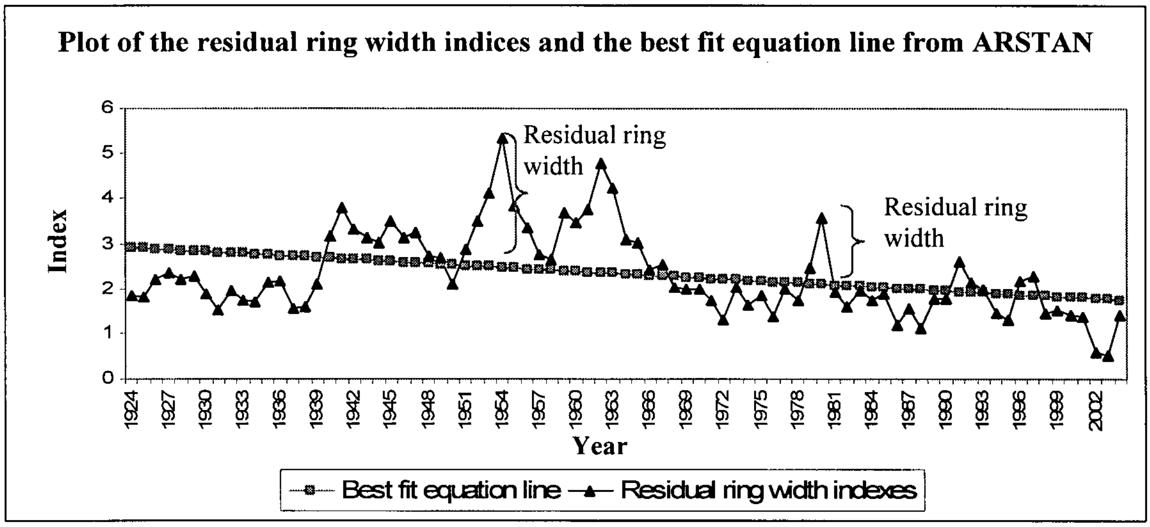

Figure 2.5: Residual ring-width indices (black triangles) along with the ARSTAN best fit equation line (grey squares) from Qualicum Beach (core 2BL) chronology establishment in 1924 until 2004. Note the difference between the residual ring-width index and the best fit equation line from ARSTAN is the residual ring-widths used in the regression analysis.

A Shapiro-Wilk test was utilized to ensure all ring-width residuals were normally distributed (SAS Institute 1989-2004). Simple linear regression plots of residual ring width and residual climate variables were constructed for each of the 18 cores in the site chronology. In addition, cumulative climate residuals were calculated using data from the past 2 and 3-years in order to see if there was a lagged effect of climate on the ring-width residuals.

2.3.4.2 SAS Analysis of Variance

At the Qualicum Beach site, increment cores were taken from two dead trees. By statistically crossdating ring widths from the dead trees against the chronology from live trees at the site, it was estimated that these two trees died in 1998. Based on this observation, and the fact that 1998 was a very hot and dry year, it was hypothesized that dieback began in 1998. The idea was to compare average BAI values before and after the proposed onset of dieback in 1998 to see if there was a difference between these two time periods amongst dieback and non-dieback trees. Average BAI values were calculated for the 7-year periods of 1991-1997 and 1998-2004 using Equation 2.1:. In order to adequately compare dieback and non-dieback trees, comparable dominance classes had to be used. Thus, five co-dominant and two intermediate dieback and non-dieback trees were compared. Four groups were thus compared in the analysis of variance: dieback BAI's from 1991-1997 and 1998-2004 and non-dieback BAI's from 1991-1997 and 1998-2004.

2.3.4.3 Threshold Analysis

One of the main goals of this thesis project was to address potential management implications of future changes in climate, particularly in the case of redcedar growth on eastern Vancouver Island. A threshold analysis was developed to address this issue. This analysis was designed in Excel to determine the magnitude of change in climate variables that would cause a significant change in ring-width indices. The first step was to select climate variables and calculate the residual values for each year based on subtraction from the mean for the 30-year period of 1975-2004. Once the residuals were calculated, the percent difference between these residuals was calculated by dividing the residual by the mean of the time period and multiplying by 100%. The residual ring widths derived from the regression analysis were used to compare with the climate % difference values. Eight different thresholds (positive and negative) were developed for the climate variables based on their % difference distribution, and five thresholds (positive and negative) were developed for the residual ring widths. For each year, if the % difference in climate or the residual ring-width exceeded (in a positive or negative direction) the set threshold, a 1 (+1 for greater than threshold, -1 for less than threshold) was assigned.

Next, the 1's from the climate and ring width analyses were combined and added if both analyses produced either two -1's or two +1's. A subsequent analysis also counted cases where both climate and ring widths did not exceed the thresholds (1's and 0's) (i.e. when climate and ring width acted in the same way 1, or both had no change 0). However, it is difficult to interpret results considering both cases, so focus will be put only on the "1's only" data (i.e. when both climate and ring-width acted in the same way).

2.4 Results

2.4.1 Forest Composition and Structure

Out of the 512 trees sampled, only 27 trees were classified as having dieback (Table 2.5, Figure 2.6). Four of the 16 study sites included redcedar with dieback and these sites were located in three of the four BEC units (CDFmm, CWHxm1, and CWHxm2). Thus, dieback was limited to the three drier BEC units. No dieback was noted in the higher elevation, wetter, CWHmm unit. The most extensive dieback was found at Qualicum Beach (CDFmm), where 15 trees (47% of the sampled trees) exhibited some dieback. The Cowichan Lake site (CWHxm2) had the least amount of dieback (6%) amongst affected sites, with only two trees classified as showing the first signs of dieback (class 1 based on Table 2.2). Shawnigan Lake, in the south, had 16% of the trees showing signs of dieback, and the Fluxnet site, in the north, also had 16% of trees affected.

Table 2.5: Summary of site characteristics, including the site name, average redcedar age on each site, BEC unit, elevation (meters above sea level, m.a.s.l.), stand density (number of stems/ hectare), density of redcedar per hectare, redcedar basal area per hectare (m^2/ha), average redcedar dominance class and average age.

Site #	Name	BEC Unit	Elevation (m.a.s.l.)	% Dieback out of 32 sample redcedar	Stand Density (# stems/ha)	Density of redcedar /ha	Basal area of all species (m^2/ha)	Average redcedar dominance class	Average redcedar age
1	Burnt Mt. 1	CWHmm	706	0	1438	325	47	2	45
2	Burnt Mt. 2	CWHmm	689	0	1138	338	79	2	45
3	Galiano Island	CDFmm	88	0	438	175	89	2	84
4	Shawnigan Lake	CWHxm1	136	16	863	263	87	3	69
5	Cowichan Lake	CWHxm2	167	6	288	113	98	2→3	87
6	Skutz Falls 6	CWHxm1	173	0	588	113	70	2	63
7	Skutz Falls 7	CWHxm2	175	0	650	138	96	2→3	60
8	Royal Roads	CDFmm	164	0	250	100	101	3	96
9	Qualicum Beach	CDFmm	78	47	938	438	77	3	87
10	Qualicum Bay	CDFmm	80	0	988	388	131	2	123
11	Horne Lake	CWHxm1	146	0	788	238	90	2	64
12	Bacon Lake	CWHmm	441	0	1113	163	64	3	36
13	Ranald Main	CWHmm	615	0	675	325	53	2	29
14	Flux net	CWHxm2	315	16	825	163	62	3	48
15	Gray Lake/Fry	CWHxm2	263	0	1475	300	71	2	57
16	BC Timber Sales	CWHxm1	210	0	713	363	62	2	53

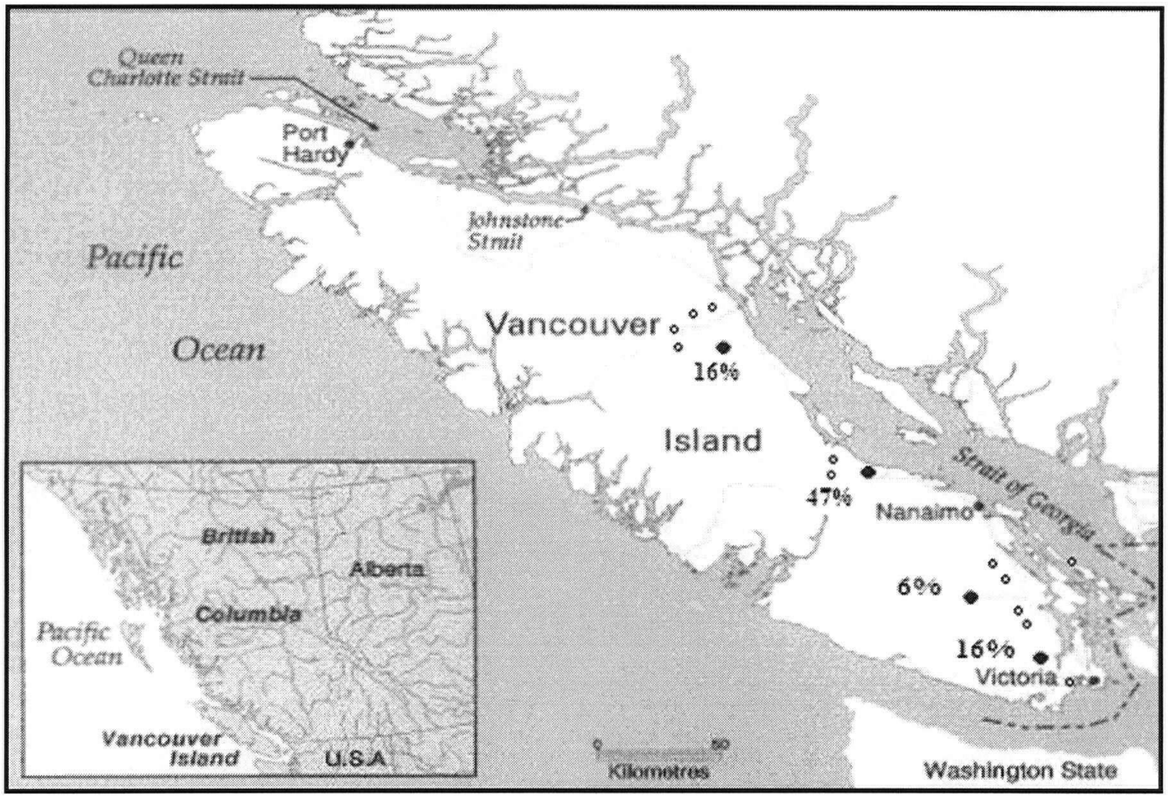

Figure 2.6: Location and percentage (32 redcedar sampled per site) of dieback redcedar (solid circles) and other non-dieback sites (open circles) on Vancouver Island (modified from Integrated Land Management Bureau 2005). From top to bottom of figure: 16% FluxNet site, 47% Qualicum Beach, 6% Cowichan Lake, and 16% Shawnigan Lake.

Most trees showed only mild evidence of top foliage thinning and drop and trees in dominance class 2 were the most prevalent of all dieback trees (Figure 2.8). In reference to dieback classes, the majority (63%) of dieback trees amongst all dieback sites were in the class 1 category, indicating that the majority of dieback trees were beginning to show only the first signs of dieback. However, there were also approximately 30% which were in class 2, having dropped a quarter to one-half of their foliage. Finally, there were about 7% of the dieback trees with very little foliage left on the crown (class 4, or were dead). No trees were noted in the class 3 category, although since dieback class was assessed visually there may have been trees in class 2 which could have been on the borderline to class 3. The majority of dieback trees were classed as co-dominant (dominance class 2), with suppressed trees (dominance class 4) as second, intermediate trees (dominance class 3) as third, and dominants (dominance class 1) as fourth.

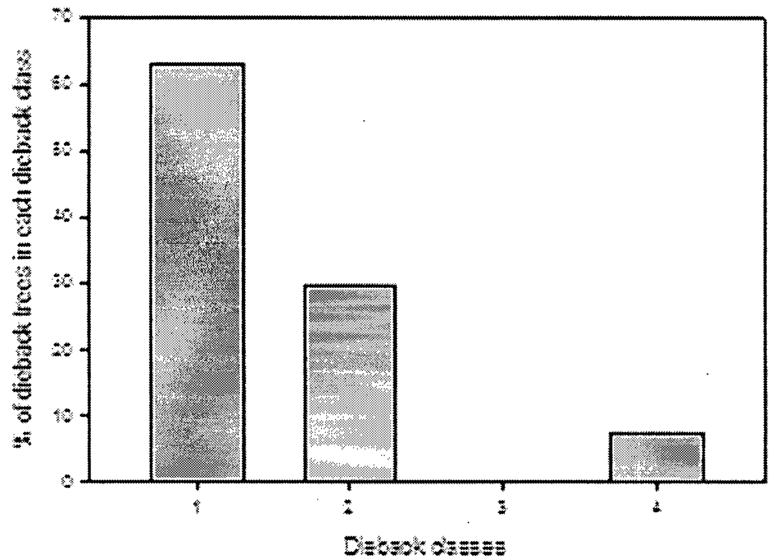

Figure 2.7: Average percent of dieback trees on each site that were in each dieback class (1-4: where 1 is healthy to slight thinning of foliage, 2 is at least ¼ of foliage dropped with overall thinning to half of foliage dropped, 3 is significant foliage loss to very little foliage left on tree crown and 4 is dead).

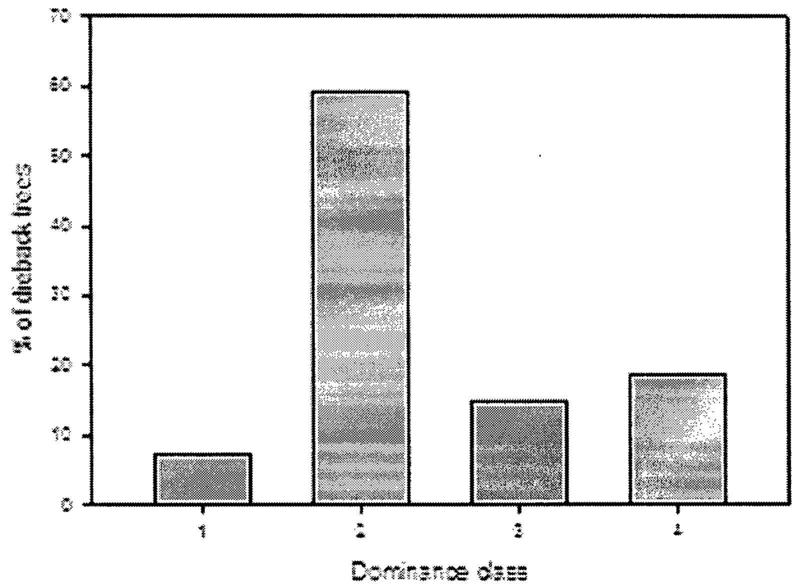

Figure 2.8: Average percent of dieback trees in each dominance class (1-4: where 1 is dominant, 2 is co-dominant, 3 is intermediate, and 4 is suppressed).

2.4.2 Soils

Bulk density (g/cm^3) was highest at Cowichan Lake (0.97 g/cm^3) indicating high soil compaction and decreased amounts of organic matter (Table 2.6). Shawnigan Lake, however, had the lowest bulk density (0.4 g/cm^3) indicating lower soil compaction and higher amounts of organic matter. Coarse fragment content was highest at Skutz Falls 6 (76%) and lowest at BC Timber Sales (2%). Organic matter content was highest at Skutz Falls 6 (29%) and lowest at BC Timber Sales (6%). Therefore, despite higher rocky fragments in Skutz Falls 6 substrate, the soil contained more organic matter capable of holding more water in the soil compared to the BC Timber Sales site. Thus, soils with the higher organic matter contents would be less prone to drought effects since organic matter can uptake and hold water for longer than sandy coarse textured soils with little organic matter. According to Table 2.6, Skutz Falls 6 should be less prone to drought compared to BC Timber Sales or Qualicum Beach sites. Rooting depth was deepest at the most extensive dieback site, Qualicum Beach (100 cm) and shallowest at Fluxnet (40cm). In addition, the majority of soils were either sandy loam or loamy sand in texture and well drained.

Table 2.6: Average soil properties of study sites listed by location (north=N and south=S) and BEC unit. Note that grey shaded sites had dieback.

Site #	Location	Name	BEC Unit	Average Bulk density of mineral soil (g/cm3)	Coarse fragment content (%)	Organic Matter content of mineral soil (%)	Tree rooting depth (cm)	Soil texture	Drainage
1	S	Burnt Mt. 1	CWHmm	0.60	59	21	75	sandy loam	well drained
2	S	Burnt Mt. 2	CWHmm	0.57	60	26	90	loam	moderately well drained
3	S	Galiano Island	CDFmm	0.93	73	11	45	sandy loam	well drained
4	S	Shawnigan Lake	CWHxm1	0.40	69	20	80	loamy sand	well drained
5	S	Cowichan Lake	CWHxm2	0.97	45	15	110	sandy loam	well drained
6	S	Skutz Falls 6	CWHxm1	0.68	76	29	80	loamy sand	well drained
7	S	Skutz Falls 7	CWHxm2	0.91	36	12	90	loamy sand	well drained
8	S	Royal Roads	CDFmm	0.75	5	12	110	silty clay loam	well drained
9	N	Qualicum Beach	CDFmm	0.88	28	7	100	loamy sand	well drained
10	N	Qualicum Bay	CDFmm	0.78	60	13	103+	loamy sand	imperfectly drained
11	N	Horne Lake	CWHxm1	0.84	36	13	65	loamy sand	rapidly drained
12	N	Bacon Lake	CWHmm	0.62	49	19	70	loamy sand	rapidly drained
13	N	Ranald Main	CWHmm	0.70	62	17	60	sandy loam	well drained
14	N	Flux net	CWHxm2	0.81	52	13	40	sandy clay loam	well drained
15	N	Gray Lake/Fry	CWHxm2	0.57	42	19	55	sandy loam	well drained
16	N	BC Timber Sales	CWHxm1	0.65	2	6	65	loamy sand	well drained

2.4.3 Dendrochronology

2.4.3.1 Dendrochronology Statistics

Eleven to 31 cores out of 32 cores sampled at each site were included in the site-level ring-width chronologies. The chronology time interval, defined by the oldest core on each site, ranged from 143 years at Royal Roads to 31 years at Ranald Main (Table 2.7). Mean sensitivity refers to the relative difference in width from one ring to the next (Fritts 1976). The data tend to show low mean sensitivity values because many of the study trees had complacent ring-widths indicating low interannual variation in the factors limiting tree growth. The standard deviation measures the scatter of ring-width data from the mean ring-width value. Level-1 autocorrelation (AC (1)) is a measure of temporal autocorrelation which indicates whether growth conditions in the current year have an influence on the ring growth in the current and following year. Note that this autocorrelation is partially quantified and removed with the dendrochronology tools ARSTAN and DendroClim 2002. Finally, the overall mean correlation is the average correlation among all ring-width series or cores in the dataset.

Table 2.7: Dendrochronology summary statistics and characteristics along with the number of cores used in the analysis. The overall mean correlation was not calculated for Ranald Main due to the short chronology at this site (only 32 years).

#	Site	Number of cores used in analysis	Interval Time Span	Mean standard ring width	Mean sensitivity	Standard Deviation	AC(1)	Overall Mean Correlation
1	Burnt Mt.	30	1953-2004	0.99	0.12	0.21	0.64	0.52
2	Burnt Mt.	24	1953-2004	0.94	0.11	0.32	0.89	0.59
3	Galiano Island	17	1912-2004	0.97	0.14	0.18	0.50	0.28
4	Shawnigan Lake	11	1929-2004	0.96	0.13	0.21	0.76	0.33
5	Cowichan Lake	22	1875-2004	0.93	0.15	0.31	0.86	0.44
6	Skutz Falls	27	1938-2004	0.94	0.14	0.32	0.85	0.51
7	Skutz Falls	19	1941-2004	0.95	0.14	0.24	0.71	0.27
8	Royal Roads	18	1862-2004	0.94	0.15	0.28	0.78	0.11
9	Qualicum Beach	22	1865-2004	0.96	0.19	0.34	0.67	0.36
10	Qualicum Bay	17	1866-2004	0.97	0.11	0.18	0.70	0.26
11	Horne Lake	15	1936-2004	0.97	0.14	0.18	0.49	0.13
12	Bacon Lake	31	1960-2004	0.95	0.17	0.22	0.51	0.45
13	Ranald Main	31	1975-2004	1.00	0.20	0.33	0.64	-
14	Fluxnet	20	1953-2004	0.96	0.15	0.21	0.49	0.18
15	Gray Lake/Fry	16	1940-2004	0.96	0.14	0.20	0.59	0.32
16	BC Timber Sales	24	1945-2004	0.93	0.13	0.28	0.84	0.31
	Mean	**22**	**1925-2004**	**0.96**	**0.14**	**0.25**	**0.68**	**0.34**

The overall chronology time span was from 1862-2004, but the common time period for comparison between sites was 1975-2004. The average mean sensitivity for the chronologies was 0.14 with a standard deviation of 0.25, which is lower than has been found for other species in the Interior of B.C. (Daniels and Watson 2003). This is likely because sites were not selected to maximize the climate signal in the ring-width series; instead, sites were selected in order to assess where dieback was occurring on the east coast of the island and within which BEC units. The first-order autocorrelation coefficient was on average 0.68 among sites, indicating that growth in a given year may be conditioned by climate conditions in the previous growth years (i.e. there may be a cumulative impact of interannual climate variation on growth).

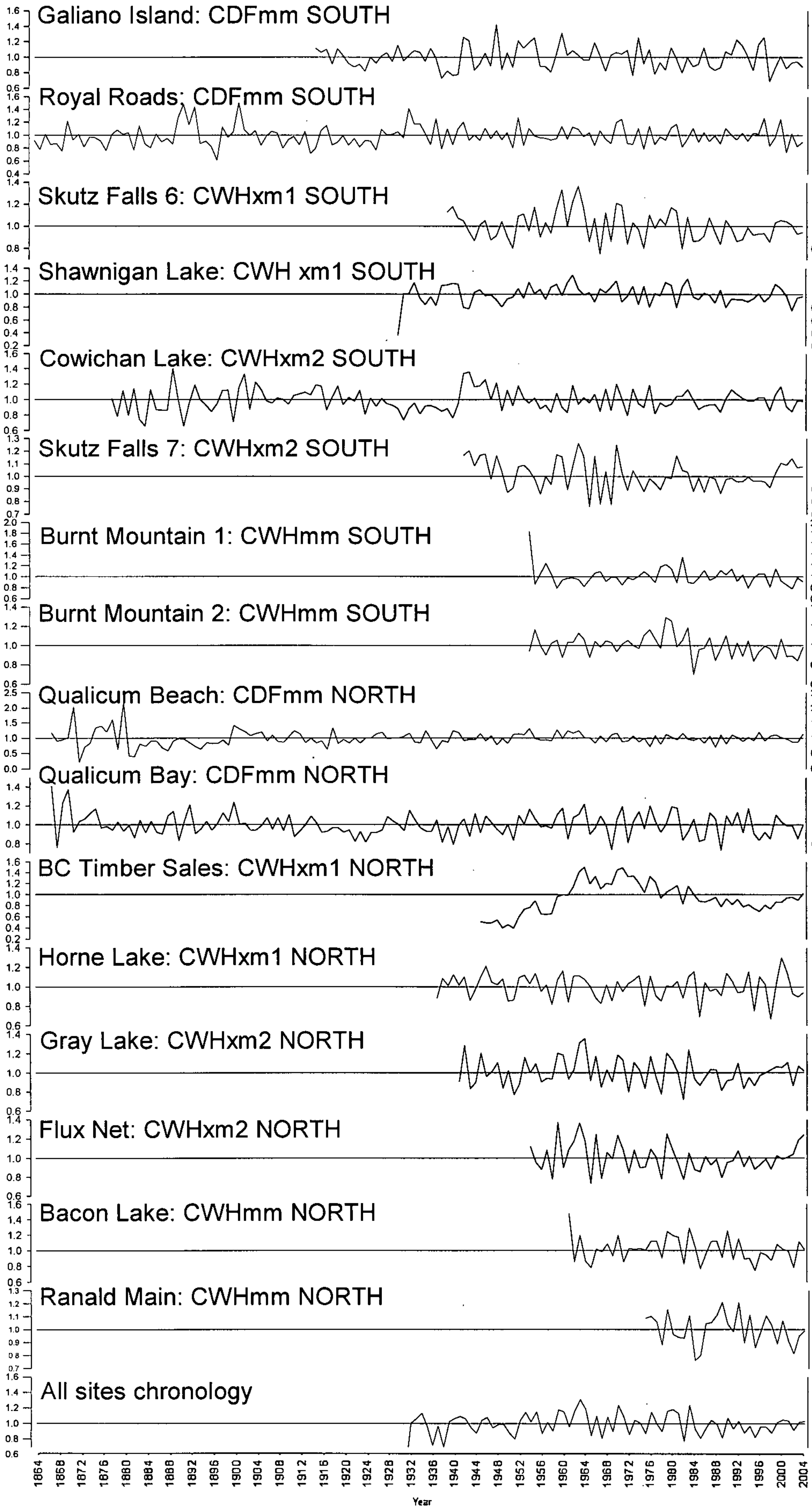

Figure 2.9: Residual ring-width indices for each study site versus year, along with the BEC unit and study location (north or south) from tree establishment until 2004.

2.4.3.2 Pearson Correlation Matrix

Out of the 16 sites, nine were significantly correlated with at least four other sites, thus, over half showed common radial growth patterns (Table 2.8). The other seven sites: Cowichan Lake, Galiano Island, Burnt Mountain 1, Qualicum Beach, Ranald Main, Shawnigan Lake and Skutz Falls 7, are correlated with less than four other study sites. Interestingly, three out of these sites had dieback and had two different age cohorts growing within the stand. At Cowichan Lake, trees established in 1871-1910 and 1930-1940. At Qualicum Beach trees established in 1865-1900 and 1924-1927, and at Shawnigan Lake trees established in 1911-1927 and around 1945. The presence of two cohorts may have skewed growth patterns between these sites compared with single cohort stands. Three other stands with low correlations were Burnt Mountain 1 which established around 1955, Ranald Main established around 1975 and Skutz Falls 7 which established around 1945 and were three of the younger study sites examined.

Table 2.8: Correlation matrix of Pearson correlation coefficients calculated between each of the site residual ring width index chronologies. Highlighted cells indicate statistical significance at or beyond the 0.05 level.

Pearson Correlations	Bac	Cow	Gal	Gray	Horne	Burnt 1	Burnt 2	BC T	Oyster	Q Bay	Q Bea	Ran	RR	Sha	SK6	SK7
Bacon Lake	-	0.25	0.17	0.72	0.46	-0.02	0.49	0.62	0.53	0.55	-0.10	0.44	0.14	0.23	0.52	0.12
Cowichan Lake	0.25	-	0.49	0.31	0.57	0.13	0.08	0.11	0.14	0.33	-0.09	0.09	0.51	0.01	0.30	0.28
Galiano Island	0.17	0.49	-	0.15	0.43	0.09	0.17	-0.04	0.18	0.20	-0.21	0.21	0.59	-0.21	0.18	-0.05
Gray Lake	0.72	0.31	0.15	-	0.41	-0.27	0.39	0.46	0.74	0.46	-0.01	0.38	0.13	0.22	0.54	0.29
Horne Lake	0.46	0.57	0.43	0.41	-	-0.11	0.11	0.20	0.30	0.47	-0.08	0.18	0.50	0.00	0.49	0.29
Burnt Mt. 1	-0.02	0.13	0.09	-0.27	-0.11	-	0.24	-0.14	-0.19	-0.26	0.16	0.06	0.00	0.45	-0.14	-0.30
Burnt Mt. 2	0.49	0.08	0.17	0.39	0.11	0.24	-	0.46	0.31	0.28	0.17	0.56	0.03	0.38	0.38	0.02
BC Timber sales	0.62	0.11	-0.04	0.46	0.20	-0.14	0.46	-	0.42	0.55	-0.27	0.12	0.09	0.02	0.51	0.20
Oyster river-FluxNet	0.53	0.14	0.18	0.74	0.30	-0.19	0.31	0.42	-	0.39	0.00	0.28	0.04	0.05	0.37	0.40
Qualicum Bay	0.55	0.33	0.20	0.46	0.47	-0.26	0.28	0.55	0.39	-	-0.17	0.12	0.35	-0.24	0.64	0.29
Qualicum Beach	-0.10	-0.09	-0.21	-0.01	-0.08	0.16	0.17	-0.27	0.00	-0.17	-	0.09	-0.35	0.54	-0.22	0.06
Ranald Main	0.44	0.09	0.21	0.38	0.18	0.06	0.56	0.12	0.28	0.12	0.09	-	-0.05	0.19	-0.01	-0.23
Royal Roads	0.14	0.51	0.59	0.13	0.50	0.00	0.03	0.09	0.04	0.35	-0.35	-0.05	-	-0.30	0.41	0.10
Shawnigan	0.23	0.01	-0.21	0.22	0.00	0.45	0.38	0.02	0.05	-0.24	0.54	0.19	-0.30	-	-0.06	-0.19
Skutz Falls 6	0.52	0.30	0.18	0.54	0.49	-0.14	0.38	0.51	0.37	0.64	-0.22	-0.01	0.41	-0.06	-	0.47
Skutz Falls 7	0.12	0.28	-0.05	0.29	0.29	-0.30	0.02	0.20	0.40	0.29	0.06	-0.23	0.10	-0.19	0.47	-

2.4.3.3 Preliminary SAS analysis

The SAS analysis of variance did not meet the assumptions of normality or of equal variances, so power transformations were attempted to stabilize the variances. This was unsuccessful, so the graphs were interpreted in light of the failure to meet the assumptions. Since there were major interactions between the BAI values for each BEC unit, only a brief discussion of the general output trends will be presented.

Overall, location 1 (southern) sites had higher basal area increments (average of 1842 cm^2 from 1981-2004) compared to location 2 (northern) sites (average of 1603 cm^2 from 1981-2004) (Figure 2.10 and Figure 2.11). There were a few climate periods where all four BEC units showed similar patterns on the southern sites. For example, BAI values were consistently low for 1989 and 1999, but were relatively large in 1997 and 2000. In the north, there appeared to be reduced growth during 1982, 1985, 1993, 1998, and 2003, and increased growth during 1988, 1992, 1994, 2001 and 2004.

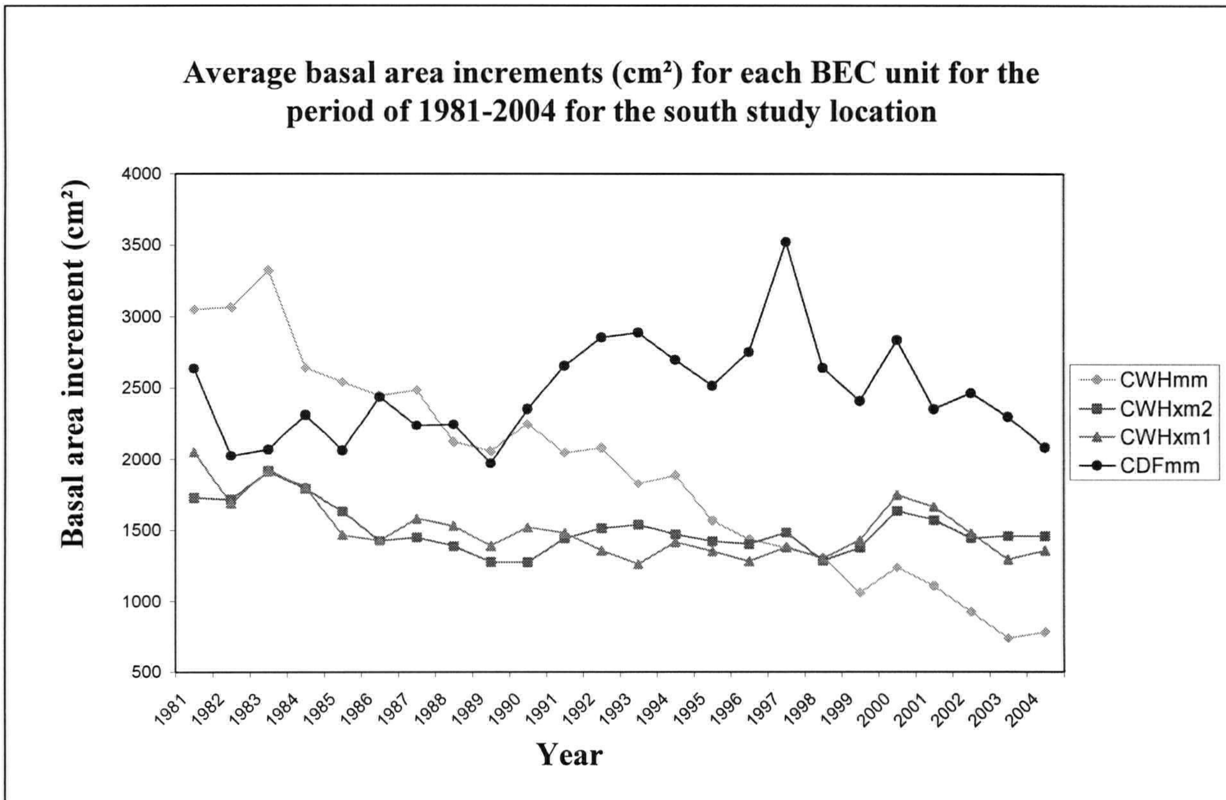

Figure 2.10: Average BAI values for the southern study location from 1981-2004

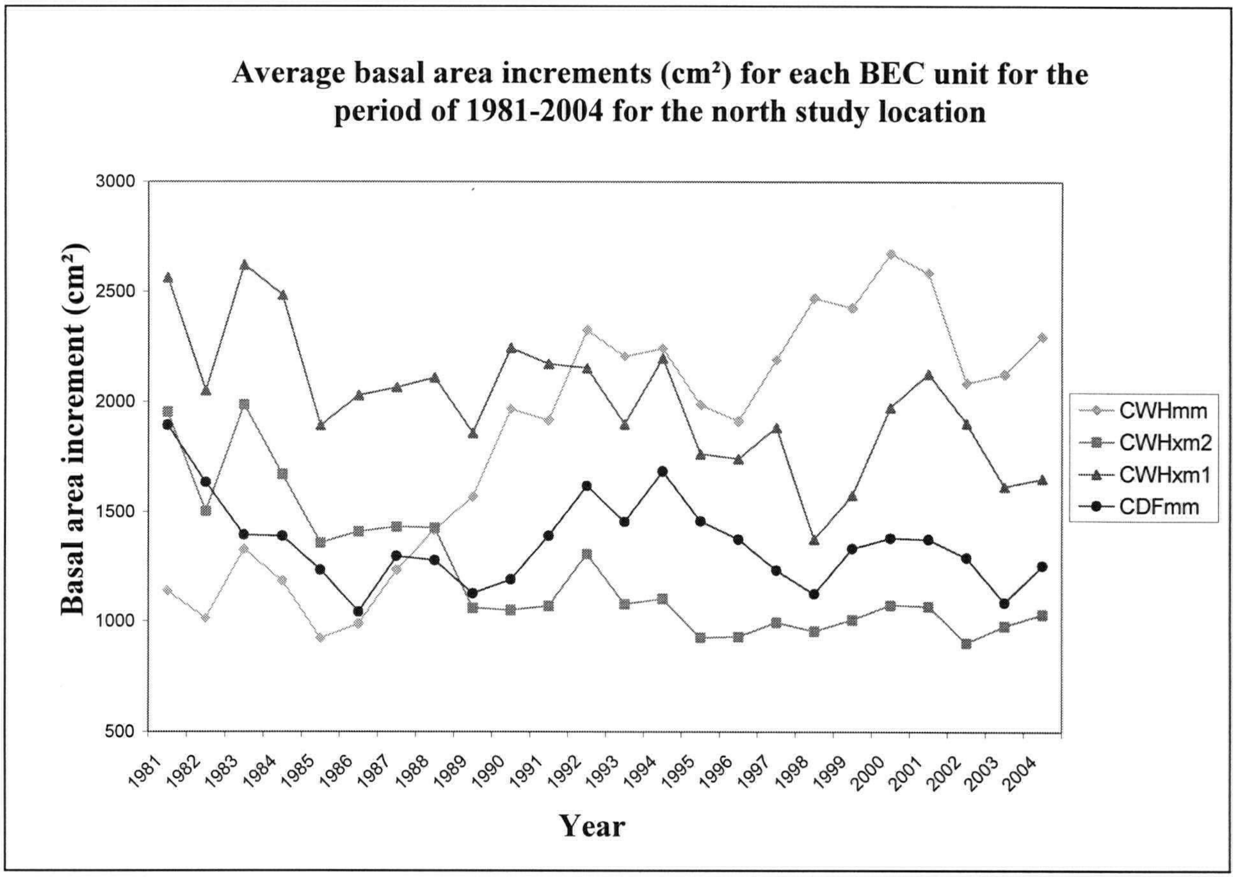

Figure 2.11: Average BAI values for the northern study location from 1981-2004

The CDFmm unit had higher average BAI values after 1989 compared to the three other BEC units. This is not what would be expected since redcedar trees growing in the CDFmm unit should be more stressed for water and on the lower limit of their distribution range.

2.4.3.4 Marker Ring Analysis

Four years had common residual ring-width index signals between 1975 and 2004 (Table 2.9). The years 1976 and 1980 were wider than average rings, while 1989 and 1998 were narrower than average rings. Note also that 1979 (wide) and 1982 (narrow) had 56% of sites showing a common signal.

Table 2.9: *List of deviations from the mean for each site with pale grey cells being significant. On the far right of the table, the % of sites showing either common positive (%POS) or negative (%NEG) marker rings are displayed with greater than 60% of sites indicating a marker ring (shaded dark grey).

YEAR	BAC	COW	GAL	GRA	HOR	B1	B2	BCT	FN	QBAY	QBEA	RAN	RR	SHA	SK6	SK7	%NEG	%POS	Marker
1975	-0.01	-0.09	-0.08	-0.17	-0.20	0.08	0.11	0.10	-0.10	-0.04	0.01	0.09	-0.20	0.13	-0.21	-0.14	38	19	
1976	0.10	0.19	0.11	0.17	0.11	0.00	0.16	0.40	0.09	0.20	-0.27	0.10	0.15	-0.19	0.10	-0.03	6	69	Wide
1977	0.11	-0.17	-0.22	-0.05	-0.09	-0.12	0.07	0.30	0.00	0.03	0.09	0.06	-0.13	0.02	-0.03	-0.07	31	6	
1978	-0.11	-0.03	-0.06	-0.23	-0.15	0.17	-0.03	0.00	-0.23	-0.08	-0.19	-0.12	-0.01	-0.01	0.06	-0.12	44	6	
1979	0.23	-0.08	-0.16	0.20	0.01	0.21	0.29	0.11	0.25	0.00	0.12	0.15	-0.06	0.19	0.01	-0.02	6	56	
1980	0.18	-0.05	0.13	0.13	0.00	0.14	0.26	0.16	0.08	0.19	0.04	-0.04	0.13	0.15	0.17	-0.03	0	63	Wide
1981	0.15	0.05	-0.01	0.00	0.06	-0.12	-0.01	0.23	-0.06	0.17	-0.05	-0.06	0.18	-0.19	0.13	0.15	13	38	
1982	-0.19	0.06	-0.20	-0.28	-0.12	0.35	0.06	-0.11	-0.24	-0.16	0.16	-0.07	-0.17	0.12	-0.21	0.03	56	19	
1983	0.28	0.14	0.00	0.24	0.10	-0.11	0.19	0.22	0.05	-0.07	-0.02	0.11	-0.04	0.24	0.08	0.02	6	50	
1984	0.03	0.01	-0.11	-0.07	0.16	-0.13	-0.30	0.07	-0.13	0.06	-0.06	-0.24	0.12	-0.03	-0.14	-0.13	44	13	
1985	-0.25	-0.12	-0.08	-0.14	-0.31	-0.02	-0.04	-0.05	-0.15	-0.17	0.01	-0.20	-0.09	-0.07	-0.14	-0.02	50	0	
1986	-0.07	-0.07	0.13	-0.06	0.04	0.11	-0.03	-0.07	0.01	-0.15	-0.14	0.04	0.05	0.03	-0.09	-0.14	19	13	
1987	0.10	-0.06	-0.11	0.03	-0.05	-0.07	0.08	-0.04	-0.08	0.13	0.07	0.05	-0.08	-0.01	0.07	-0.02	6	6	
1988	0.10	-0.05	-0.16	0.03	-0.02	-0.02	-0.15	0.02	-0.02	0.06	-0.28	0.11	0.00	-0.13	-0.06	-0.03	25	13	
1989	-0.11	-0.15	-0.13	-0.19	-0.10	0.11	-0.03	-0.15	-0.21	-0.26	0.10	0.21	-0.12	0.08	-0.17	-0.15	63	13	Narrow
1990	0.24	0.02	0.08	-0.09	0.14	0.03	0.10	-0.01	-0.05	0.09	-0.17	0.04	0.12	-0.19	0.05	-0.04	13	25	
1991	-0.14	0.14	0.04	-0.08	0.06	0.14	-0.14	-0.12	-0.04	-0.01	0.11	-0.02	0.02	-0.06	-0.02	-0.03	19	19	
1992	0.13	0.08	0.23	0.09	-0.06	-0.09	0.03	-0.02	0.07	0.13	0.03	0.20	-0.05	-0.07	-0.14	-0.06	6	25	
1993	-0.12	0.03	0.15	-0.17	-0.05	0.03	-0.11	-0.16	-0.10	-0.09	-0.10	-0.11	0.05	-0.07	-0.12	-0.05	38	6	
1994	-0.12	-0.01	0.01	-0.06	0.16	-0.21	0.05	-0.12	0.02	0.17	0.04	0.11	-0.08	-0.10	-0.02	-0.02	25	19	
1995	-0.27	-0.01	-0.17	-0.14	-0.25	-0.03	-0.16	-0.18	-0.13	-0.09	-0.07	-0.14	0.04	-0.06	-0.08	-0.05	50	0	
1996	-0.04	0.04	0.17	-0.04	0.10	0.04	-0.06	-0.23	-0.08	-0.16	0.19	-0.02	0.03	0.02	-0.07	-0.05	13	19	
1997	-0.08	0.03	0.27	-0.01	0.02	0.04	-0.01	-0.12	-0.02	-0.08	-0.08	0.10	0.28	-0.11	-0.07	-0.05	13	19	
1998	-0.14	-0.13	-0.31	0.03	-0.34	-0.20	-0.03	-0.19	-0.12	-0.15	0.08	0.03	-0.15	-0.03	-0.15	-0.10	69	0	Narrow
1999	0.06	0.07	-0.12	0.06	0.03	0.14	-0.14	-0.07	0.02	0.10	0.12	-0.11	-0.02	0.16	0.03	0.01	19	25	
2000	0.00	0.18	0.02	0.05	0.30	-0.08	0.07	-0.07	-0.02	0.03	0.03	0.06	0.26	0.10	0.05	0.09	0	25	
2001	-0.02	-0.08	-0.14	0.10	0.14	-0.16	-0.11	0.01	0.01	-0.01	-0.02	-0.09	-0.26	-0.02	0.04	0.08	25	13	
2002	-0.23	-0.14	-0.06	-0.14	-0.07	-0.22	-0.11	0.02	0.04	-0.01	-0.11	-0.19	0.03	-0.24	0.01	0.13	50	6	
2003	0.10	-0.01	-0.05	0.07	-0.11	-0.03	-0.16	-0.03	0.18	-0.14	-0.13	-0.05	-0.16	-0.04	-0.07	0.06	31	6	
2004	0.00	-0.01	-0.12	0.02	-0.06	-0.10	-0.02	0.09	0.24	0.00	0.13	-0.01	-0.09	-0.02	-0.06	0.06	6	13	

*Note: BAC=Bacon Lake, COW=Cowichan Lake, GAL=Galiano Island, GRA=Gray Lake, HOR=Horne Lake, B1=Burnt Mt. 1, B2=Burnt Mt. 2, BCT=BC Timber Sales, FN=Fluxnet, QBAY=Qualicum Bay, QBEA=Qualicum Beach, RAN=Ranald Main, RR=Royal Roads, SHA=Shawnigan Lake, SK6=Skutz Falls 6, SK7=Skutz Falls 7

2.4.3.5 DendroClim results

Growing season temperature and precipitation significantly influenced the growth of redcedar at many, but not all, sites (Table 2.10 to Table 2.13; Appendix 1) There was a general negative correlation (five out of 16 sites, and "all sites") with current-year June mean temperature, indicating that the warmer the June, the lower the residual ring-width index and the cooler the June, the higher the index (Table 2.10). This is expected because when there are hot June temperatures there will likely be lower soil moisture available for tree growth.

Generally, current June and July minimum temperatures appeared to be negatively correlated at a few of the sites (Table 2.11). The positive correlation found with previous-year December minimum temperature could be due to autocorrelation effects from the previous year.

More significant relationships were found with maximum monthly temperature compared to minimum temperatures (Table 2.12). Since warm temperatures were limiting to growth, the climate-growth relationships were intensified when tested using the higher maximum temperatures. June maximum monthly temperatures were negatively correlated with residual ring-width indices.

Total precipitation did not produce many significant relationships to residual ring-width index (Table 2.13). However, it is interesting to note that the three driest sites (Galiano Island, Royal Roads, and Qualicum Beach) did have positive correlations with either April, May, June or July total precipitation; the higher the total precipitation in any of these growing season months, the greater the residual ring-width index.

Table 2.10: Bootstrap response function coefficients for mean monthly temperature (°C) with residual ring-width indices for redcedar at 16 sites and for a regional chronology*. Light grey cells are significant positive correlations and dark grey cells are significant negative correlations (p = 0.05).

Site	Mean temperature (°C)																		
	Previous Year									Current Year									
	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct
Burnt Mt. 1	0.221	-0.071	0.127	0.237	0.195	-0.047	-0.081	-0.081	0.133	-0.305	-0.181	-0.012	-0.208	-0.080	0.087	-0.121	-0.086	-0.131	0.043
Burnt Mt. 2	-0.324	-0.154	0.027	0.004	-0.114	-0.135	0.046	-0.172	0.394	-0.308	-0.045	0.053	0.089	0.215	-0.164	-0.054	-0.006	0.010	0.005
Galiano Island	0.179	-0.066	0.000	0.193	-0.236	0.028	-0.222	-0.023	0.035	0.038	-0.052	0.112	0.065	0.161	-0.206	-0.120	0.026	-0.126	0.167
Shawnigan Lake	-0.256	-0.017	0.224	0.126	0.238	0.006	0.079	-0.125	0.099	-0.218	-0.077	0.037	-0.066	-0.066	0.142	-0.223	-0.155	-0.216	-0.059
Cowichan Lake	-0.084	-0.072	0.156	0.158	0.070	0.255	-0.204	0.058	0.114	0.116	0.157	0.126	-0.112	0.112	-0.187	-0.160	-0.196	0.004	-0.100
Skutz Falls 6	-0.042	-0.273	0.176	-0.084	-0.004	0.046	0.140	-0.176	0.371	0.028	0.192	-0.064	0.000	-0.113	-0.484	-0.051	-0.038	0.042	0.035
Skutz Falls 7	-0.207	-0.256	0.085	0.130	0.030	0.121	0.067	0.193	0.181	0.123	0.092	-0.084	-0.136	-0.042	-0.149	0.099	0.090	0.103	-0.032
Royal Roads	0.146	0.122	0.138	0.048	-0.190	-0.065	-0.096	-0.035	-0.027	0.001	0.197	-0.090	0.017	-0.124	-0.209	-0.118	0.064	-0.015	0.043
Qualicum Beach	-0.222	0.199	-0.048	0.065	0.054	0.040	-0.047	0.004	0.049	-0.315	0.053	0.004	0.081	0.036	0.158	0.057	0.162	0.012	-0.151
Qualicum Bay	0.016	0.136	0.042	-0.137	-0.034	-0.036	0.026	0.009	0.221	0.095	0.255	-0.079	0.091	-0.090	-0.374	-0.165	-0.030	-0.002	0.094
Horne Lake	-0.004	0.161	0.066	-0.030	-0.052	-0.021	0.040	-0.052	0.024	0.135	0.013	0.076	0.152	-0.129	-0.345	-0.307	-0.075	-0.057	-0.036
Bacon Lake	-0.090	-0.222	0.297	-0.061	0.033	0.043	0.110	0.004	0.220	-0.056	0.026	0.208	0.023	-0.142	-0.258	-0.216	0.020	-0.152	-0.020
Ranald Main	-0.122	-0.130	-0.066	-0.004	-0.077	0.100	0.107	-0.110	0.178	-0.040	-0.059	0.108	0.216	0.111	-0.049	-0.201	0.056	0.036	0.140
Flux net	-0.152	-0.011	0.281	0.309	-0.074	-0.083	0.126	-0.033	0.209	-0.020	0.174	-0.069	0.073	-0.039	-0.073	-0.191	-0.009	-0.028	0.032
Gray Lake/Fry	-0.241	-0.219	0.267	0.144	-0.049	0.122	0.101	-0.035	0.145	0.129	0.212	0.121	-0.024	-0.005	-0.315	-0.082	-0.133	-0.081	0.110
BC Timber Sales	-0.195	-0.237	0.217	0.071	-0.221	0.116	0.091	-0.007	0.047	0.203	0.158	-0.025	0.049	0.063	-0.326	-0.088	0.035	0.012	0.034
All sites	-0.179	-0.271	0.266	-0.030	-0.197	0.056	0.089	-0.043	0.196	0.012	0.209	0.169	0.042	-0.045	-0.425	-0.129	-0.011	0.016	0.063

*** All individual sites in are listed with their relationship to mean monthly temperature. At the bottom of the table, the same climate variable was run against a residual ring-width index developed for the entire east coast of Vancouver Island (all sites), and this chronology was compared with the climate variables to assess regional ring-width influences.**

Table 2.11: Bootstrap response function coefficients for minimum monthly temperature (°C) with residual ring-width indices for redcedar at 16 sites and for a regional chronology. Light grey cells are significant positive correlations and dark grey cells are significant negative correlations (p = 0.05).

Site	Minimum temperature (°C)																		
	Previous Year									Current Year									
	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct
Burnt Mt. 1	-0.24	-0.08	-0.06	-0.27	-0.15	0.18	0.12	0.00	-0.05	-0.17	0.10	-0.03	0.16	-0.03	-0.11	0.24	0.04	-0.01	0.06
Burnt Mt. 2	-0.35	-0.17	-0.01	-0.04	0.06	-0.04	0.14	-0.27	0.29	-0.28	0.00	-0.07	-0.01	0.15	-0.05	-0.05	0.00	0.21	-0.05
Galiano Island	0.07	-0.10	0.01	0.14	-0.13	-0.05	-0.18	0.01	-0.02	-0.02	-0.09	0.01	0.20	0.10	0.02	-0.04	0.19	-0.11	-0.03
Shawnigan Lake	-0.25	-0.13	0.14	0.13	0.26	0.16	0.13	-0.23	0.02	-0.25	-0.09	0.08	-0.15	-0.12	0.17	-0.22	-0.18	-0.09	0.10
Cowichan Lake	-0.19	-0.06	0.25	0.16	0.04	-0.15	-0.20	0.17	0.03	0.07	0.07	0.01	-0.05	0.14	-0.12	0.01	0.11	0.14	-0.16
Skutz Falls 6	-0.20	-0.24	0.15	-0.10	0.04	0.11	0.12	-0.15	0.27	-0.01	0.12	0.00	0.07	-0.02	-0.32	-0.10	0.06	0.26	-0.24
Skutz Falls 7	-0.15	-0.27	0.18	0.16	0.02	0.24	-0.11	0.18	0.21	0.14	-0.03	-0.11	-0.06	-0.03	-0.14	0.08	0.07	0.24	-0.03
Royal Roads	0.09	-0.01	0.08	0.01	-0.19	-0.01	-0.06	0.03	0.06	-0.05	0.18	-0.13	0.13	-0.03	-0.09	-0.07	0.10	-0.05	-0.08
Qualicum Beach	-0.08	0.14	0.14	0.04	0.13	0.29	0.17	-0.06	0.01	-0.24	0.04	-0.06	-0.10	-0.07	0.08	0.07	-0.03	-0.03	-0.15
Qualicum Bay	0.00	0.12	0.02	-0.08	-0.01	0.02	-0.04	0.01	0.28	0.09	0.28	-0.07	0.12	-0.07	-0.30	-0.23	0.02	0.09	0.01
Horne Lake	-0.05	0.15	0.06	0.07	0.03	0.01	-0.03	-0.02	0.11	0.11	-0.02	0.03	0.26	-0.07	-0.30	-0.29	-0.02	0.00	-0.15
Bacon Lake	-0.19	-0.30	0.13	-0.03	-0.09	0.09	0.05	0.08	0.25	-0.01	0.09	0.12	0.13	0.00	-0.20	-0.18	-0.02	0.01	-0.04
Ranald Main	-0.04	-0.18	-0.14	-0.09	0.01	0.05	0.02	-0.02	0.27	0.00	-0.02	-0.01	0.09	0.07	-0.01	-0.10	0.10	0.20	0.13
Flux net	-0.07	0.03	0.17	0.18	0.03	-0.04	0.12	-0.08	0.20	-0.04	0.12	0.01	-0.03	-0.10	-0.14	-0.23	0.03	0.12	0.04
Gray Lake/Fry	-0.28	-0.34	0.19	0.20	-0.05	0.14	0.09	0.00	0.12	0.10	0.21	0.11	-0.05	0.07	-0.28	-0.13	-0.14	0.21	0.08
BC Timber Sales	-0.19	-0.33	0.15	0.09	-0.20	0.06	0.11	0.06	0.11	0.26	0.17	-0.04	-0.04	0.12	-0.25	-0.06	0.07	0.20	-0.02
All sites	-0.26	-0.31	0.30	-0.04	-0.12	0.09	0.02	0.07	0.29	-0.02	0.24	0.08	0.06	0.14	-0.32	-0.16	0.12	0.11	-0.08

Table 2.12: Bootstrap response function coefficients for maximum monthly temperature (°C) with residual ring-width indices for redcedar at 16 sites and for a regional chronology. Light grey cells are significant positive correlations and dark grey cells are significant negative correlations (p = 0.05).

Site	Maximum temperature (°C)																	
	Previous Year									Current Year								
	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct
Burnt Mt. 1	0.23	-0.07	0.12	0.26	0.19	-0.04	-0.03	-0.04	0.03	-0.33	-0.19	0.06	-0.14	-0.03	0.05	-0.10	-0.13	-0.09	0.07
Burnt Mt. 2	-0.16	-0.17	0.09	0.07	-0.22	-0.12	0.05	-0.04	0.39	-0.24	-0.18	0.15	0.15	0.19	-0.15	-0.08	-0.02	-0.15	0.11
Galiano Island	0.10	-0.02	0.03	0.11	-0.21	0.10	-0.18	-0.11	0.05	-0.02	0.02	0.08	-0.11	0.14	-0.28	-0.09	0.06	-0.07	0.15
Shawnigan Lake	-0.14	0.02	0.21	0.05	0.18	-0.08	0.00	-0.04	0.13	-0.19	-0.08	0.05	0.05	-0.05	0.07	-0.21	-0.17	-0.21	-0.03
Cowichan Lake	0.02	-0.04	0.00	0.11	0.08	0.39	-0.13	0.01	0.01	0.08	0.16	0.16	-0.11	0.03	-0.22	-0.19	-0.24	-0.12	-0.01
Skutz Falls 6	0.10	-0.20	0.16	-0.01	-0.09	-0.01	0.12	-0.06	0.33	0.09	0.06	-0.08	0.12	-0.07	-0.47	-0.02	-0.06	-0.13	0.23
Skutz Falls 7	-0.18	-0.23	-0.01	0.09	-0.05	0.10	0.17	0.21	0.09	0.11	0.06	-0.08	-0.11	-0.07	-0.14	0.05	0.06	0.00	0.00
Royal Roads	0.14	0.11	0.18	0.03	-0.11	-0.02	-0.10	-0.06	-0.07	0.02	0.14	-0.07	-0.05	-0.12	-0.26	-0.12	0.03	-0.05	0.05
Qualicum Beach	-0.24	0.14	-0.17	-0.02	0.01	-0.03	-0.22	0.05	0.07	-0.29	0.01	0.09	0.21	-0.01	0.04	-0.03	0.08	-0.03	-0.02
Qualicum Bay	0.02	0.16	0.05	-0.13	-0.03	-0.03	0.11	0.03	0.22	0.03	0.16	-0.10	0.07	-0.10	-0.40	-0.11	0.02	-0.08	0.14
Horne Lake	0.01	0.14	0.09	-0.05	-0.11	-0.01	0.08	-0.08	0.00	0.13	0.01	0.05	0.01	-0.15	-0.37	-0.27	-0.11	-0.10	0.04
Bacon Lake	0.12	-0.12	0.32	0.04	-0.01	0.03	0.21	-0.05	0.18	0.06	0.01	0.21	0.10	-0.11	-0.22	-0.17	0.11	-0.21	0.05
Ranald Main	-0.14	-0.08	-0.05	0.07	-0.16	0.23	0.19	-0.14	0.14	-0.06	-0.09	0.25	0.20	0.10	-0.04	-0.16	0.08	0.01	0.08
Flux net	-0.18	-0.02	0.33	0.33	-0.14	-0.04	0.08	0.01	0.18	-0.01	0.17	-0.07	0.11	0.01	-0.11	-0.18	0.00	-0.09	0.05
Gray Lake/Fry	-0.14	-0.09	0.26	0.16	-0.09	0.07	0.14	-0.07	0.13	0.21	0.18	0.09	0.11	-0.03	-0.24	-0.09	-0.06	-0.22	0.07
BC Timber Sales	-0.15	-0.16	0.25	0.07	-0.22	0.11	0.12	-0.07	0.04	0.22	0.09	0.04	0.21	-0.01	-0.23	-0.09	0.02	-0.13	0.06
All sites	-0.06	-0.19	0.28	0.01	-0.21	0.03	0.15	-0.09	0.15	0.10	0.10	0.16	0.15	-0.12	-0.35	-0.12	0.00	-0.13	0.15

Table 2.13: Bootstrap response function coefficients for total monthly precipitation (mm) with residual ring-width indices for redcedar at 16 sites and for a regional chronology. Light grey cells are significant positive correlations and dark grey cells are significant negative correlations (p = 0.05).

Site	Total monthly precipitation (mm)																	
	Previous Year									Current Year								
	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct
Burnt Mt. 1	-0.24	-0.08	-0.06	-0.27	-0.15	0.18	0.12	0.00	-0.05	-0.17	0.10	-0.03	0.16	-0.03	-0.11	0.24	0.04	-0.01	0.06
Burnt Mt. 2	-0.11	-0.03	-0.25	-0.07	0.10	0.07	0.11	-0.27	0.03	-0.22	0.14	-0.08	-0.08	-0.11	0.15	0.24	-0.12	0.02	-0.02
Galiano Island	0.20	-0.08	-0.10	0.00	0.21	-0.30	0.12	-0.05	0.09	0.14	-0.05	-0.02	0.30	0.18	0.32	-0.08	-0.02	0.02	-0.01
Shawnigan Lake	-0.14	-0.05	-0.18	-0.02	-0.29	0.26	-0.11	0.02	-0.03	-0.01	0.19	-0.10	-0.14	-0.01	-0.05	0.33	-0.04	0.06	0.07
Cowichan Lake	-0.12	-0.28	0.02	-0.01	0.01	-0.23	0.18	0.23	0.15	0.03	0.14	0.01	0.08	0.09	0.16	0.23	0.14	-0.04	0.09
Skutz Falls 6	-0.26	-0.16	-0.21	0.14	-0.06	-0.02	-0.10	-0.09	0.26	-0.07	0.07	-0.01	-0.20	0.04	0.18	-0.19	0.12	0.16	-0.20
Skutz Falls 7	-0.08	-0.09	-0.02	-0.05	-0.08	-0.13	-0.05	0.03	0.30	0.00	-0.11	-0.13	-0.05	-0.22	0.21	-0.05	0.03	0.09	0.05
Royal Roads	-0.02	-0.12	-0.17	-0.11	-0.04	0.14	0.01	0.12	0.12	-0.04	0.08	0.04	0.21	0.24	0.22	-0.06	-0.06	-0.03	-0.09
Qualicum Beach	0.08	0.14	0.14	0.06	-0.04	0.07	0.00	0.12	0.10	-0.05	0.24	-0.18	0.00	-0.22	-0.27	0.32	-0.03	0.07	0.10
Qualicum Bay	-0.04	-0.06	-0.01	0.06	-0.01	-0.03	-0.17	0.02	0.08	0.12	0.06	-0.10	-0.13	0.04	0.16	0.06	0.01	-0.09	-0.07
Horne Lake	-0.08	-0.11	0.02	0.01	-0.08	-0.12	-0.14	0.04	-0.05	-0.12	0.02	-0.14	-0.11	0.09	0.20	0.17	0.01	0.05	-0.14
Bacon Lake	-0.09	-0.22	0.30	-0.06	0.03	0.04	0.11	0.00	0.22	-0.06	0.03	0.21	0.02	-0.14	-0.26	-0.22	0.02	-0.15	-0.02
Ranald Main	0.10	0.04	-0.41	0.06	0.21	-0.14	-0.28	-0.06	0.05	0.12	0.01	-0.10	-0.19	-0.10	0.20	0.19	0.07	-0.03	-0.08
Flux net	0.30	-0.18	-0.18	-0.23	0.18	-0.09	0.03	-0.07	0.06	-0.01	-0.06	0.04	-0.13	-0.09	0.03	0.11	-0.01	0.05	-0.01
Gray Lake/Fry	-0.05	-0.23	-0.16	-0.07	0.19	-0.07	-0.08	-0.06	0.14	-0.07	0.24	0.04	-0.11	-0.05	0.18	-0.12	-0.19	0.14	-0.11
BC Timber Sales	0.05	-0.24	-0.19	0.02	0.23	-0.25	-0.03	-0.05	0.11	-0.05	0.11	0.05	-0.29	0.06	0.20	-0.14	-0.19	0.12	-0.14
All sites	-0.04	-0.15	0.03	0.19	0.13	-0.14	-0.05	-0.29	0.02	-0.03	0.25	-0.07	-0.11	0.00	0.12	-0.07	0.05	0.26	0.04

2.4.4 Dieback analysis

Ring-width z-scores were highly variable between adjacent trees at individual sites (Figure 2.12 to Figure 2.15), and among trees between each of the dieback sites. For this reason, the in-depth dieback analysis focused only on the most extensive dieback site, Qualicum Beach. The following sections present results of the detailed dieback analyses.

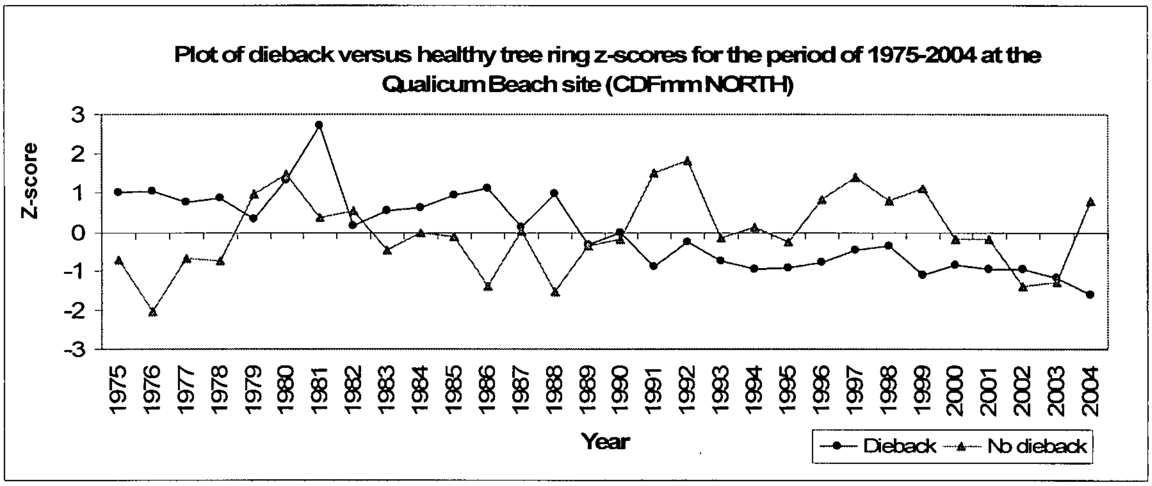

Figure 2.12: Dieback versus healthy tree z-scores on Qualicum Beach study site from 1975-2004

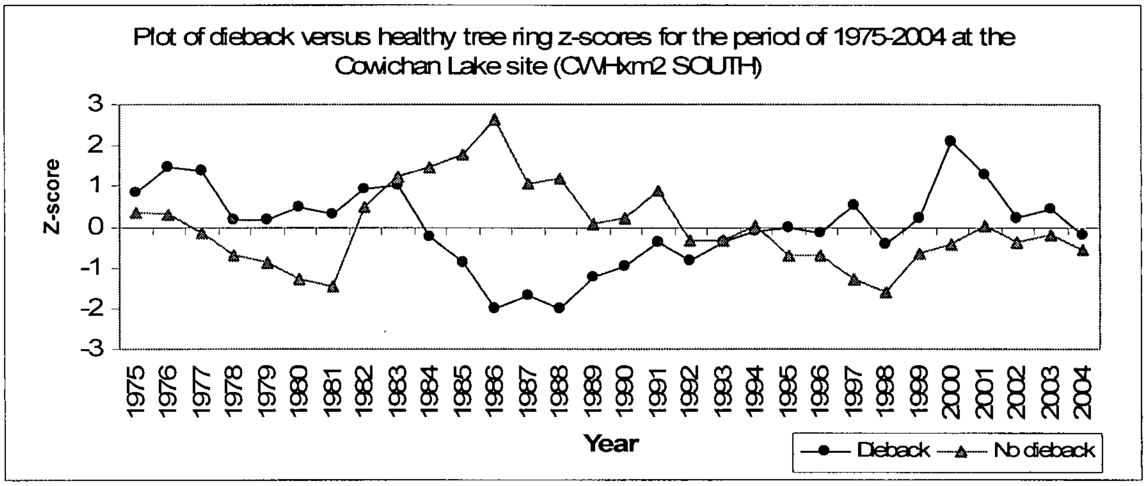

Figure 2.13: Dieback versus healthy tree z-scores on Cowichan Lake study site from 1975-2004

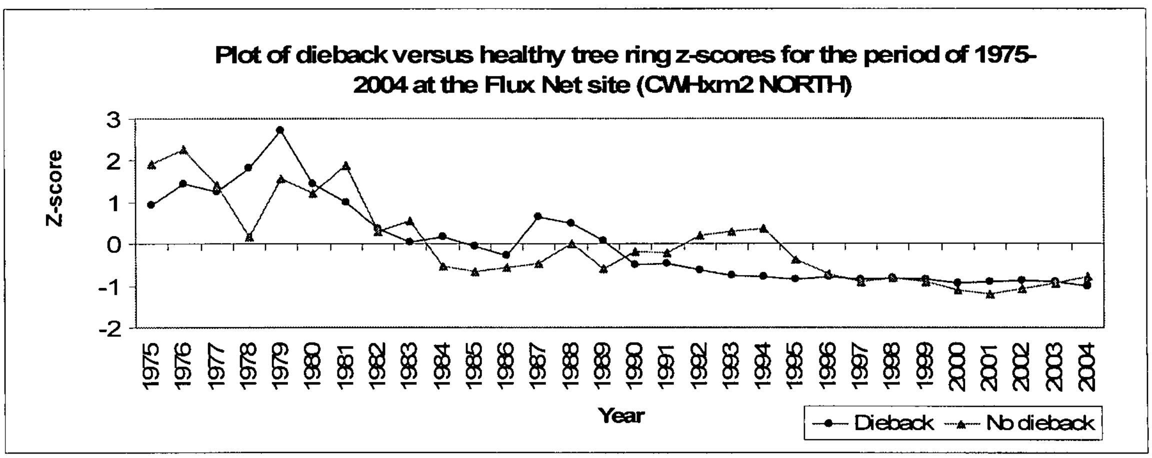

Figure 2.14: Dieback versus healthy tree z-scores on Fluxnet study site from 1975-2004

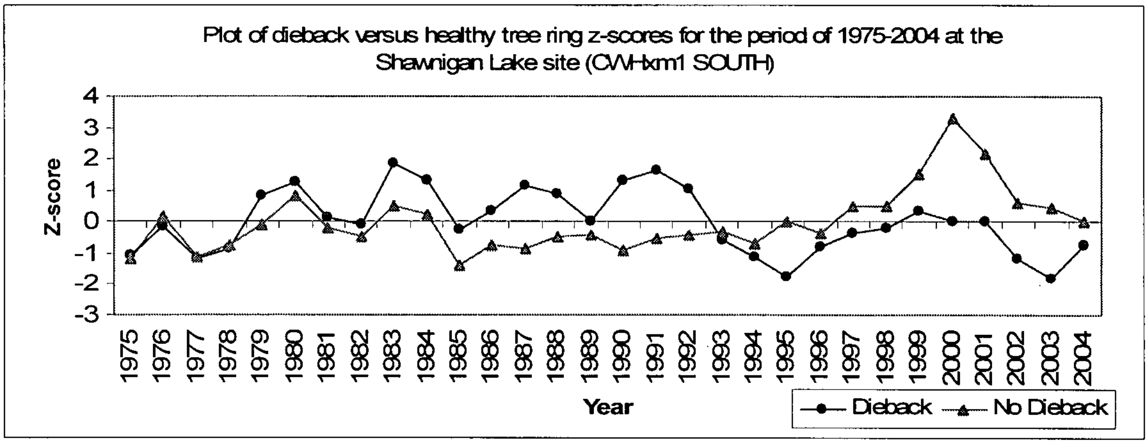

Figure 2.15: Dieback versus healthy tree z-scores on Shawnigan Lake study site from 1975-2004

2.4.4.1 Regression Analysis

Out of the 32 trees cored on the Qualicum Beach site, 18 were included in the site tree ring chronology, and of these trees, 8 had dieback and 10 did not. The regression analysis indicated differences in the significant influences of climate on growth of trees with and without dieback (Table 2.14 and 2.15). In four of the cores, summer mean temperature had significant negative relationships with the ring-width residuals and winter total precipitation had a significant positive relationship for the cores with dieback. In the cores without dieback, three cores showed negative relationships to summer mean temperatures, and three cores showed positive relationships to total winter precipitation. Four of the cores also showed positive relationships to June total precipitation.

Additionally, cumulative climate indices were compared to residual ring-width indices and found to have generally higher regression coefficients than current year climate indices. Thus, trees may likely be responding to 2-3 successive years of climate, such as two very dry growing seasons in a row, which is more likely to suppress ring-widths compared to just one dry year. This factor, also known as autocorrelation, produces a response lag of ring-width growth for a number of years depending on the site and species in question (Fritts 1976). As was noted in Table 2.7, the autocorrelation coefficient averaged 0.68, suggesting that lagged effects of previous climate years may indeed greatly influence current growth years.

Table 2.14: **Regressions associated with analysis of dieback cores (ex. 2BL = core #2 back left of PCQ quadrant, and 5TL = core #5 top left of PCQ quadrant) against climate variables (Jul = July, Summ = summer, and GS = growing season). Significant negative relationships are shaded dark grey and significant positive relationships are shaded light grey.**

CORES WITH DIEBACK														
2BL	**Mean Temp**							**Total ppt**						
	June	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**	**June**	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**
Current year	0.0458	0.0094	0.0006	0.0248	0.0013	0.0309	0.0282	0.0759	0.0163	0.0083	0.0475	0.0433	0.0357	0.0717
Cum. 2 years	0.0112	0.0003	0.0107	0.0025	8.00E-05	1.52E-02	0.0007	0.0675	0.0393	0.0043	0.113	0.1361	0.0524	0.1739
Cum. 3 years	0.0002	0.0327	0.0614	0.0039	0.0002	0.0019	0.015	0.0464	0.0013	0.0054	0.0471	0.2627	0.0163	0.2155
3BL	**Mean Temp**							**Total ppt**						
	June	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**	**June**	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**
Current year	0.0013	0.0503	0.1568	0.1326	0.0577	0.0649	0.1214	0.0535	0.0059	0.0029	0.1	0.0013	0.0566	0.0247
Cum. 2 years	0.023	0.1329	0.3078	0.2414	0.0812	0.0761	0.2498	0.0286	0.0115	0.0227	0.0716	0.0091	0.1244	0.0096
Cum. 3 years	0.0166	0.0813	0.2832	0.287	0.1204	0.1474	0.2532	0.0109	0.0227	0.0432	0.0872	0.0605	0.1833	0.0014
4BL	**Mean Temp**							**Total ppt**						
	June	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**	**June**	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**
Current year	0.0231	0.1572	0.1292	0.321	0.074	0.1074	0.2311	0.0036	2.00E-05	0.0003	0.0007	0.0186	0.0035	0.0022
Cum. 2 years	0.0538	0.2513	0.1999	0.4415	0.0756	0.2916	0.3483	0.0066	0.0018	5.00E-05	0.0052	0.0942	0.0155	0.0183
Cum. 3 years	0.0842	0.2461	0.2376	0.5006	0.1265	0.4282	0.4189	1.00E-06	0.0391	0.002	0.0263	0.1718	0.0345	0.0193
4BR	**Mean Temp**							**Total ppt**						
	June	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**	**June**	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**
Current year	0.033	0.0251	0.0385	0.1323	0.0477	0.0651	0.094	0.0179	0.0186	2.00E-05	0.0051	0.0004	0.1152	0.001
Cum. 2 years	0.0046	0.0639	0.0004	0.0364	0.035	0.0548	0.0202	0.1243	0.1211	0.001	0.0655	0.0179	0.0937	0.0254
Cum. 3 years	0.0087	0.015	0.0078	0.0998	0.0566	0.0402	0.0104	0.1847	0.0461	0.0005	0.0457	0.0805	0.0958	0.0529
5TL	**Mean Temp**							**Total ppt**						
	June	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**	**June**	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**
Current year	0.0464	0.0049	0.0096	0.0021	0.0244	0.0008	0.0177	0.0221	0.0395	0.0233	0.044	0.0001	0.0639	0.0181
Cum. 2 years	0.0506	0.0368	0.0193	0.0382	2.47E-02	5.78E-02	0.0786	0.0011	0.088	0.1211	3.00E-05	7.00E-05	0.1464	0.0009
Cum. 3 years	0.0675	0.2058	0.0523	0.1177	0.0171	0.0019	0.1766	0.0031	0.0429	0.1328	0.0001	0.0007	0.2179	0.0005
6BR	**Mean Temp**							**Total ppt**						
	June	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**	**June**	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**
Current year	0.0025	0.0071	0.0945	0.08	0.046	0.0245	0.0795	0.032	0.0001	0.0079	0.0738	8.00E-05	0.1516	0.0179
Cum. 2 years	0.0045	0.0435	0.129	0.1577	0.0317	0.058	0.1153	0.0134	0.0152	5.56E-02	0.0439	0.0318	0.1797	0.0002
Cum. 3 years	0.0001	0.0022	0.0961	0.1206	0.0521	0.0791	0.06	1.62E-02	0.0139	0.1194	0.0799	0.0783	0.3174	0.0006
7BL	**Mean Temp**							**Total ppt**						
	June	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**	**June**	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**
Current year	0.0387	0.0255	0.0054	0.1288	0.0247	0.0336	0.0263	0.0525	0.0079	0.0187	0.0668	0.0228	0.0001	0.1287
Cum. 2 years	0.0175	0.0915	0.0182	0.192	0.0521	0.004	0.058	5.00E-05	0.0746	0.005	0.0014	0.0122	0.0073	0.0192
Cum. 3 years	0.0099	0.0799	0.0225	0.26	0.131	0.019	0.0922	0.0031	0.1295	0.0032	0.0021	0.0007	0.0001	0.0053
8BL	**Mean Temp**							**Total ppt**						
	June	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**	**June**	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**
Current year	0.0182	0.025	0.0221	0.0793	0.0346	0.0408	0.072	0.0126	0.0162	0.0025	0.0131	0.0253	0.012	0.0417
Cum. 2 years	0.0294	0.0441	0.0326	0.093	0.0429	0.0763	0.0967	0.0002	0.0237	0.0224	0.0003	0.0574	0.0232	0.0412
Cum. 3 years	0.0901	0.1932	0.1054	0.1895	0.059	0.1348	0.2196	0.0016	0.042	0.069	4.00E-05	0.1089	0.0414	0.0673

Table 2.15: Regressions associated with regression analysis of cores without dieback (ex. 3BR = core #3 back right of PCQ quadrant, and 4TL = core #4 top left of PCQ quadrant) against climate variables (Jul = July, Summ = summer, and GS = growing season). Significant negative relationships are shaded dark grey and significant positive relationships are shaded light grey.

CORES WITHOUT DIEBACK														
3BR	**Mean Temp**							**Total ppt**						
	June	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**	**June**	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**
Current year	0.0251	0.0802	0.0948	0.2938	0.0483	0.1031	0.2167	0.0378	1.00E-05	0.0014	0.0032	0.0109	0.061	2.00E-05
Cum. 2 years	0.0308	0.1117	0.0519	0.2754	0.0366	0.1747	0.1624	0.1316	0.0006	0.001	0.0003	0.0786	0.0976	0.0268
Cum. 3 years	0.0235	0.0962	0.0289	0.2822	0.0279	0.2872	0.1454	0.131	0.0029	0.0088	0.0009	0.219	0.0553	0.0718
4TL	**Mean Temp**							**Total ppt**						
	June	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**	**June**	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**
Current year	0.0037	0.0041	0.0312	0.0265	0.005	0.0272	0.0334	0.0071	0.0286	0.0154	0.0669	0.0023	0.0694	0.0202
Cum. 2 years	0.0074	0.0014	0.0246	0.0009	0.0016	0.0035	0.0018	0.0301	0.0594	0.0465	0.0018	0.0154	0.0937	0.0024
Cum. 3 years	0.0053	0.0141	0.0008	0.0002	0.0043	0.024	0.0012	0.0956	0.0381	0.007	0.0001	0.0376	0.1155	0.0111
4TR	**Mean Temp**							**Total ppt**						
	June	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**	**June**	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**
Current year	0.0208	0.0071	0.0116	0.0658	0.0297	0.0304	0.042	0.025	0.0295	0.0002	0.0134	0.0013	0.1227	4.00E-04
Cum. 2 years	4.00E-06	0.0204	0.0211	0.0382	0.0132	0.0109	1.00E-05	0.1558	0.1629	0.0015	0.108	0.0079	0.117	0.0281
Cum. 3 years	0.0067	0.0034	0.1194	0.0004	0.0019	1.77E-02	0.0551	0.1537	0.0347	0.0245	0.0454	0.1145	0.0139	0.0655
5BR	**Mean Temp**							**Total ppt**						
	June	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**	**June**	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**
Current year	0.0127	0.1177	0.0491	0.1744	0.0027	0.075	0.098	0.0279	0.0186	0.0024	0.0195	5.00E-05	0.0137	0.018
Cum. 2 years	0.0236	0.1441	0.0815	0.2203	0.0179	0.1292	0.1354	0.0618	0.0031	3.00E-06	0.0033	0.0259	0.0283	0.0006
Cum. 3 years	0.0016	0.0451	0.044	0.2338	0.0682	0.2425	0.1167	0.0446	0.0358	0.0053	0.0028	0.0889	0.0208	0.0087
6BL	**Mean Temp**							**Total ppt**						
	June	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**	**June**	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**
Current year	0.0194	0.0547	0.004	0.0128	0.0003	0.0027	0.0073	0.2279	0.0014	0.0014	0.1712	0.0276	0.042	1.36E-02
Cum. 2 years	3.76E-02	0.0218	0.0174	0.0382	0.0007	0.0008	3.00E-03	0.2206	0.0007	0.0282	0.1156	0.007	0.0661	0.0424
Cum. 3 years	0.0293	0.0196	0.0198	3.00E-06	0.0025	3.30E-03	0.001	0.0452	0.0102	0.058	0.0692	0.0079	0.089	0.1016
6TL	**Mean Temp**							**Total ppt**						
	June	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**	**June**	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**
Current year	0.0294	0.0209	0.0506	0.1842	0.1024	0.1175	0.0723	0.125	0.0196	2.30E-03	0.1105	0.007	0.0195	0.1045
Cum. 2 years	0.0199	0.1064	0.1083	0.0036	0.1169	0.1267	0.1624	0.0616	0.0222	0.0061	0.0643	0.0059	0.0937	0.0296
Cum. 3 years	0.0049	0.0872	0.1637	0.4255	0.2083	0.1482	0.2261	0.068	0.0642	0.0124	0.1068	0.0277	0.0421	0.0271
6TR	**Mean Temp**							**Total ppt**						
	June	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**	**June**	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**
Current year	0.0279	0.0319	0.0313	0.0058	0.0797	4.00E-07	0.0129	0.0124	0.0021	0.0099	0.0057	0.0019	0.1452	0.0022
Cum. 2 years	0.0353	0.0406	0.0464	0.0001	0.0665	0.0195	0.0412	0.0501	0.0355	0.0708	0.0512	0.021	0.0937	0.0299
Cum. 3 years	0.0215	0.0827	0.0685	0.0009	0.0414	0.0252	0.0658	0.1111	0.0251	0.118	0.0351	0.0303	0.2841	0.0327
7TL	**Mean Temp**							**Total ppt**						
	June	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**	**June**	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**
Current year	0.0014	0.0074	0.0052	0.0013	0.0008	6.00E-05	0.0027	0.0774	0.0774	0.0006	0.1707	0.31	0.0044	0.3532
Cum. 2 years	1.00E-04	0.0764	0.021	0.018	0.0284	0.0015	0.0244	0.0335	0.0048	0.0054	0.0958	0.2319	0.0083	0.1757
Cum. 3 years	0.0029	3.40E-03	0.0123	1.00E-05	0.0002	0.0215	0.0003	0.0338	0.0025	0.0523	0.0496	0.2362	7.00E-05	0.1446
7TR	**Mean Temp**							**Total ppt**						
	June	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**	**June**	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**
Current year	0.0426	0.0065	0.0774	0.0489	0.0217	0.0853	0.0864	0.0062	0.0372	0.0176	0.0177	0.0628	0.006	0.0236
Cum. 2 years	0.0225	0.037	0.0963	0.1257	2.34E-02	3.13E-01	0.1516	0.0539	0.0594	0.0518	0.116	0.079	1.00E-06	8.00E-05
Cum. 3 years	0.0275	0.1514	0.1563	0.2299	0.0108	0.0019	0.2537	0.0997	0.0202	0.0854	0.2077	0.1115	0.0129	0.0028
8TL	**Mean Temp**							**Total ppt**						
	June	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**	**June**	**Jul**	**Spring**	**Summ**	**Fall**	**Winter**	**GS**
Current year	6.00E-05	2.00E-06	0.001	0.0003	8.00E-05	2.00E-03	5.00E-05	0.0007	0.0019	0.0007	0.0124	0.0819	0.0249	0.0286
Cum. 2 years	0.0001	0.0031	0.0403	0.0295	0.001	0.1351	0.037	0.14	0.04	0.0515	0.1983	0.0925	0.0937	0.006
Cum. 3 years	0.0107	0.0403	0.1552	0.0869	0.0003	0.2962	0.146	0.223	0.0929	0.0629	0.2909	0.0874	0.0431	0.0258

2.4.4.2 SAS Analysis of Variance

Dieback trees appeared to have lower BAI values compared to non-dieback trees based on the mean and median values (Table 2.16). Additionally, both tree types had slightly lower mean values in the 1998-2004 period compared to the 1991-1997 period. If dieback started in 1998, it would be expected that the average BAI values for both dieback and non-dieback trees should be roughly the same prior to 1998, but this is not the case.

The analysis of variance showed no significant difference between the dieback and non-dieback trees, or between the 1991-1997 and 1998-2004 time periods at a 0.05 significance level (p value = 0.3960), despite the fact that the preliminary distribution appeared to show a difference in growth between dieback and non-dieback cores.

Table 2.16: Distribution statistics of dieback and non-dieback trees for time period of 1991-1997 and 1998-2004 to determine if dieback may have commenced in 1998.

DIEBACK		DIEBACK		NO DIEBACK		NO DIEBACK	
1991-1997		1998-2004		1991-1997		1998-2004	
Mean	896.69	Mean	843.39	Mean	1143.29	Mean	1114.38
Median	598.40	Median	703.40	Median	1104.40	Median	1081.50
Std Dev	707.51	Std Dev	461.50	Std Dev	631.96	Std Dev	469.10
Std Err Mean	101.07	Std Err Mean	65.93	Std Err Mean	90.28	Std Err Mean	67.01
upper 95% Mean	1099.91	upper 95% Mean	975.95	upper 95% Mean	1324.81	upper 95% Mean	1249.12
lower 95% Mean	693.47	lower 95% Mean	710.83	lower 95% Mean	961.77	lower 95% Mean	979.64

2.4.4.3 Threshold Analysis

At the Qualicum Beach site, for a 0.05-1% change in the growing season total precipitation, there was a 1% significant change in residual ring-widths (Table 2.17). This analysis was only a first attempt to identify critical thresholds in climate which might cause changes in residual ring-width. Preliminary analysis of this method provides evidence that this technique could provide valuable information if further investigated. Additional manipulation of the thresholds employed and the climate variables could provide useful information for forest managers in predicting the effects of climate change on growth of redcedar.

Table 2.17: Output from threshold analysis. Note that when climate and ring-width thresholds were exceeded in the same direction a 1 was listed in the table as being significant (highlighted grey). The right hand table lists the number of times both thresholds were exceeded (to be significant, at least 21 thresholds needed to be exceeded during the 30-year time span).

%change in June total ppt		1's only					Count # 1's				
		RW Residuals									
		0.01	0.1	0.5	1	1.5	0.01	0.1	0.5	1	1.5
	0.05	1	0	0	0	0	22	15	9	1	1
	0.5	1	0	0	0	0	21	14	8	0	0
	1	1	0	0	0	0	21	14	8	0	0
	5	0	0	0	0	0	17	13	7	0	0
	10	0	0	0	0	0	15	12	7	0	0
	30	0	0	0	0	0	9	7	4	0	0
	50	0	0	0	0	0	2	2	1	0	0
	70	0	0	0	0	0	1	1	1	0	0

2.5 Discussion

Out of the 16 study sites, only four sites exhibited dieback and were located within the three lower elevation, drier BEC units. This lends support to the hypothesis that dieback may be moisture related since none of the higher elevation (CWHmm), moist study sites showed any evidence of dieback presence. The site with the most dieback was Qualicum Beach (almost half of trees affected in the transect), with the other three sites only having minor dieback. The four dieback sites were located in three different BEC units (CDFmm, CWHxm1, CWHxm2) and had different site characteristics.

The Shawnigan Lake site (CWHxm1) was located within a provincial park near Shawnigan Lake and was the southernmost site exhibiting dieback. At this site, 16% dieback was concentrated in a particular area along the transect adjacent to an old railway bed where there was evidence of shallow rooting and high water table conditions during certain times of the year. Therefore, this site may not be experiencing the same zonal site conditions as the other sites. Excess water and root-kill during wet times of the year may have caused the dieback in this case. Typically, root and microbial respiration in periodically flooded areas will deplete available oxygen and nutrients and less atmospheric oxygen and nutrients can diffuse back into the soil due to waterlogging, thereby causing overall reduced root and tree growth (Nilsen and Orcutt 1996).

The Cowichan Lake site was within an old-growth patch adjacent to the Cowichan Lake Research Station and only had two dieback trees. There was minimal residential development nearby, and a paved road running into the research station was approximately 50 m from the last center-point on the transect. The trees at this site were, on average, around 82 years old and crown thinning of the two dieback trees might not have been the same as the dieback observed at Qualicum Beach since all other trees on this site appeared healthy.

The Fluxnet site has been in use by the University of British Columbia and Fluxnet Canada, a research network which combines university and government scientists to study the influence of climate and disturbance on carbon cycling in Canadian forest and peatland ecosystems (for further information refer to the following website: http://www.fluxnet-canada.ca/). This site had a localized patch of dieback, and swampy conditions were noted beneath the observed dieback area. Thus, dieback on this site was also questionable in similarity to Qualicum Beach dieback due to wetter boggy conditions where dieback trees were found.

The Fluxnet, Shawnigan Lake and Cowichan Lake sites are suspect as to whether dieback on these sites was comparable to the dieback at Qualicum Beach. The reason for this is that the microsites at these sites where dieback was noted showed signs of boggy conditions, such as skunk cabbage, muddy patches and shallow rooting depths; evidence that these locations may have an excess of water at certain times of the year, rather than a water deficit. Thus precipitation was likely not limiting at these three sites. On boggy sites, excess moisture also lowers oxygen levels in soils, causing root death and tree dieback (Lyr and Hoffman 1967). In addition, sites with excess moisture are frequently colder than dry soils thereby decreasing mycorrhizal activity and decreasing tree nutrient uptake. In addition, boggy site conditions lead to shallower root systems. If these boggy sites tend to dry out during the summer, the shallow roots may not have access to deeper water sources, and certain roots may die which may also be an explanation for dieback noted in these boggy locations.

Comparison of the soil moisture contents measured at each of these sites (see Chapter 2.3.2) in September found: Fluxnet- 24% water based on dry weight, Cowichan Lake- 15%, Shawnigan Lake- 14%, and Qualicum Beach- 11%. Therefore, Qualicum Beach had the lowest soil moisture content amongst the dieback sites, providing support that the other three sites may not have had as high of a moisture deficit during the summer months. In regards to other soil conditions, Qualicum Beach had the deepest soil profile (>1.65 m, with tree roots only going down about 1 m) which was composed mostly of sandy material, and having the lowest organic matter content of the mineral soil (7%) compared to the other three sites (Table 2.6). Thus, when precipitation falls on this site, water drains quickly out of the soil profile due to the sandy substrate, and is not held well within the mineral soil due to the low organic material in the soil; leading to a moisture deficit for the trees on this site. Anecdotal observation also indicated that there was considerable dieback present along the upper island highway near Qualicum Beach. Pollution, or exposure might be additional causes for this dieback along the highway, however, these causes will not be examined further in this preliminary analysis.

These factors lead to the conclusion that dieback noted on the Fluxnet, Shawnigan Lake and Cowichan Lake sites may not have been a similar type of dieback as that noted at Qualicum Beach. For this reason, and due to the fact that extensive dieback was also noted in the area surrounding the Qualicum Beach site, the dieback analysis focused primarily on data from this site. To assess whether or not the dieback on these other three sites is the same as that on Qualicum Beach, further analyses of soil aeration and moisture content during different times of the year would have to be completed.

Types of trees affected by dieback were primarily class 2 dominance trees (59% co-dominant, 7% were dominant, 14% intermediate and 18% suppressed). Thus most of the redcedar showing dieback were co-dominant with either western hemlock or Douglas-fir. This result is rather unexpected since water movement to the tops of tall trees is limited by the length of the path the water must flow, and the permeability of the wood cells. If tree height is a factor in dieback abundance, then one would have predicted there should have been more dieback in dominant versus co-dominant redcedar. One explanation is that dominant redcedar may be growing on more favorable microsites where they posses the ability to tolerate moisture stress which the co-dominant redcedar cannot. Alternatively, there may be a heritable trait in dominant redcedar which facilitates the capability to better deal with moisture stress in comparison with co-dominants.

The dieback class of the study trees indicate that most trees (63%) were in the class 1 category (slight thinning of foliage and first signs of dieback), and 30% dieback were in class 2. It is possible that this study has documented dieback in its initial stages at Qualicum Beach which may become more noticeable in the following years in the surrounding area. However, it is difficult to say whether these trees will move to class 3 or 4 over the next few years, or make a full recovery. It would be beneficial if this study could be repeated in the next 5-10 years to observe the state of the dieback trees and document signs of improvement or further dieback progression.

The analysis of variance of BAI values amongst the four BEC units aimed to decipher differences in growth between drier and wetter units. The southern BEC unit (CDFmm) was found to have higher BAI values post-1989 compared to the other three units (Figure 2.10). One reason for the higher BAI values at the southern CDFmm sites may be due to the lower average stand density (344 stems/ha) as opposed to 469-1288 stems/ hectare at the other units. With an overall lower stand density, redcedar present on the site have greater access to resources, and less stress from inter-tree competition, thereby allowing them to put on higher BAI every year (Table 2.18).

Table 2.18: Summary statistics of stand dynamics on north and south locations including the average stand density, average density of redcedar, average basal area increment, total stand average basal area, average age of redcedar, and the BEC unit.

Location	BEC Unit	Ave Stand Density (#stems/ha)	Ave Density of redcedar (# redcedar/ha)	Ave BAI (cm^2)	Ave Total Stand BA	Ave redcedar age (yrs)
South	CDFmm	344	138	2471	95	90
	CWHxm1	726	188	1507	79	66
	CWHxm2	469	126	1503	97	71
	CWHmm	1288	332	1890	63	45
North	CDFmm	963	413	1354	104	105
	CWHxm1	751	301	1998	76	59
	CWHxm2	1150	232	1219	66	53
	CWHmm	894	244	1841	58	33

During 1989 and 1999 lowered BAI values were found amongst all BEC units and increased growth during 1997 and 2000. However, there were also years in which growth at the northern sites did not correspond to growth patterns at the southern sites. This is likely because the northern sites may be responding to a lagged climate signal, climate is different between these two locations, or site factors are influencing growth more than climate during certain years.

2.5.1 Redcedar growth in drier and wetter BEC units

The preliminary SAS analysis found mixed results comparing BAI across BEC units. Overall, southern sites had higher basal area increments from 1981-2004 compared to northern sites during this time period. This may also be due to more favorable warmer temperatures and decreased precipitation falling as snow on the southeast portion of the island (Table 2.19). Additionally, stand dynamics may have had a significant influence on tree BAI response among units. In particular, stand density appeared to influence resource availability for redcedar increment growth because, in both locations, stands with the highest stand density had the lowest average BAI values.

Table 2.19: List of average yearly climate variables for comparison of northern and southern study sites (Environment Canada 2006).

Average yearly climate values	Victoria Int. Airport (SOUTH)	Campbell River Airport (NORTH)
Mean temperature (°C)	9.7	8.6
Maximum temperature (°C)	14.1	13.5
Minimum temperature (°C)	5.3	3.8
Snowfall (cm)	43.8	109
# Days/ year <= 2°C	95.3	147.3

Comparing northern and southern parts of Vancouver Island, temperatures are on average warmer in the south with less snowfall (Environment Canada 2006). Grossnickle and Russell (2006) found that at 4°C or less, no shoot growth or mitotic activity occurs in redcedar. Thus, since Campbell River has 147 days less than or equal to 2°C, and

Victoria has only 95 days, overall there are fewer growing days in the north versus in the south and potentially reduced overall BAI growth.

In addition to stand dynamics, underlying soil conditions may also influence annual BAI. For instance, if the sites had higher bulk density values, low percent organic matter content, and a high percentage of coarse fragments, these sites may be less capable of retaining water, and could be predisposed to water shortages. However, despite higher bulk densities, trees may still be able to have deep rooting, thereby allowing access to water sources at depth to counterbalance freely draining soils.

Based on site soil data, the Galiano Island site should have been the most stressed for water, yet no dieback was found on this site. A possible reason for lack of dieback on this site may have been due to underground water drainage from a wetland located above the study site (Figure 2.16). Underground seepage from this wetland may supply adequate water for the redcedar trees on this site which may buffer water deficits due to drought during the summer and fall.

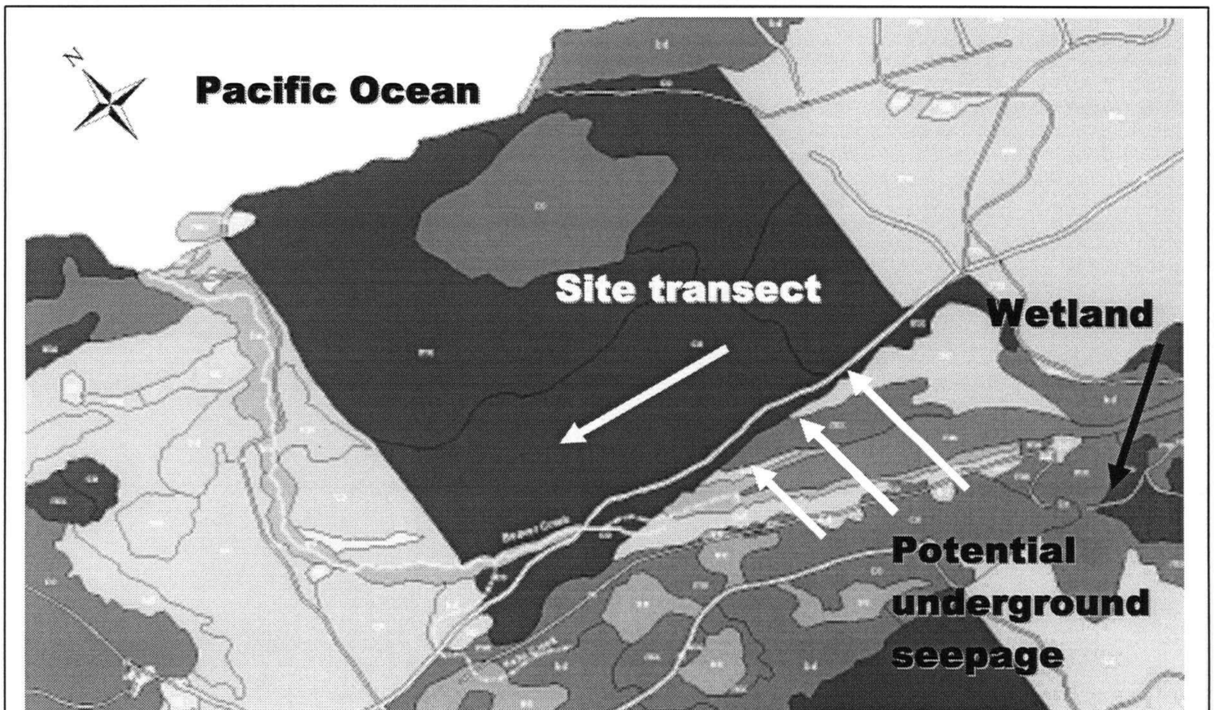

Figure 2.16: Location of transect on Galiano Island with noted wetland uphill from the study transect. Potential underground seepage from the wetland may buffer the effect of drought on this site which might be why no dieback is noted at this location (modified from Galiano Conservancy Association 2004).

Overall, higher elevation sites were generally from younger stands of redcedar, whereas lower elevation sites had older, larger redcedar. This observation is likely due to the fact that the higher elevation sites had been harvested within the past 40-100 years, whereas the lower elevation sites were located within parks, residential areas, or protected areas which had not been recently harvested (within the last 100 + years). Nevertheless, stand dynamics did play a significant role in redcedar growth on all sites and may have masked evidence of dieback in tree rings.

2.5.2 Climate signal in redcedar growth

Dobrý *et al.* (1996) found a marker ring in redcedar in 1959 which was linked to a climatically extreme year in 1958 known to have had the highest average July temperature and yearly average temperature for the studied 99-year climate period. Another study compared radial growth of this species to climate variables and found significant relationships using a stepwise multiple regression analysis (Laroque 2003). Thus, this species has been used in the past for various dendroclimatic analyses, and a climate relationship was also present within the tree ring chronologies in this study. The average first-order autocorrelation value was fairly high (0.68); an indication that preceding climate years may influence growth in the year of study. Higher autocorrelation values were also found in a study of yellow-cedar on Vancouver Island (0.62-0.81) (Laroque and Smith 1999). It appears that lower elevation sites generally had lower overall mean correlation values, indicating that local site conditions may influence growth of specific trees on each site and that these lower elevation sites are more complacent than higher elevation sites.

The correlation analysis between sites found that more than half of the study sites correlated well with at least four other sites (Table 2.8). The seven sites which did not correlate well with many other sites likely were either being influenced by multi-cohort growth patterns, or site factors and dynamics of newly developing stands. Growth at these sites might have been influenced by specific site factors and stand dynamics rather than common climate signals. If higher p-values were used in the analysis, such as $p = 0.1$, or $p = 0.3$, the number of sites being significantly correlated with at least four other sites would increase to 11 and 16, respectively. There were 4 marker rings which stood out: wide rings in 1976 and 1980, and narrow rings in 1989 and 1998. In comparison to climate records from the Nanaimo Airport, which was the most central climate station used, it does appear that these years were either cool and wet (wide rings), or hot and dry (narrow rings) (Figure 2.17).

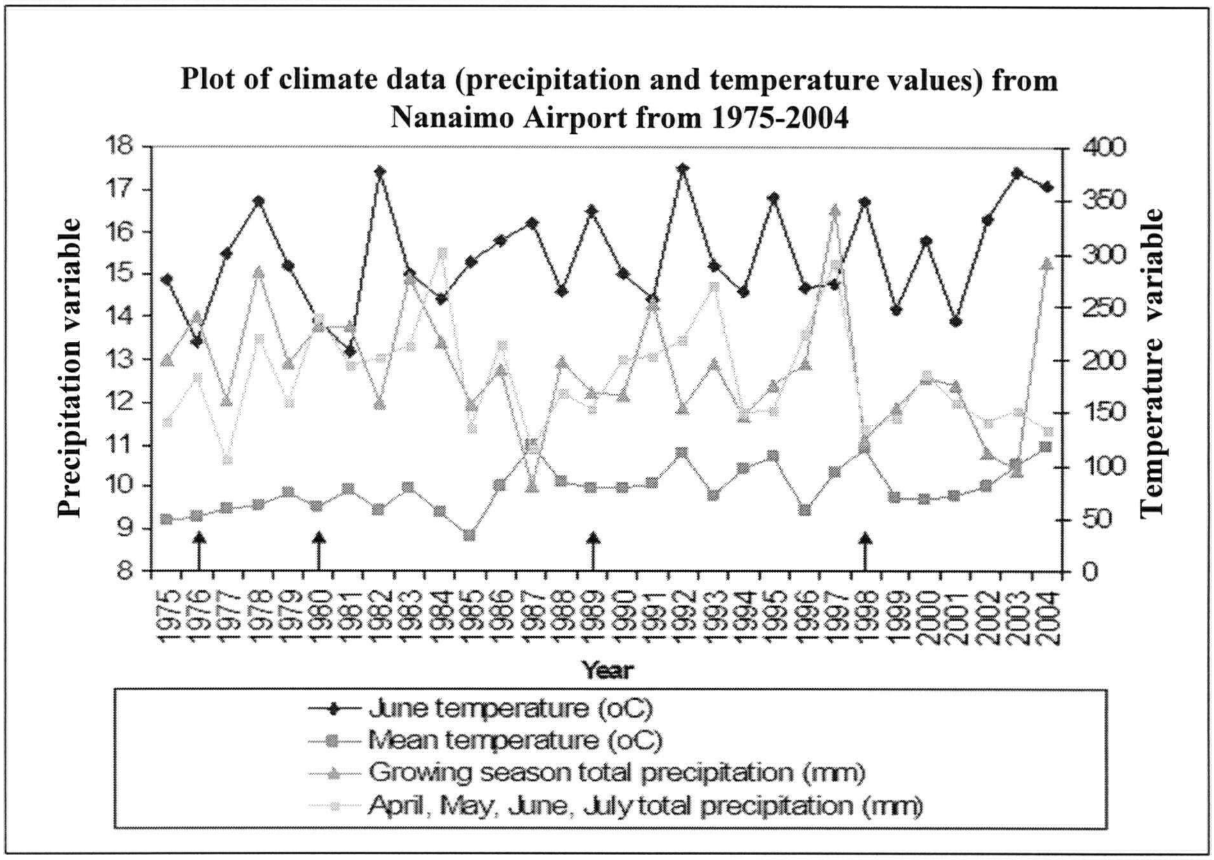

Figure 2.17: Plot of climate variables for Nanaimo Airport from 1975-2004 highlighting with arrows marker rings and corresponding climate data.

2.5.3 Climate variable influence on radial growth increment

DendroClim-2002 results indicated a negative relationship between ring-width and June mean, minimum and maximum temperatures at five sites, indicating that with increasing June temperatures, residual ring-width of redcedar decreased. Conversely, increases in either April, May, June or July precipitation were found to cause an increase in residual ring width index on the three driest study sites. The following tables highlight these site relationships in terms of site ranking based on average site temperature and precipitation values (Table 2.20 and Table 2.21).

Table 2.20: Left- Shaded grey cells are sites with significant negative relationships to temperature (mean, max or min)
Table 2.21: Right- Shaded grey cells are sites with a significantly positive relationship to precipitation (mm)

Sites with negative relationships between residual ring-width indices and June temperature (°C)	
Burnt Mt. 2	Coolest-wettest
Burnt Mt. 1	
Flux net	
Ranald Main	
Bacon Lake	
Cowichan Lake	
Gray Lake/Fry	
Horne Lake	
BC Timber Sales	
Skutz Falls 7	
Skutz Falls 6	
Shawnigan Lake	
Qualicum Bay	
Qualicum Beach	
Royal Roads	
Galiano Island	Warmest-driest

Sites with positive relationships between residual ring width indexes and April, May, June or July total precipitation (mm)	
Burnt Mt. 2	Coolest-wettest
Burnt Mt. 1	
Flux net	
Ranald Main	
Bacon Lake	
Cowichan Lake	
Gray Lake/Fry	
Horne Lake	
BC Timber Sales	
Skutz Falls 7	
Skutz Falls 6	
Shawnigan Lake	
Qualicum Bay	
Qualicum Beach	
Royal Roads	
Galiano Island	Warmest-driest

Sites having a negative relationship to June temperature are six of the warmer and drier study sites examined, and three of the driest study sites had positive relationships to early summer precipitation. It may be that residual ring-width growth slows when a critical temperature in June is reached due to higher soil temperatures slowing earlywood growth production. Larsen (1940) found that redcedar was less tolerant of high soil temperatures when compared to Englemann spruce, grand fir or Douglas-fir. However, a negative relationship to higher temperatures in June may also be linked to corresponding lower precipitation values during this month. Thus, a combination of temperature and precipitation might provide the best relationship between residual ring-width indices and climate. A positive relationship between ring-width and June temperature was found for yellow-cedar by Laroque and Smith (1999). This may be because this species grows at higher elevations, therefore, increases in June temperature would also increase the amount of radiation available for photosynthesis allowing yellow-cedar to extend its earlywood growth period. However, they did find that high August temperatures decreased growth, which they claim is due to radial growth cessation when hastened by high temperatures thereby negatively impacting radial growth the following season. Lower elevation redcedar may be responding to earlier monthly high temperatures since more extreme high temperature fluctuations would be found at these lower elevations.

In regards to precipitation, the three driest sites were most sensitive to dry spring and summer months (April-July), which indicates that if summers become drier on the coast these sites might see a further reduction in radial growth. This observation was also found in a study of soil moisture deficit in Douglas-fir plantations in coastal B.C. (Bower *et al.* 2005). Oppenheimer (1967) studied drought resistance of redcedar seedlings and found foliage to be susceptible to excessive transpiration because of the lack of cutin and wax, which thereby decreases drought resistance of this species. Additionally, Sanesi and Sulli (1973) found reduced soil moisture during the growing season to be detrimental to redcedar growth. However, a study of freezing tolerance and shoot water relations of redcedar found that this species has an overall high level of stress resistance to drought (Grossnickle 1992).

In reference to the phenology of redcedar, processes which might be affected by temperature or precipitation in the late spring and early summer are shoot growth and radial growth (Figure 2.18).

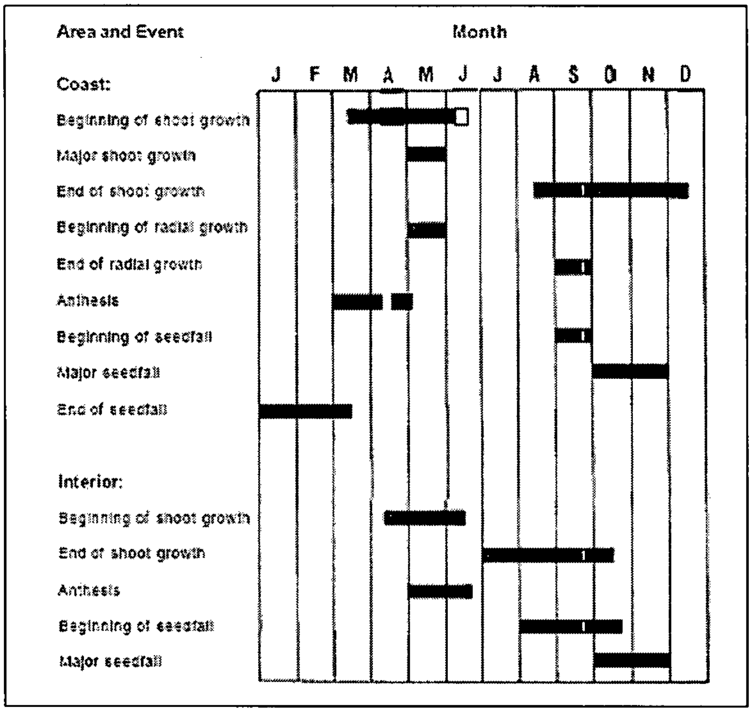

Figure 2.18: Major phenological processes occurring during specified months of the year of redcedar on the coast and in the Interior of B.C. from January (J) until December (D) (Minore 1983).

Thus hot and dry late springs and summers will cause an overall decrease in radial increment growth and a decrease in the rate of shoot elongation of redcedar. Should these conditions occur on sites predisposed to drought, dieback onset may occur.

2.5.4 Dieback Discussion

Dieback of redcedar has been attributed to drought and moisture stress based on palynological studies (R. Hebda pers. comm. 2005). This study found that dieback was limited to the three hotter and drier of the four units studied. This observation supports the contention that dieback onset may be influenced by site moisture and temperature. It was noted that radial growth between and within sites was extremely variable, which may be influenced by stand dynamics, stand age and microsite variability. This observation further complicated the dieback analysis because no clear pattern of growth reduction as a result of dieback could be discerned among sites. For this reason, the most severe dieback site, Qualicum Beach was studied in detail to try and understand how the healthy looking trees on this site compared to the dieback trees. The DendroClim-2002 analysis found a positive relationship between total monthly precipitation and residual ring-width index at Qualicum Beach, however, no significant relationship to temperature was found at this site.

The regression analysis did find subtle differences between the dieback and non-dieback trees, but these differences were quite small and not consistent between all cores. Because two trees from this site were seen to have died in 1998, the dieback was hypothesized to have begun within this year since 1998 was hotter and drier than usual. A test of the 7-year period before and after 1998 was undertaken to see whether growth was different between dieback and non-dieback trees. Overall, dieback trees appeared to have reduced growth compared to the non-dieback trees, though the 2-way analysis of variance failed to show this difference as being significant. Finally, a threshold analysis was proposed as a new method to try and further understand how trees respond to measurable changes in climate; further work with this analysis is needed to determine its utility for forest management implications.

2.5.4.1 Dieback Cause Discussion

I hypothesize that four factors, drought, insects, pathogens and human impacts to soil drainage, may interact to contribute to the dieback of redcedar in the study area. I found evidence that ring-width on the driest study sites was influenced by precipitation over the growing season which indicates that drought could exacerbate dieback symptoms. Also, it appears that drought may be an inciting factor to dieback on sites with deep coarse-textured soils that are predisposed to drought.

At the Qualicum Beach site, only one of the dieback trees showed evidence of insect exit holes, which were identified as *Trachykele blondeli* or western redcedar powderworm (J. Mclean pers. comm. September 2005). This insect is not known to directly kill healthy trees unless the tree is already stressed. Therefore, insects are not likely to be the primary cause of dieback since they were not prevalent on all dieback trees. However, insects may prove to be a contributing factor in the dieback if trees were already stressed prior to insect infection.

Only four out of the 27 dieback trees had stem rot. Therefore, it is also unlikely that a pathogen caused dieback onset in redcedar (M. Cleary, pers. comm. October 24th, 2006). In addition, trees on Galiano Island were found to be almost entirely hollow as a result of butt rot yet none showed signs of dieback. Pathogen infection might simply be a contributing factor to already stressed trees.

Many dieback trees were noted along the upper Island highway, from Nanaimo to Campbell River, B.C. leading to the suggestion that altered drainage or exposure of trees previously sheltered in closed stands could have contributed to the dieback. Trees along the highway may be more sensitive to climate effects. As a consequence, sites were selected well away from roads and development to ensure little human influence.

Is a comprehensive explanation for dieback of redcedar possible? Based on the above analyses and personal observation, it appears that underlying soil substrate in combination with climatically-induced summer drought may be the primary cause of redcedar dieback. Since the Qualicum Beach site had the deepest soil horizon with sandy textures and small litter/humus horizons, this site is at greatest risk to this combination of dieback determinants. The trees on this site may have less access to stored water and therefore become moisture deficient during dry growing seasons. If climate change causes warming and drying in the summer on this site, especially successive hot and dry years, dieback onset could be incited in already sensitive trees. Finally, insects and pathogens might contribute further to dieback progression because additional stress would be added to the tree. Thus, the observed dieback phenomenon may have been caused by a combination of predisposing, inciting and contributing factors.

2.5.5 Future outlook for redcedar on Vancouver Island

Model projections of redcedar distribution predict that this species will be lost from most of Vancouver Island within the next hundred years if climate continues to become warmer and drier (R. Hebda, pers. comm. 2005). However, this species is known to be very resilient having an advantage over other species due to an indeterminate growth pattern and the capability to photosynthesize during the fall and winter if temperatures permit (Grossnickle and Russell 2006). Another sign of redcedar resiliency is the capability in older trees to "stem strip", whereby strips of cambium die over part of the tree circumference and death to part of the crown occurs (Matthes *et al.* 2002). One hypothesis for the cause of this phenomenon is that it may enhance the survival of a tree by allowing it to sacrifice parts of the root system which are growing in unfavorable conditions in order to ensure the survival of the rest of the tree (Matthes *et al.* 2002). Stem stripping might be similar to the observed crown dieback because, similar to the manner in which unproductive root systems are cut off, top foliage requiring an energy to transport water and nutrients to the top of the tree can be abscissed during unfavorable site conditions allowing sustainability of the rest of the tree. However, this phenomenon may also simply be a forced response of the tree to drought conditions. Kelly *et al.* (1992) noticed a period of increased growth for the first few years after stem stripping began in the Niagra Escarpment with *Thuja occidentalis* L., which may also be a similar process occurring in redcedar of Vancouver Island. Stressful conditions may cause redcedar to drop crown foliage which allows the lower portion of the tree to benefit from the re-allocation of resources, thereby increasing growth after dieback onset. In addition, healthy trees surrounding dieback trees would potentially also show an increase in growth after dieback onset due to the increased light conditions due to top foliage drop of surrounding dieback trees. Since redcedar apical crown dieback of younger trees seems to be a newly observed phenomenon, examination of the period from 1997-2004, the following general pattern emerges on the Qualicum Beach site (Figure 2.19).

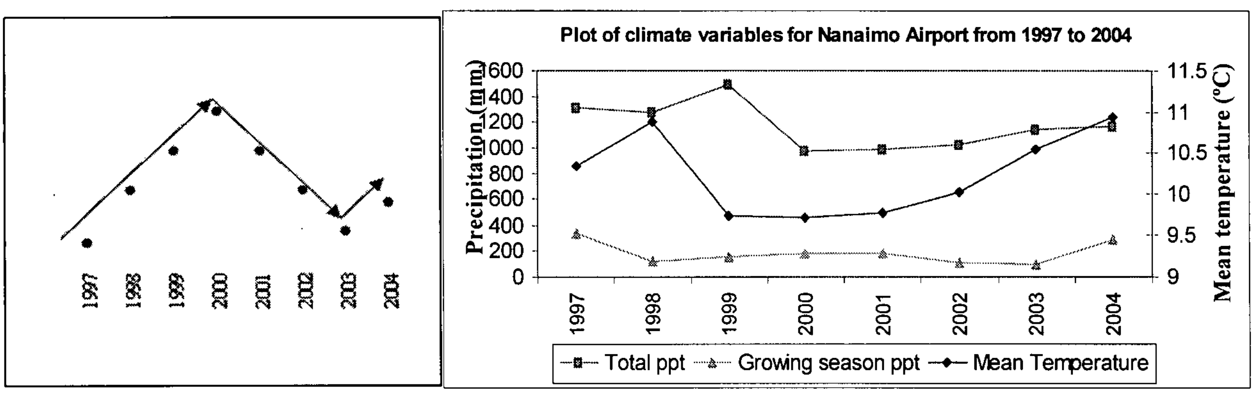

Figure 2.19: Left- General growth pattern amongst the majority (59-82%) of dieback and non-dieback trees at Qualicum Beach (Not to scale, figure meant to show general growth trend only). Right- Climate data from Nanaimo Airport for the period of 1997-2004.

If dieback was hypothesized to have commenced around 1998, based on the above figure, there is a period of increased growth from 1998-2000 which might be a response to the re-allocation of resources during this time after crown dieback. However, from 2000-2003 growth is generally reduced which could either be a delayed response to the dieback, or a climate response to lower overall total precipitation during these years.

Breast-height ring width may not be sensitive to dieback because lower foliage is living thereby maintaining ring growth lower in the tree stem while top-foliage is dropped. Thus resources previously used in the crown may be redistributed to the lower canopy, thereby masking a decrease in breast-height ring-width. Coring at breast height for age determination has been problematic for certain tree species, such as the Coast redwood (*Sequoia sempervirens* (D. Don) Endl.) (Waring and O'Hara 2006). Additionally, responses of diameter at breast height ring widths to drought may be more pronounced higher up the tree, or may be masked by stand dynamics at the base of the tree. Further studies using stem analysis of redcedar would be necessary to clarify responses to disturbance along the length of the tree stem, and which coring height would pick up the highest response to this disturbance.

Candelabra growth forms typical of redcedar are created when the main tree leader dies, as a result of wind, drought, or pathogen and lower branches turn up to take over as new leaders once apical dominance has been lost. This observation is supported by Van Pelt (2001) who has studied and documented the largest trees on the Pacific Coast (Figure 2.20).

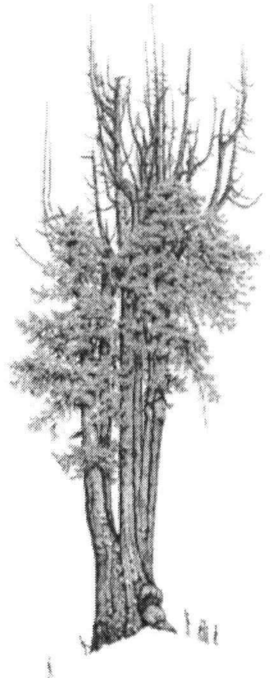

Figure 2.20: Sketch of the Niawiakum Giant, at 154 feet tall, located in southwestern Washington; it is known to be one of the world's largest redcedar (Van Pelt 2001). Note the multiple dead tops and candelabra growth form which are likely created during past drought or windstripping events which kills the main leader and allows lower branches to be released from apical dominance and take new vertical form during more favorable growth years.

This growth mechanism of new apical dominant leaders could be another acclimation device that redcedar has to deal with adverse growing conditions.

Based on the above studies and observations, it would appear that overall, redcedar is a very resilient species. For this reason, it would seem unlikely that the dieback phenomenon would cause complete elimination of all redcedar on Vancouver Island if climate continues to warm and dry over the growing season. However, a decline of redcedar trees growing on deep sandy soils prone to drought may occur because of moisture stress.

Nevertheless, redcedar on more favorable growing sites may be able to acclimate to shifting climate conditions via indeterminate growth thereby taking advantage of warmer winters and springs. Stem-stripping may cause death of the main leader, but lower branches may be able to take over as new leaders during more favorable climate years when apical dominance of the main leader is lost.

Another similar study used the Tree-ring radial expansion estimator (TREE) to estimate future radial growth patterns of a number of tree species on Vancouver Island (Laroque and Smith 2005). This model uses stepwise multiple regression equations between radial growth increments and climate variables to predict radial growth trends over the following 20 years. Future climate data was obtained from Coupled-General Circulation climate models (CGCM2). The pair used high elevation redcedar as one of the species for analysis, and found the following results (Table 2.22).

Table 2.22: *Graph of percent radial growth changes in the face of changing climate scenarios from a tree growth model. The ultimate alteration in radial growth is defined for species, with average growth represented by 1.0 and deviations above or below this number representative as above or below normal growth. The year of stabilization of the growth increment is displayed in brackets after each growth increment. An asterisk (*) within this bracket signifies a significant alteration in radial growth under the selected climate scenario. Arrow marks likely climate scenario for redcedar (modified from Laroque and Smith 2005).

Seasonal climate scenario	MH	YC	WH	WRC	DF
Cooler (1°) – wetter spring (+1 SD, MAM)	0.91 (4*)	0.99 (5)	0.99 (1)	0.97 (2)	1.09 (5*)
Warmer (1°) – drier spring (–1 SD, MAM)	1.09 (4*)	1.01 (5)	1.01 (1)	1.03 (2)	0.91 (5*)
Cooler (1°) – wetter summer (+1 SD, JJA)	1.17 (6*)	1.09 (6*)	1.41 (10*)	1.40 (2*)	1.28 (4*)
Warmer (1°) – drier summer (–1 SD, JJA)	0.83 (6*)	0.91 (5*)	0.59 (10*)	0.60 (2*) ←	0.72 (4*)
Cooler (1°) – wetter autumn (+1 SD, SON)	1.00 (1)	0.91 (7*)	0.95 (4)	0.89 (3*)	1.06 (6*)
Warmer (1°) – drier autumn (–1 SD, SON)	1.00 (1)	1.09 (7*)	1.05 (3)	1.11 (3*)	0.94 (6*)
Cooler (1°) – wetter winter (+1 SD, DJF)	0.97 (3)	0.97(3)	1.03 (5)	0.97 (3)	0.97 (1)
Warmer (1°) – drier winter (–1 SD, DJF)	1.03 (3)	1.03 (3)	0.97 (5)	1.03 (3)	1.03 (1)

***Note MH = mountain hemlock; YC = yellow cedar; WH = western hemlock; WRC = western redcedar; DF = Douglas-fir; MAM = March, April, May; JJA = June, July, August; SON = September, October, November; DJF = December, January, February**

In regards to redcedar, with the scenario of a warmer and drier summer in June, July and August, radial growth is expected to decline; and subsequently, with cooler and wetter summers, redcedar growth is predicted to increase. A previously published paper by the pair found that radial growth response of high elevation redcedar will maintain overall average values until just before 2100 (Laroque and Smith 2003) (Figure 2.21).

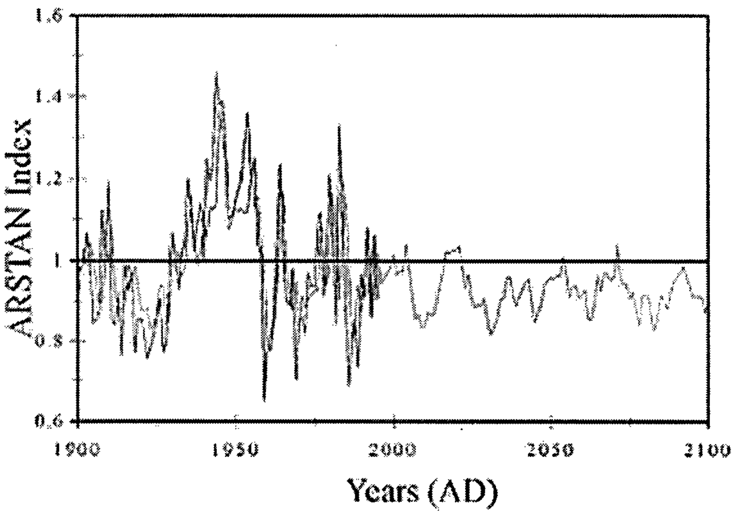

Figure 2.21: Forecasted radial growth response (ARSTAN index) of redcedar from 2000 until 2100 (Laroque and Smith 2003).

It is important to note that this forecast is for higher elevation redcedar (average of 645m) on Vancouver Island, whereas lower elevation redcedar may show a more pronounced decrease in radial growth due to the drier and hotter conditions expected in the future. Nevertheless, it is interesting to note that the higher elevation redcedar may not be as severely impacted at the same extent as other species such as mountain hemlock, western hemlock, yellow-cedar and Douglas-fir in these high elevations with future climate predictions (Laroque and Smith 2003).

Another study which modeled vulnerability and resilience of a number of tree species in the Interior of B.C. employed an aspatial risk-analysis model TACA (Tree and Climate Assessment) (Nitschke 2006). This model uses a variety of climate variables including growing degree day thresholds, basal temperature, minimum temperature, drought and frost in order to determine species presence or absence with predicted future climate data. TACA projected that redcedar would be present on non-water deficit sites in the Interior cedar-hemlock (ICH), Interior Douglas-fir (IDF) and Ponderosa pine (PP) BEC zones but was not modeled on any water-deficit sites in the study area (TFL 49). In the face of changing climates, however, redcedar was predicted to become absent from the IDF and PP zones by 2085, with redcedar at lower elevations vulnerable to climate change (Nitschke 2006). However, at the higher elevations in the ICH, Montane spruce (MS) and Englemann spruce sub-alpine fir (ESSF) zones, redcedar will take advantage of changing climates and likely become more abundant. This finding supports the predictions of related studies that redcedar may be resilient and resistant to climate change at higher elevations (Laroque and Smith 2003, Laroque and Smith 2005).

Based on the above studies, it appears overall that redcedar may become less abundant in lower elevation BEC zones, but may become more abundant and expand its range to higher elevation zones in the face of future climate predictions.

2.6 Conclusion

Fieldwork showed that dieback was limited to the drier BEC units and concentrated around the Qualicum Beach area. One likely explanation for the prevalence of dieback at this site is due to the deep sandy soils which have overall lower soil moisture holding ability making redcedar on this site more prone to droughty conditions. The dendrochronological analysis found that hotter and drier June conditions decreased residual ring-width indices. Due to the fact that no obvious dieback onset date was found, it was difficult to determine whether or not the dieback phenomenon reduces breast height ring-width, or perhaps increases it for the first few years after top foliage is dropped. It is expected that site conditions and low climate sensitivity of the study trees masked patterns in growth which may have been discernable in the dieback trees. The main hypothesis that dieback is directly caused by moisture stress could not be fully supported. Overall, it was concluded that the primary dieback cause may be climate related, with inciting dieback factors being drier BEC units with deep sandy substrate. However, redcedar is a very resilient tree species with a number of acclimation mechanisms which might facilitate its survival during adverse periods. Thus, it is possible that if climate continues to warm and dry in the future, redcedar growing on sites with inciting dieback factors may decline, however, trees in more favorable growing conditions may be able to withstand warmer and drier climates. Additionally, redcedar growing at higher elevations may continue to thrive or even increase in abundance.

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Chapter 3 : Water Balance Modeling and Redcedar Growth

3.1 Introduction

Soil moisture comprises only a small fraction of the total amount of water on earth, however, this water can significantly influence overlying vegetation composition and growth rates, soil processes such as nutrient cycling, and soil organism composition. Movement and storage of soil water underlying forested areas has attracted much attention and study due to the strong linkage of soil moisture to surface vegetation (Kimmins 2004). There are numerous factors which control soil moisture movement and transportation, such as soil type, porosity, topography and meteorology (Western *et al.* 2002). Due to the complexity of soil systems, modeling soil moisture dynamics is extremely challenging and many models have been developed to try and best tackle this complex issue. In addition, different soil models have been developed for diverse regions and forest types (Arp and Yin 1992).

The model "PROSPER" was developed for eastern North American deciduous forests (Goldstein et al. 1974), "ASPCON" for the Rocky Mountains (Jaynes 1978), "SOIL" for forests in Sweden, "YIELD-II" for southwestern United States (Ffolliott and Guertin 1988), or "WTRYLD" for the Sierra Nevada (Combs et al. 1988). One of the major limitations of the abovementioned models is the limited validation of these models with field data (Arp and Yin 1992). As such, another model, "FORHYM" developed by Arp and Yin (1992) addressed all major water fluxes through forests along with validation of model output with throughfall, snowpack, forest floor percolate, soil water content, and streamflow with field data from Ontario and Quebec, Canada. This model simulates hydrologic processes by considering precipitation inputs: throughfall, stemflow, interception by the canopy, and forest floor percolation. Water outputs are determined based on streamflow (runoff) and potential evapotranspiration (PET) as indicated in the model diagram (Figure 3.1)

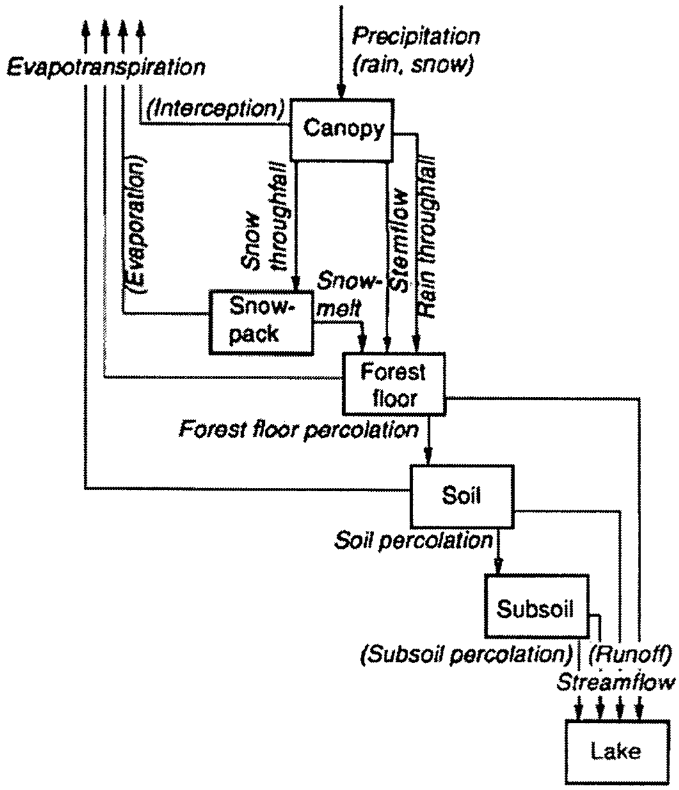

Figure 3.1: Flowchart of the FORHYM model structure (Arp and Yin 1992).

One of the primary limitations of this model is that FORHYM uses a PET equation based on relationships with air temperature (Seely *et al.* 1997). However, another recent model, ForWaDy, considers an energy budget approach to drive the calculation of PET (Seely *et al.* 1997). The benefit of the energy budget approach is that the model can partition evapotranspiration into its primary components which enables water competition to be easily modeled (Seely *et al.* 1997). Thus, this model was chosen to compare residual ring-width indexes with transpiration deficit index (TDI) outputs from ForWaDy.

3.1.1 ForWaDy

The ForWaDy model developed at the University of British Columbia, is a two-dimensional forest hydrology model designed to simulate forest hydrology dynamics and plant water competition (Seely *et al.* 1997) (Figure 3.2). ForWaDy was also designed to function as a hydrological submodel for the forest ecosystem management model, FORECAST (Kimmins *et al.* 1999). While FORECAST includes explicit representations of light and nutrient competition and their impacts on plant and tree growth, it presently includes only an implicit representation of the effect of soil moisture on tree growth and nutrient cycling. Thus, the long-term goal is to eventually connect FORECAST and ForWaDy to better represent ecosystem processes.

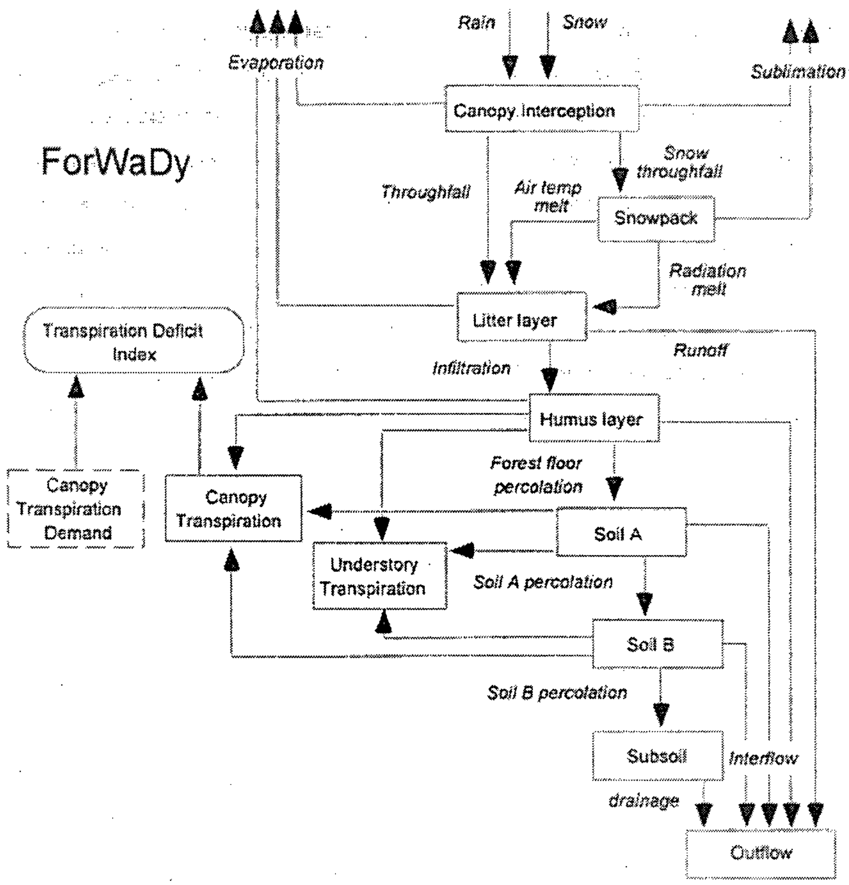

Figure 3.2: Flowchart of the basic structure of ForWaDy. Boxed compartments are water storage components, whereas those in italics are the flow mechanisms and pathways (Seely *et al.* 1997).

ForWaDy was designed for use in forest management applications, and thus data required for model use was kept to a minimum. The primary equation employed is a potential evapotranspiration (PET) algorithm which is driven via an empirically-based energy budget approach (Seely *et al.* 1997). Incoming solar radiation energy (the main driver of evapotranspiration in ForWaDy) is apportioned among three layers (canopy trees, understory plants, and the forest floor) depending on the amount of light each layer intercepts, and the amount of light reflected from each layer. Once the amount of energy available for evapotranspiration is determined for each layer, the amount of available soil moisture is calculated. The difference between the amount of soil water available for tree uptake, and the energy-limited demand for transpiration (accounting for canopy resistance) is used as the basis for a calculation of a cumulative water stress index (transpiration deficit index or TDI) for the canopy trees. This unitless index can be used as a measure of tree water stress as a function of current or historical climate data, soil properties and competition from minor vegetation. The following Equation 3.1: summarizes how TDI is calculated:

Equation 3.1:

$$TDI = \Sigma_{(i=t \text{ to } i=0)} \frac{CanT_{(total)\,i} - CanT_{(actual)\,i}}{CanT_{(total)\,i}}$$

Where $CanT_{(total)}$ is the total energy-limited canopy transpiration demand and $CanT_{(actual)}$ is the simulated actual transpiration based on soil water availability and root occupancy. The following table summarizes the data requirements for ForWaDy (Table 3.1).

Table 3.1: Data requirements for ForWaDy; climate, vegetation, forest floor and soil data.

Data Requirements		
Climate data (daily)	**Vegetation data**	**Forest floor & soil data**
• Mean, max, min temperature • Solar radiation • Total precipitation • Snow fraction	• Percent cover by conifers & hardwoods • Conifer and hardwood leaf area index (LAI) • Rooting depths for canopy trees • Rooting depths for minor vegetation	• Litter mass per area • Humus depth • Depth of soil layers (rooting zone) • Texture class of each soil layer • Coarse fragment content of soil layers

The model has been validated on the east coast of Vancouver Island with data from a replicated-thinning fertilizer study (Crown and Brett 1975) in Douglas-fir plantations at Shawnigan Lake (Seely *et al.* 1997) and a study exploring the impact of canopy removal on forest floor moisture content in a montane forest near Campbell River, B.C. (Titus *et al.* 2006). In both cases, the model performed well in simulating soil moisture contents and, in the case of the Shawnigan lake study, canopy interception under different thinning regimes. Seely *et al.* (1997) also examined the potential changes in TDI with varying future climate scenarios, involving either a 50% increase in spring and summer rainfall, or a 50% decrease in rainfall during spring and summer. It was found that the increase in rainfall lead to a 22% drop in TDI, whereas the decrease in rainfall lead to a 43% increase in cumulative TDI over a three year period (Seely *et al.* 1997).

3.1.2 Project Objective

As described above, one of the long-term goals in linking ForWaDy with the ecosystem management model FORECAST is to be able to project and explore the correlation, for example, between simulated tree water stress (as measured by annual TDI) and observed trends in redcedar growth (as measured by a corrected ring width index). ForWaDy was parameterized and used to project tree water stress based on historical climate data for each of the field sites described in Chapter 2. Data collected during the summer of 2005 were used to estimate the vegetation and soil parameters for each field site in ForWaDy. It is expected that simulated TDI will be have a strong negative correlation with annual ring-width index. A good correlation would provide evidence of the value of the model for predicting how redcedar growth might be affected in the face of changing climate scenarios in the future.

Main Chapter Question:

1. Are simulated TDI values correlated with redcedar tree ring widths?

3.2 Materials and Methodology

3.2.1 Sampling

Sampling for this portion of the project was undertaken at the same time and location as the dendrochronological sampling as described in Chapter 2 of this thesis. To adequately calibrate and use the ForWaDy model, soil information and canopy cover information were gathered (see Chapter 2 section 2.3.2).

To estimate leaf area index, canopy cover information was obtained using a fish-eye lens and camera (4 Mega pixel- Nikon Coolpix 4500 with a Nikon FC-E8 fish-eye lens). Using the same transect established for the dendrochronology work (see Chapter

2), four random center points were chosen at which two 180° fish-eye photos of the overhead canopy were taken. The photos were taken either on cloudy days, in the early morning or late evening in order for uniform sky conditions and for maximum contrast between canopy cover and sky. A tripod and level were used to ensure horizontal camera setting, and a compass to orient the camera north to maintain consistency between photos. Camera settings were set to centrally-weighted metering, manual exposure, with an aperture of f/2.6 and shutter speed of 1/500.

3.2.2 Fish-Eye Photo Analysis

Because many of the fish-eye photos were underexposed, they were lightened using standard image processing software. The fish-eye photos were analyzed with a program called the Gap Light Analyzer 2.0 (Frazer *et al.* 1999). This program is a Windows-based software application created to extract forest canopy characteristics and gap light transmission values from hemispherical canopy photographs. This software calculates "canopy and site openness, effective leaf area index (Le), sunfleck frequency distribution and daily duration, and the amount of above- and below-canopy (transmitted) direct, diffuse, and total solar radiation incident on a horizontal or arbitrarily inclined receiving surface" (Frazer *et al.* 1999). Since photos were taken with a digital camera, transfer and analysis of photos in this program was very simple.

Images were first registered with reference to a bright fish-eye photo to clearly see the boundaries of the photo. The configuration settings were adjusted for each site with the following variables changed: latitude, longitude, elevation, growing season (April 15th → October 15th); all other variables were unchanged.

The GLA program requires each image to be classified by separating pixels within the image array into sky and non-sky classes using the threshold tool (Figure 3.3). To calculate the thresholds, five different locations within the photo were zoomed into and the threshold tool was activated. The threshold was then adjusted to match the open sky portion on the original photo. Threshold pixel intensity varied between 0 and 255 which defines the boundary at which image pixels will become white (represents sky) or black (represents foliage). The five different threshold measurements were then averaged to obtain a threshold value for each of the four photos analyzed from each site. If there were sections of the photo with reflective bark/ foliage, these segments of the photos were manually colored in dark.

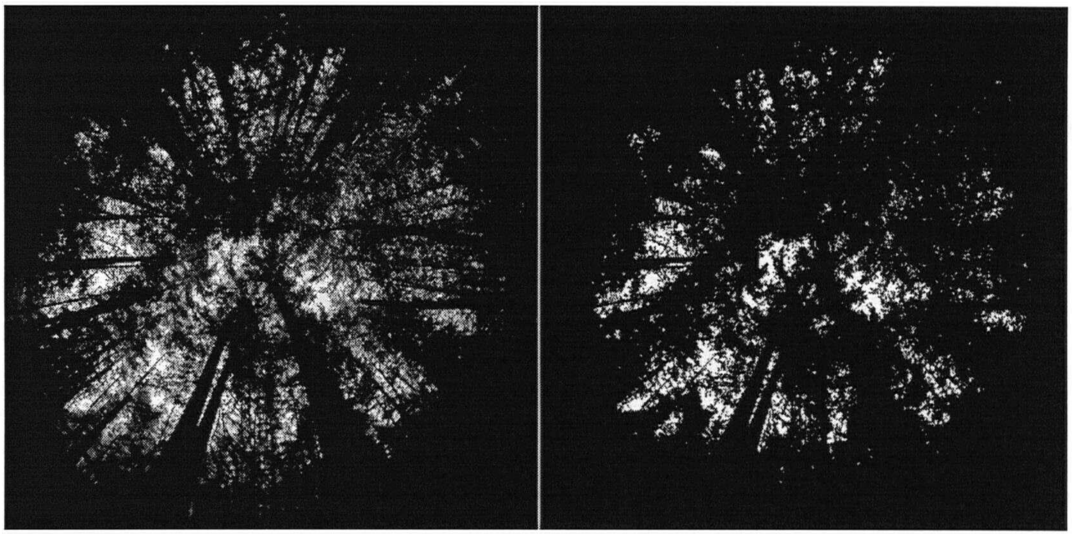

Figure 3.3: Photo on the left is the original; the one on the right is the registered image after being adjusted with the threshold tool in Gap Light Analyzer 2.0.

Three other factors were estimated for each photo and included: the % canopy openness (% of open sky seen from beneath a forest canopy), the LAI 4 ring (the effective leaf area index integrated over the zenith angles 0 to 60°), and the LAI 5 ring (the effective leaf area index integrated over the zenith angle 0 to 75°) (Summarized in Table 3.2).

Table 3.2: Summary of % canopy openness, LAI 4 and 5 and the thresholds used in photo analysis (Frazer *et al.* 1999).

Site	% Canopy Openess	LAI 4 Ring	LAI 5 Ring	Threshold
Burnt Mt. 1	4.4	3.8	3.9	160.0
Burnt Mt 2	4.8	3.9	3.7	139.3
Galiano 3	1.1	6.0	5.3	90.5
Shawnigan Lake 4	7.6	2.9	3.0	144.0
Cowichan 5	5.8	3.5	3.7	118.3
Skutz 6	7.2	3.3	3.3	133.5
Skutz 7	6.6	3.3	3.7	128.0
Royal Roads 8	3.0	4.6	4.1	112.8
Qualicum Beach 9	3.5	4.1	3.8	133.5
Qualicum Bay 10	5.1	3.7	3.7	121.3
Horne Lake 11	4.0	4.2	3.9	113.0
Bacon Lake 12	5.1	4.1	4.0	118.3
Ranald Main 13	7.1	3.1	3.1	105.5
Flux Net 14	5.3	3.6	3.8	138.8
Fry Lake 15	4.6	3.8	3.7	127.3
BC Timber Sales 16	4.9	3.8	3.9	129.5

Since this program only calculated the estimated leaf area index (Le), and ForWaDy requires true LAI values, further manipulation of the Le values was undertaken. The LAI 5 (0-75°) zenith angle was used to estimate the corrected leaf area index; an estimate of true leaf area index was calculated according to the following Equation 3.2 (Frazer *et al.* 2000):

Equation 3.2:
Corrected Le = leaf shape factor (1.18 for flat leaves) * (weighted clumping factor)*Le (GLA)

The leaf shape factor was determined based on flat needles, the weighted clumping factor was calculated based on the basal area proportions of species present on the site, and the projected needle-to-shoot area ratios of species on each site were calculated in Frazer *et al.* (2000) (Table 3.3).

Table 3.3: Summary table of the original LAI 5 values, the weighted clumping factors used to convert Le to a corrected estimate of true LAI, and the corrected LAI 5 values for each site.

Site	Original LAI 5	Weighted Clumping Factor	Corrected LAI 5
Burnt Mt. 1	3.9	19.1	5.7
Burnt Mt. 2	3.7	18.0	5.1
Galiano Island	5.3	27.5	7.6
Shawnigan Lake	3.0	17.3	5.8
Cowichan Lake	3.7	14.7	3.8
Skutz Falls 6	3.3	17.7	5.6
Skutz Falls 7	3.7	17.3	5.5
Royal Roads	4.1	20.0	5.4
Qualicum Beach	3.8	20.7	6.1
Qualicum Bay	3.7	19.1	5.8
Horne Lake	3.9	21.1	6.3
Bacon Lake	4.0	22.0	6.9
Ranald Main	3.1	14.6	4.3
Fluxnet	3.8	21.9	7.4
Gray Lake/Fry	3.7	19.5	5.9
BC Timber Sales	3.9	18.5	5.4

3.2.3 Climate data

Daily climate data including maximum and minimum temperature (°C), and total precipitation (mm) were obtained from the National Climate Data and Information Archive (Environment Canada 2006). A number of the higher elevation sites did not have nearby climate stations with similar elevations. Thus, to obtain a better estimate of the climate at such sites, a climate extrapolation model (MT-CLIM-XL) was employed. MT-CLIM-XL, also known as the "Mountain Microclimate Simulator", extrapolates climate data from a lower elevation base climate station to higher elevation sites (Table 3.4). The model allows for corrections in elevation, slope and aspect between the base climate station and the study site of interest (Hungerford *et al.* 1989, Jolly 2003). It uses inputs of max/min temperature, total precipitation, base elevation, site elevation, site aspect/ slope, and base and site annual precipitation isohyets to extrapolate temperature and precipitation values to higher elevation sites. Precipitation isohyet values were based on a climate map obtained from Environment Canada. Each site was run for the period of 1965-2004 since climate information before 1965 was not complete at all of the climate stations.

Table 3.4: Summary of climate stations used in MT-CLIM and study site climate extrapolated based on these stations.

Climate Station	Station Latitude (°)	Station Longitude (°)	Station Elevation (m)	Sites to extrapolate	Site Latitude (°)	Site Longitude (°)	Site Elevation (m)
Campbell River Airport	50.0	-125.3	105.5	BC Timber Sales	50.0	125.5	210.0
				Gray Lake	50.1	125.6	263.0
				Ranald Main	50.0	125.7	615.0
				Bacon Lake	50.0	125.6	441.0
				FluxNet	49.9	125.3	315.0
Cowichan Lake Forestry	48.8	-124.1	176.8	Skutz Falls 6	48.8	124.0	173.0
				Skutz Falls 7	48.8	123.9	175.0
				Cowichan Research	48.8	124.0	167.0
Nanaimo Airport	49.1	-123.9	28.4	Burnt Mt 1	49.0	124.0	706.0
				Burnt Mt 2	49.0	124.0	689.0
				Horne Lake	49.3	124.7	146.0
				Qualicum Bay	49.4	124.7	80.0
				Qualicum Beach	49.4	124.5	78.0
				Galiano Island	48.9	123.5	88.0
Shawnigan Lake	48.7	-123.6	138.0	Shawnigan Lake	48.8	124.0	136.0
Victoria International Airport	48.7	-123.4	19.2	Royal Roads	48.4	123.5	164.0

To estimate the daily shortwave radiation data required by ForWaDy, a second model, (Mtn. Rad), based on the model published by (Nikolov and Zeller 1992) and written in STELLA 7.0.3, was used to estimate daily total solar radiation (MJ/m^2/day) for a site of a given latitude, elevation, slope, and aspect. Two calibration runs were completed before the final run for each site to initiate the model for monthly average change in temperatures, solar incidence angles, and hourly solar elevations. Since the modeling period was over the past 30 years, and this model only allows a maximum of a four year simulation period, eight consecutive runs for each site were completed. All climate data (modeled and otherwise) were formatted and entered into ForWaDy to facilitate the simulation of forest hydrological dynamics including calculation of annual TDI values for the 30-year simulation period.

3.2.4 ForWaDy Simulations

Fieldwork data were entered into the model and yearly TDI values were output to compare with ring-width indices. The following table summarizes data input into the model along with a brief summary of how data were derived (Table 3.5).

Table 3.5: Summary of climate, vegetation, forest floor and soil data input into ForWaDy including a brief summary of how data was obtained or calculated.

Data Input into ForWaDy		
Climate data (daily)	**Vegetation data**	**Forest floor & soil data**
• Daily mean, max, min temperature, total precipitation (obtained from Environment Canada website – adjusted with Mt.Clim program) • Solar radiation (derived from Mt.Rad model) • Snow fraction (if daily temperature <0°C, then 100% of daily precipitation data considered snow)	• Percent cover by conifers (100%; did not consider hardwoods because they were generally a minor component of site) • Conifer leaf area index (LAI) (estimated using fish-eye photographs and GLA program along with literature values) • Rooting depths for canopy trees (estimated over time based on measured field depths. If site >30 years in age, assumed rooting depth did not change over simulated period (kept measured depth constant); if site <30 years, exponential growth function used to estimate previous years rooting depths). • Rooting depths for minor vegetation (kept constant at 30cm for all sites for all time periods)	• Litter mass per area (calculated based on depth of forest floor layer) • Humus depth (from average soil pit humus depth) • Depth of soil layers (from soil pit) • Texture class of each soil layer (from average of soil textural samples) • Coarse fragment content of soil layers (constant for all layers from soil coarse fragment data)

The model was run in eight stages for the eight different time periods since the model can only run in four-year intervals and we wanted to simulate the period from 1974-2004. Soil information such as rooting depth and root occupancy of each soil layer was modified for the time period to account for an increase in depth and occupancy over time. In addition, leaf area index, was modified using estimates of foliage biomass projected in FORECAST at different stand ages and leaf area index estimates were extrapolated from this data for the simulation time period. Finally, climate data of precipitation, temperature, and solar radiation for 1974-2004 were input into the model.

Model execution was extremely easy once data were entered, each run taking only seconds to complete. For each site eight runs were completed for each time interval for a total of 128 runs. Simple linear regression was completed using JMP software to determine whether the relationship between TDI and ring-width indices was significant (SAS Institute 1989-2004).

3.3 Results

Simulated annual TDI values and associated residual ring-width index values are shown for all sites for the 30-year simulation period in Appendix 3. In general, the years with higher TDI values had corresponding lower ring-width indices and when TDI values were low, ring-width indices were high. However, there were also cases where TDI values were high, and residual ring width indices were also high (for example in 1987).

On average, Ranald Main had the lowest TDI values of all the simulated sites (up to 80 in 1987), whereas Galiano Island had the highest (up to 185 in 1977) (see Appendix 3 graph of Galiano Island). Over the period of 1974-2004, there were a number of years which had either very high or very low TDI's. In particular, higher TDI values - indicating years with moisture deficit – were found for 1985, 1987, 1991, 1992, 1998, 2000, and 2003. Lower TDI values - indicating years with moisture surplus – were found for 1976, 1980, 1983, 1984, 1986, 1988, 1989, 1997, 2001, and 2004. The 1987 simulated TDI values were consistently high at all sites. This is a reflection of a consistent trend in the climate data for all sites, including a dry growing season in combination with high short wave radiation inputs (low cloud cover) during this year. In regards to residual ring width index, six out of the 16 sites had correspondingly low residual ring-width indexes which included: Burnt Mountain 1, Fluxnet, Galiano Island, Horne Lake, Royal Roads, Shawnigan Lake. Four of these sites were the warmest and driest of all sites sampled.

A summary table was compiled listing the relationships between TDI values, growing season precipitation and residual ring-width indices showing the relationship slope, R^2 value, and p-value (Table 3.6).

Table 3.6: Summary table of the relationships between TDI, growing season precipitation (mm), and residual ring-width indices, with shaded cells being significant relationships and the slope describing the nature of this relationship (positive or negative).

	TDI vs Growing season ppt			TDI vs Residual ring width		
Site	Slope	R^2	P-value	Slope	R^2	P-value
Burnt Mt. 1	-7.76	0.45	<0.0001	-0.0026	0.14	0.04
Burnt Mt. 2	-7.67	0.39	0	-0.0016	0.05	0.23
Galiano Island	-0.61	0.22	0.01	-0.0020	0.04	0.28
Shawnigan Lake	-2.73	0.62	<0.0001	0.0001	0.00	0.96
Cowichan Lake	-4.80	0.39	0	-0.0021	0.55	<0.0001
Skutz Falls 6	-3.76	0.56	<0.0001	-0.0017	0.09	0.09
Skutz Falls 7	-4.40	0.45	<0.0001	-0.0006	0.02	0.46
Royal Roads	-2.08	0.54	<0.0001	-0.0040	0.29	0.00
Qualicum Beach	-6.23	0.41	0	-0.0004	0.00	0.79
Qualicum Bay	5.66	0.34	0	0.0009	0.02	0.48
Horne Lake	-6.08	0.39	0	-0.0020	0.06	0.20
Bacon Lake	-5.86	0.36	0	-0.0004	0.00	0.79
Ranald Main	-6.12	0.40	0	-0.0003	0.00	0.85
Fluxnet	-4.45	0.60	<0.0001	0.0011	0.03	0.36
Gray Lake/ Fry	-4.15	0.65	<0.0001	0.0007	0.01	0.60
BC Timber Sales	-3.65	0.40	0	0.0009	0.00	0.85

The relationship between TDI and growing season precipitation for all sites was significantly negative, indicating that when growing season precipitation is low, TDI is high. TDI and ring-width index, however, were only significantly negatively related in 3-4 out of the 16 sites (Burnt Mt. 1, Cowichan Lake, Royal Roads and almost in Skutz Falls 6).

3.4 Discussion

ForWaDy has typically been used to simulate forest hydrological dynamics for a period of less than four years. This study was the first to apply the model to estimate historical water stress over a longer time period (30 years) during which forest vegetation characteristics were likely to change. TDI, which incorporates temperature, precipitation, soil and vegetation variables into a single index, was expected to be a better predictor of residual ring-width index relative to single or grouped climate variables as was undertaken in the dendrochronological analysis of this thesis (see Chapter 2).

As part of the dendrochronological analysis, marker rings were identified to cross-date cores (see Chapter 2 section 2.3.2.4). These marker rings indicate years in which trees had either exceptionally wide or narrow rings. The marker rings identified in this study included years 1976 and 1980 (wide rings), and 1989 and 1998 (narrow rings). Three of the four marker rings corresponded to simulated annual TDI values at the majority of sites (1976, 1980, and 1998). It is interesting that the 1989 narrow ring did not show up as having a higher than average TDI value at all of the sites.

Ranald Main had the lowest TDI values of all the simulated sites, whereas Galiano Island had the highest values. This observation was expected since Ranald Main was one of the highest elevation and wettest sites and Galiano was the hottest and driest. Higher TDI's were only found at Cowichan Lake, Shawnigan Lake, Skutz Falls 6, Skutz Falls 7 and Royal Roads which were all more southerly sites. A likely explanation for the lower TDI in the majority of sites is due to the fact that the climate stations used (Nanaimo Airport and Campbell River Airport) had higher growing season precipitation relative to the climate stations (Victoria Airport, Shawnigan Lake Station, Cowichan Lake Research Station) used for the five sites which had higher TDI's in 1989. ForWaDy uses an energy budget approach, whereby different parts of the forest (canopy, understory, and forest floor) intercept a certain amount of energy for evapotranspiration with losses to surface reflection. For this reason, TDI values are significantly influenced by solar radiation, temperature and precipitation values, which would explain why the five sites with higher solar radiation and lower growing season precipitation showed higher TDI values while the other sites did not.

3.4.1 Relationship between residual ring width index and TDI

The fact that simulated annual TDI showed a strong negative correlation with growing season precipitation for all sites provided support for its use as an indicator of tree water stress. Growing season precipitation should, in theory, be a good indicator of tree moisture stress in these relatively mild forest types with small snow accumulations and relatively dry summers (particularly in the lower elevation sites). However, despite the fact that three of the four key marker rings were consistent with TDI values, the regressions of TDI and residual ring-width index were only significant in three of the 16 sites. This may be due to the highly variable nature of the tree ring data due to site or competition influences which masked a strong climate signal.

Trees selected along the lower boundary range of a species are likely to be influenced by moisture, whereas trees selected along the upper boundary range of a species are influenced more by temperature (Fritts 1976). It is possible that selected study sites may not quite have been at the boundary range of the species and therefore did not show an exceptional relationship to moisture stress. In addition, it may be that the trees on the selected sites were responding to cumulative climate changes, and that perhaps 2 or 3 consecutively hot and dry years would be needed to see a significant reduction in growth. Additionally, there may be a delay in the ring width response of redcedar by one or more years because 1987 was known to be very hot and dry, whereas a marker narrow ring was found in 1989. Thus, redcedar growth may be strongly influenced by the previous or past 2 years of climate. These observations could be further explanations for the overall low correlation to current year TDI values amongst residual ring-width indices found in this study.

3.4.2 Predictions of future climate with ForWaDy

This study has found that calculated TDI values were comparable to residual ring-width indices in three of the 16 study sites. Despite this low correlation with sites, it should be noted that the dendrochronological data had overall low sensitivity to climate data, which may have been caused by site competition influences or stronger relationships to cumulative climate changes. If further studies were to choose more climatically sensitive redcedar trees or sites with limited inter-tree competition, it is expected that the relationships to TDI would be stronger. If stronger relationships are found, then a threshold analysis could be employed to see how redcedar growth is being affected by changes in TDI over time. The goal of creating ForWaDy, was to design a forest hydrology model which could be incorporated into the stand-level ecosystem models FORECAST and FORCEE (Seely *et al.* 1997). The output from ForWaDy can be used along with the ecosystem models to determine how the growth of a stand will change in the face of climate change scenarios. In future studies, predicted climate data from general circulation models such as the Canadian Global Circulation Models I and II, Hadley Center Global Circulation Model III, or ClimateBC could be used to generate future climate data to drive ForWaDy which in turn would generate TDI values for use in modifying expected tree growth. Because the general response of ring-width indices to TDI values can be attained from historical analysis of ring-width indices over time, including years with variable climate (as was completed in this study), forecasted TDI values could be used to estimate future tree growth response.

3.5 Conclusion

ForWaDy was designed as a water balance model for the examining soil water dynamics of temperate forest ecosystems (Seely *et al.* 1997). Annual TDI values were calculated based on input of site field data and locally adjusted climate data. TDI values and growing season precipitation were significantly correlated at all sites, however, only three of the sites showed significant relationships between TDI and residual ring-width index. Low correlations were likely caused by low climate sensitivity of the study trees, or compounding factors of site dynamics and competition. Nevertheless, use of this model did provide interesting information on its use in estimating historical water stress on a variety of study sites. Related studies predict that redcedar will become less abundant at lower elevation BEC units (see discussion Chapter 2), but more abundant and resistant to climate change at higher elevations (Laroque and Smith 2003, Laroque and Smith 2005, Nitschke 2006). Through sampling of more climatically sensitive redcedar on Vancouver Island or in other parts of British Columbia, along with further analysis of ForWaDy TDI values, combined with linkage of the water balance model to FORECAST and FORCEE, predictions of redcedar distribution in the face of changing climates is possible.

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Chapter 4 : Overall discussion of redcedar dieback related to dendrochronology and water balance modelling

4.1 General Discussion

Redcedar is a very valuable, resilient and dynamic tree species which is of great importance for B.C. and Canada. Recent concern for this species' future has arisen due to the observation of apical crown dieback of numerous trees on Vancouver Island. This study examined the extent of dieback and potential causes. Two separate analyses were undertaken in order to examine influences on summer moisture stress on redcedar growth: a dendrochronological analysis and a water balance modelling analysis.

Dieback was noted in three of the four driest BEC units on the island (CDFmm, CWHxm1, CWHxm2), but absent in the highest and wettest unit examined (CWHmm). The site with the most extensive dieback was at Qualicum Beach (CDFmm) with almost half of the studied trees showing some level of dieback. These observations, and the lack of dieback in higher elevation, cooler-wetter units suggests that summer moisture stress may be closely related to dieback events. The most extensive dieback site had a deep soil profile (>1.3m) of sandy materials which would have exacerbated moisture loss after rainfall, predisposing this site to water deficits.

The dendrochronological analysis found that high June temperatures in the current year growing season were related to a depression in breast-height residual ring-width index. Low April to July total precipitation correlated with a decrease in residual ring-width index at the three driest study sites. These findings imply that warmer and drier growing seasons may lead to a decline in breast-height diameter growth of redcedar, a conclusion supported in an analysis of high elevation redcedar on Vancouver Island (Laroque and Smith 2005).

However, the dendrochronological data showed low sensitivity in ring-width indices to the monthly climate variables examined (total monthly precipitation and mean monthly temperature). In addition, correlational analysis with growing season temperature and precipitation also showed few significant correlations with ring-width data. This may have either been because dieback is a consequence of local site factors such as soils and/or spatial variability in soil moisture (and therefore in individual tree moisture availability), along with moisture competition between other species. Detailed analysis of dieback trees versus healthy trees at Qualicum Beach did not provide much information as to dieback determinants, but dieback trees generally had lower growth rates compared to healthy trees.

Coarse textured soil with rapid drainage is likely a predisposing factor for dieback. Thus, trees growing on deep sandy soils in the driest BEC units are, therefore, more susceptible to dieback. Periods of drought may trigger the onset of dieback in redcedar in the study area; secondary pathogens and insects may contribute to the progression of dieback (Manion 1991). However, there is little evidence to support the deterministic relationship between ring-width growth and insects and pathogens in this thesis.

TDI was negatively correlated with residual ring-width index in only three of the 16 study sites. Galiano Island, the driest site, had the highest overall TDI values over the 30-year period, while Ranald Main, one of the highest elevation and wettest climates had the lowest TDI values. The low correlation with residual ring-width indices was likely due to the low sensitivity of the studied trees to climate. Nevertheless, this study did show the utility of ForWaDy for calculating historical water stress indices of sites on Vancouver Island, and with more climatically-sensitive tree ring data, this model could provide interesting results when connected to the ecosystem-based model FORECAST.

Redcedar growing on low elevation sites with low field capacity soils will likely experience increased dieback with a change to hotter and drier summers. In contrast, higher elevation redcedar trees may benefit from warmer winter and spring conditions, and redcedar growth may increase with the species expanding its range to higher elevations than at present in the study area. Two other recent studies also suggest that redcedar will not be lost from higher elevation zones both on Vancouver Island and the Interior of B.C. under future climate scenarios (Laroque and Smith 2003, Nitschke 2006).

4.2 Recommendations for future redcedar dieback studies

A major limitation of this study was the small number of dieback trees actually sampled for analysis. This was due to the sampling design because sites were not selected based on whether or not they had dieback, but instead sites were based on the BEC unit in which they were located. This design was selected because the first objective of the study was to determine in which BEC units dieback was prevalent. Therefore, sites were randomly selected within the four driest BEC units on the island regardless of dieback presence or absence to test whether or not the driest sites did have the most dieback or not. Further dieback analysis of redcedar should consider the following recommendations:

1. Sample adequate number of dieback and healthy trees: This study only had a total of 27 sampled redcedar dieback trees to compare with healthy trees, of which the majority was on one study site. Future studies of this dieback phenomenon should aim to sample at least 20 dieback and 20 adjacent healthy redcedar trees in a number of plots in the most extensive dieback sites (Qualicum Beach area and Shawnigan Lake) in order to properly compare growth of healthy and dieback trees.

2. Stem analysis: In order to obtain a more accurate estimate of dieback onset date, a stem analysis of dieback trees would need to be undertaken. This may be accomplished by either removing cores from increments up the tree (for example, every 10 m), or by felling a number of trees to remove entire stem disks for analysis. This process would ensure that disks or cores from above and below crown dieback could be compared to determine in what year the dieback began. Climatic sensitivity of breast-height diameter growth could also be compared with diameter growth at different tree heights, to determine the optimal sampling location along a tree for dieback studies.

3. Select more suitable trees and stands: The trees that were studied had overall low sensitivity to the available climate data. In order to eliminate the masking effects of other determinants of breast-height ring growth, selection of study trees of comparable age, growing in open stands and with limited competition from other species would be preferred. Ideally, sampling in redcedar plantations would ensure limited cross-species competition effects. Additionally, selection of study trees closer to the lower elevation boundary of this species would be preferable because the ring-width climate signal should be greater in these zones. Studies of dieback redcedar in the southern Interior of B.C. might also be helpful due to the limited range of this species in this area which would guarantee that trees would be sampled across critical portions of the moisture availability gradient.

In this study, I restricted site selection to stands where redcedar was either dominant or co-dominant in order to sample a sufficiently large number of redcedar on each site based on the PCQ method (see Chapter 2). One limitation of site selection in this manner is that more favorable stands may have been preferentially chosen because redcedar is primarily found in abundance on wetter, more nutrient-rich sites (Minore 1983). This may be another reason explaining the higher complacency of redcedar sampled in this study, thus future studies of redcedar dieback should focus not only on co-dominant and dominant redcedar sites, but also on sites where redcedar is a more minor stand component.

4. Carbon isotope analysis: Confirmation that reduced tree ring growth and dieback are related to drought and not to wind or some unidentified pathogen may be obtained using $\delta 13C$ and water-use efficiency analysis (WUE) (Guy and Holowachuk 2001). For such an analysis, cores would have to be removed from paired trees with and without crown dieback symptoms, and analysis of core sections from stressed and non-stressed growth years. Sites for this sampling would need to be chosen within areas where extensive dieback was noted in the fieldwork of 2005.

4.3 Implications for management

It is difficult to make firm recommendations for forest managers in regards to redcedar on Vancouver Island due to the fact that dieback onset date and major determinants are still being debated. However, based on the finding that redcedar growth is influenced by growing season precipitation and temperature at a number of sites, regeneration of this species should be promoted on moist, higher elevation, more northward sites. In the face of changing climate, it is predicted that redcedar abundance will decline at lower elevations in drier BEC zones, but may increase in abundance in higher wetter elevations zones (Laroque and Smith 2003, Nitschke 2006). Thus, planting trials of redcedar along an elevational gradient might be beneficial as well as planting at higher latitudes in the interior of B.C. Higher elevations will experience warmer winters, longer growing season, and there will be an overall increase in CO_2 concentrations with climate warming. In general, these conditions would likely cause an increase in growth and productivity of redcedar at higher elevations. However, this increase will likely be offset by an overall decrease due to increased moisture deficits along with increases in major forest disturbances such as fire, insect outbreaks, and extreme weather events (Warren *et al.* 2004).

Another consideration is the potential for loss of wood quality in dieback trees. Deformation of redcedar stems with progressive dieback may lead to a loss of useable harvestable volume due to multiple dead tops of dieback trees. Dieback of the main leader may also lead to inner heartwood rot due to loss of the main leader, thus overall losses of volume may also need to be considered in management of redcedar with dieback. Since redcedar growth is related to moisture and temperature on a site, this tree may be lost as a commercial species in the drier BEC units on the island (CDFmm, CWHxm1 and CWHxm2). Thus, if redcedar are to be managed in these drier units, regeneration should be focused on more nutrient rich, wetter site series within these BEC units.

4.4 Overall Conclusion

This thesis studied western redcedar and evidence of dieback on the east coast of Vancouver Island using dendrochronology and water balance modeling. Dieback was noted in three of the four driest BEC units on the island however, it was concentrated near the Qualicum Beach area (CDFmm). Warm and dry summer climate was found to reduce radial growth of redcedar on certain study sites, yet the hypothesis that moisture stress is the sole cause of dieback could not be supported. Other determinants of dieback include predisposing well drained coarse textured soil conditions, inciting drought events over the growing season, and contributing factors such as insects and pathogens although little evidence of these contributing factors was found in this study. Water balance modelling found a relationship between TDI and residual ring width index at a limited number of sites; the low number of significant relationships was likely caused by the low climate-sensitivity of breast-height tree ring data in redcedar growing on zonal sites. Low sensitivity may have been exacerbated by stand dynamics and competition since study sites were located in mixed stands with multiple age cohorts. ForWaDy, once linked to FORECAST could provide useful information on water stress and future growth of redcedar. It is unlikely that redcedar will be lost from Vancouver Island completely due to the resilient and acclimative nature of this species, however, redcedar growing on low elevation sites vulnerable to drought may experience increased dieback occurrences and eventual decline in these areas. Recommendations for future studies and considerations for management were also provided. Changing climates and global warming may lead to loss of redcedar in drier BEC units, as such, management of this species within drier BEC units should focus regeneration on higher elevation and more northern latitude - wetter site series.

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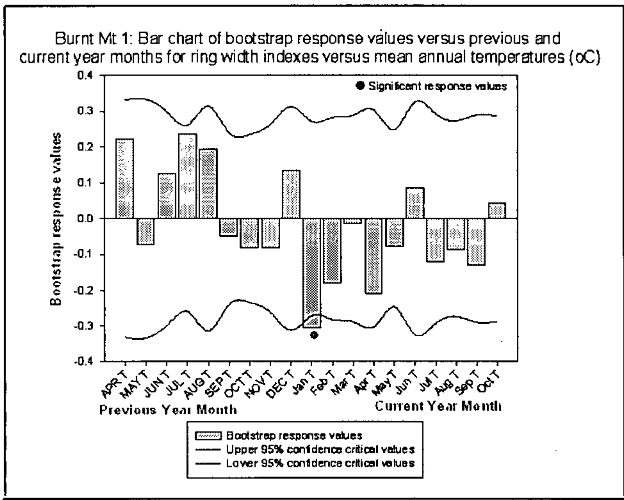
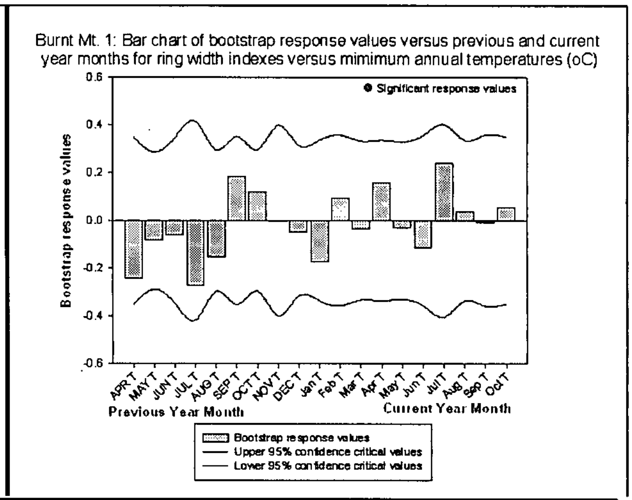
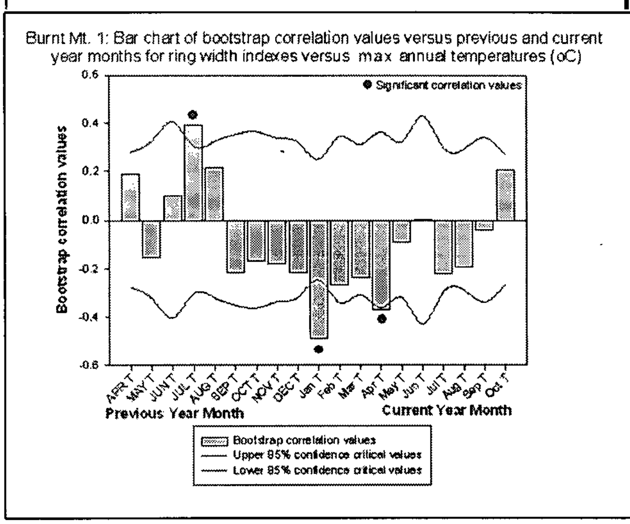
Appendix 1: DendroClim summary graphs

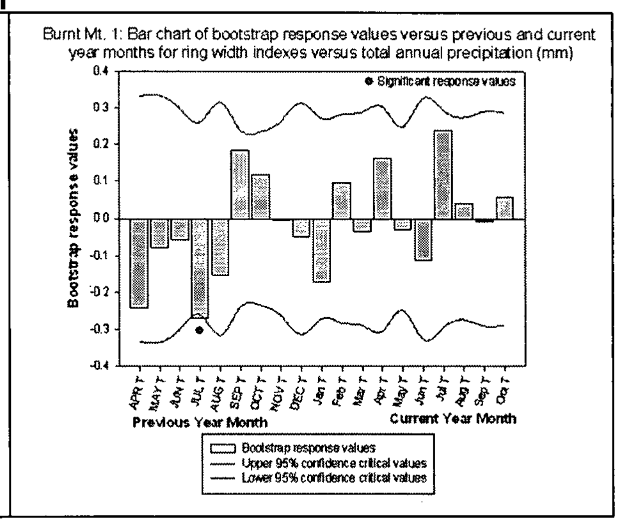
DendroClim graphs showing the relationship between monthly climate variables and residual ring width indices for 16 study sites.

Burnt Mountain #1:



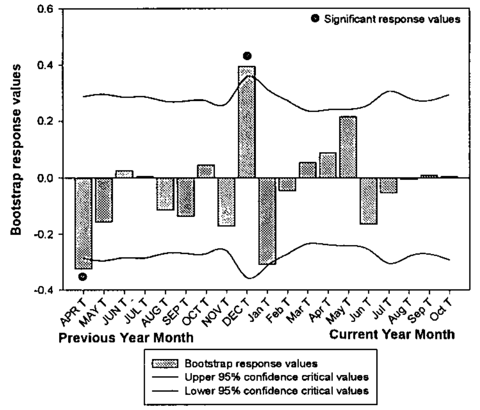




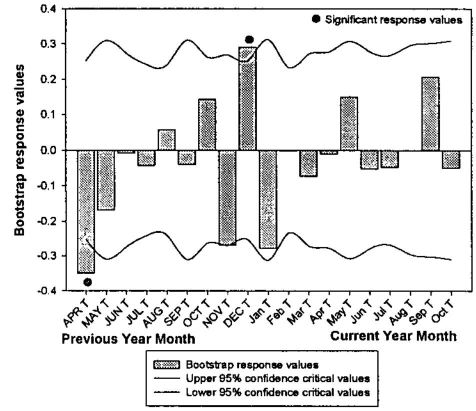


Burnt Mountain #2:

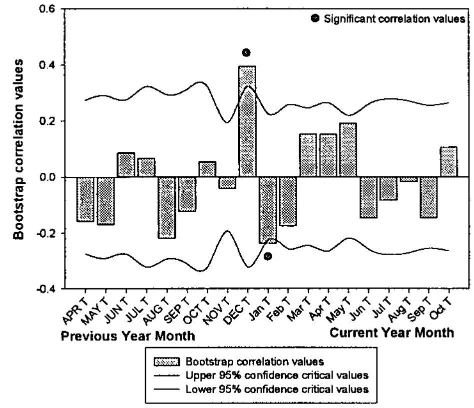
Burnt Mt. 2: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mean annual temperatures (oC)



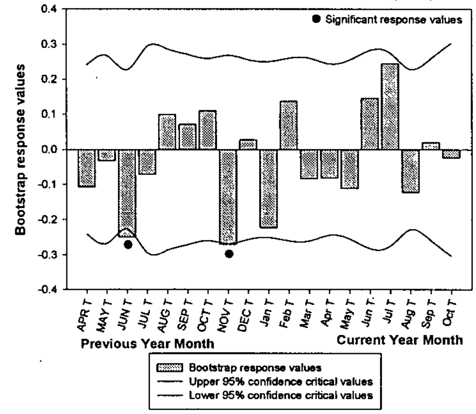
Burnt Mt. 2: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mimimum annual temperatures (oC)



Burnt Mt. 2: Bar chart of bootstrap correlation values versus previous and current year months for ring width indexes versus max annual temperatures (oC)

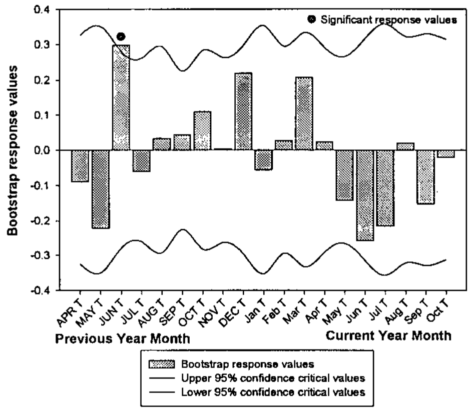


Burnt Mt. 2: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus total annual precipitation (mm)

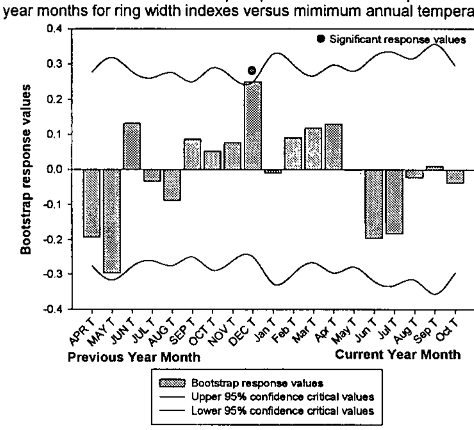


Bacon Lake:

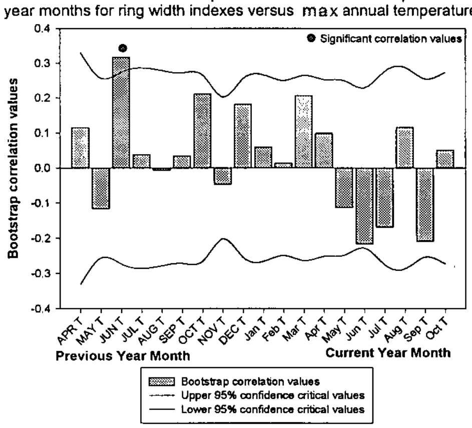
Bacon Lake: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mean annual temperatures (oC)



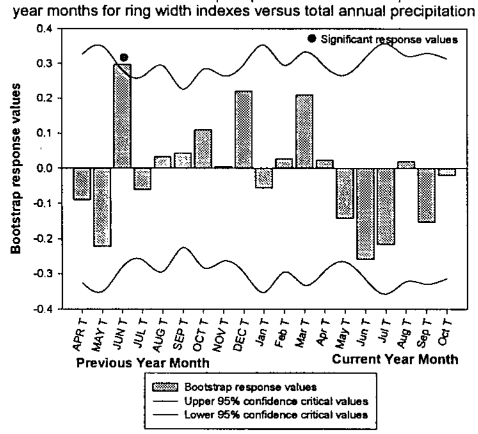
Bacon Lake: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mimimum annual temperatures (oC)



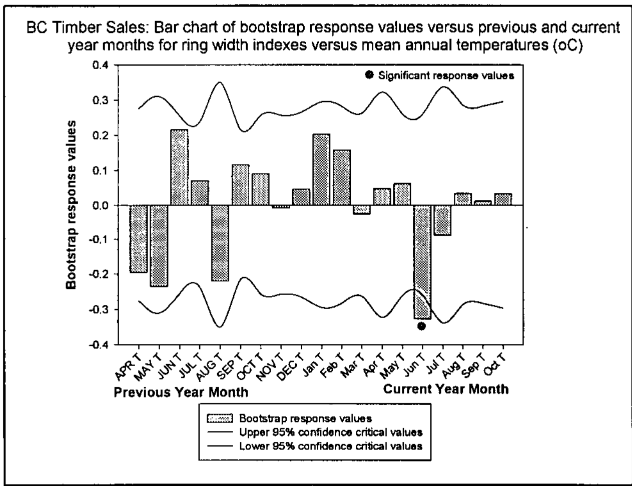
Bacon Lake: Bar chart of bootstrap correlation values versus previous and current year months for ring width indexes versus max annual temperatures (oC)

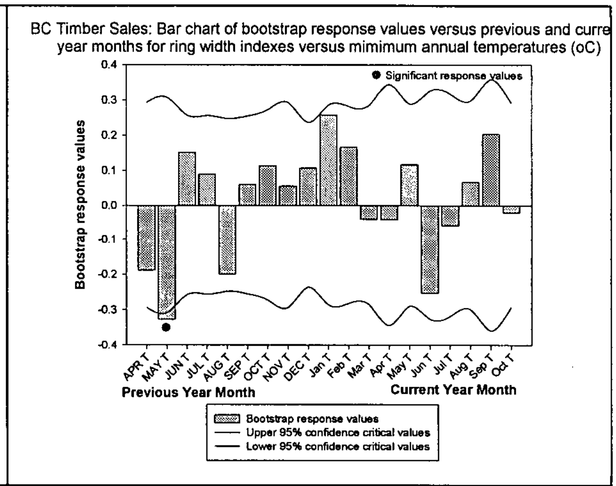


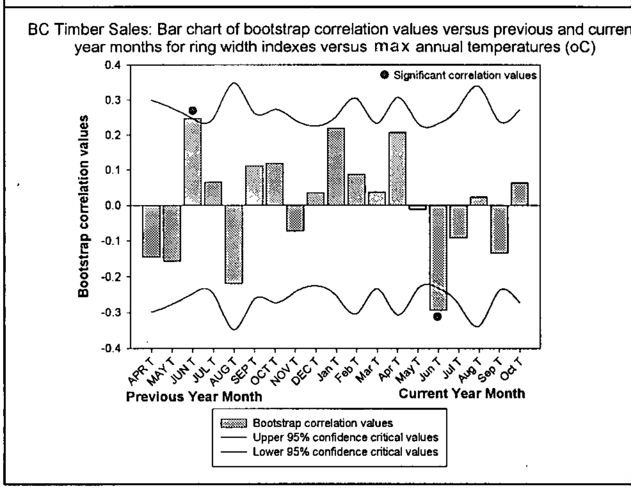
Bacon Lake: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus total annual precipitation (mm)

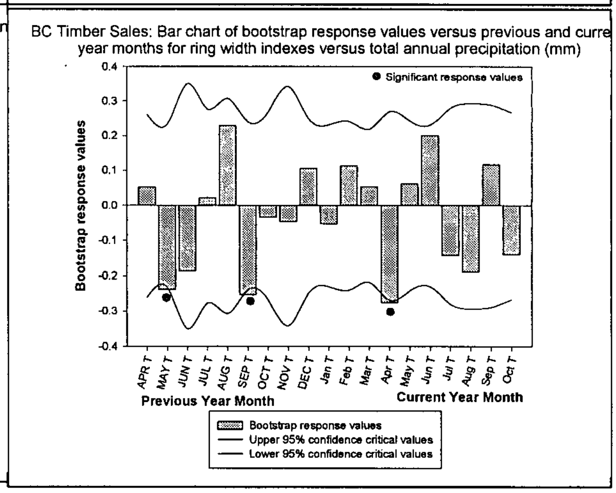


BC Timber Sales:

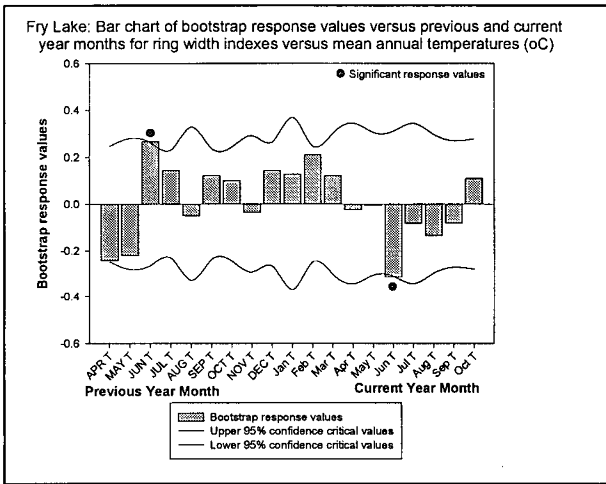




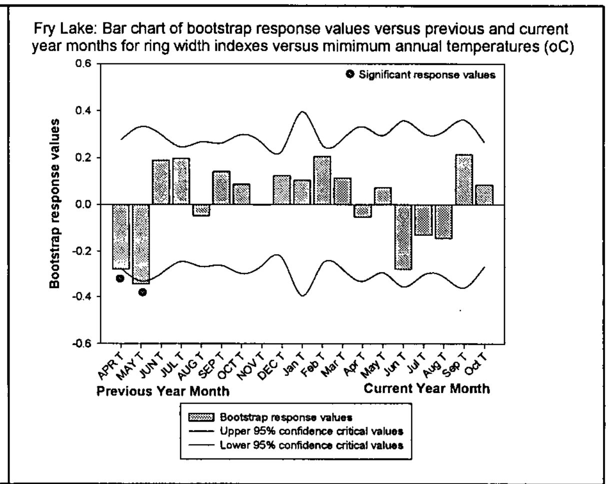




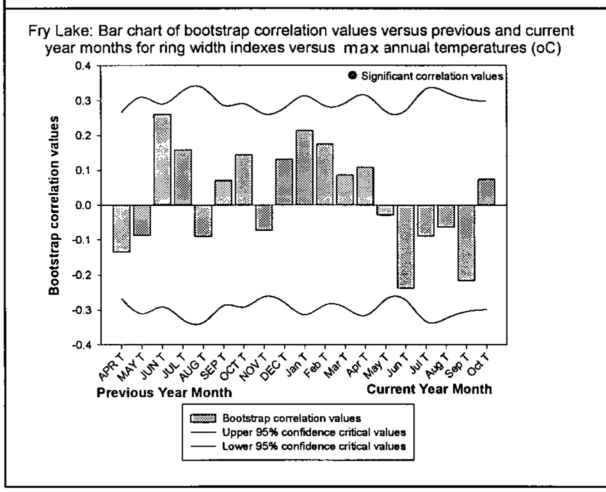
Fry Lake:



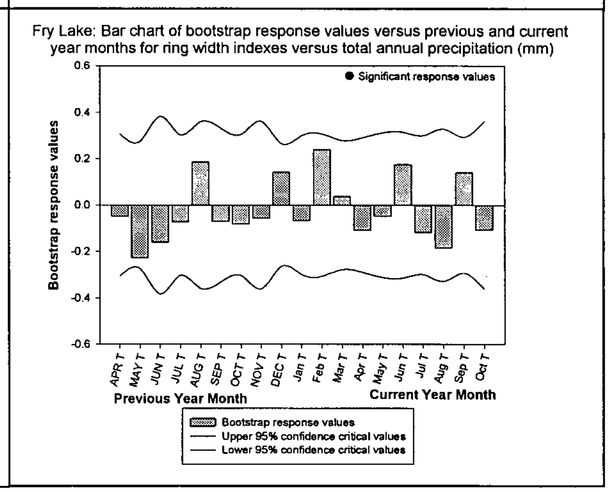
Fry Lake: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mean annual temperatures (oC)
Significant response values
Bootstrap response values
Previous Year Month
Current Year Month
Bootstrap response values
Upper 95% confidence critical values
Lower 95% confidence critical values



Fry Lake: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mimimum annual temperatures (oC)
Significant response values
Bootstrap response values
Previous Year Month
Current Year Month
Bootstrap response values
Upper 95% confidence critical values
Lower 95% confidence critical values

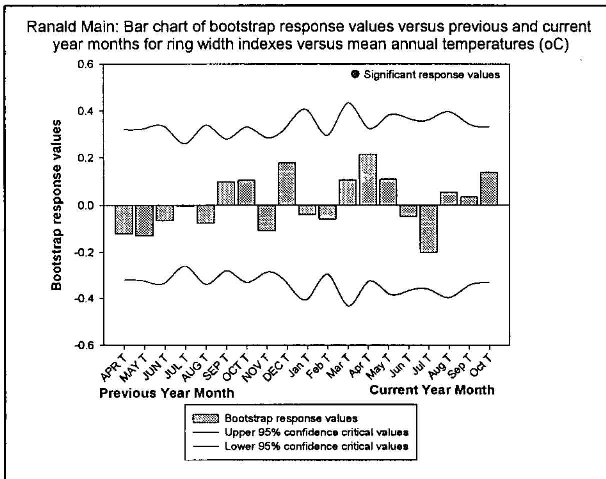


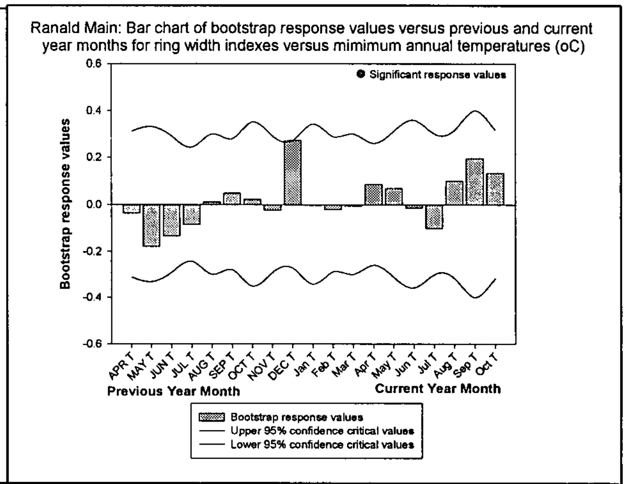
Fry Lake: Bar chart of bootstrap correlation values versus previous and current year months for ring width indexes versus max annual temperatures (oC)
Significant correlation values
Bootstrap correlation values
Previous Year Month
Current Year Month
Bootstrap correlation values
Upper 95% confidence critical values
Lower 95% confidence critical values

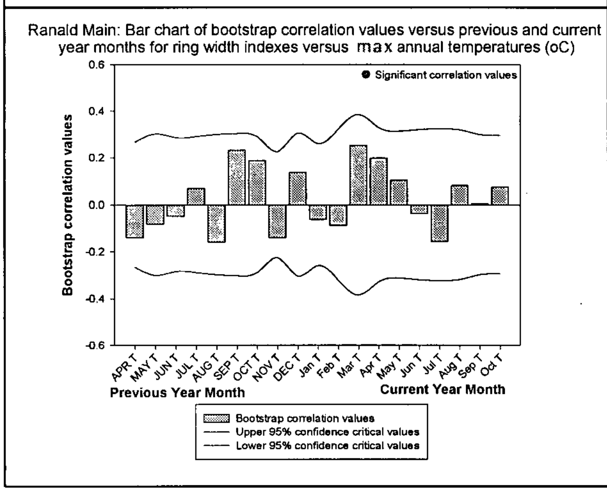


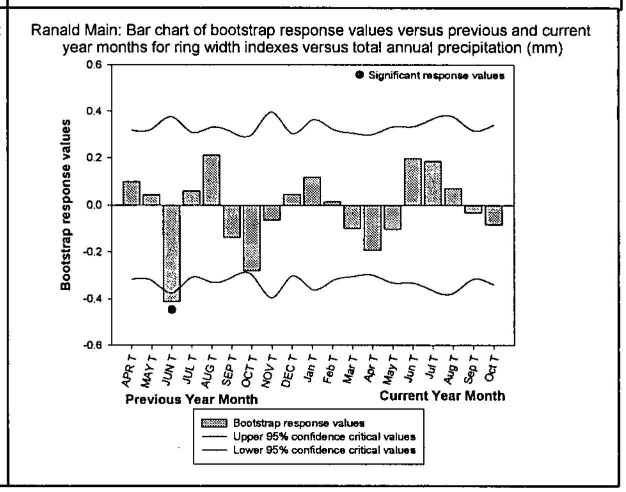
Fry Lake: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus total annual precipitation (mm)
Significant response values
Bootstrap response values
Previous Year Month
Current Year Month
Bootstrap response values
Upper 95% confidence critical values
Lower 95% confidence critical values

Ranald Main:


Ranald Main: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mean annual temperatures (oC)
Significant response values
Bootstrap response values
Previous Year Month
Current Year Month
APR T MAY T JUN T JUL T AUG T SEP T OCT T NOV T DEC T Jan T Feb T Mar T Apr T May T Jun T Jul T Aug T Sep T Oct T
Bootstrap response values
Upper 95% confidence critical values
Lower 95% confidence critical values

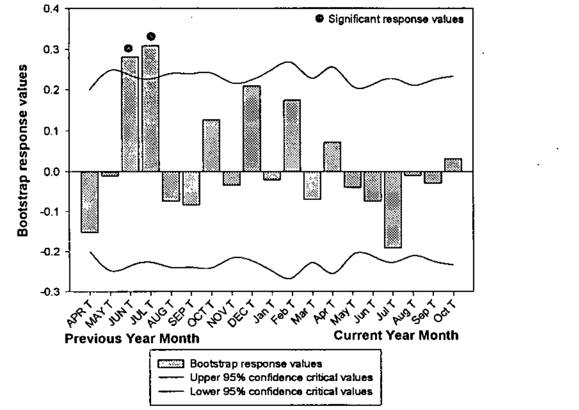

Ranald Main: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mimimum annual temperatures (oC)
Significant response values
Bootstrap response values
Previous Year Month
Current Year Month
Bootstrap response values
Upper 95% confidence critical values
Lower 95% confidence critical values


Ranald Main: Bar chart of bootstrap correlation values versus previous and current year months for ring width indexes versus max annual temperatures (oC)
Significant correlation values
Bootstrap correlation values
Previous Year Month
Current Year Month
Bootstrap correlation values
Upper 95% confidence critical values
Lower 95% confidence critical values

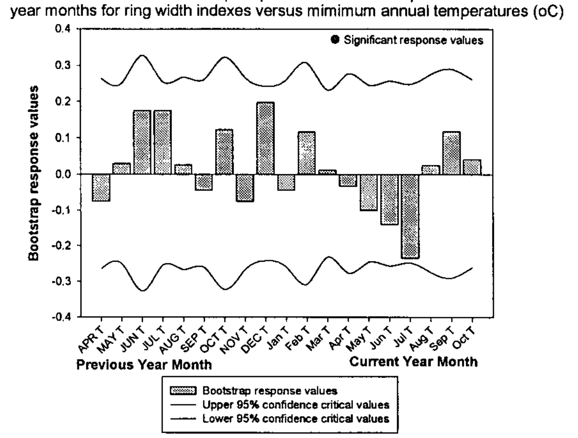

Ranald Main: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus total annual precipitation (mm)
Significant response values
Bootstrap response values
Previous Year Month
Current Year Month
Bootstrap response values
Upper 95% confidence critical values
Lower 95% confidence critical values

Fluxnet Site:

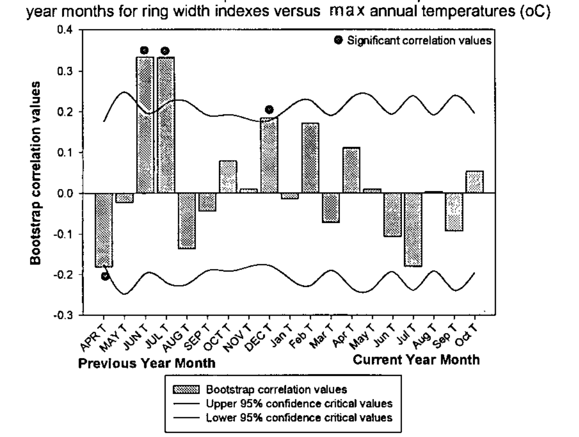
Flux Net: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mean annual temperatures (oC)



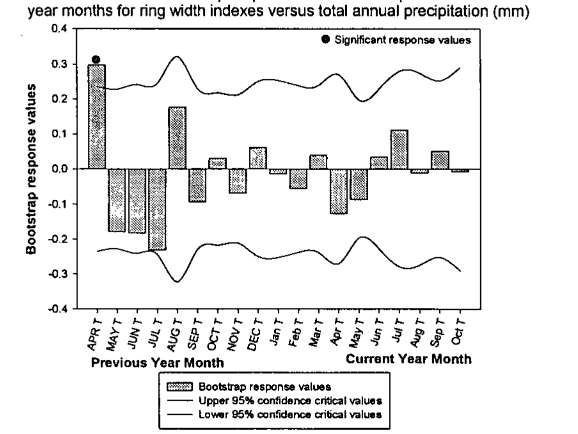
Flux Net: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mimimum annual temperatures (oC)



Flux Net: Bar chart of bootstrap correlation values versus previous and current year months for ring width indexes versus max annual temperatures (oC)

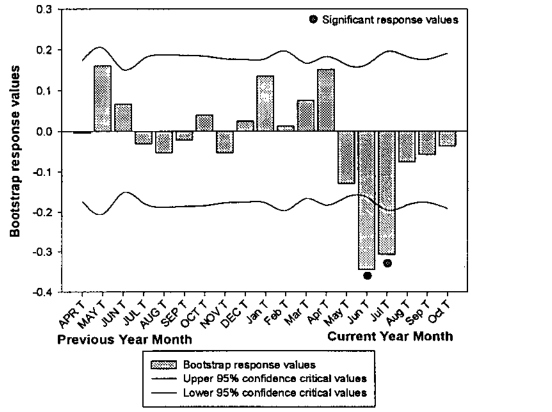


Flux Net: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus total annual precipitation (mm)

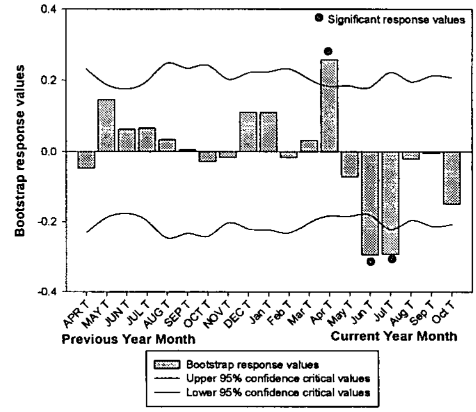


Horne Lake:

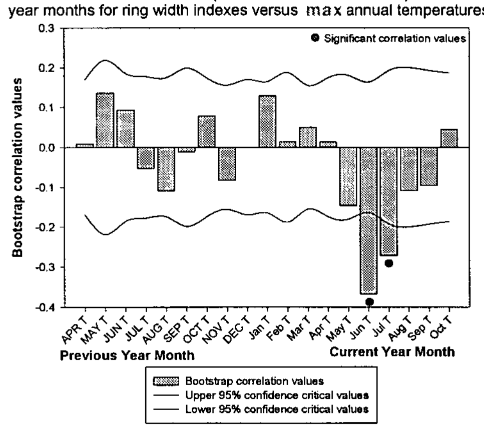
Horne Lake: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mean annual temperatures (oC)



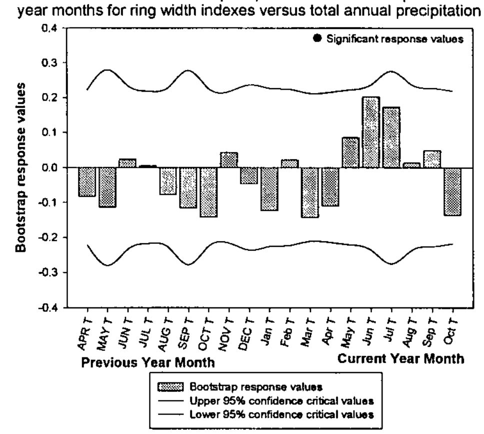
Horne Lake: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mimimum annual temperatures (oC)



Horne Lake: Bar chart of bootstrap correlation values versus previous and current year months for ring width indexes versus max annual temperatures (oC)

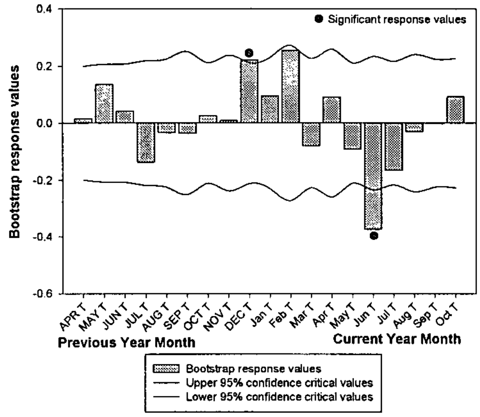


Horne Lake: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus total annual precipitation (mm)

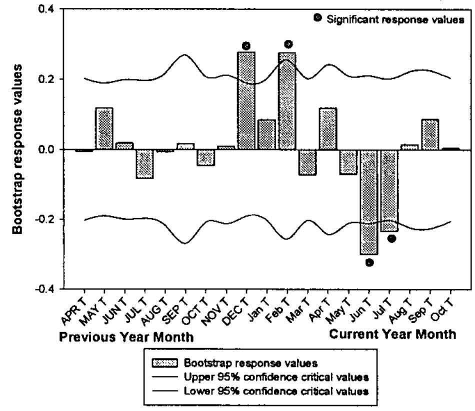


Qualicum Bay:

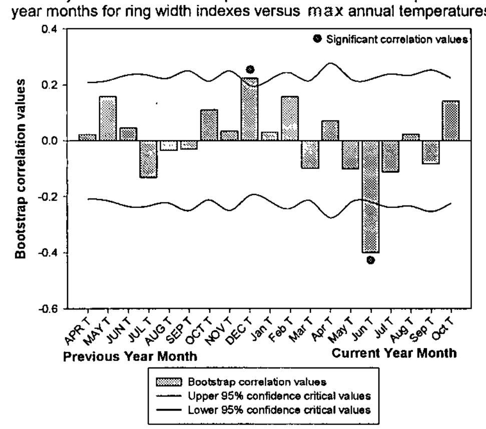
Qualicum Bay: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mean annual temperatures (oC)



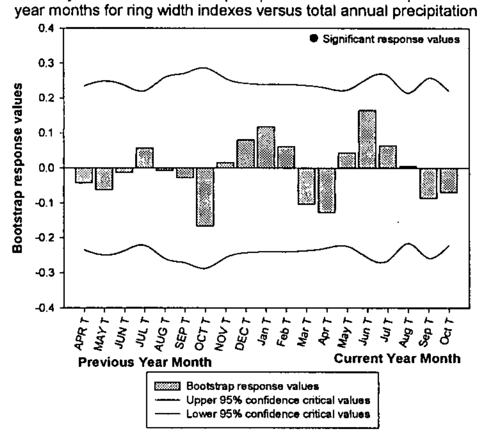
Qualicum Bay: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mimimum annual temperatures (oC)



Qualicum Bay: Bar chart of bootstrap correlation values versus previous and current year months for ring width indexes versus max annual temperatures (oC)

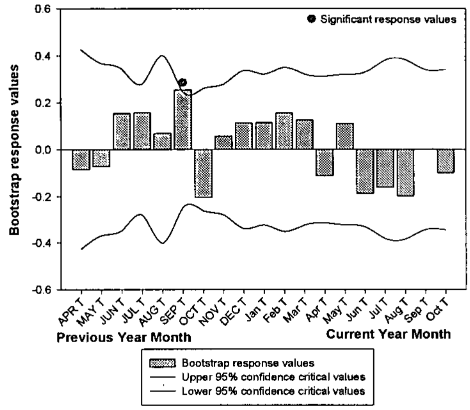


Qualicum Bay: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus total annual precipitation (mm)

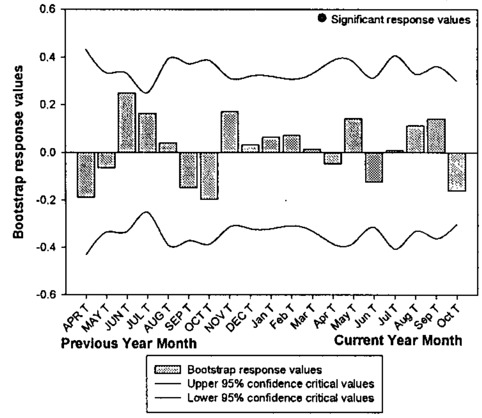


Cowichan Lake:

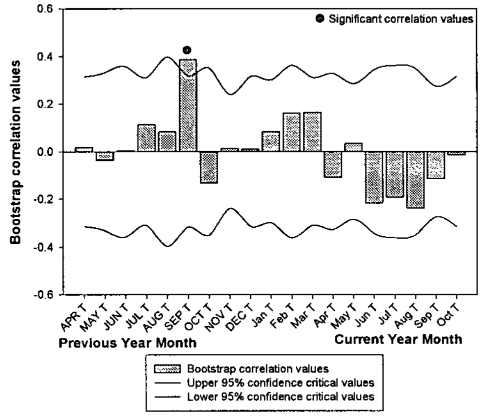
Cowichan Lake: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mean annual temperatures (oC)



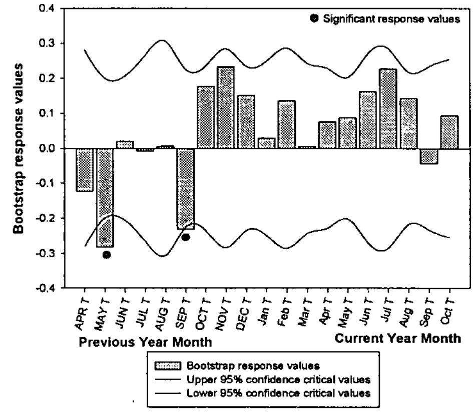
Cowichan Lake: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mimimum annual temperatures (oC)



Cowichan Lake: Bar chart of bootstrap correlation values versus previous and current year months for ring width indexes versus mean max temperatures (oC)

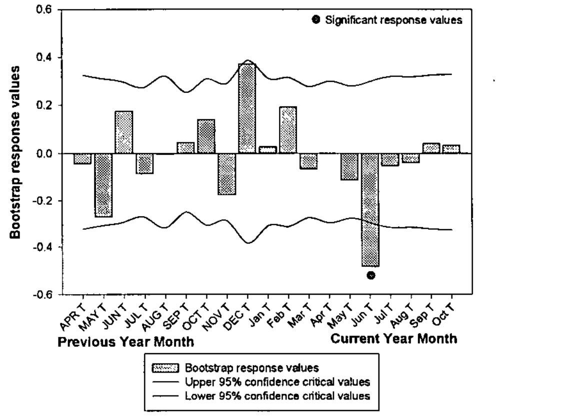


Cowichan Lake: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus total annual precipitation (mm)

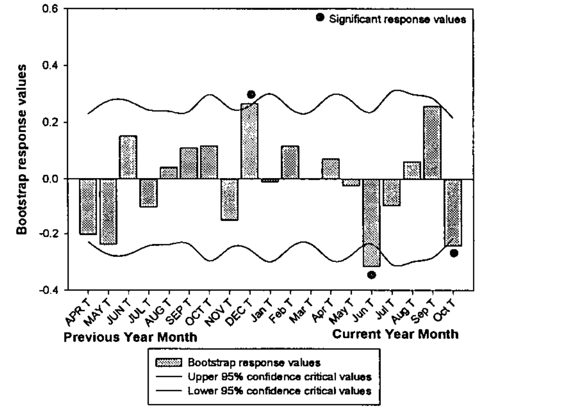


Skutz Falls #6:

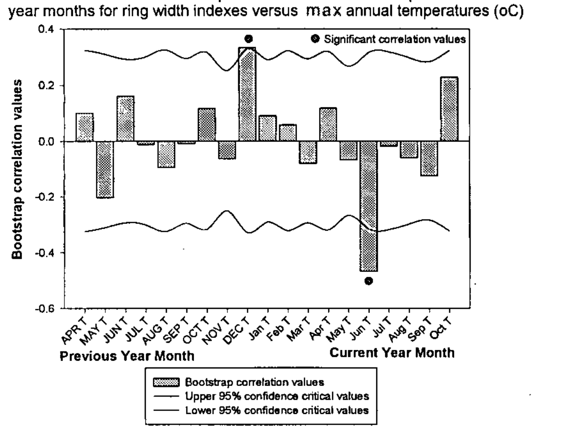
Skutz Falls 6: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mean annual temperatures (oC)



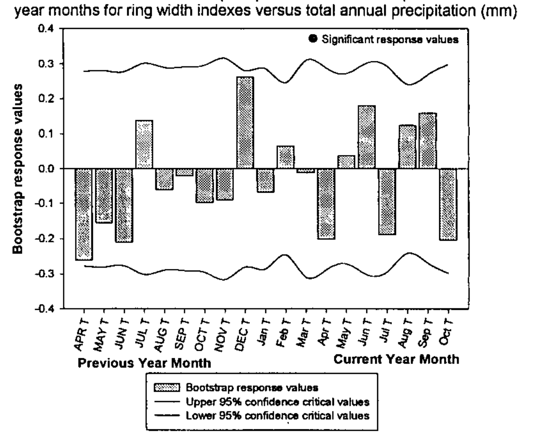
Skutz Falls 6: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mimimum annual temperatures (oC)



Skutz Falls 6: Bar chart of bootstrap correlation values versus previous and current year months for ring width indexes versus max annual temperatures (oC)

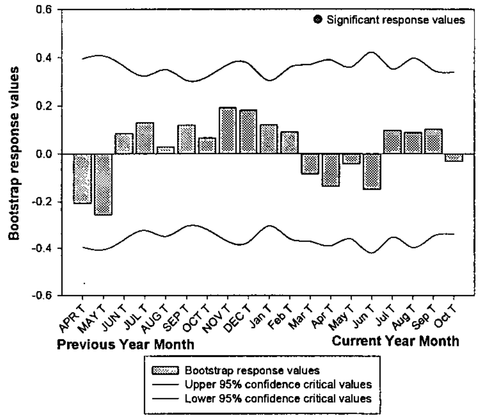


Skutz Falls 6: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus total annual precipitation (mm)

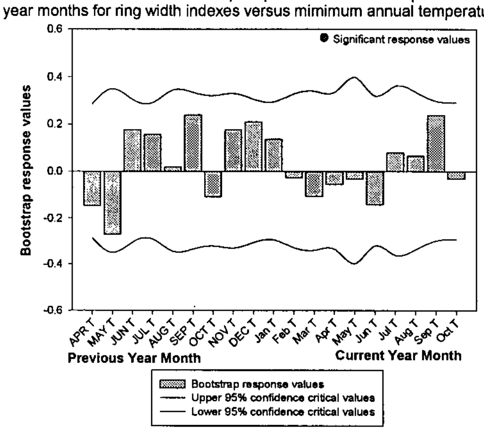


Skutz Falls #7:

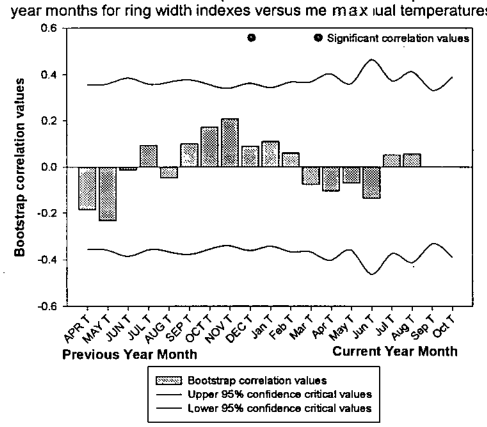
Skutz Falls 7: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mean annual temperatures (oC)



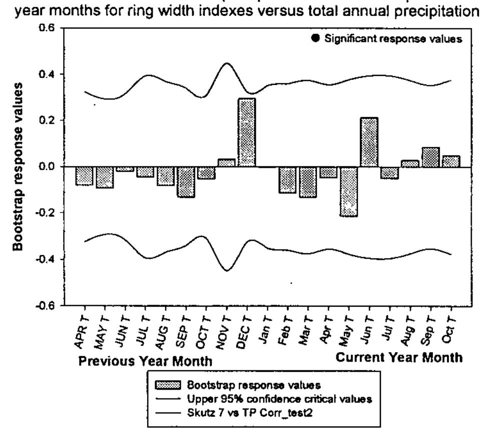
Skutz Falls 7: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mimimum annual temperatures (oC)



Skutz Falls 7: Bar chart of bootstrap correlation values versus previous and current year months for ring width indexes versus me max ual temperatures (oC)

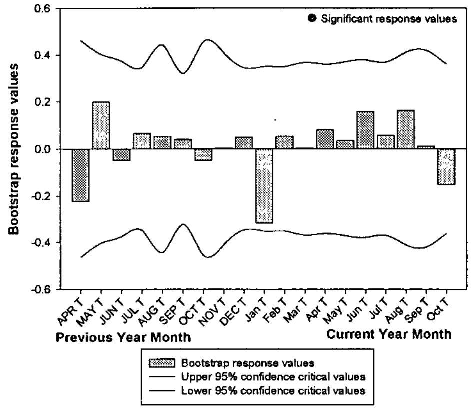


Skutz Falls 7: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus total annual precipitation (mm)

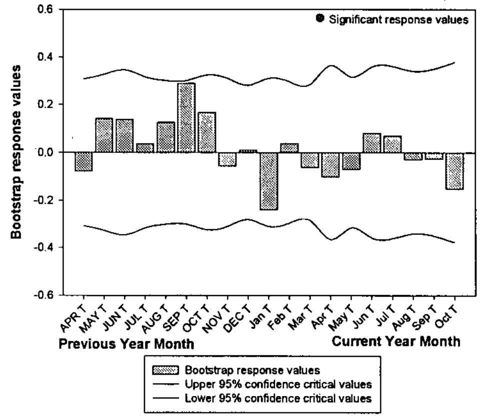


Qualicum Beach:

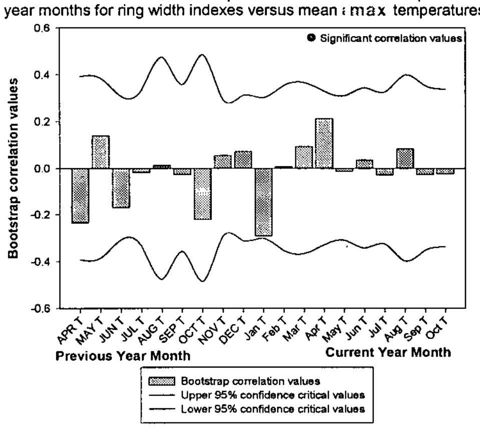
Qualicum Beach: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mean annual temperatures (oC)



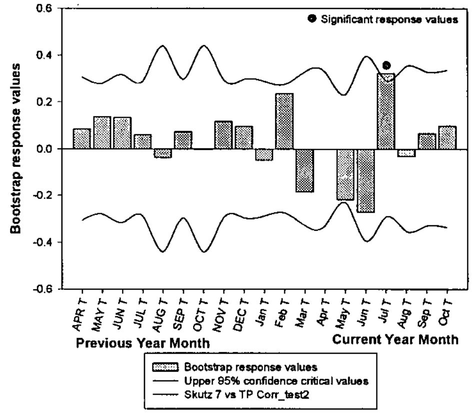
Qualicum Beach: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mimimum annual temperatures (oC)



Qualicum Beach: Bar chart of bootstrap correlation values versus previous and current year months for ring width indexes versus mean : max temperatures (oC)

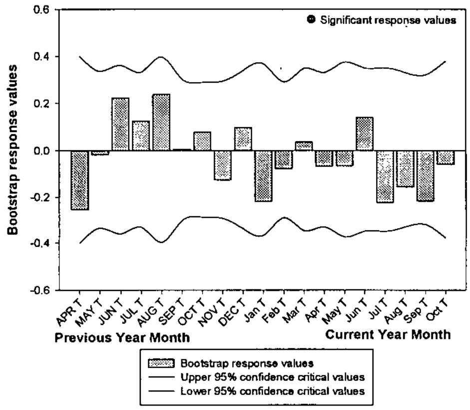


Qualicum Beach: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus total annual precipitation (mm)

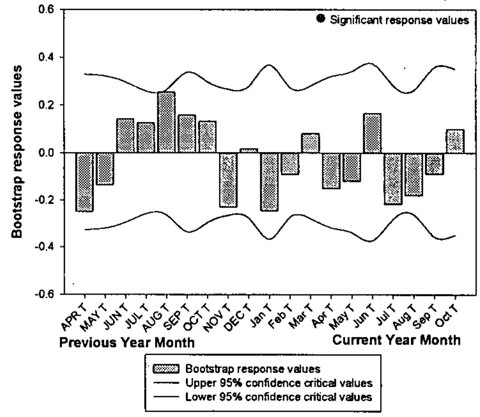


Shawnigan Lake:

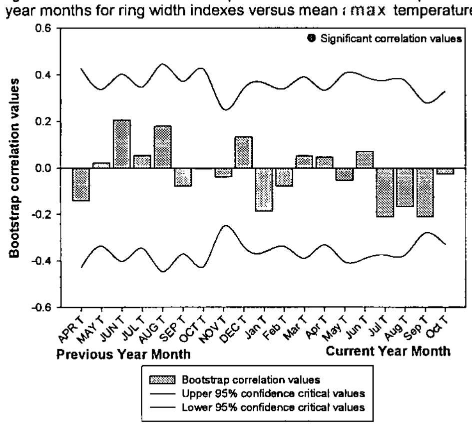
Shawnigan Lake: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mean annual temperatures (oC)



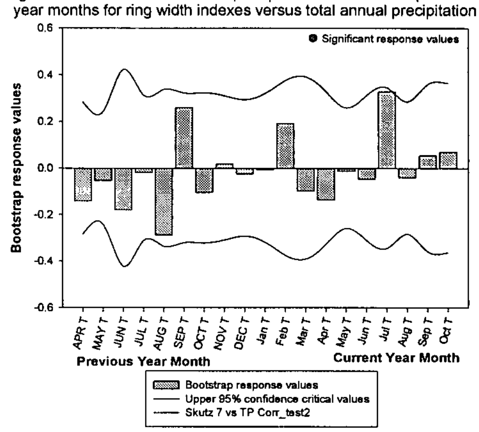
Shawnigan Lake: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mimimum annual temperatures (oC)



Shawnigan Lake: Bar chart of bootstrap correlation values versus previous and current year months for ring width indexes versus mean max temperatures (oC)

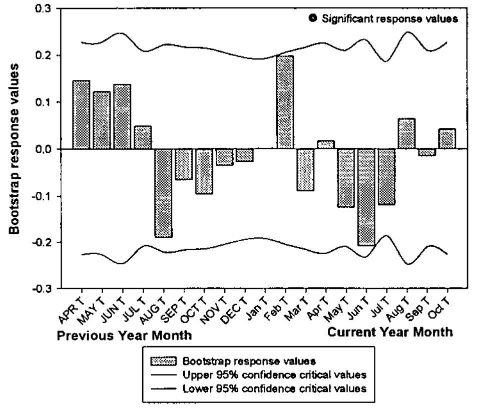


Shawnigan Lake: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus total annual precipitation (mm)

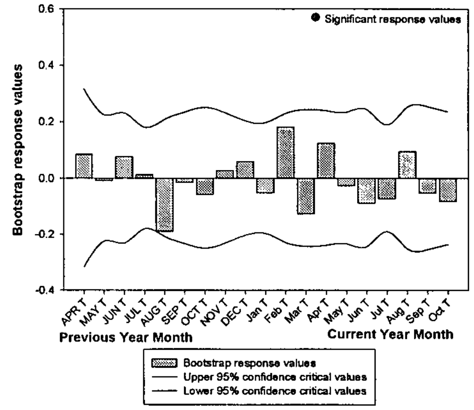


Royal Roads:

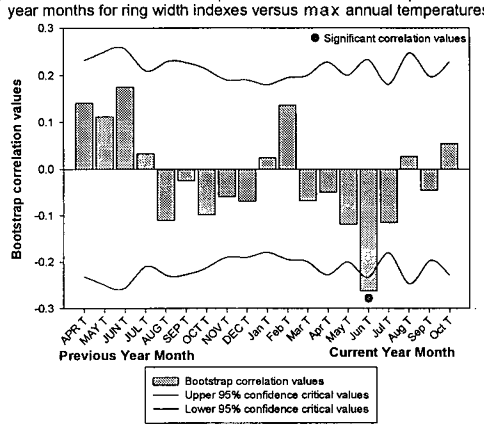
Royal Roads: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mean annual temperatures (oC)



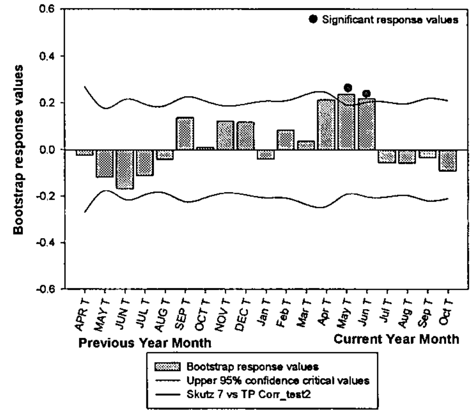
Royal Roads: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mimimum annual temperatures (oC)



Royal Roads: Bar chart of bootstrap correlation values versus previous and current year months for ring width indexes versus max annual temperatures (oC)

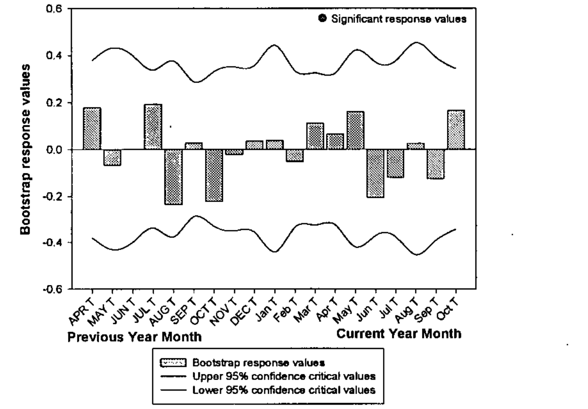


Royal Roads: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus total annual precipitation (mm)

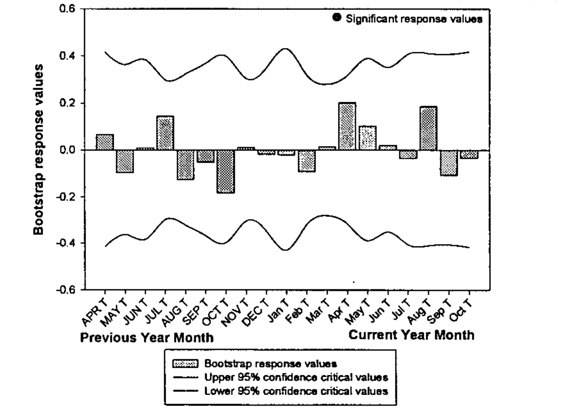


Galiano Island:

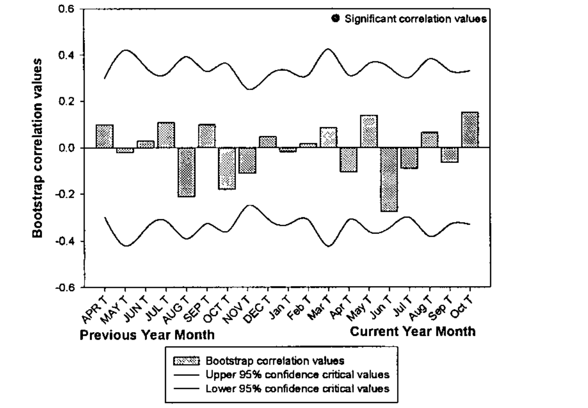
Galiano: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mean annual temperatures (oC)



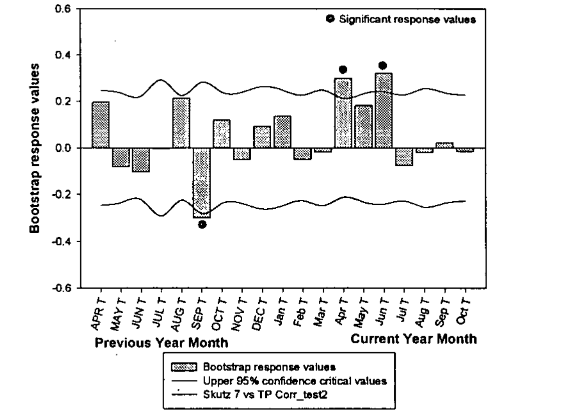
Galiano: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus mimimum annual temperatures (oC)



Galiano: Bar chart of bootstrap correlation values versus previous and current year months for ring width indexes versus max annual temperatures (oC)



Galiano: Bar chart of bootstrap response values versus previous and current year months for ring width indexes versus total annual precipitation (mm)



Appendix 2: Soil Analysis Methods

The first soil moisture sampling method involved placing the samples in a small cylinder of known volume and adding a pre-determined amount of soil to emulate estimated field bulk density (L. Lavkulich, UBC pers. comm. October 2005). Next, a perforated tray was filled with sand, covered with a screen, and saturated with water. A filter paper was placed on the tray under each cylinder so that none of the sample was lost into the sand. The samples were left to saturate for 24 hours. The next day, the samples were removed, weighed and placed on a new tray with dry sand to drain. Finally, after 24, 48 and 72 hour intervals, the cylinders were re-weighed to estimate the % moisture remaining in the soil sample (Figure A1).

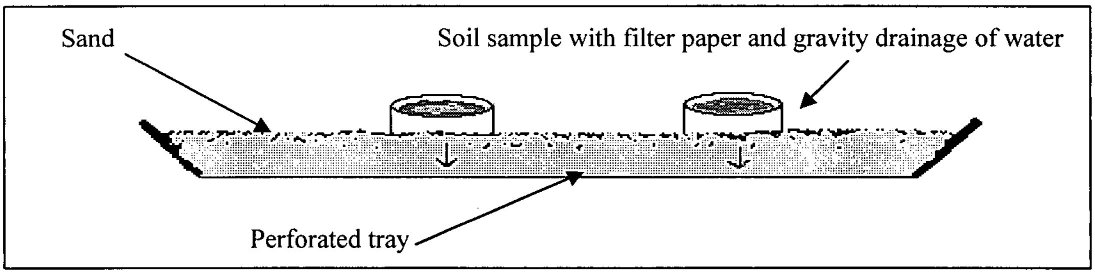


Figure A1: Sand drainage method used to estimate the field capacity of each sample.

The second method used pressure plates to determine soil moisture (Richards 1986). This method involves again placing soil samples in cylinders and then on a pressure plate while saturating the samples (Figure A2). Once samples are saturated, the pressure plate apparatus is sealed and the pressure gauge is set to 10 kPa of pressure (simulates the field capacity of loamy mineral soil samples) (M. Novak, pers. comm., October 2005). The samples are left for 48 hours at this pressure, weighed, saturated again and placed on the pressure plates with pressures now turned to 33 kPa (simulates field capacity of humus samples). After another 48 hours, the samples were weighed and the estimates of both humus and mineral samples were calculated.

http://waterquality.montana.edu/docs/photo/pressure_plate.shtml

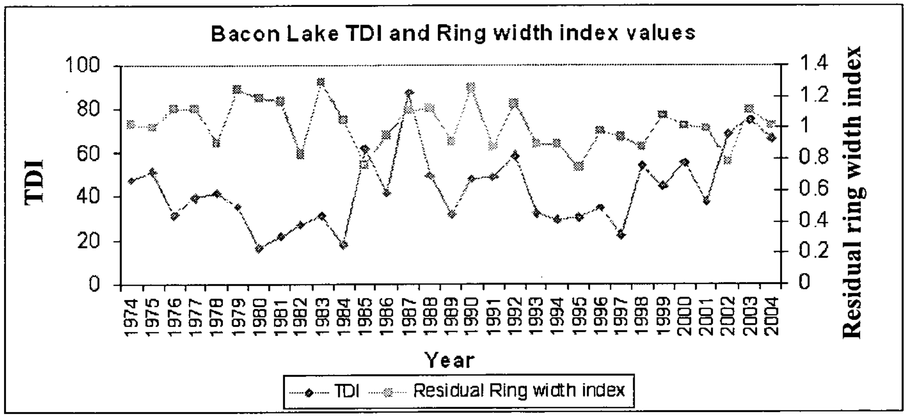
Figure A2: Pressure plate apparatus with soil samples placed in plastic cylinders. A lid covers the metal pressure plate apparatus and pressures can be set at any pressure to estimate the field capacity of different types of samples.

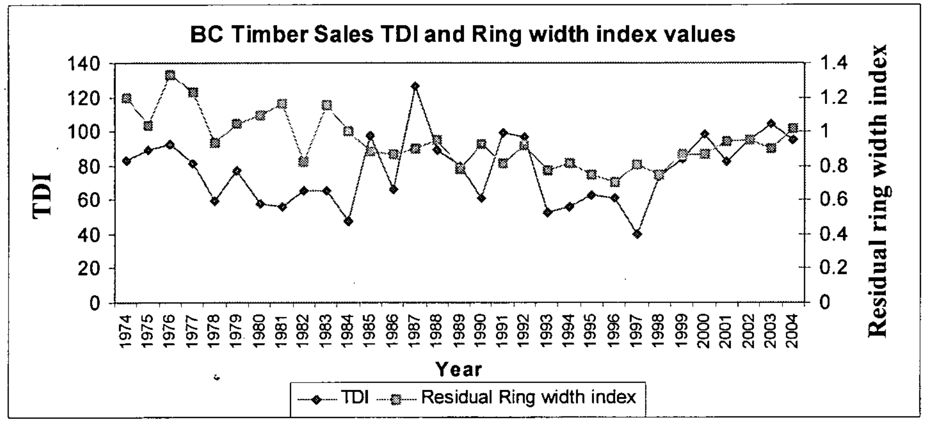
Literature Cited

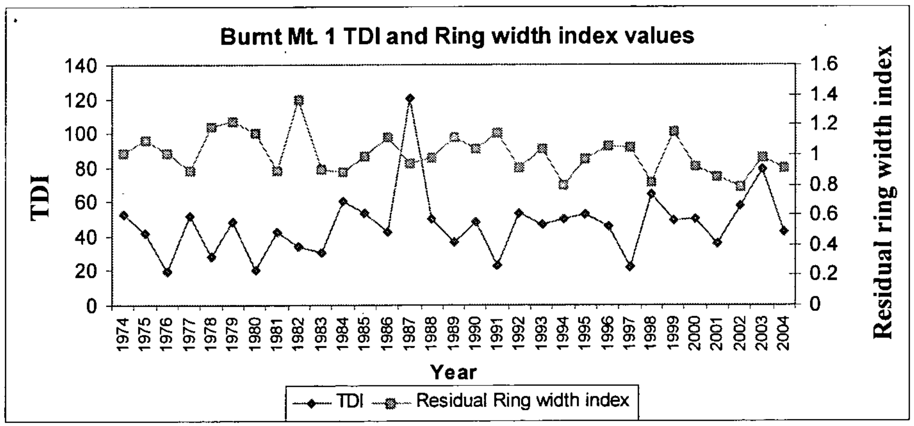
Richards, L. A. (1986). Methods of soil analysis: Physical condition of water in soil. Agronomy; no. 9. A. L. Page, R.H. Miller, D.R. Keeney (eds.). Madison, Wisconsin, American Society of Agronomy: Soil Science Society of America: 128-137.

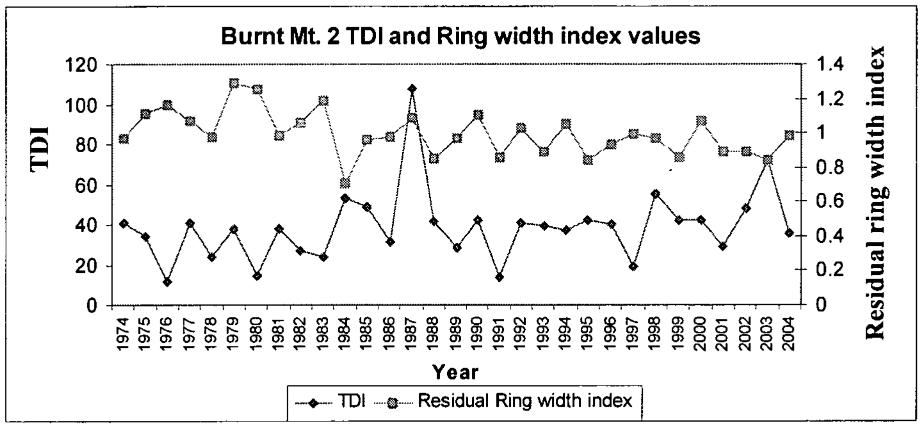
Appendix 3: TDI and Residual Ring-Width Curves

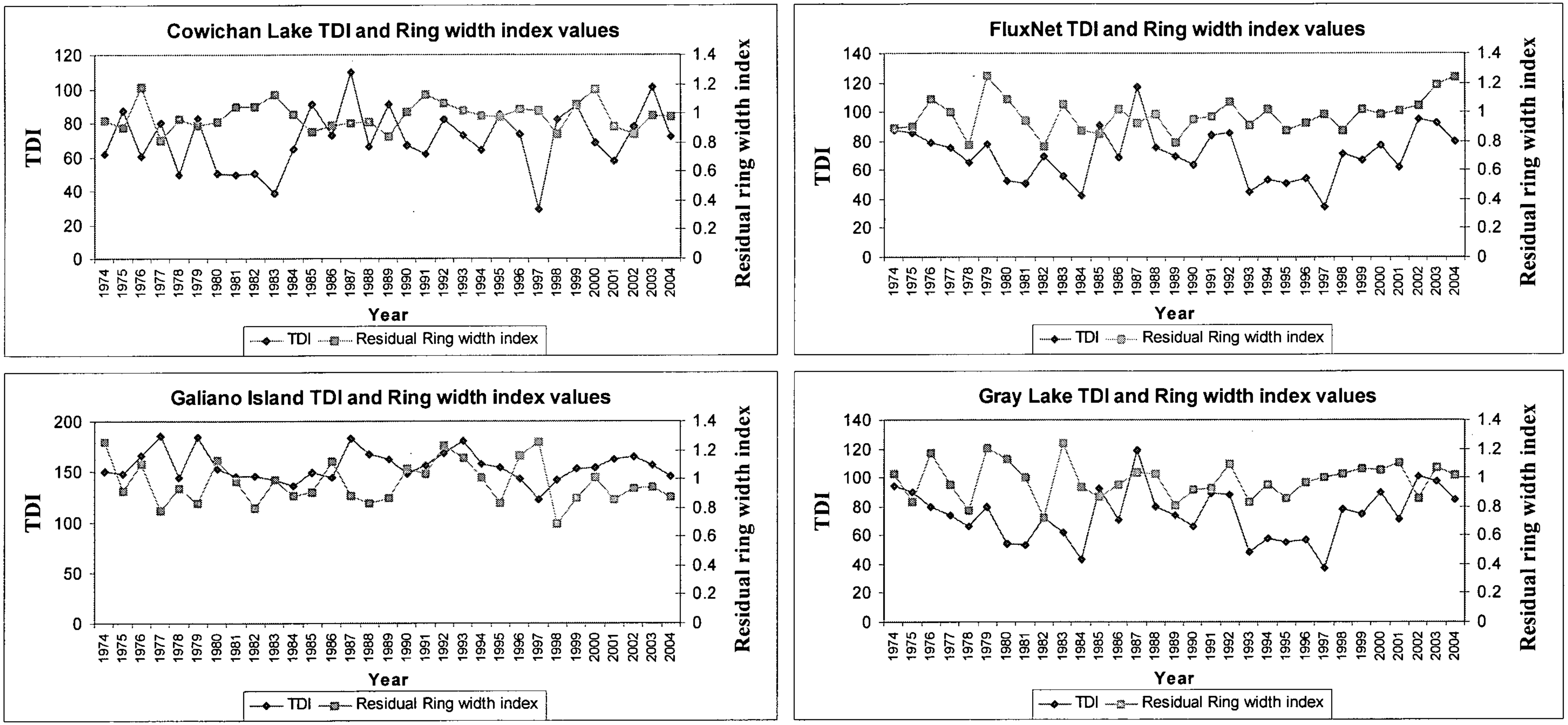
Plots of calculated ForWaDy TDI values versus residual ring width indices calculated from dendrochronological work for the 16 study sites.



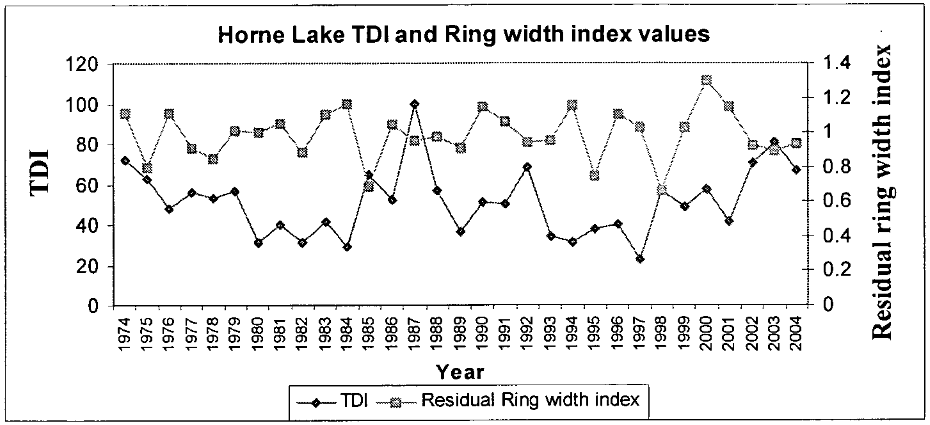








Cowichan Lake TDI and Ring width index values
TDI
Residual ring width index
Year
TDI
Residual Ring width index
FluxNet TDI and Ring width index values
TDI
Residual ring width index
Year
TDI
Residual Ring width index
Galiano Island TDI and Ring width index values
TDI
Residual ring width index
Year
TDI
Residual Ring width index
Gray Lake TDI and Ring width index values
TDI
Residual ring width index
Year
TDI
Residual Ring width index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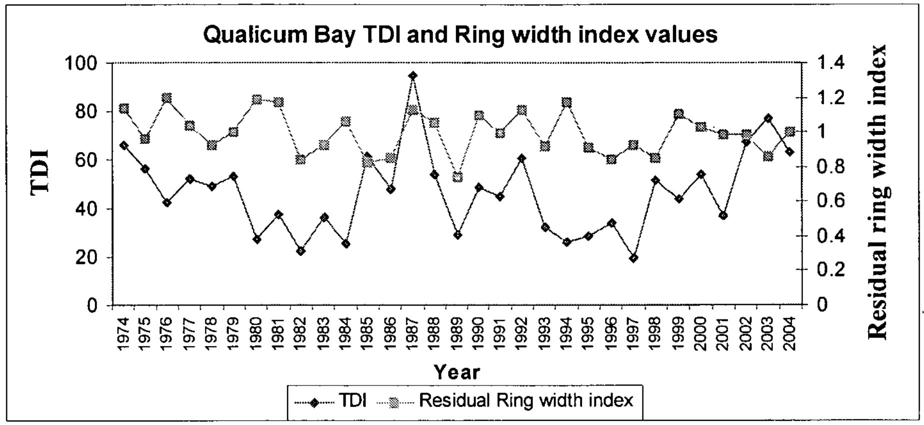
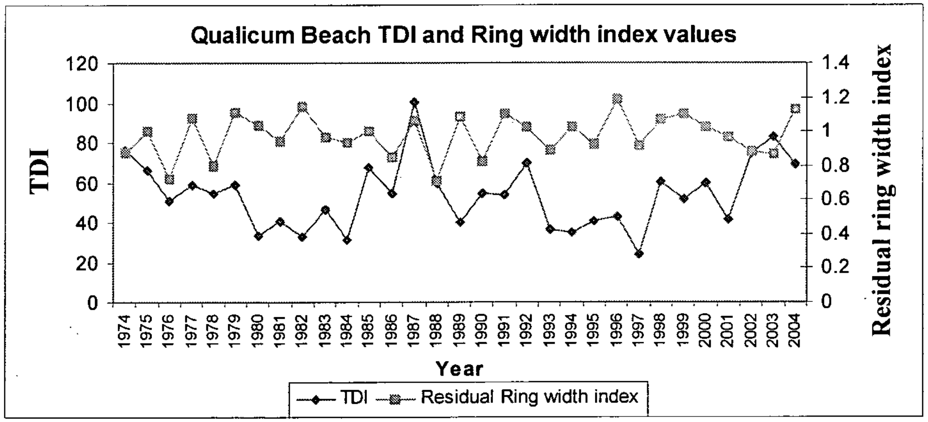
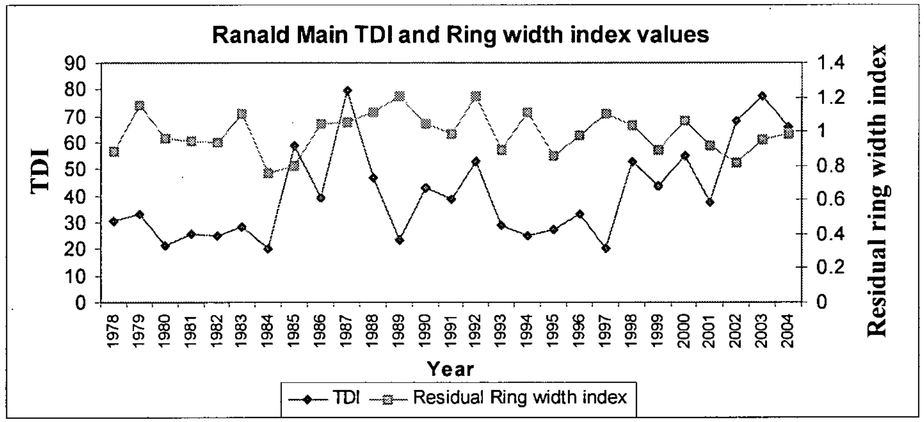
TDI
Residual ring width index
Year
TDI
Residual Ring width index


Qualicum Bay TDI and Ring width index values
TDI
Residual ring width index
Year
TDI
Residual Ring width index


Qualicum Beach TDI and Ring width index values
TDI
Residual ring width index
Year
TDI
Residual Ring width index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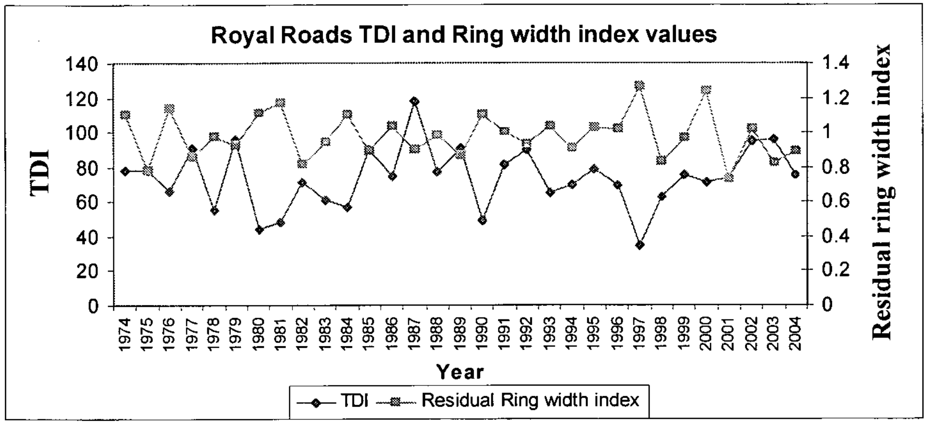
TDI
Residual ring width index
Year
TDI
Residual Ring width index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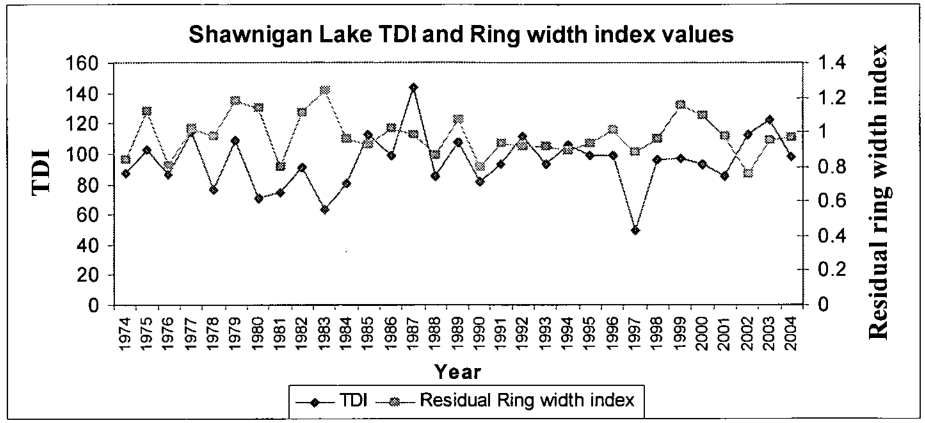
TDI
Residual ring width index
Year
TDI
Residual Ring width index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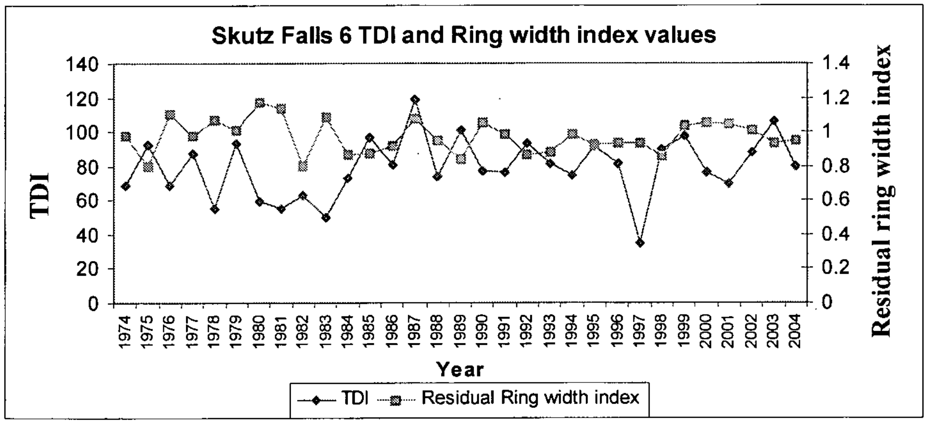
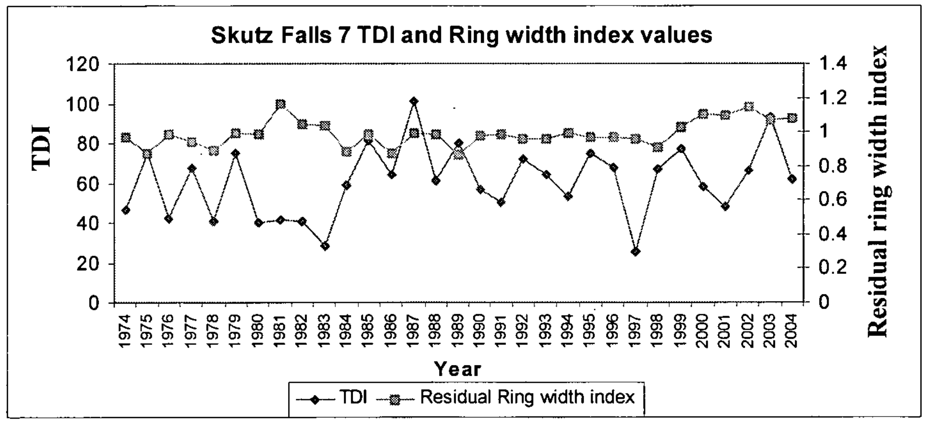
TDI
Residual ring width index
Year
TDI
Residual Ring width index


Skutz Falls 6 TDI and Ring width index values
TDI
Residual ring width index
Year
TDI
Residual Ring width index


Skutz Falls 7 TDI and Ring width index values
TDI
Residual ring width index
Year
TDI
Residual Ring width index