SITE - FOREST PRODUCTIVITY RELATIONSHIPS AND THEIR MANAGEMENT IMPLICATIONS IN COASTAL LOWLAND ECOSYSTEMS OF EAST GRAHAM ISLAND, QUEEN CHARLOTTE ISLANDS

by

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ABSTRACT

Relationships between soil, physiographic, floristic, and stand properties were examined in second-growth stands on a range of imperfectly to poorly drained ecosystems on east Graham Island, Queen Charlotte Islands. The major objective was to describe ecological factors associated with variation in tree growth, as expressed by site index of western redcedar.

Cedar site index was found to be strongly correlated with soil nutrient content, particularly total N and exchangeable Mg, expressed on a kg/ha basis. Decreasing site index was associated with decreasing rooting depth, due to slowly permeable horizons, and poor soil aeration, reflected by high volumetric moisture content. A simple model using total N content and volumetric moisture content summarized the relationship between cedar site index and soil properties, and accounted for 78% of the site index variation.

Three site index classes used as sampling strata (redcedar site index $\leq$15, 16-20, and >20 m/50 yrs. b.h. age) could be successfully differentiated by soil properties using discriminant analysis. Natural structure in the soils data revealed through principal components analysis and cluster analysis also reflected, with minor overlap, these three site index classes. Understory vegetation could be used to differentiate the poorest site index class, however the remaining two classes could not be floristically differentiated. A simple model relating cedar site index to reciprocal averaging scores derived from vegation data, and the frequency of the nutrient-medium indicator species group only explained 44% and

31% respectively of site index variation.

Site index of Sitka spruce, western hemlock, and lodgepole pine were all highly correlated with redcedar site index. Hemlock and pine showed similar height growth patterns to cedar, while spruce was markedly different, showing slower height growth than cedar on poorer sites and greater height growth on better quality sites. The sensitivity of spruce to limiting site conditions was also reflected in its increasing stand volume composition with improving site quality. The sampled sites generally supported high stand volumes given the site limitations, with MAI averaging 5 $m^3ha^{-1}yr^{-1}$ on the poorest sites (site index class 1) to 13 $m^3ha^{-1}yr^{-1}$ on the best sites (site index class 3).

Management strategies were recommended based on relationships observed in the study. Preferred tree species to manage are: for site index class 1 - cedar, pine, and hemlock; for site index class 2 - cedar, hemlock, pine, (with minor spruce); for site index class 3 - hemlock, spruce, cedar. Site productivity of these ecosystem may be improved by increasing the volume of aerated soil exploitable by tree roots. This could be achieved by site preparation which created relatively low, but wide mounds.

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LIST OF SYMBOLS

1. Soil chemical properties:

CA	exchangeable calcium: kg/ha except where indicated
HUMCN	carbon/nitrogen ratio in the forest floor
HUMPH	pH ($CaCl_2$) in the forest floor
K	exchangeable potassium: kg/ha except where indicated
MG	exchangeable magnesium: kg/ha except where indicated
MINCN	carbon/nitrogen ratio in the root zone mineral soil
MINPH	pH in the root zone mineral soil
MINN	mineralizable nitrogen: kg/ha except where indicated
P	available phosphorus: kg/ha except where indicated
TC	total carbon: kg/ha except where indicated
TN	total nitrogen: kg/ha except where indicated

2. Soil physical and morphological properties:

AIR	air filled porosity in the root zone mineral soil (%/100)
CAP	thickness of the eolian cap (cm)
CFPM	coarse fragment content in parent material (% by volume)
CLAY	percent clay in the mineral soil
D1ROOTM	primary rooting depth from the mineral surface (cm)
D1ROOTS	primary rooting depth from the ground surface (cm)
D2ROOTM	secondary rooting depth from the mineral surface (cm)
D2ROOTS	secondary rooting depth from the ground surface (cm)
DH2OM	depth to free water from the mineral surface (cm)
DH2OS	depth to free water from the ground surface (cm)
FFDEP	forest floor thickness (cm)
MOTL	depth to distinct or prominent mottles from mineral surface (cm)
PAN	depth to a "pan" from mineral surface (cm)
POR	total porosity in the root zone mineral soil (%/100)
SAND	percent sand in the mineral soil
SILT	percent silt in the mineral soil
SLOPE	slope (%)
VMC	volumetric moisture content in the root zone mineral soil (%/100)

CEM	presence of cemented horizon (2 classes)
CONS	consistence of mineral soil (2 classes)
CHROMA	chroma of mineral soil (Munsell notation)
H2OST	free water status (4 classes)
HUE	hue of mineral soil (Munsell notation)
PM	parent material type (5 classes)
ROOT	rooting density in mineral soil (4 classes)

SHAPE	ground surface shape (5 classes)
TEXTPM	field texture of parent material (CSSC textural classes)

3. Soil water properties:

DO	dissolved oxygen (ppm)
SC	specific conductance (dS/m)

4. Soil oxidation zone index:

AZ1	depth of 1st zone, method A (cm)
AZ2	depth of 2nd zone, method A (cm)
AZ3	depth of 3rd zone, method A (cm)
BZ1	depth of 1st zone, method B (cm)
BZ2	depth of 2nd zone, method B (cm)

5. Stand properties:

Cw	western redcedar (*Thuja plicata*)
Hw	western hemlock (*Tsuga heterophylla*)
Pl	lodgepole pine (*Pinus contorta*)
Ss	Sitka spruce (*Picea sitchensis*)
CWSI	site index of Cw (m/50 yrs b.h. age)
HWSI	site index of Hw (m/50 yrs b.h. age)
PLSI	site index of Pl (m/50 yrs b.h. age)
SSSI	site index of Ss (m/50 yrs b.h. age)
MAI	mean annual increment, total volume ($m^3ha^{-1}yr^{-1}$)

6. Data analysis:

DA	discriminant analysis
RA	reciprocal averaging

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1.0 INTRODUCTION

An extensive area of Crown land along the east side of Graham Island, Queen Charlotte Islands, has recently been the focus of considerable interest for potential forest management. The main area of interest comprises some 35000 hectares representing the southern portion of the Graham Island Crown Land Plan area (Ministry of Lands, Parks, and Housing 1980). An additional 15000 hectares in the northern portion of the Plan area (north of Port Clements, east of Masset Inlet, west of Naikoon Park) are also recognized as having forestry potential. In the past, the forestry value of this area was considered low. Holland (1964) characterized the area as being comprised largely of muskeg with sparse timber cover, with Alley and Thompson (1978) characterizing it similarly. Together with an old and inaccurate forest inventory, this information has led to uncertainties about the extent and quality of the forest resource. However, an inventory update conducted in 1983-84 revealed considerable area of good quality stands occupying sites apparently capable of sustaining long term forest production (Pollack 1985). This recent data, along with increasing pressure to expand local forest harvesting activities, has prompted the Ministry of Forests to include the area in a proposed provincial forest. However, prior to initiating forestry development, some basic information is required to assist in management planning.

Earlier studies (Day 1957) and recent observations made during the inventory update identified a considerable range of productivity in the predominantly second-growth, fire-regenerated stands. This variation has been attributed largely to rather subtle differences in site properties; however, specific relationships have only been speculated on and not studied. The existing, floristic-based ecological classification (Banner *et al.* 1987) has been of limited use in site identification because of difficulties associated with poor understory development. A majority of the area has been excluded from AAC calculations and timber supply forecasts because of uncertainties regarding the potential productivity of these sites (B.C. Forest Service 1982).

In addition to extensive second-growth stands, a relatively large area of poor quality old-growth western redcedar (*Thuja plicata* - Cw) and western hemlock (*Tsuga heterophylla* - Hw) stands occur in the study area. Successional relationships between these ecosystems and the more productive second-growth ecosystems are poorly understood. There is uncertainty whether these represent distinctly different sites, or different successional stages on essentially the same site. Understanding site properties associated with tree growth expressed in second-growth stands will be useful in estimating the potential of sites currently supporting decadent old-growth stands.

Appropriate management regimes for the study area are also unclear, particularly in regard to suitable tree species and site preparation. Information is required on the role of Sitka spruce (*Picea sitchensis* - Ss) in stand composition over the range of sites in the area because of its high value (Siurtain 1981). There is also interest in the suitability of lodgepole pine (*Pinus contorta* - Pl) as a crop species on these sites (R. Pollack, pers. comm. 1987). The occurrence of past fires have had a major impact on stand development and possibly productivity through most of the study area (Day 1957). Thus there is considerable interest in the potential role of prescribed burning as a site preparation tool, particularly following harvesting of old-growth stands. Finally, the operable forest land base in the Queen Charlotte Islands has been reduced from the recent creation of the South Moresby National Park. There is interest in silvicultural treatments aimed at improving the natural productivity potential of remaining ecosystems available for forest management.

Increased understanding of the relationships between ecological properties and potential forest productivity will contribute substantially to the recognition of sites suitable for forest management, and to the development of appropriate silvicultural treatments for these sites. This information would also be applicable to similar coastal lowland ecosystems occurring within the Hecate Depression (Holland 1964).

The basic objectives of the study are:

i) to examine relationships between ecological factors and forest productivity, expressed by site index of western redcedar, in even-aged second-growth stands on a range of coastal lowland ecosystems on east Graham Island.

ii) to examine stand properties, including relative performance of commercial tree species, associated with the above range of ecosystems.

iii) to interpret the above information in relation to suitable silvicultural strategies for these sites.

2.0 SITE/PRODUCTIVITY[1] RELATIONSHIPS - A REVIEW

2.1 Approaches

Relationships between tree growth and site quality have been the subject of intense research worldwide. In the United States alone more than 160 papers were published between 1929 and 1974 (Carmean 1975). While the number of studies has decreased since the peak in the late 1960's, enthusiasm for research on site/productivity relationships remains intense. In general, the two major objectives of these studies have been: i) to predict productivity, typically inferred through site index, and ii) to determine which ecological factors influence tree growth.

The first objective primarily seeks an alternative means of estimating site index for stands which are unsuitable for direct use of site index curves. Reliable estimates of site index from age and height measurements can only be obtained from stands that i) contain the species of interest; ii) are even-aged and have a closed canopy; iii) are free of damage or disease; and iv) are between a certain minimum and maximum age (Hagglund 1981). Estimation of site index from age and height relationships is often limited in its applicability because of these restrictions. For example, site index curves can only be used reliably on 30 to 40% of the total Swedish forest land base (Haggland 1977); a similar proportion was estimated for major British Columbia coastal Timber Supply Areas (Green 1987).

[1] refers to forest productivity

The second objective aims at increasing knowledge of the basic site factors that influence forest productivity. While such information is useful for the prediction of productivity, perhaps its greatest value is in developing management practices with a better understanding of their impacts on tree growth (Campbell 1978, Adams and Jack 1970). Quantification of relationships between productivity and site properties, in combination with knowledge of the effects of various management practices on these properties, will assist foresters in designing treatment regimes which successfully improve site quality (White 1982, Schmidt and Carmean 1988).

A number of approaches have been investigated to try to meet these objectives. The use of understory vegetation is an intuitively logical approach to estimating site index since plants act as "phytometers" of site quality by reflecting the integrated effect of complex environmental properties (Carmean 1975). The most common method uses classification of stable (climax or late-seral) plant communities to derive "site types" which have characteristic site qualities. For example, site index has been related to habitat types in the western U.S. (Monserud 1984, Mathiasen *et al.* 1986), and to site units of the biogeoclimatic ecosystem classification system in B.C. (Green *et al.* 1989). Rather than focussing on plant communities, another approach uses individual understory species as indicators of site quality. This method recognizes that some species demonstrate a relatively narrow amplitude in relation to certain site factors such as soil moisture regime and soil nutrient regime. The relative frequency or occurrence of important indicator species in an ecosystem can therefore be used to estimate site quality and in turn, site index (Hodgkins 1970, MacLean and Bolsinger 1973, Green *et al.* 1989).

The more common approach to studying site/productivity relationships has focussed on physiographic and soil factors. Typically these studies examine a wide variety of topographic and soil physical, morphological, and chemical variables which are related to site index through correlation, multiple regression, or multivariate data analyses (Carmean 1975). In many cases, the studied factors are indirect indices of the more basic growth-controlling factors of climate, soil moisture, soil nutrients, and soil aeration. Quantification of these basic site factors should provide the best basis for studying site/productivity relationships. However this has proved difficult because of limitations in measurement techniques and in knowledge of ecologically meaningful ways of expressing these factors. Many studies which aim at predicting site index have focussed only on variables which are easily recognized in the field, in order to meet practical needs. Generally these are limited in their precision and application, and may lead to spurious results when any variable is included regardless of its ecological relevance to tree growth (Hagglund 1977, Ford 1983). Other studies have recognized the importance of soil chemical properties for tree growth and have combined these with other soil morphological, physical, and physiographic properties for a more comprehensive analysis (Pritchett and Fisher 1987). While the results are more limited in field application because of measurement difficulties, they provide more insight into site/productivity relationships. In many cases the strength of the relationships is improved by including chemical properties (Johnson *et al.* 1987).

More recently, attempts have been made to relate site index to quantitative measures of soil moisture and soil nutrients to derive a more direct model of tree growth. Klinka and Carter (1989) found promising results in relating Douglas-fir (*Pseudotsuga menziesii*) site index to actual evapotranspiration, water deficit, and mineralizable nitrogen in the root zone, although the results were inferior to more conventional approaches using categorical variables defined by vegetation-derived site units and qualitative assessments of soil moisture and nutrients. Further improvement is required in the reliable quantification of site factors.

In general, the selection of variables to include in site/productivity studies involves a compromise between intuition, the desire to be comprehensive, and the ease with which measurements can be made (Ford 1983). For efficiency in deriving meaningful results, the variables should be based on existing ecological knowledge, and should reflect the basic site factors important to tree growth (Hagglund 1977).

2.2 Limitations

In spite of the considerable effort in studying site/productivity relationships, some difficulties have been encountered in obtaining reliable results, leading Ford (1983) to suggest soil/productivity studies are "blunt instruments" for detecting how environmental factors control tree growth. There are several common problems which can limit the success and application of these studies. Relationships between productivity and soil factors have been found to vary with different geographic areas, often reflecting different effects of climate, physiography, or major parent materials and bedrock (Schmidt and Carmean 1988). For example Cook *et al.* (1977) found that relationships between Scots pine (*Pinus sylvestris*) growth and site factors differed considerably in two different areas of northeast Scotland. Area-specific relationships were also found between Sitka spruce yield and site properties in northern Scotland (Blyth and McLeod 1978). To accommodate such variation, large heterogeneous study areas should be subdivided initially into more uniform strata within which relationships are examined separately (Carmean 1975). Hagglund (1977) divided Swedish data into more homogeneous "processing groups" based on major tree species, soil, and forest types, for deriving site/productivity relationships for Scots pine and Norway spruce (*Picea abies*). Relationships between southern U.S. hardwoods and site properties were also improved considerably when the sample population was subdivided into more uniform strata (Broadfoot 1969). Because of the area-specific nature of many site/productivity relationships, studies examining such relationships should have a precise statement defining the population studied, and results should only be extrapolated beyond this population with caution (Carmean 1975).

Site/productivity studies may also be limited because variables selected for analysis do not reflect adequately the properties really important for tree growth (Broadfoot 1969). This is particularly true of studies focussing on field-recognizable variables which only indirectly imply basic site factors, often with limited precision (Carmean 1975). In more comprehensive approaches, selected variables may be in an unsuitable form to uncover meaningful relationships, or more variables than those measured may influence growth (Hagglund 1977). Site quality and hence, site productivity is a function of the integrated effect of many complex environmental factors. As a result, many of theses factors are interrelated in their effects on growth; separating their effects in quantitative studies has been difficult (Mader 1977). Data analysis should pay close attention to intercorrelation of variables to try to minimize this effect on resulting models (Carmean 1975).

Unsatisfactory results of site/productivity studies may be a result of sampling limitations. Inherent high spatial variability of soil properties (particularly chemical properties), weaknesses in consistently assessing qualitative variables, and possible errors in measurement can all contribute to unexplained residual error in the analysis (White 1982). Sampling design has also limited the success of some studies where the middle portion of the site productivity range is oversampled and the extremes undersampled. It is important to balance the sampling distribution across the full range encountered in the study area (Carmean 1975). Finally, error in the estimation of the common dependent variable, site index, can limit the success of these studies. Haggland (1977) estimated that five to six percent error in site index estimates from available site index curves was added to their site/productivity models. The suitability of site index as a productivity index has been questioned; however, most of the problems involved inaccuracies associated with older anamorphic site index curves. Improved precision is now being realized with newer polymorphic site index curves based on stem analysis and nonlinear regression models (Schmidt and Carmean 1988).

Studies relating productivity to site quality inferred from understory vegetation may be limited by floristic variation associated with non-site factors. Successional stage, understory light conditions, disturbance history, and chance can influence species composition and abundance on any given site (Spurr and Barnes 1980, Spies and Barnes 1985). This is particularly true of approaches utilizing indicator species. More successful results are generally obtained when productivity is related to site units derived from stable (late seral, near-climax, or climax) plant communities representing "biologically-equivalent" sites (Klinka and Carter 1989).

2.3 Results

The majority of site/productivity studies confirm Coile's (1954) observations that site productivity "is largely determined by soil properties or other site features that influence the quality and quantity of growing space for tree roots". Added to this is climate, which can have an overriding impact on site productivity (Schmidt and Carmean 1988). Most of the successful site/productivity studies reviewed by Carmean (1975) explained 65 to 85% of the variation in site index using physiographic and soil properties. Surface soil depth, subsoil texture, aspect, and slope were the most common properties related to site index, although few of the studies examined soil nutrient properties. Schmidt and Carmean (1988) explained 65 to 83% of the variation in jack pine (*Pinus banksiana*) site index in Ontario using physical properties such as depth to a root-restricting layer, thickness of the A horizon, coarse fragment content, slope, as well as soil pH. The relationships differed in the four parent material-defined strata. Similar properties explained 66% of the variation in red maple (*Acer rubrum*) site index in Wisconsin and Michigan (Johnson *et al.* 1987). The inclusion of soil nutrient properties improved the fit of these models; however, they were not utilized because of the focus on field-application of results.

Certain soils of the southeast coastal plain in the U.S. share some similar properties with those of the east Graham Island study area. These soils are characterized by shallow fluctuating water tables because of low relief, high precipitation inputs relative to evapotranspiration, and slowly permeable soils (Buol 1978). Soil chemical properties, and thickness of the aerated root zone, are important to the productivity of the predominantly pine forests. Features such as topographic position, physical properties of the least permeable soil layer, and depth to mottling or a watertable are therefore commonly related to site index (Klawitter 1978). For example, Klawitter (1978) found that loblolly pine (*Pinus elliottii*) site index increased steadily as the surface soil depth increased from 15 cm to 60 cm. As long as the watertable was greater than 50-60 cm from the surface during the growing season, soil aeration was not seriously reduced and sites remained productive.

Sitka spruce tolerates imperfectly to poorly drained sites in Scotland, Ireland, and Britain, however growth varies widely. Blyth and MacLeod (1981b) found that a small number of variables, particularly total P in the humus form and mottling depth, accounted for 60 to 86% of local yield class variation across several different study areas. In a related study they also found total N in the humus form to relate strongly with growth (Blyth and MacLeod 1981a). Growth generally decreased as drainage became poorer from brown earth through to podzol, gleyed podzol, and finally gley soils. Worrel (1987) found that restricted rooting depth due to indurated, excessively clayey, very wet, or very shallow soils had a negative impact on potential yield class of Sitka spruce in northern Britain. Better growth of Sitka spruce was also related to improved soil aeration in peaty gley soils in Britain, with a relatively small increase in depth to an anaerobic layer associated with a large increase in growth (Armstrong *et al.* 1976). In ecosystems which feature limited rooting volume due to unfavourable subsoils, rooting volume generally shows a curvilinear relationship to growth. Available rooting volume becomes increasingly important as rooting depth becomes more limited (Carmean 1975). This is particularly true in soils featuring high watertables where the quality of an already limited root zone can be negatively affected by reduced aeration (Pritchett and Fisher 1987). According to Day's (1957) observations of soils on east Graham Island, the predominantly fine-textured tills with thick humus forms or shallow peat have marked drainage impedance which in combination with physical soil restrictions, limits the rooting space and decreases soil aeration which negatively affects tree growth.

3.0 STUDY AREA

The study area occurs on the east side of Graham Island, the northern and largest island of the Queen Charlotte archipelago. It encompasses the area of Crown land north of Miller Creek, east of TFL 39, and south of Naikoon Park, as well as the area between Masset Inlet and Naikoon Park to approximately 8 km north of Port Clements (Figure 1).

3.1 Climate

The study area falls entirely within the Submontane Wet Hypermaritime Coastal Western Hemlock (CWHwh1) biogeoclimatic variant which occupies lower elevations on the drier, leeward side of the Queen Charlotte Mountains (Banner *et al.* 1987). The climate of the CWHwh1 can be described as a hypermaritime wet, cool, mesothermal type (Klinka *et al.* 1989). Summers are cool and moderately wet with occasional dry warm spells. Late fall and early winters are very wet, while winters are cool, mild, and rainy. Strong winds occur with high frequency (Banner *et al.* 1987). The study area occurs within the drier range of the CWHwh1 variant because of the more pronounced rainshadow effect in the easterly localities. A climatic summary from long term climate stations at Tlell and Sandspit is shown in Table 1. These stations may be considered relatively representative of much of the study area, although there is a tendency towards slightly cloudier, moister conditions

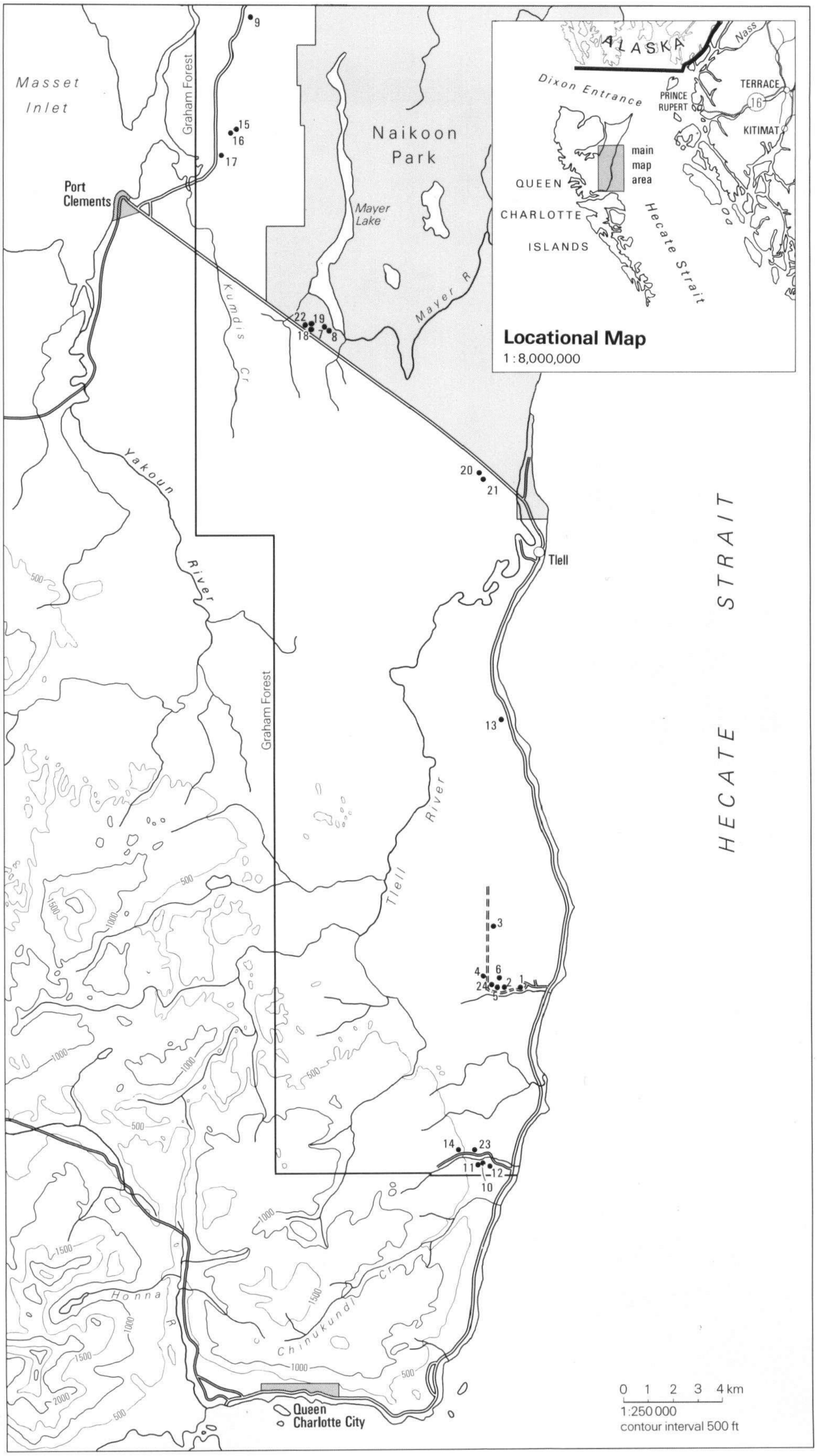

Figure 1. Study area (within "Graham Forest") and sample plot locations.

in the northwestern portion. The low-lying coastal plain has a relatively low precipitation gradient, with annual precipitation means varying from 1200 mm along the coast to 1500 mm near the boundary with the Skidegate Plateau (Karanka 1986). The rainshadow effect occurring across Graham Island can be appreciated by comparing the eastern stations to one at a similar elevation on the windward side of the Queen Charlotte Mountains (Gospel Point, north of Skidegate Channel - Table 1). Less than half the amount of precipitation falls in the eastern localities, while temperatures remain similar. However because of the relatively low potential evapotranspiration experienced in the study area relative to warmer climates in coastal B.C., no water deficit occurs during the growing season.

Table 1. Climate summary for Tlell, Sandspit, and Gospel Point (abridged from Banner *et al. 1987)*

Variable	Tlell	Sandspit	Gospel Point
No. years record	23-24	32-34	7
Elevation (m)	5	5	34
Precipitation:			
Mean annual ppt. (mm)	1152	1281	2340
Mean mo. May-Sept ppt.	64	57	98
Mean mo. Oct-April ppt.	119	142	264
Driest mo. total ppt.	51	43	60
Wettest mo. total ppt.	172	194	355
Temperature:			
Mean annual T (°C)	7.4	7.9	7.0
Mean mo. May-Sept T	12.0	12.4	11.1
Mean T warmest mo.	14.2	14.7	13.4
Mean T coldest mo.	1.3	2.0	1.2
Extreme max. T	32.2	27.8	--
Extreme min. T	-16.7	-13.9	--
Grow. deg. days (>5°C)	1283	1385	--

3.2 Physiography and Bedrock Geology

The study area is situated within the Queen Charlotte Lowland physiographic region which encompasses the majority of the northeastern half of Graham Island (Holland 1964). It is characterized by flat to very gently undulating terrain with elevations mainly below 160 m. The southern portion of the study area near Lawn Hill and Miller Creek begins to rise gradually towards the Skidegate Plateau further to the west. The northern extremity of the study area occupies the Argonaut Plain, a very subdued, extensive deposit of post-Pleistocene outwash sands and gravels which dominates the northeastern tip of Graham Island (Holland 1964). Most of the study area is underlain by late Tertiary sedimentary bedrock of the Skonun Formation which includes sandstone, siltstone, and shale as well as some conglomerates. A relatively small area of Masset Formation basalt outcrops in the Lawn Hill area, while a small post-tectonic pluton of granodiorite occurs in the extreme southern portion of the study area near Miller Creek (Sutherland Brown 1968).

3.3 Surficial Materials and Soils

The predominant surficial material throughout most of the study area is till of Pleistocene origin (Alley and Thomson 1978). Tills are fine textured (typically sandy clay loams) with less than 25% coarse fragment content, and have high bulk densities. Glaciofluvial sands and gravels associated with the Argonaut Plain characterize the northern extremity of the study area. Marine deposits ranging from fine silts and clays to gravelly sands occur adjacent to the coastline. Because of isostatic rebound following the last glaciation, these may occur up to 15 m above the present sea level (Alley and Thomson 1978, J. Clague 1988, pers. comm.). Sand-textured dunes also occur near the coast, particularly near Tlell. Alluvial silts occur along the main rivers and streams, while localized fluvial deposits may occur within the till plain. Organic deposits overlying predominantly morainal and glaciofluvial materials form extensive and localized peat bogs and fens. Of the sites sampled, the majority (92%) were on morainal material, while the remainder occurred on glaciofluvial and alluvial deposits.

An interesting feature observed while sampling was a uniform surface capping of fine-textured sediments which occurred throughout the study area. This deposit was typically silt loam textured, free of any coarse fragments, of low bulk density, and distinctly different from the underlying parent material. Its thickness averaged 16 cm and varied little, ranging from 11-20 cm in 70% of the 84 soil pits in which it was found. Thicker deposits were generally associated with secondary accumulation from slopewash on gentle concave slopes or depressions. The principal source of this deposit is not certain;, however, based on its characteristics it is most likely eolian (J. Clague, H. Luttmerding 1988, pers. comm.). The probable origin is the extensive glaciofluvial plain to the north which, before vegetation establishment, would have generated considerable windblown sediments during periods of strong dry northwesterly winds (T. Lewis 1988, pers. comm.). The sediments are not as well sorted as typical eolian sediments (J. Clague 1988, pers. comm.); however, this is consistent with the relatively short distance they would have travelled. A particulary interesting feature of these sediments is the occurrence of partly decomposed plant fibers and occasional small logs which were distributed within the capping or buried at its base. This was most prevalent on the wettest sites occurring on subtly depressional terrain. It suggests vegetation was present during initial deposition of the sediments, or secondary slopewash took place after vegetation became established. This eolian capping is very important to forest productivity in the study area as it represents the principal mineral soil rooting substrate.

Soils in the sample population are strongly influenced by poor aeration. More than 80% of soil profiles examined had distinct or prominent mottles or strong gley colours within 50 cm of the mineral surface. This results from slowly permeable soils, high precipitation relative to evapotranspiration, and subdued topography which, in combination, limit free drainage. Soils are predominantly Humic Podzols with true Gleysols occurring less frequently. Dark coloured Bh horizons averaging 10-12 cm thick typically occur between the surface eolian capping and a slowly permeable layer which is either cemented or inherently dense. Pyrophosphate-extractable iron and aluminum averaged 0.1% and 1.4% respectively, with 7.6% total carbon in several horizons tested. This type of soil is typically found on wet sites and gleying is therefore common within the Great Group, but is not explicitly stated in Subgroup names (CSSC 1978). The Bh horizons found in the study area were generally coarser textured than both adjacent horizons and were the location of most soil water concentration. Orstein, or near-orstein (moderately strong cementation) horizons were frequently encountered, with placic horizons occasionally forming in the upper few centimeters. Better aerated Ferro-Humic Podzols were encountered rarely and only in association with better quality sites. Gleyed subhorizons were also present in these soils.

Humus forms were predominantly Residuohumimors (Klinka *et al.* 1981).

3.4 Disturbance History and Stands

The most significant factor affecting stand establishment has been fire. The majority of stands in the study area regenerated naturally following an extensive fire approximately 110 to 130 years ago. A more recent fire 70 to 80 years ago swept through the extreme southern portion near Miller Creek, while the northern extremes of the study area (7-8 km north of Port Clements) burned approximately 160-170 and as early as 290 years ago. Evidence of the oldest fire was found in the form of common charcoal fragments mixed through the eolian capping under a decadent stand of cedar and hemlock with a salal understory. Fire is apparently a relatively frequently recurring feature of the ecology of east Graham Island. This is somewhat unusual for the Queen Charlotte Islands and other central and northern coastal ecosystems where wind, and to a lesser extent, mass wasting are the major disturbance factors (Banner *et al.* 1987).

Fire-regenerated stands are predominantly even-aged, densely stocked, and comprised of mixtures of western redcedar, western hemlock, lodgepole pine, and Sitka spruce. The relative proportions of these species vary, depending largely on the site characteristics. Charred cedar snags commonly occur throughout the fire-regenerated stands, indicating that cedar formed a major component of the original old-growth forest. These snags often have strong taper and candelabra branching characteristic of the "spike-top" cedar present in existing old-growth forests.

A considerable area [approximately 5000 ha (Pollack 1985)] of these old-growth forests occurs within and adjacent to the fire-regenerated stands, apparently having been missed by the fires. These stands are dominated by cedar and hemlock of poor form and very slow growth. Density is low and most of the cedar have dead tops. A dense, tall cover of salal (*Gaultheria shallon*) typically, but not always, dominates the understory.

4.0 METHODS

4.1 General Approach

Based on field observations and previous studies, particularly Day's (1957) insightful observations on possible productivity relationships occurring on Graham Island, a working hypothesis regarding ecological properties important for tree growth can be proposed. Forest productivity can be considered a function of climate, soil moisture, soil nutrients, and soil oxygen (Ralston 1964, Bakuzis 1969). In the east Graham Island study area, climate is relatively uniform and may be excluded as a factor contributing to productivity variation. Shortage of soil water is not limiting, with soil moisture ranging from fresh to wet regimes (Klinka *et al.* 1984). Soil nutrients are most likely important, given the variation in potential nutrient reserve defined by available soil rooting zone and soil chemical properties, as well as possible soil water nutrient inputs. Soil oxygen ("soil aeration") is very important to tree growth in the study area, interacting with the above factors in defining the quantity of soil exploitable by tree roots, and the quality of this soil in relation to root development and function. All of these factors are influenced largely by the subdued physiography and soil physical properties such as fine-textures and compacted or cemented layers which limit soil drainage and rooting depth.

The approach of the study is to examine forest productivity in relation to a number of ecological variables which express as closely as possible these key site factors. In many respects this approach is similar to those discussed in Section 2.1. Forest productivity is inferred through site index. Although site index has some limitations (Monserud 1984), it is still the best available index of growth which is easy to estimate and relatively free of stand density effects (Hagglund 1981). The most recent site index equations derived from stem analysis data (Mitchell and Polsson 1988) were used in the study, so site index estimates should be as precise as currently possible, short of actually using stem analysis. The sample population is restricted to fully stocked, second-growth stands which are essentially even-aged and within the acceptable range for reliable site index estimation (20 to 150 yrs, Mitchell and Polsson 1988). Although mean annual increment (MAI) varied somewhat with density and age within these stands, it should be a reasonable reflection of natural potential productivity and is used as an additional descriptive variable. The sample population is also restricted to mineral soils to limit variation in major parent material.

The focus of the study is to improve understanding of site/productivity relationships in the area, and emphasis is placed on a comprehensive array of continuous environmental and floristic variables to achieve this. Both continuous and categorical variables which can be readily identified in the field were also be examined for practical application of site/productivity relationships. The full range of productivity found in the study area will be sampled with a balanced distribution of plots to maximize the strength of any relationships which may occur. Data analysis is of an exploratory nature, employing a number of techniques to assess structure in the data, and to examine relationships between the various properties studied.

4.2 Sampling Design

The sample population is represented by fully stocked, even-aged fire-regenerated stands established on mineral soil. Sampling strata were defined to obtain a balanced sample across the productivity range of the population. Site index of western redcedar was used to infer forest productivity because it forms a major component in most stands. Based on the frequency distribution of cedar site index in the 1983/84 inventory data (Figure 2), three site index classes were recognized (Table 2).

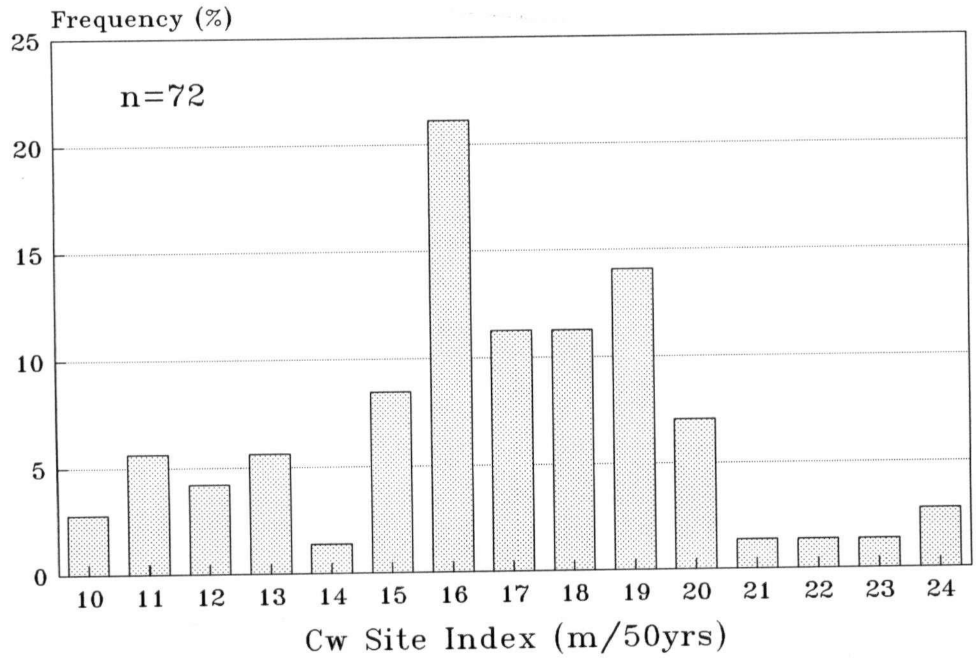

Figure 2. Frequency histogram of Cw site index in the inventory update data. Site index is m/50 yrs. b.h. age.

Table 2. Site index classes.

Strata	Cw Site Index[1]
1	≤ 15
2	16 - 20
3	> 20

[1] m/50 yrs. b.h. age

The classes essentially divide the observed distribution into thirds representing the lower, middle, and upper ranges of site index. As Cw site index was approximately normally distributed in the inventory sample, stratum 2 was the most strongly represented, with stratum 1 and particularly stratum 3 occurring less frequently. More refined stratification was not considered, given the relatively limited range of site index (14 m), the difficulty in establishing a greater number of meaningful breaks in the sample distribution, and the greater difficulty in distributing plots evenly in a larger number of classes. Eight stands from each strata were selected for sampling, following a reconnaissance of the study area. A single plot was established in each stand, yielding a total of 24 sample plots.

4.3 Sampling Methods

Square, 400 m^2 (20 m x 20 m) sample plots were established within portions of each stand which were as homogeneous as possible in stand structure, understory vegetation, and site properties. Plots were located within these portions using a random bearing and distance.

4.3.1 Vegetation and physiography

Vegetation was described following the methods of Walmsley *et al.* (1980). All vascular plants and bryophytes growing on the principal substrate (forest floor and decaying wood) were listed and their percentage cover estimated. Nomenclature of vascular species followed that of Taylor and MacBryde (1977), mosses and hepatics follow Crum *et al.* (1973), and lichens follow Hale and Culberson (1970). One deviation from this, *Kindbergia oregana*, follows Ochyra (1982).

Physiographic description included elevation, slope, aspect, and slope shape. Slope shape refers to the general physiography influencing the plot and includes depressional concave, receiving concave, elevated (convex), level, and sloping. All these slope shapes are expressed rather subtly in the study area because of the subdued topography.

4.3.2 Soil

Within each sample plot, 16 subsample points were located systematically using a 4 row X 4 row grid centered over the plot (rows were located at 2.5, 5, 5, 5, and 2.5 m intervals along two adjacent plot sides). If a subsample fell on an "unsuitable" substrate such as rocks, stumps, and decaying logs, it was relocated to the nearest suitable location or to a new random point. One subplot was randomly rejected to leave 15 subplots for soil chemical sampling. In addition, one subplot was randomly selected from each of the four north-south rows to provide 4 locations for detailed soil description.

At each of the detailed subplots, a soil pit was excavated to a depth of one meter or less depending on the presence of very dense layers. Principal layers were identified which reflected obvious pedological discontinuities such as parent material, density, particle size, organic matter content, etc. Since the focus was not on soil classification, these layers did not necessarily coincide with soil horizons. On average, three to four layers were recognized in mineral soil profiles. The following morphological properties were described for each soil profile:

1. for each layer; the layer thickness, coarse fragment content, soil texture, structure, consistence, colour, mottles, roots, cementation, and presence of charcoal fragments were described or measured. The forest floor thickness, selected morphological properties, and humus forms were also described.

2. for the profile, the depth from the mineral soil and ground surface to the following properties was measured:

- free water present in the soil
- pan (cemented or high density).
- primary root zone (to bottom of zone of majority of rooting)
- secondary root zone (to bottom of all rooting). Often the primary and secondary root zones coincided because of abrupt root restrictions.
- mottles (distinct and prominent).

In addition, the "free water status" for the profile was described using the following classes:

1 - absent

2 - slow: very slow seepage into pit; no appreciable standing water.

3 - moderate: seepage water moving slowly but steadily into the pit; standing water present but does not accumulate to substantial depth.

4 - rapid: seepage water moves quickly into the pit, filling it to substantial depth.

At each detailed subplot, samples of the forest floor and root zone mineral soil were collected for bulk density measurement. Rectangular blocks of forest floor were extracted using a pruning saw and subsequently trimmed with shears. The dimensions were measured on all sides and averaged to give values for the three axes from which the sample volume was calculated. A 500-cm^3 bulk density core was used to collect mineral soil samples of known volume since the root zone was generally restricted to the coarse fragment-free eolian capping. If large roots interfered with the core a new sample was taken. In a few cases where rooting extended into underlying materials containing appreciable coarse fragments, the bulk density sample was collected using the glass bead displacement technique (Klinka *et al.* 1981).

At each of the 15 subplots, forest floor thickness was measured, and a sample of forest floor and root zone mineral soil was collected. Mineral soil samples were randomly bulked in the field in groups of five to produce three composite samples per plot. Forest floor samples were bulked in a similar manner following drying and preliminary grinding in the lab. In two plots, all subsamples of forest floor and mineral soil were individually retained for analysis to provide information on within-plot variability of chemical properties.

4.3.3 Stand

In each plot, all trees greater than 7.5 cm dbh were tallied according to species, dbh, and pathological symptoms (B.C. Forest Service 1983). In addition, "stem form" was assessed for lodgepole pine to provide information on the relative frequency of stem irregularities, while "crown thinning" (Table 3) was assessed for all species to detect any apparent decline in crown vigour.

Table 3. Crown thinning and stem form classes

Class	Description
a. Crown thinning:	
Full	full crown; no indication of thinning foliage
Moderate thinning	crown beginning to thin out; loss of foliage apparent
Severe thinning	crown very thin; poor foliage retention, dead branches, etc.
b. Stem form:	
Smooth	no obvious surface irregularities
Moderately irregular	noticeable bumps, flutes, etc. but not pronounced
Very irregular	very pronounced bumps, flutes, etc.; likely to affect wood quality significantly.

Height and breast-height age measurements for site index estimation were made on six dominant trees of redcedar and four dominant trees of the remaining species on the plot. These "site trees" had to be free of damage and disease. Trees which exhibited suppressed early growth were rejected. Occasionally insufficient site trees were found within the plot, in which case adjacent trees outside the plot boundaries, but on the same site, were selected. Site trees were also measured for dbh and were supplemented with height and dbh measurements of several trees from a range of diameters. This information was used for the derivation of species-specific height/diameter equations.

4.3.4 Soil Water Quality

Because of the important role of soil water in the study area, two aspects of water quality were assessed to attempt to understand its relationship to tree growth and other site properties. Specific conductivity and dissolved oxygen were measured *in situ* in saturation zone water through a 2 inch diameter aluminum standpipe with a solid bottom and a number of 5 mm holes drilled along the sides. The standpipe was inserted in a bore hole drilled with a soil auger to a depth of approximately 80 cm (or less, depending on the density of the soil). This was located in a representative portion of the plot, avoiding decaying logs or other atypical microsites. Once inserted, the stand pipe was capped with a rubber stopper and allowed to settle for a period of two hours. The water thus collected was felt to represent the water within the general ecosystem boundaries (Binkley 1980). In six plots, insufficient water was present in the soil to collect a sample and measurements were not taken.

4.3.4.1 Specific conductivity

Specific conductivity was measured *in situ* using a YSI Model 33 conductivity meter and cell. The cell was inserted into the stand pipe and submerged fully in the soil water present. Measurements were taken according to the manufacturer's instructions, with the resulting conductivity values expressed in dS/m[2] at 25°C.

The specific conductivity meter and cell were checked four times during the sampling period using a standard solution of saturated $CaSO_4$ [2.63 g/l $CaSO_4$ yields a specific conductance of 2.205 dS/m @ 25°C (Richards 1954)]. The average meter reading of 1.365 dS/m was considerably lower than the actual value and is most likely due to contamination of the cell electrode. When the platinum-coated electrode becomes contaminated with use, less "active" electrode surface area is exposed to the sample resulting in a lower cell constant. Meter readings can be corrected by applying a factor based on the ratio of the actual and measured values (B. von Spindler, 1988, pers. comm.). In this case, all readings were corrected with a factor of 1.62.

4.3.4.2 Dissolved Oxygen

Dissolved oxygen in the soil water was measured in situ using a YSI Model 51B dissolved oxygen meter. This employs a polarographic method with a membrane-covered electrode. Dissolved oxygen diffuses across the membrane from the sample and is reduced

[2] 1 dS/m equals 10^{-3} umhos/cm

and subsequently read at the polarized electrode. The method is well-suited to field testing because of its simplicity, the fact samples can be measured in situ rather than requiring collection, and the lack of interference by suspended sediments and other impurities (Franson 1976).

To take a measurement, the probe was attached to a 1 m long rod and lowered into the stand pipe so the electrode was fully submerged in the water. Readings were taken according to the manufacturer's instructions. To avoid localized depletion of dissolved oxygen around the electrode, it was gently moved up and down within the water sample while the probe stabilized and a reading was taken. The resulting readings were expressed in parts per million. The probe's membrane and electrolyte were replaced regularly at the end of each day.

4.3.5 Soil Oxidation Zone Index

One of the difficulties in studying site/productivity relationships in ecosystems featuring waterlogged soils is the quantification of soil aeration. In this study, air-filled porosity, and volumetric moisture content of the soil, as well as dissolved oxygen in the soil water were measured for this purpose. Some measure of oxygen content in the soil would be desirable; however, currently available platinum electrode techniques generally yield results of questionable reliability (McIntyre 1970). As an alternative, McKee (1978) tested a simple technique for estimating the depth of oxygenated soil in sites influenced by high water tables. The length of rusting on iron rods driven into waterlogged soils proved to be a reliable indicator of the depth to the average water table level over a 16-week period in coastal South Carolina. The basis for the method is that an iron rod will oxidize in the aerated zone of soil but will not oxidize in the non-aerated zone. This was tested in this study by driving six mild steel rods (6 mm x 1 m) into the soil to a depth of 80 cm (less if a barrier was encountered). These were distributed in each plot adjacent to the four detailed soil pits plus two additional randomly selected subplots. The rods were removed and measured on August 25-26, 1987, leaving a 4- to 6-week period for the rods to oxidize. By spanning the period from July through August, the depth of oxidation should provide an index of the average maximum zone of aerated soil when water tables are at their lower levels. At the time of removal, the length of rod featuring signs of oxidation was measured from the ground surface.

4.4 Laboratory Analysis and Data Preparation

4.4.1 Soil chemical analysis

Following air-drying, mineral soil samples were crushed with a rolling pin and passed through a 2 mm sieve to remove coarse fragments, then stored in air-tight plastic containers. Forest floor samples were air-dried, coarsely ground with a Waring blender for compositing, then fine-ground with a Wiley mill and stored in air-tight containers prior to analysis. Mineral soil and forest floor pH was determined potentiometrically using a Radiometer pH meter on a 1:2 soil to $CaCl_2$ slurry. Total carbon was determined using a LECO induction furnace and C analyzer. Total nitrogen was measured colorimetrically with a Technicon

Autoanalyzer on a semi-micro Kjeldahl digest. Mineralizeable N was measured colorimetrically from a 1 N KCl extractant following a Waring-Bremner 2-week anaerobic incubation (30^0 C). Initial ammonium N was not deducted from the total. Available phosphorus was measured colorimetrically using the ascorbic acid method, on a 1:10 soil:solution Mehlich extract (Mehlich 1978). Exchangeable calcium, magnesium, and potassium were determined with the 1 M ammonium acetate (pH 7) method, using a Perkin-Elmer atomic absorption spectrophotometer.

Subsamples of the three composite samples of mineral soil were further bulked to form one sample per plot for which particle size analysis was undertaken using the pipette method. The sand content was determined by wet sieving. The above methods are described by Lavkulich (1978).

4.4.2 Determination of soil physical properties

In the laboratory, bulk density samples were placed in paper bags, weighed, then dried in an oven at 105°C for at least 24 hours. Depending on moisture content, forest floor samples occasionally required over 36 hours drying. Dry weights were recorded and samples were then passed through a 2 mm sieve. Mineral soil aggregates and coarse, but weathered organic debris were gently crushed with a rolling pin. The remaining coarse fragments >2 mm in size were separated into mineral and organic, and weighed. The volume of mineral coarse fragments was determined through water displacement. The volume of organic coarse fragments was determined by approximating individual pieces to three-dimensional figures (cylinders, rectangular parallelepipeds, prisms, or frustums), measuring them, and summing their volumes. Although there were some measurement errors, it was felt to be more precise than using water displacement as organic fragments would absorb water, and were difficult to displace accurately because of their tendency to float.

Coarse-fragment-free bulk density was calculated using the following equation (Klinka *et al.* 1981):

BDcff = (Md - Mcf)/ (Vh - Vcf)

where BDcff is the coarse-fragment-free bulk density, Md is the dry weight of the sample, Mcf is the coarse fragment weight, Vh is the volume of the excavated sample, and Vcf is the coarse fragment volume.

The volumetric composition of the soil in relation to porosity and water content was determined for the root zone mineral soil, corrected for coarse fragment (>2 mm diameter) content. Coarse fragment volume was excluded from the total soil volume since coarse fragments may occupy appreciable volume in a soil sample without making a commensurate contribution to the porosity or water capacity of the soil (Gardner 1965).

Porosity represents the proportion of a volume of soil occupied by water and air. Porosity was calculated using the following formula (Brady 1974):

POR = 1 - (BDcff/particle density)

where POR is the total pore space (proportion) of the <2 mm soil fraction, and BD is the coarse-fragment-free bulk density (Mg/m^3). Because of the relatively high proportion of organic matter in some soils, a weighted particle density was calculated as follows:

$$WPD = (1.3OM) + (2.65(1\text{-}OM))$$

where WPD is the weighted particle density (Mg/m^3), OM is the organic matter content calculated from [1.7carbon(%)]/100 (Brady 1974), and 1.3 and 2.65 are the approximate particle densities of organic matter and mineral soil respectively (Brady 1974).

Volumetric water content represents the proportion of the soil volume occupied by water. It was calculated as follows (Black 1988):

$$VMC = (Ww/Dw)(Ds/Ws)$$

where VMC is the volumetric water content (proportion), Ww is the mass of water (wet sample mass - oven-dried mass), Dw is the density of water (1.0), Ds is the coarse-fragment-free soil bulk density (Mg/m^3), and Ws is the mass of soil (<2 mm fraction).

Air-filled porosity is the proportion of the soil volume occupied by air-filled pores, and was calculated as follows (Vomocil 1965):

$$AIR = POR - VMC$$

Moisture content and air-filled porosity obviously vary with the actual soil moisture conditions at the time of sampling. In this study they reflect mid-growing season conditions during a climatically stable period in which limited precipitation fell (Figure 3). In spite of the variation in absolute values of porosity and water content, the relative differences between sites at the time of sampling should provide useful insight into productivity relationships.

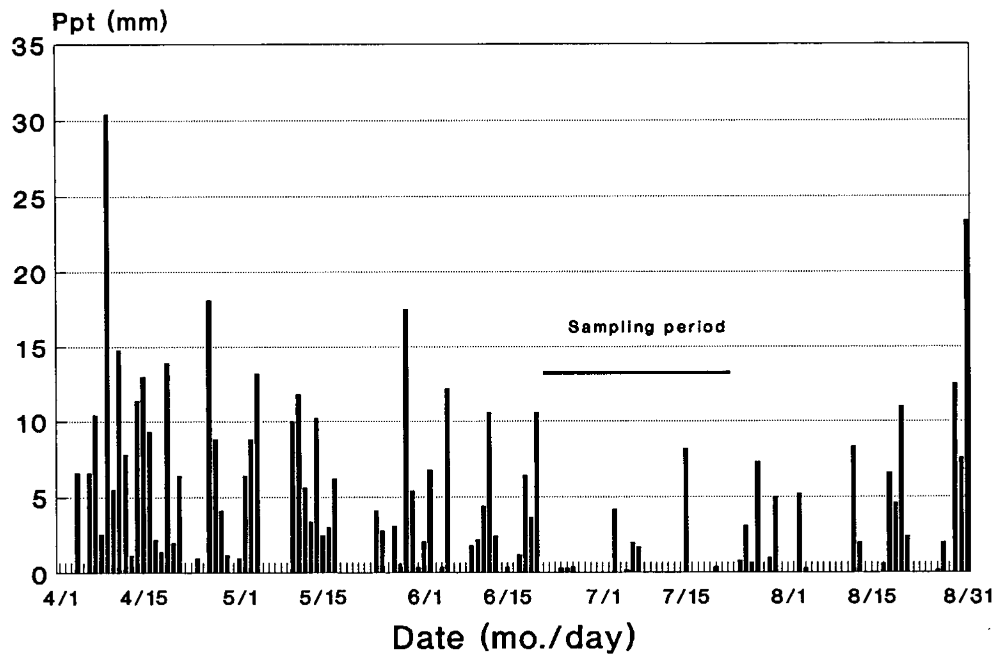

Figure 3. Daily precipitation for April 1 to August 31, 1987.

4.4.3 Conversion of soil chemical concentrations to mass/area basis

Soil chemical properties (other than pH) were initially expressed as concentrations by mass in the <2 mm fraction. A more ecologically meaningful expression of soil nutrients is the total quantity (in kg/ha) present within the available root zone. This integrates concentrations of soil nutrients with soil physical properties such as bulk density and thickness, resulting in a better representation of the total nutrient reserve potentially available to trees (Lewis 1976). Several site/productivity studies have examined soil nutrients expressed on a mass/area basis, often finding better relationships with site index compared to expressions of nutrient concentrations (Adams *et al.* 1970, Blyth and McLeod 1981a, White 1982, Johnson *et al.* 1987).

The conversion of concentration data to quantities expressed as kg/ha was done using the procedure described by Kabzems [1985 - based on Lewis (1976) and Roy (1984)]. The initial nutrient concentration values used in the conversion are means from the three composite samples of forest floor and mineral soil for each plot. The coarse-fragment-free bulk density values used for the forest floor and mineral soil are means of the four samples taken within each plot. The forest floor thickness is a mean of the 15 subplot measurements. The rooting depths are means of the four measurements made in each plot. The quantity of nutrients was calculated separately for the forest floor, mineral soil in the primary root zone, and mineral soil in the secondary root zone. These were then combined to give two expressions of soil nutrients - total kg/ha in the forest floor plus mineral soil in the primary root zone, and in the secondary root zone. Formulas used for converting concentration data to kg/ha are given in Appendix B.

4.4.4 Stand Properties

4.4.4.1 Site index

Site index was estimated for all site trees using recent polymorphic site index equations derived from stem analysis data. Various definitions of site height were used in these models, while dominant height was used in the selection of site trees in this study. These discrepancies in tree selection procedures should, however, have little effect on site index estimates (Mitchell and Polsson 1988). Tree ages are at breast height in all cases.

Western redcedar site index was estimated using the equation of Kurucz [1985 - in Mitchell and Polsson (1988)]. Site index was calculated for each site tree using the following formula derived from the original model (R. Drummond 1986, pers. comm.):

$$SI = 2500\left[\frac{(H-1.37)(0.05027 + 0.01411A + 0.000097667A^2)}{A^2 - (H-1.37)(-3.11785 - 0.02465A + 0.00174A^2)}\right] + 1.37$$

if $A > 50$ then $H = H - ADJ$, where $ADJ = .02379545H - 0.000475909A(H)$, A = breast height age, and H = total height.

Western hemlock site index was estimated using Wiley's [1978 - in Mitchell and Polsson (1988)] equation, with the Kurucz (1981) correction for B.C. The B.C. correction causes the height growth curves to fall off more quickly in older ages compared to Washington and Oregon where the original curves were developed. Thus, for use in B.C., this correction improves the curves for older ages , while biasing them for younger (<50 year) ages. As the stands in the study area ranged from 75-120 years of age, and occurred at considerably higher latitudes than Washington and Oregon, it was felt the B.C. correction would provide a more accurate estimate (K. Mitchell, pers. comm. 1988). Site index was estimated for each tree, using computer-generated tables of site index for a range of ages and heights, determined from the original equations.

Sitka spruce site index was estimated using the equations of Barker and Goudie [1987 - in Mitchell and Polsson (1988)]. This model was developed from data collected in the Queen Charlotte Islands and is directly applicable to the study area. Site index was estimated for each site tree in a manner similar to that used for hemlock.

Site index for lodgepole pine was estimated using the equations developed by Goudie (1984). Two caveats must be recognized in using this source for Pl growing in the study area. First, Goudie's models are based on trees growing in continental climates of B.C. and Alberta. No site index data for coastal Pl is available. Goudie's model does however, include a "wet site coefficient" which was estimated from site trees growing on wetter than average sites. This coefficient results in height growth being sustained longer than on drier sites. Applying this coefficient should provide a reasonably accurate estimate of site index in the study area where soil moisture deficits do not occur. The second caveat is that some site trees in the study area were outside the upper range of the data used to derive the model. However, the model has been found to perform well at the edges of the data (J. Goudie 1988, pers. comm.). Site index was estimated for each site tree using a similar method to that used for Ss and Hw.

4.4.4.2 Mensuration

Prior to calculating stand volumes, height/diameter equations were derived for each tree species. A quadratic model was selected to best represent the height/diameter relationship expressed in scatter plots. A comparative evaluation indicated better fits of the quadratic models relative to linear models. A procedure for testing for different slopes and intercepts, described by Cunia (1971), was used to determine whether the data for each species should be pooled, or fitted to separate equations for each site index class. For Cw and Hw, it was found that separate site index class equations would best represent the data. For Pl, separate equations were fitted to class 1, and pooled classes 2 and 3. All data were pooled for Ss to produce a single equation. Table 4 summarizes the final equations selected for subsequent volume calculations.

Table 4. Equations for calculating tree height from dbh, according to tree species. Fit of the equations indicated by coefficient of multiple determination (R^2) and standard error of the estimate (Se).

Species	Site Index Class	Equation[1]
Cw	1	$HT=5.112 + 0.854DBH - 0.011DBH^2$ (R^2=0.606 Se=1.81 n=68)
	2	$HT=11.223 + 0.547DBH - 0.004DBH^2$ (R^2=0.693 Se=1.98 n=66)
	3	$HT=12.113 + 0.459DBH - 0.002DBH^2$ (R^2=0.715 Se=2.42 n=46)
Hw	1	$HT=2.349 + 1.139DBH - 0.015DBH^2$ (R^2=0.712 Se=2.09 n=48)
	2	$HT=6.458 + 0.896DBH - 0.007DBH^2$ (R^2=0.797 Se=2.27 n=51)

Table 4. Continued

Species	Site Index Class	Equation[1]
Hw	3	$HT=9.312 + 0.842DBH - 0.006DBH^2$ (R^2=0.700 Se=3.01 n=36)
Pl	1	$HT=6.431 + 0.870DBH - 0.012DBH^2$ (R^2=0.530 Se=1.27 n=41)
	2&3	$HT=10.812 + 0.661DBH - 0.005DBH^2$ (R^2=0.554 Se=2.28 n=63)
Ss	1-3	$HT=10.923 + 0.624DBH - 0.003DBH^2$ (R^2=0.820 Se=3.48 n=77)

[1] HT=total tree height, DBH=diameter at breast height

Tree volumes were calculated using whole stem cubic meter volume equations from B.C. Forest Service (1976). Only one utilization standard, total stem volume to a 7.5 cm minimum dbh, was used. No deductions were made for decay, waste, and breakage. Cruise data for each plot were processed through a BASIC computer program to calculate volume/hectare, basal area/hectare, stems/hectare, and quadratic mean diameter by species and for live and dead trees.

4.5 Data Analysis

The general approach to data analysis was to i) examine ecological and stand properties in relation to the three site index classes defined for sampling; ii) assess the inherent structure defined by the ecological properties themselves; and iii) examine functional relationships between site index and ecological properties. The selection of variables used in the analyses was made from an initial screening of the complete variable set which identified the most promising ones. These variables were assessed for within-plot variability using coefficients of variation. This provided some relative measure of the variability contained in the plot means which were used in all subsequent analyses. Sample size calculations (Freese 1962) were made to express within-plot variability in the more practical terms of sampling requirements.

Differences between site index classes expressed in categorical variables was assessed using contingency tables. The Tukey HSD multiple comparison test was used to assess differences expressed in continuous variables. A multivariate examination of the relationship of site index classes to soil properties, in effect a "test" of these classes, was done using discriminant analysis.

Inherent structure present in the soil data, irrespective of site index classes, was examined using a combination of principal components analysis to produce a geometrical ordination of samples, and cluster analysis to impose an "objective" classification on the data. The vegetation data were examined using reciprocal averaging which produces a simultaneous ordination of samples and species on coordinated scales, and is useful for observing structural relationships between species and samples (Hill 1973).

Functional relationships between site index and selected ecological properties were examined using multiple linear regression. A number of models were evaluated which related site index to original soil variables, field-recognizable variables, and understory vegetation expressed as reciprocal averaging scores and indicator species groups. Model evaluation and variable selection procedures described by Chatterjee and Price (1977) and Zar (1984) were used to determine the best models for the data. More detailed descriptions of these and other statistical analyses outlined previously will be presented in Section 5.0, preceding discussion of the relevant results.

5.0 RESULTS AND DISCUSSION

5.1 Description of the Data

A large number of continuous and categorical variables were initially generated from the raw data (Table 5).

Table 5. Summary of available variables

Code	Variable	Type	Expr.	Source[1]
1. Soil chemical properties:				
TC	total carbon	C	PM	CS
TN	total nitrogen	C	PM	CS
MINN	mineralizeable nitrogen	C	PM	CS
P	available phosphorus	C	PM	CS
CA	exchangeable calcium	C	PM	CS
MG	exchangeable magnesium	C	PM	CS
K	exchangeable potassium	C	PM	CS
HUMCN	carbon/nitrogen ratio in forest floor	C	PM	CS
HUMPH	pH in forest floor	C	PM	CS
MINCN	carbon/nitrogen in mineral soil	C	PM	CS
MINPH	pH in the mineral soil	C	PM	CS
2. Soil physical properties:				
D1ROOTM	1^0 rooting depth from mineral surface	C	PM	ISP
D1ROOTS	1^0 rooting depth from ground surface	C	PM	ISP
D2ROOTM	2^0 rooting depth from mineral surface	C	PM	ISP
D2ROOTS	2^0 rooting depth from ground surface	C	PM	ISP
DH2OM	depth to free water from mineral surf.	C	PM	ISP
DH2OS	depth to free water from ground surf.	C	PM	ISP
POR	total porosity in mineral soil[2]	C	PM	ISP
AIR	air filled porosity in mineral soil	C	PM	ISP
VMC	volume. moisture cont. in mineral soil	C	PM	ISP
FFDEP	forest floor thickness	C	PM	SP
PAN	depth to a "pan" from mineral surface	C	PM	ISP
CAP	thickness of eolian cap	C	PM	ISP
MOTL	depth to mottles from mineral surface	C	PM	ISP
CLAY	percent clay in mineral soil	C	PM	CS

Table 5. Continued

Code	Variable	Type	Expr.	Source[1]
SILT	percent silt in mineral soil	C	PM	CS
SAND	percent sand in mineral soil	C	PM	CS
CFPM	coarse frag. content of par. material[3]	C	PM	ISP
SLOPE	slope	C	P	CP
H2OST	free water status	K	PM	ISP
ROOT	rooting density in mineral soil	K	PM	ISP
HUE	hue of mineral soil	K	PM	ISP
CHROMA	chroma of mineral soil	K	PM	ISP
TEXTPM	field texture of parent material	K	PM	ISP
CONS	consistence of mineral soil	K	PM	ISP
CEM	presence of cemented horizon	K	PM	ISP
SHAPE	ground surface shape	K	P	CP
PM	parent material type	K	P	CP
3. Soil water properties:				
SC	specific conductance	C	P	CP
DO	dissolved oxygen	C	P	CP
4. Soil aeration index:				
AZ1	depth of 1st zone, method A	C	PM	SP
AZ2	depth of 2nd zone, method A	C	PM	SP
AZ3	depth of 3rd zone, method A	C	PM	SP
BZ1	depth of 1st zone, method B	C	PM	SP
BZ2	depth of 2nd zone, method B	C	PM	SP
5. Stand properties:				
CWSI	site index of Cw (m/50 yrs)	C	PM	ST
HWSI	site index of Hw (m/50 yrs)	C	PM	ST
PLSI	site index of Pl (m/50 yrs)	C	PM	ST
SSSI	site index of Ss (m/50 yrs)	C	PM	ST
MAI	mean annual inc., standing gross vol.	C	P	CP

[1] Type: C=continuous, K=categorical
Expression: PM=plot mean, P=plot (no subsamples)
Source: CS=composite samples, ISP=intensive soil pits, SP=soil subplots, CP=complete plot, ST=site tree

[2] Mineral soil in the root zone

[3] Predominant subsoil below the root zone

The soil nutrient properties (TC,TN,MINN,P,CA,MG,K) were expressed in the following ways:

1. concentrations in the forest floor and mineral soil
2. quantity (kg/ha) in the forest floor
3. quantity in the primary root zone mineral soil
4. quantity in the secondary root zone mineral soil
5. quantity in the combined forest floor plus primary root zone mineral soil
6. quantity in the combined forest floor plus secondary root zone mineral soil

Plot "means" of categorical variables represent the predominant class described for the four intensive soil pits in each plot. Analysis of categorical soils data was undertaken separately (see section 5.5.1) following the principal analyses which focussed only on continuous data. Soil water properties and soil aeration index were examined independently from the remaining site variables.

5.1.1 Selection of principle variable sets.

The first step in the analysis of site/productivity relationships is generally to reduce the number of variables to those which show some trend with the dependent tree growth variable (Broadfoot 1969, Campbell 1973, Carmean 1975, McQuilkin 1976). The complete set of continuous soil variables (except as indicated above) was therefore screened using scatter plots and Pearson correlation analysis to examine relationships with site index of redcedar (CWSI). Variables which showed no or poor relation to site index were deleted from the list. A process similar to that of White (1982) was used to determine the best method for expressing soil nutrient properties. The six expressions described in the previous section (p. 46) were each examined in relation to CWSI using correlation analysis, with the one showing the strongest overall relationships being selected for all subsequent analyses. A total of 14 variables were selected, with soil nutrients best expressed as the content (kg/ha) in the combined forest floor plus secondary root zone. Water table depth and secondary rooting depth measured from the ground surface were selected to be consistent with the expression of soil nutrient content. Table 6 shows the correlation coefficients amongst the selected variables while Figure 4 graphically summarizes their correlation structure.

Table 6. Pearson correlation matrix for the 14 selected variables.

	CWSI	VMC	AIR	DH2OS	D2ROOTS	TC	TN	MINN	CA	MG	K	HUMCN	HUMPH	MINCN	MINPH
CWSI	1.000														
VMC	-0.632	1.000													
AIR	0.627	-0.966	1.000												
DH2OS	0.556	-0.721	0.690	1.000											
D2ROOTS	0.712	-0.547	0.575	0.623	1.000										
TC	0.642	-0.519	0.551	0.453	0.705	1.000									
TN	0.800	-0.452	0.476	0.453	0.578	0.781	1.000								
MINN	0.665	-0.526	0.503	0.539	0.314	0.478	0.795	1.000							
CA	0.689	-0.660	0.659	0.542	0.551	0.605	0.639	0.619	1.000						
MG	0.796	-0.666	0.689	0.513	0.730	0.749	0.755	0.619	0.822	1.000					
K	0.596	-0.846	0.824	0.693	0.640	0.692	0.649	0.665	0.683	0.771	1.000				
HUMCN	-0.457	-0.099	0.059	0.020	-0.102	-0.099	-0.554	-0.577	-0.316	-0.269	-0.040	1.000			
HUMPH	0.480	-0.312	0.319	0.356	0.231	0.165	0.528	0.546	0.699	0.532	0.350	-0.509	1.000		
MINCN	-0.543	0.159	-0.157	-0.137	-0.217	-0.145	-0.573	-0.546	-0.253	-0.351	-0.211	0.532	-0.271	1.000	
MINPH	0.569	-0.330	0.381	0.236	0.287	0.172	0.560	0.627	0.507	0.614	0.366	-0.630	0.745	-0.609	1.000

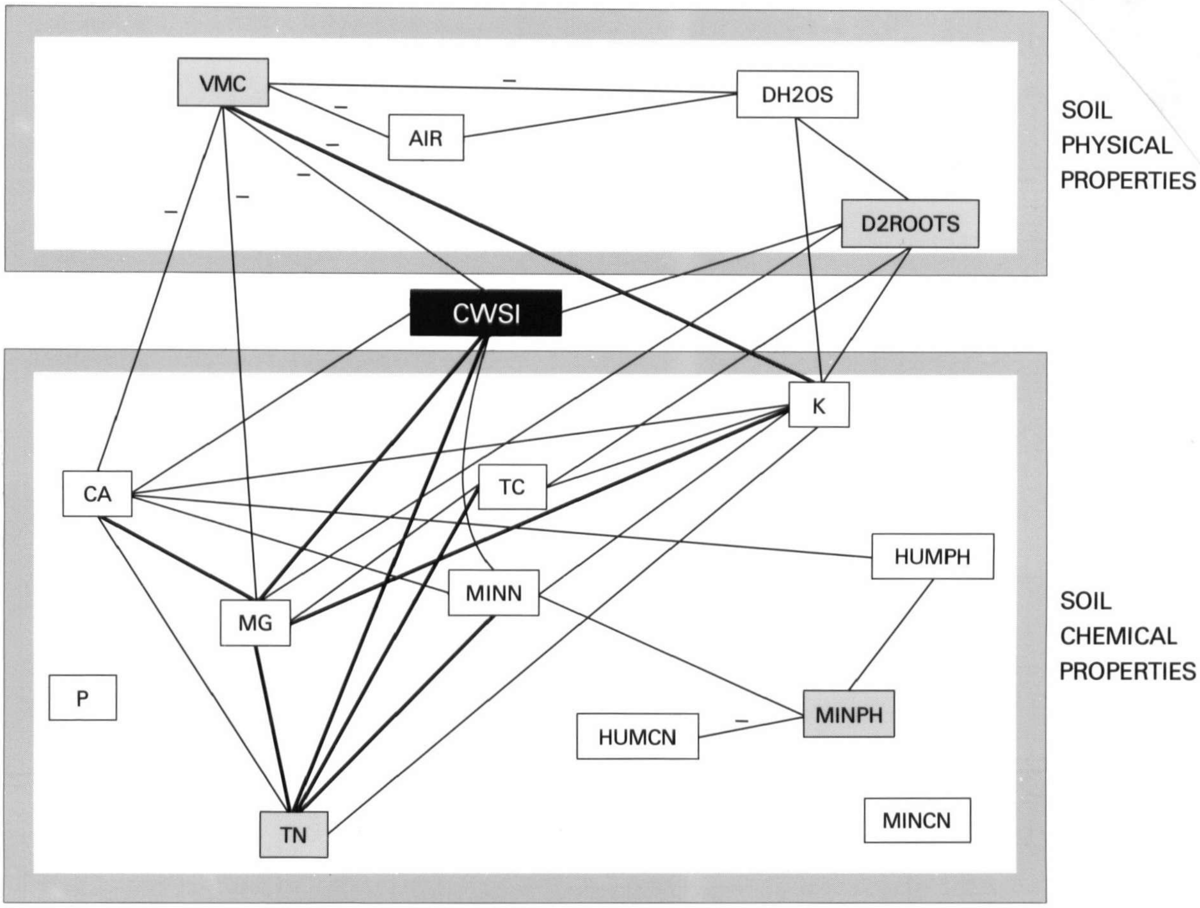

Figure 4. Correlation structure diagram for selected soil variables and CWSI. The thin line connects variables with r > 0.62 (significant at alpha=0.999); the thick line connects variables with r > 0.75; the variables indicated with shaded boxes are the key variables.

All soil properties were positively correlated with site index with the exception of the volumetric moisture content and C/N ratios. Nitrogen and magnesium showed the strongest relationship to site index, while pH and C/N ratios of the forest floor and mineral soil, the depth to free water, and air-filled porosity were the weakest. A large number of intercorrelations occurred amongst the variables, with the stronger relationships shown in the correlation structure diagram. Volumetric moisture content and air-filled porosity have a relatively strong negative correlation which is expected since the former is used in the calculation of the latter. Depth to free water is correlated to both VMC and AIR, with shallower depths associated with increasing moisture and decreasing air-filled porosity. Most of the selected soil nutrients were correlated with each other, with TN and MG showing strong correlation with the largest number of nutrients. The pH and C/N ratios tend to stand apart from the remaining nutrients, except for HUMPH which shows relatively strong correlation with CA, and MINPH which is related positively with MINN and MG. MINPH is negatively correlated with both MINCN and HUMCN, and positively correlated with its counterpart, HUMPH. The general trend expressed amongst the soil variables is that higher pH values are associated with lower C/N ratios, which in turn, are associated with greater nutrient contents. Nutrient contents tend to vary up or down together, and decrease consistently with increasing volumetric moisture content or decreasing air-filled porosity. Most nutrient contents tend to increase with increasing rooting depth since the latter is used in the calculation of nutrient quantity. However the strength of this relationship varies amongst nutrients.

The intercorrelation amongst many of the selected variables poses a potential problem in the multiple regression and multivariate analyses which are subsequently used in the data analysis. For example, strong linear relationships amongst independent variables in multiple regression result in ambiguous, unstable models in which the unique effects of individual variables cannot be estimated (Chatterjee and Price 1977). In discriminant analysis, strong correlation among discriminating variables renders canonical coefficients unstable and hard to interpret (Morrison 1969). To reduce these potential multicollinearity problems, the 14 selected variables were further screened to yield 4 key variables which were correlated with CWSI, and were not strongly intercorrelated themselves. These were TN, D2ROOTS, VMC, and MINPH (see Figure 4). MINPH was included as it represented well the pH and C/N properties, although it was not as strongly correlated with CWSI as the other three. TN was selected to represent the remaining soil chemical variables with which it is correlated, as it is strongly correlated with CWSI, and is not strongly correlated with the remaining key variables.

5.1.2 Within-plot variability

Because of inherent lateral variability, characterizing soil properties with a high degree of precision is commonly a problem in forest ecology studies (Mader 1963, Courtin *et al.* 1983). While composite sampling is an efficient way of characterizing soil chemical properties with reasonable precision at an acceptable cost, it is useful to have some knowledge of the variability these samples represent. In this study, all 15 subsamples of forest floor and mineral soil from one plot (#24) were individually analyzed for chemical properties. Within-plot variability was assessed through comparison of coefficients of variation (CV) for each property, and by calculation of the number of samples necessary to estimate the mean value of the property with a specified allowable error and degree of confidence. A computer program called SASCAL (Marshall 1987) was used to compute sample sizes for two allowable errors (10 and 20%) and two confidence levels (80 and 90%). A summary of the CVs and required sample sizes are shown in Table 7.

Table 7. Coefficients of variation and required sample size to estimate soil property means at .80 and .90 confidence levels, with 10, and 20% allowable error. Calculations based on concentration data.

Allowable Error and Confidence Limits	PH[1]	TC	TN	MINN	CA	MG	K	P
			Sample size					
			Mineral soil					
CV (%)	4	42	45	39	46	28	28	24
20% @ .80	1	9	10	8	10	5	5	4
20% @ .90	1	14	16	12	16	7	7	6
10% @ .80	1	30	35	26	36	14	14	11
10% @ .90	1	49	58	43	59	23	23	17
			Forest floor					
CV (%)	5	2	14	24	27	19	22	24
20% @ .80	1	1	3	4	5	4	4	4
20% @ .90	1	1	4	6	7	5	5	6
10% @ .80	1	1	5	11	13	7	10	11
10% @ .90	1	1	7	18	21	12	15	17

[1] TC-total C; TN-total N; MINN-mineralizeable N; CA, MG, K- exchangeable Ca, Mg, K respectively; P-available P

The variability trends in mineral soil properties show PH being the least variable, TN, TC, and CA the most variable, and MG, K, P, and MINN having intermediate variability. While the low and high variability of PH and CA respectively is consistent with most variability studies, the trend of higher TC and TN variability relative to other bases is not (Lewis 1976, Slavinski 1977, Kabzems 1985). The CV values were compared to those of two fresh to moist sites from Courtin *et al.* (1983) and two fresh sites from Kabzems (1985). While the CVs covered similar ranges there were some notable differences. MG, K, and P were all considerably less variable in this study than at either the Courtin *et al.* (1983) or

Kabzems (1985) sites. The other properties tended to be less variable than Courtin et al. (1983) but more variable than Kabzems (1985). The exception was TN which was more variable in both these studies. Sample size calculations show that few properties can have means estimated with a high degree of precision using 15 subsamples. This intensity of sampling can be expected to provide estimates with 20% error and 90% confidence level for all properties.

Forest floor properties were substantially less variable than mineral soil properties, with the most variable property, CA, having only 27% CV. TC was very stable across all subsamples, showing only 2% CV which was even lower than PH. TN varied 14% while the remaining properties varied from 19 to 27%. These values compared very favourably with CVs of forest floor properties from two fresh sites in Kabzems' (1985) study, and with comparable properties of forest floors from Carter (1982). Sample size calculations indicate that means of all properties can be estimated with 20% error and 90% confidence, or 10% error and 80% confidence using 15 subsamples or fewer. In fact, most properties can be estimated with 10% error and 90% confidence using this sampling intensity.

The effect of composite sampling on means and variability was assessed by comparing means and CV's of chemical properties based on the 15 individual subsamples from plot 24, and from the 3 composite samples derived from these subsamples (Table 8). Generally the means from the two sets of samples are very similar. Carter (1983) also found strong correlation between means of forest floor properties calculated from 15 subsamples and their composite sample. Variability of means from composite samples is generally substantially lower than means from the individual subsamples. This is a common feature of composite samples since each sample actually represents a mean of its component subsamples (Slavinski 1977). Composite sampling offers a method of lowering sampling costs, while obtaining means close to the individual subsample means with lower variability. However, degrees of freedom are lost which widens confidence intervals of means and weakens statistical tests on the data.

Table 8. Comparison of means and CV (%) of soil chemical properties of plot 24 based on 3 composite samples and 15 individual samples.

	Mineral soil				Forest floor			
Property	Mean 15	Mean 3	CV 15	CV 3	Mean 15	Mean 3	CV 15	CV 3
PH	3.5	3.5	4	2	3.5	3.5	5	2
TC(%)	15.2	13.2	42	18	45.8	46.0	2	1
TN(%)	0.37	0.37	45	31	0.93	0.90	14	8
MINN(ppm)	41	46	39	13	220	194	24	5
P(ppm)	2.6	2.3	24	17	35.9	31.0	24	20
CA(meq)	0.60	0.59	46	8	10.92	10.53	27	20
MG(meq)	1.68	1.77	28	17	11.84	11.80	19	10
K(meq)	0.17	0.17	28	12	1.49	1.37	22	8

Within-plot variation of soil properties was examined across all 24 sample plots. Boxplots of CVs for forest floor properties (expressed as concentrations) calculated from composite samples in each plot are shown in Figure 5. The trend in variability amongst the different properties is similar to that expressed in the 15 subsamples from plot 24. Variability of PH and TC is very low and consistent across all plots. TN and MG are also very consistent, with the majority of plots showing less than 14% CV for either property. The greatest variability is expressed in MINN, P, and CA, with a greater range in CV occurring across all plots. However, the variation is still relatively modest with most plots falling below 20% CV for all three properties.

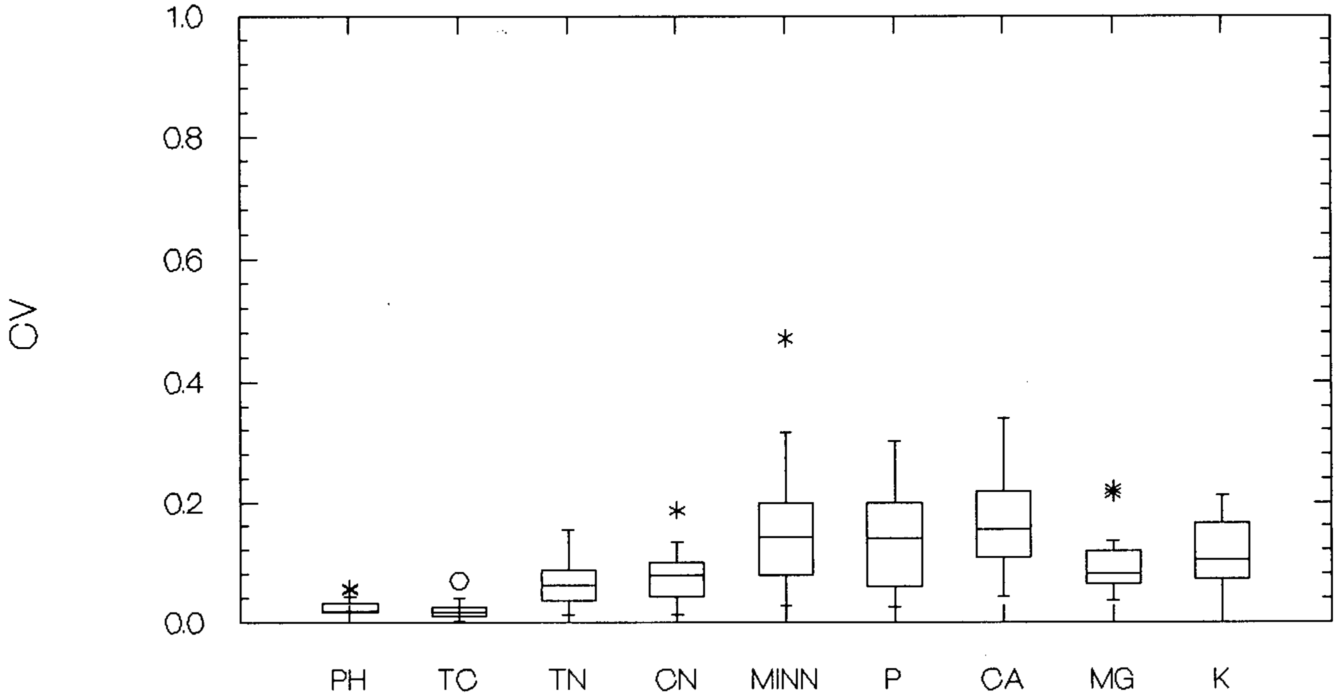

Figure 5. Boxplots of CVs for forest floor properties, calculated for each plot from composite samples. Explanation of boxplots in Appendix M. TC=total C; TN=total N; CN=C/N ratio; MINN=mineralizeable N; P=available P; CA, MG, K = exchangeable Ca, Mg, K respectively

Figure 6 shows boxplots of CVs for mineral soil chemical properties calculated from composite samples for all plots. A similar trend to the plot 24 subsamples occurs amongst properties, except P and MG variability in the subsamples appear to be in the lower range of the overall data set. P and CA show the broadest range in CV across all plots, with two outlier plots exceeding 60% CV for CA. PH is extremely consistent, while K also shows a relatively narrow range in CV across the 24 plots. The remaining properties exhibit similar ranges in CV. The majority of plots show less than 30% CV in all properties except P and CA.

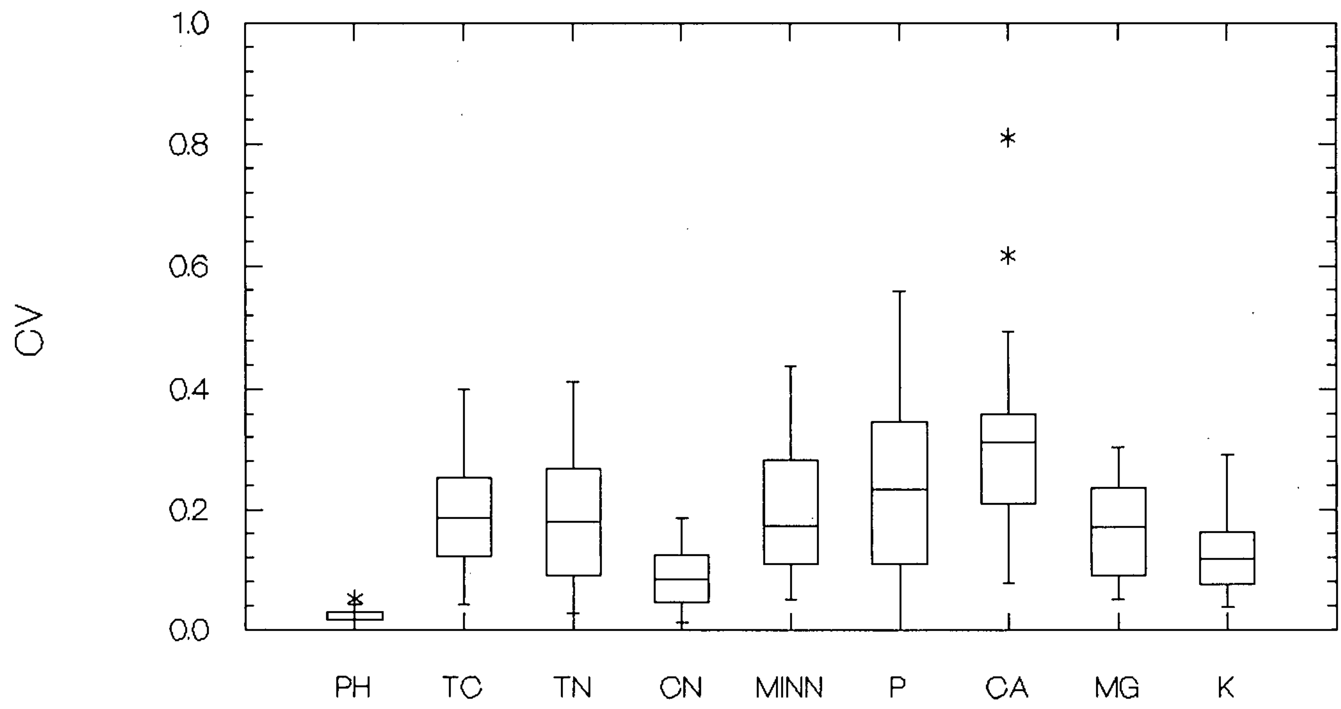

Figure 6. Boxplots of CVs for mineral soil properties, calculated for each plot from composite samples. Explanation of boxplots in Appendix M. TC=total C; TN=total N; CN=C/N ratio; MINN=mineralizeable N; P=available P; CA, MG, K = exchangeable Ca, Mg, K respectively

The within-plot variability was also examined for a number of soil physical and morphological properties which were measured in four soil pits in each plot. Figure 7 shows boxplots of CVs from all 24 plots calculated for soil morphological properties.

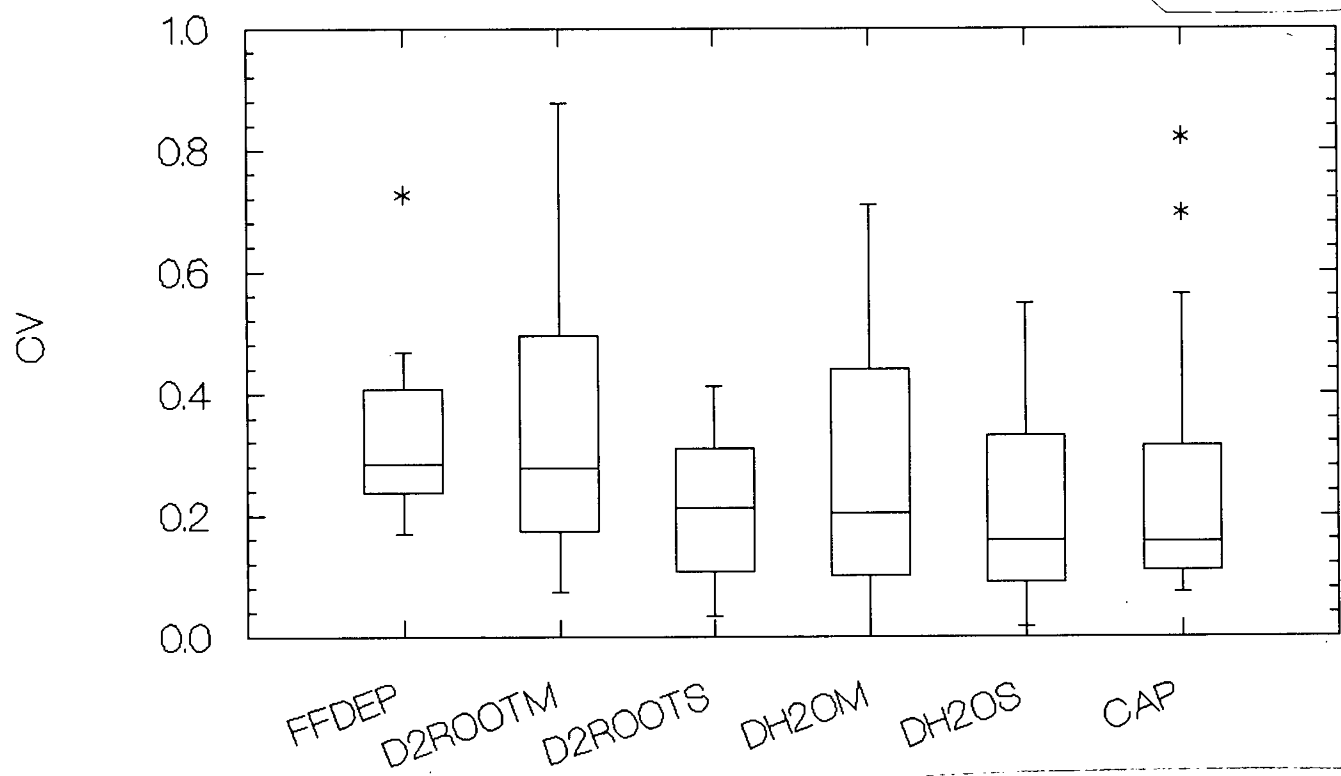

Figure 7. Boxplots of CVs for soil morphological properties, calculated for each plot from four soil pits. Explanation of boxplots in Appendix M. FFDEP=forest floor depth; D2ROOTM and D2ROOTS=rooting depth (secondary) from mineral surface and ground surface, respectively; DH2OM and DH2OS=depth to soil free water from mineral surface and ground surface, respectively; CAP=thickness of eolian surface capping.

FFDEP showed relatively high variability (20 - 40%) however the variability was quite consistent across all plots except one which exceeded 70% CV. The two properties which were measured from both the ground surface and mineral soil surface (D2ROOT, DH2O) displayed lower and more consistent variability when measured from the ground surface. This may result from a small increase in standard deviation from the addition of forest floor thickness, relative to the increase in total thickness. The majority of plots had less than 30% CV for D2ROOTS which is an important variable in later analyses. The eolian cap shows a similar pattern of variability to D2ROOTS and DH2OS except for 2 highly variable plots which featured some disturbance of surface horizons.

Boxplots of within-plot CV for soil physical properties calculated for all 24 plots are shown in Figure 8.

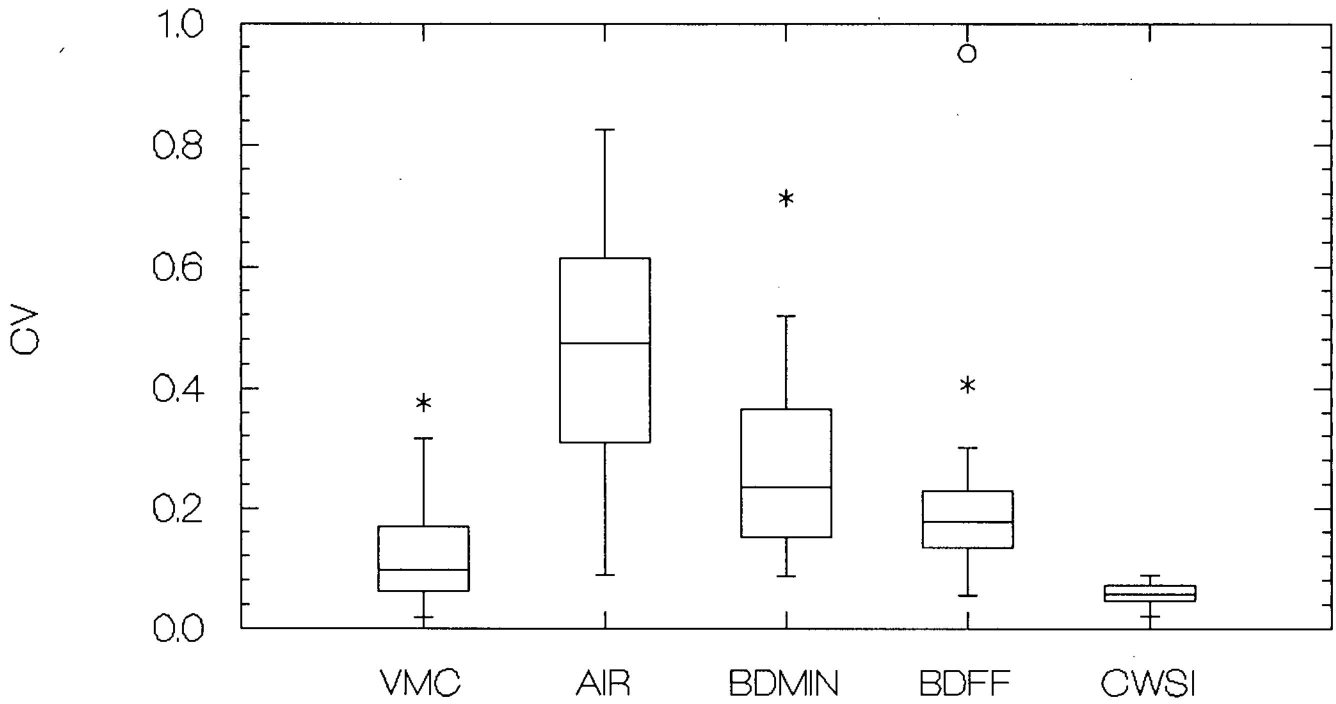

Figure 8. Boxplots of CVs for soil physical properties, calculated for each plot from four soil pits. Explanation of boxplots in Appendix M. VMC=volumetric moisture content, AIR=air-filled porosity, BDMINN-mineral soil bulk density, BDFF=forest floor bulk density, and CWSI=site index of redcedar

Within-plot variability of VMC is relatively low; less than 20% for most plots, and is quite consistent across the 24 plots. BDFF variability also covers a relatively narrow range over the data set, and averages about 20% CV. One highly variable plot featured a relatively thin Moder humus form that was difficult to sample and which may have contributed to its variability. The relatively modest and narrowly ranging variability of this forest floor physical property is consistent with its chemical properties. Greater variability was exhibited in BDMIN which may reflect sampling techniques. Roots occasionally interfered with collecting a clean sample with the fixed volume bulk density core. AIR shows the highest variability across all plots, which may reflect compounding errors in the calculation. AIR is calculated by subtracting VMC, determined from moisture content and soil volume, from total porosity, determined from bulk density and weighted particle density.

For comparative purposes, the CV of CWSI calculated from the 6 site trees in each plot is also shown in Figure 8. It varies little within a plot (5 - 8% CV), and is remarkably stable in its variability across all 24 plots.

5.2 Stand Properties

5.2.1 Stand age

The distribution of sample plots by stand age is shown in Figure 9. The majority of plots were in stands 95 to 115 years of age. These are representative of the most widespread stand type which dominated the area between approximately Lawn Hill and Port Clements. The relative uniformity in stand age and structure suggests that one or several closely spaced fires swept through this area. The younger stands around 75 years old were restricted to the southern portion of the study area in the vicinity of Miller Creek, the location of the most recent fires. One plot was established in a 160-year-old stand representative of the older wildfire history which characterizes the northern portion of the study area.

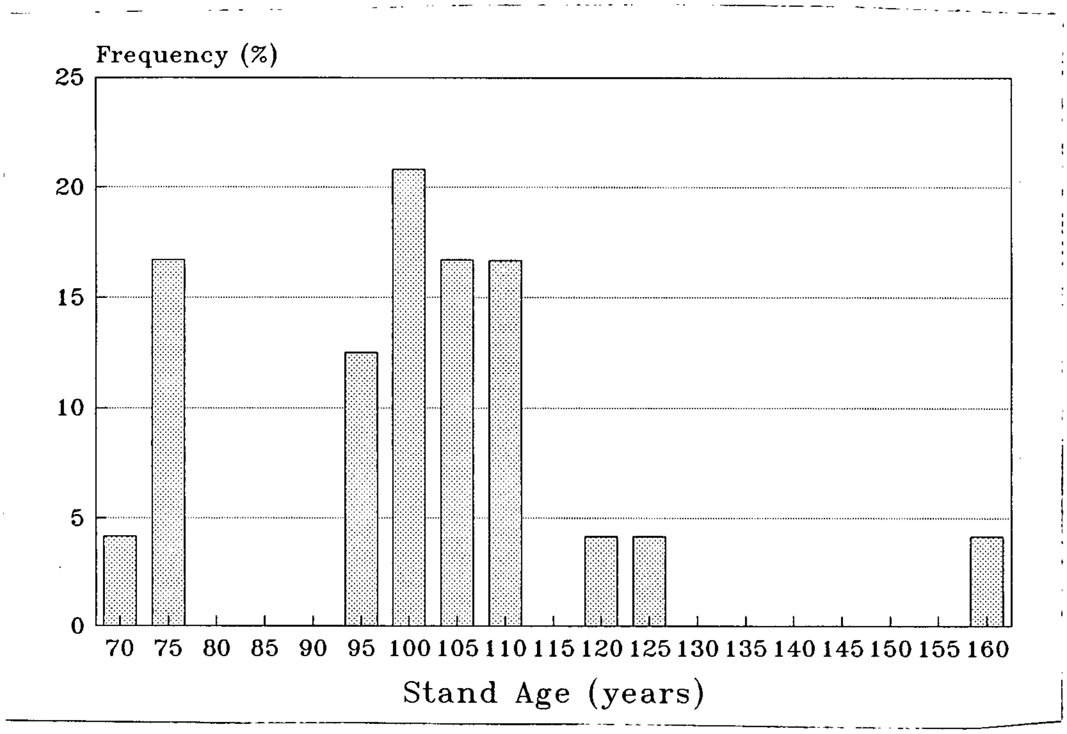

Figure 9. Sample plot distribution by stand age (age in 5 year classes - eg. 75=75-79 yrs.)

5.2.2 Site index

Cedar site index averaged 18.1 m over the whole sample, and ranged from 10.9 m to 25.1 m. The distribution of samples in relation to CWSI is shown in Figure 10. There was an apparent clustering of plots within the three site index classes which defined the sampling strata. Most plots in class 1 were in the 13-to 14-m CWSI range. One plot had a CWSI of 10 m, which was atypically low for the sample population. The majority of plots in class 2 ranged from 16 to 18 m, while 21 m was the most common CWSI for class 3 plots. This pattern of site index shown in the sample was in fact quite representative of the natural distribution of site index observed throughout the study area during the

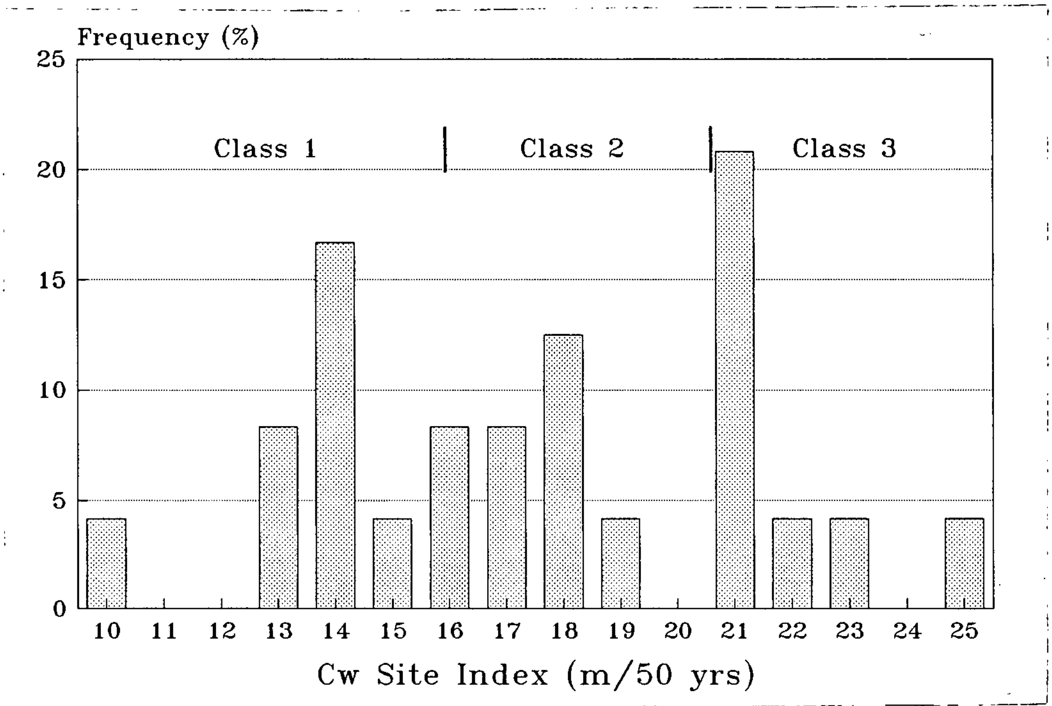

Figure 10. Sample plot distribution by Cw site index.

reconnaissance phase. In terms of geographical distribution, the most widespread stands growing on mineral soil throughout the study area were from site index class 2, with class 1 stands also occurring relatively frequently but in a more localized pattern. Stands from class 3 were uncommon, and were encountered only in the southern portion of the study area near Lawn Hill and Miller Creek. This is likely a reflection of the slightly greater relief in this area where the lowlands begin to rise up to the Skidegate Plateau.

The mean site indexes of cedar, hemlock, pine, and Sitka spruce for the three site index classes are shown in Table 9.

Table 9. Means (and standard deviation) of site index (m/50yrs b.h. age) for the three site index classes.

Variable	Site Index Class 1	2	3
n	8	8	8
CWSI	14.0 (1.4)	17.8 (1.1)	22.3 (1.3)
HWSI	12.0a[1] (1.5)	16.8b (1.8)	21.6c (3.5)
PLSI[2]	13.4a (1.5)	18.6b (2.0)	22.2c (1.4)
SSSI[3]	9.1a (2.5)	16.1b (1.7)	25.6c (4.2)

[1] classes not followed by a common letter are significantly different using the Tukey HSD test ($P \leq 0.05$). See Appendix N for procedure used to check test assumptions.
[2] n for class 3 is 7
[3] n is 5, 6, 8 for classes 1, 2, 3 respectively

All species follow a similar trend across the three classes, and are all significantly different between all pairs of classes ($P \leq 0.05$). This is not unexpected since all species are responding together to differences in site quality across the classes. The generally low within-class variability contributes to the significant differences observed between all classes. However, class 3 appears to contain the most variability, at least in relation to hemlock and Sitka spruce. The relatively high variability expressed by Sitka spruce in class 1 is likely a reflection of the smaller sample size. A more informative picture of relative species performance is revealed in the relationships between site index of cedar and the remaining three species. Figures 11 through 13 show site index of Hw, Pl, and Ss respectively, in relation to the site index of Cw.

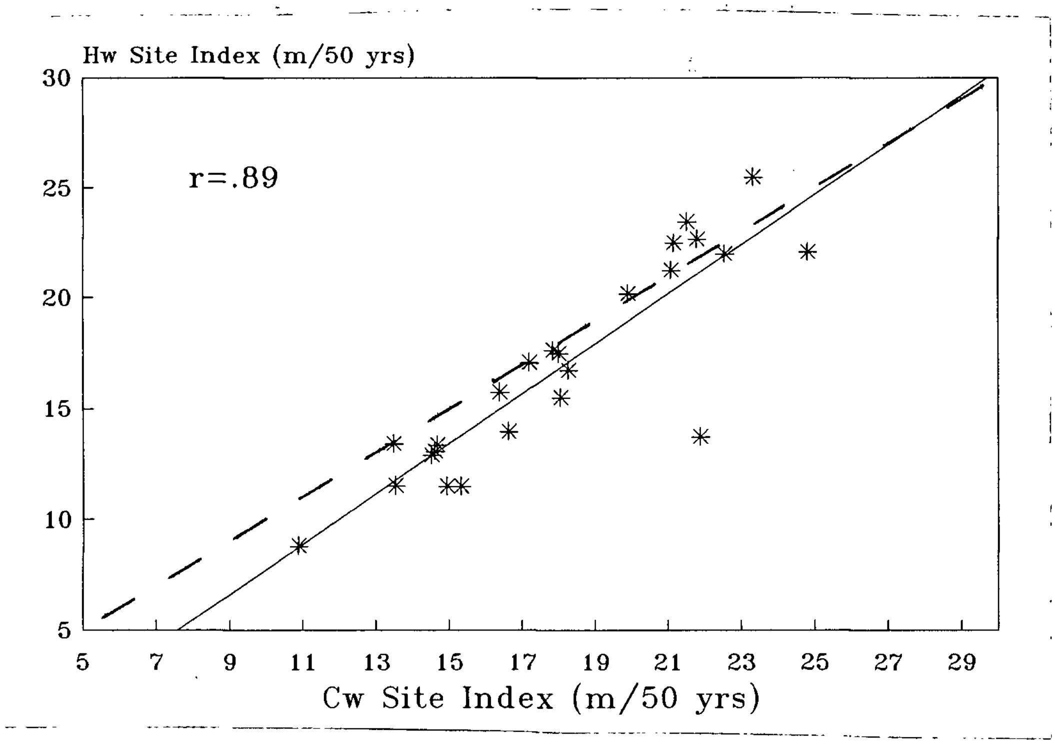

Figure 11. Relationship between Hw and Cw site index: Dashed line is a 1:1 line; solid line is a least-squares fitted line.

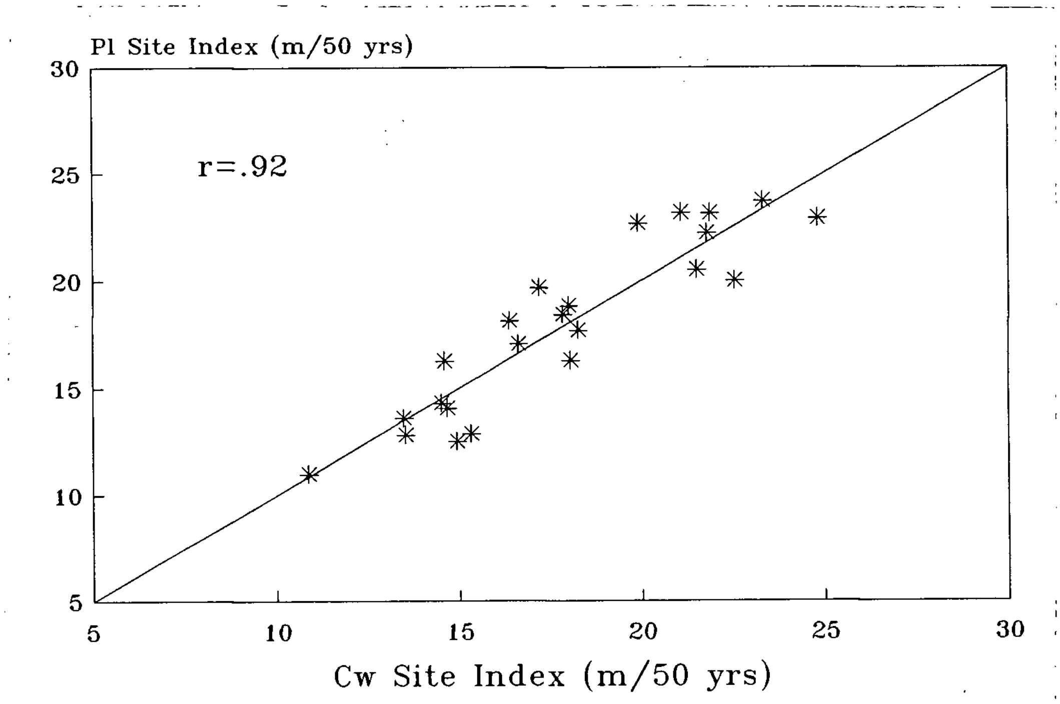

Figure 12. Relationship between Pl and Cw site index. Solid line is a least-squares fitted line.

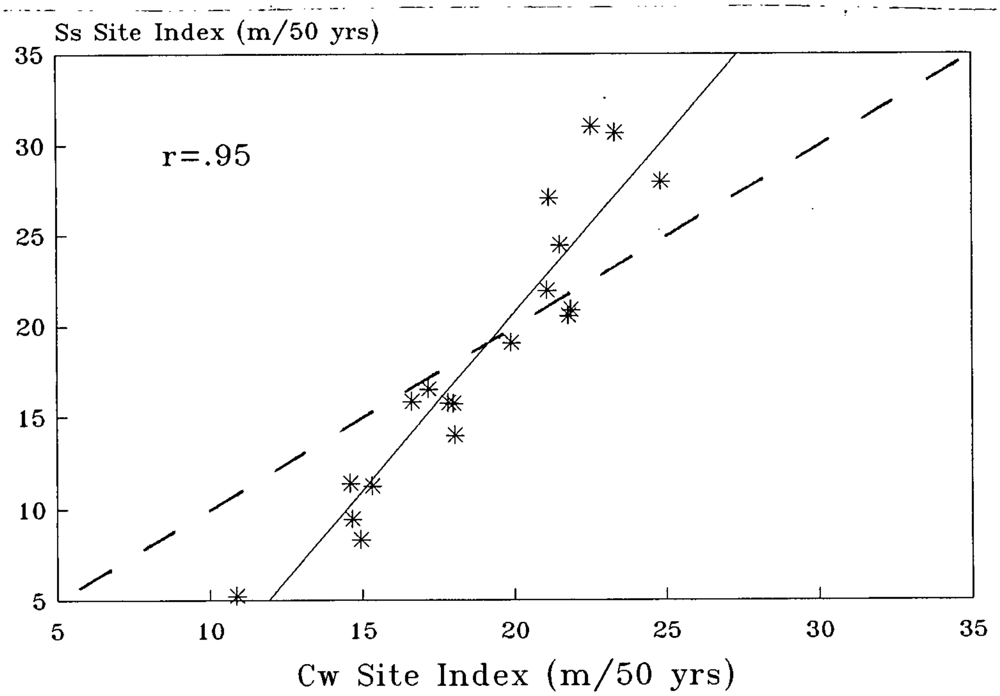

Figure 13. Relationship between Ss and Cw site index. Dashed line is a 1:1 line; solid line is a least-squares fitted line

Site indexes of Hw and Pl are both highly correlated with Cw site index and demonstrate a very similar height growth pattern. Hw appears to have slightly slower height growth than Cw on poorer sites, reflecting cedar's better adaptation to the waterlogged soils typical of these sites. Pine appears to follow an identical height growth pattern to Cw. Sitka spruce displays markedly different height growth than Cw, although site index is highly correlated between the two species. On poorer sites (less than 20 m CWSI) Ss shows substantially slower height growth than Cw, with the difference getting greater as the site gets poorer. The opposite occurs as the site quality improves (above 20 m CWSI). This reflects the sensitivity of Ss to limiting site conditions and its ability to grow rapidly when site conditions become adequate for its requirements.

Barker (1985) examined site index relationships between Ss, Hw, and Cw in a wide range of second-growth ecosystems on Moresby and adjacent islands to the south of Graham Island. He also found significant correlations between Cw and Ss, and Cw and Hw, although they were weaker than in this study. This likely reflects the small number of individual stem analyzed trees sampled over a wider range of sites, compared to plot means of site index sampled over a narrower range of sites in this study.

5.2.3 Stand volume

The range of total volume per hectare (live stems) sampled and its relationship to CWSI is shown in Figure 14.

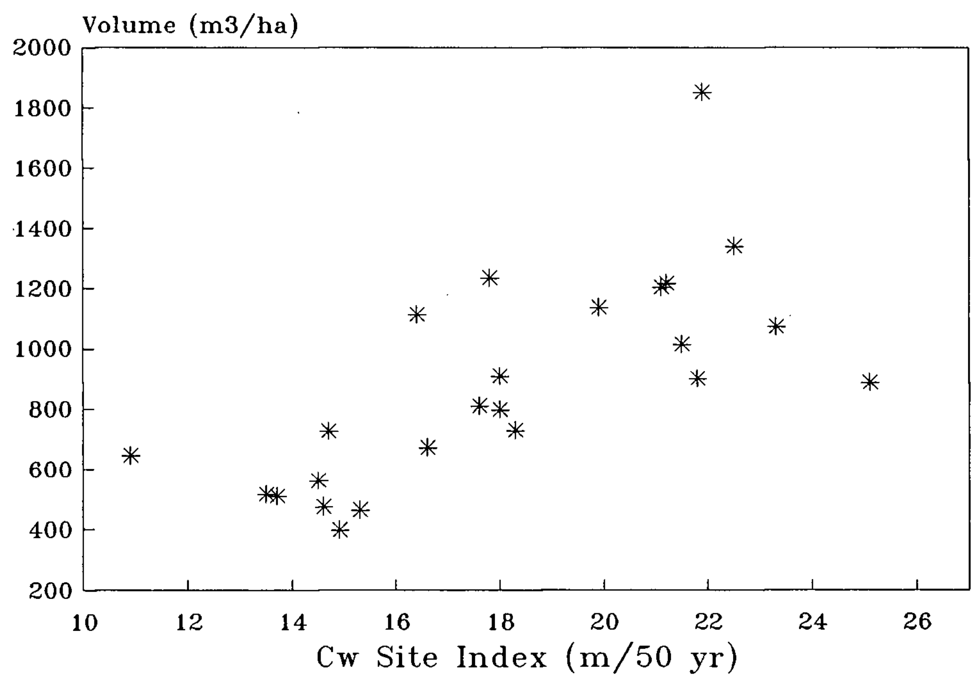

Figure 14. Relationship between total live stand volume (m^3/ha) and Cw site index.

Plots in the lowest site index class supported from about 400 to 700 m^3/ha, averaging approximately 530 m^3/ha. The intermediate sites (class 2) supported from 670 to 1230 m^3/ha with an average of about 920 m^3/ha, while the best sites (class 3) supported from about 900 to 1800 m^3/ha, averaging approximately 1200 m^3/ha. Variation in age must be considered when viewing these volumes, particularly in the class 3 plots. The four plots with the lowest volumes in this class (Figure 14) are 75 to 78 years old. If their growth were projected to an age similar to the rest of the data they should fall into the linear trend exhibited by the rest of the data. The total standing volumes described are slightly higher than merchantable volumes because of the allowance for top and stump. Barker's (1985) data showed that close utilization merchantable volume (10 cm top, 30 cm stump) ranged from 11% to 3% less than total volumes from 300 to 1700 m^3/ha respectively.

Mean annual increment is a more meaningful expression for comparing volumes amongst the sites as it reduces the differences due to age in stands approaching or somewhat past culmination age. It was found to be highly correlated with CWSI in the study plots (Figure 15). Table 10 shows mean MAI for the three site index classes - all classes were significantly different ($P \leq 0.05$). These values are generally in line with those presented by Barker (1985), although he apparently did not sample sites as poor as those from site index class 1. The comparative precision of the MAI values shown for each site index class should be viewed with a certain amount of caution due to the younger aged stands on some of the class 3 sites. Depending on culmination age, MAI for these stands may be slightly higher or lower if projected to a similar age as the rest of the data.

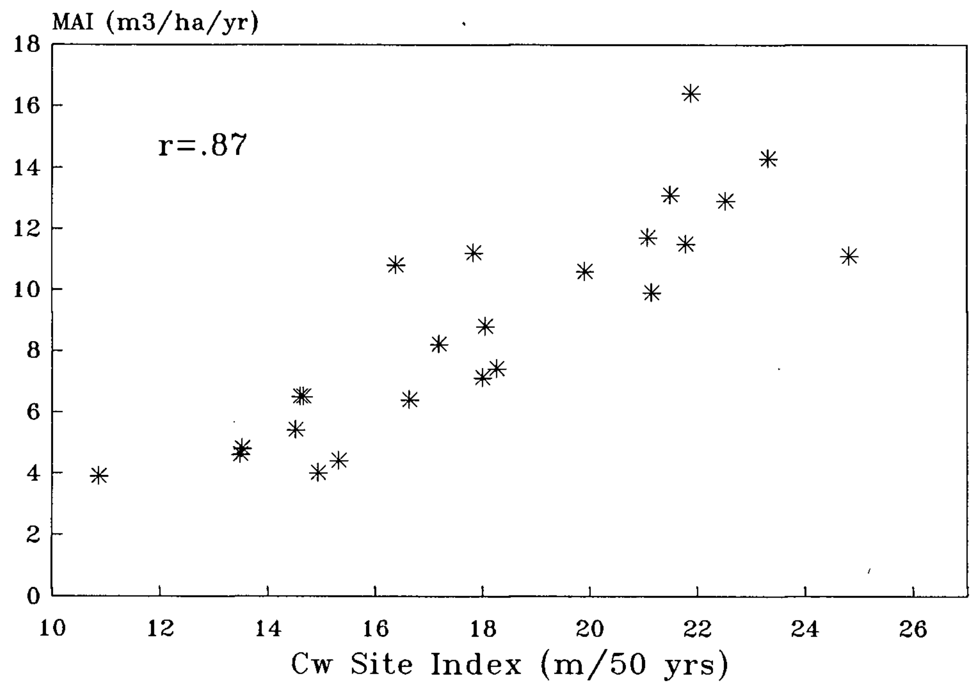

Figure 15. Relationships between MAI and CWSI

Table 10. Means and standard deviations of MAI (m^3 ha^{-1} yr^{-1} total live volume) for the three site index classes.

	Site Index Class		
Variable	1	2	3
n	8	8	8
MAI	5.0a[1]	8.8b	12.6c
Std. dev.	(1.0)	(1.9)	(2.0)

[1] classes not followed by a common letter are significantly different using the Tukey HSD test ($P \leq 0.05$). See Appendix N for procedure used to check test assumptions.

The volume and MAI data indicate that these sites are capable of supporting relatively high volumes and densities given their inherent limitations. Barker (1985) found substantially higher basal area levels occurring in older second-growth stands in the Queen

Charlotte Islands relative to published normal yield tables. While this was partly attributed to sampling deficiencies in the older normal yield table data, it is believed that mortality differences do occur such that northern latitude coastal stands are characterized by greater stem densities (Meyer 1937). It is possible that these sites are capable of supporting higher densities because transpirational demands are lower relative to warmer southern latitudes, water deficits do not occur in most sites, and tree species are moderately to strongly shade tolerant, with the exception of lodgepole pine. Such ecological conditions would reduce inter-tree competition and allow greater stand densities.

5.2.4 Tree species composition

Relative tree species composition for the three site index classes is shown in Figure 16.

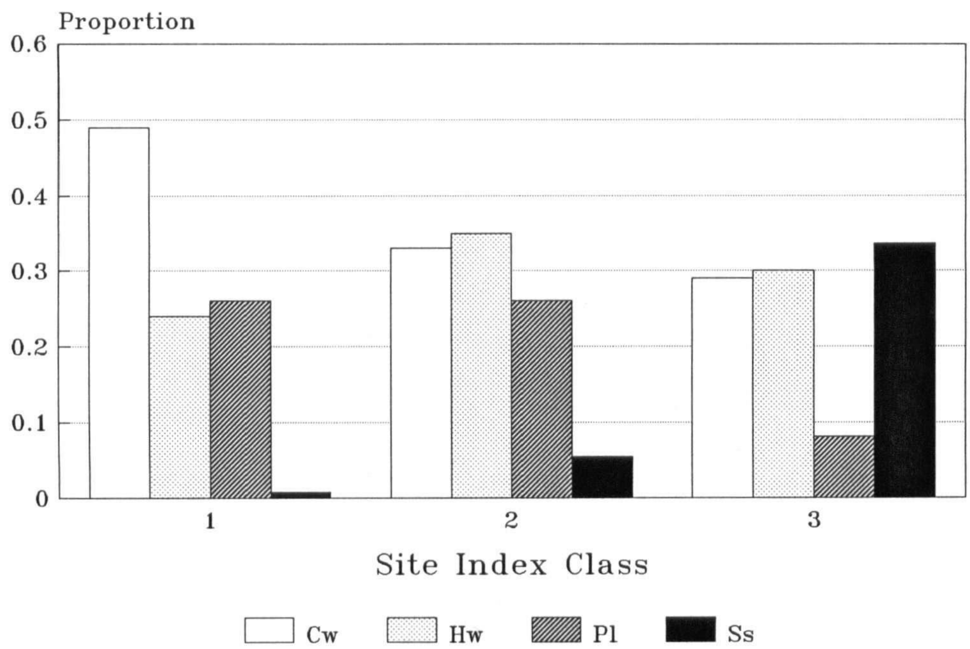

Figure 16. Relative tree species composition (proportion of total live volume).

The poorest sites are dominated by Cw, followed by Hw and Pl in approximately equal proportions. Ss is all but absent because of its inability to tolerate the limiting site conditions. The intermediate site index class supports approximately equal proportions of Cw, Hw, and Pl. Ss is present in most of these stands, but only averages about 7% of the total volume. It increases substantially in the composition of site index class 3 stands, to about equal proportions with Cw and Hw. This reflects spruce's ability to perform very well on sites which are able to adequately supply its growth requirements. Pl drops substantially as a component of these better quality sites, likely a reflection of its shade intolerance and inability to compete with the increased composition of Ss.

Examination of stem and crown conditions revealed no significant trends in relation to site index observed. Only Pl showed a marked increase in the frequency of thinning crowns in site index class 3 which again is a reflection of its decreasing competitive ability on the better quality sites.

5.3 Ecological Properties of Site Index Classes

5.3.1 Soils

Means and standard deviations of soil properties for the three site index classes are shown in Table 11. Class 1 stands apart from the other classes in its higher soil moisture content. This is a reflection of the depth to free water which is also significantly shallower in class 1 plots relative to classes 2 and 3. While air-filled porosity follows

Table 11. Means and standard deviations of soil variables for site index classes.

Variable	Site Index Class 1		2		3	
n	8		8		8	
	Mean	SD	Mean	SD	Mean	SD
VMC (%/100)	.73[a][1]	.09	.56[b]	.07	.53[b]	.08
AIR (%/100)[2]	.09[a]		.14[a]		.15[a]	
DH2OS (cm)	30[a]	6	61[b]	27	70[b]	33
D2ROOTS (cm)	26[a]	5	35[b]	5	41[b]	6
TC (kg/ha)	127102[a]	35331	152260[ab]	24597	189833[b]	42031
TN (kg/ha)	2517[a]	624	2917[a]	571	4832[b]	1310
MINN(kg/ha)	44[a]	12	59[ab]	16	98[b]	53
P (kg/ha)	13[a]	6	16[a]	4	14[a]	6
CA (kg/ha)	310[a]	93	394[a]	75	530[b]	111
MG (kg/ha)	209[a]	70	330[b]	71	461[c]	96
K (kg/ha)	130[a]	45	178[ab]	35	203[b]	36
HUMPH	3.2[a]	.1	3.3[a]	.1	3.4[a]	.2
HUMCN	54.6[ab]	4.9	59.0[a]	5.9	49.3[b]	7.4
MINPH	3.3[a]	.2	3.4[ab]	.1	3.6[b]	.2
MINCN	46.2[a]	6.4	47.7[a]	10.2	34.8[b]	5.1
SAND (%)	20.4[a]	7.2	33.9[a]	11.7	31.7[a]	14.0
SILT (%)	49.9[a]	9.9	47.8[a]	8.1	45.2[a]	9.8
CLAY (%)	26.3[a]	8.3	18.3[a]	4.6	23.1[a]	5.6
HUMDEP (cm)	13[a]	3	16[a]	2	15[a]	5

[1] classes not followed by a common letter are significantly different using the Tukey HSD test ($P \leq 0.05$). See Appendix N for procedure used to check test assumptions.

[2] test done on a logarithmic transformation; means reported as antilog of transformed means

a related trend of lower values in class 1, the difference from other classes is not significant. Rooting depth differs significantly between classes 1 and 2, and 1 and 3, and shows an increasing trend from class 1 through 3. Soil nutrient properties show a shift in class similarities, with class 3 standing apart from classes 1 and 2 in its significantly higher content of TN and CA, and its lower MINCN. Although classes 1 and 2 do not differ significantly in these properties, there is a trend of increasing nutrient content, decreasing C/N ratio, and increasing pH from class 1 through 3. TC, MINN, K, and MINPH all show an increasing trend from class 1 through 3, although classes 1 and 2, and 2 and 3 do not differ significantly. Magnesium is the only chemical property which differs significantly between all three classes. Mineral soil fine fractions did not differ significantly amongst the site index classes, although SAND was considerably lower in class 1 sites. This may be due to a difference in the deposition of the surface capping in the class 1 sites which may have involved some settling in periodic standing water.

The previous section discusses the differences in individual soil properties among the three site index classes. It would be useful to examine the combined ability of these variables to discriminate between these classes - in effect, testing the validity of the site index classes in relation to soil properties. This can be accomplished with discriminant analysis (Omi *et al.* 1979). Discriminant analysis is a multivariate technique which statistically distinguishes between several predetermined groups on the basis of a set of discriminating variables. This is accomplished by weighting and linearly combining the discriminating variables in some fashion so the groups are forced to be as statistically different as possible (Klecka 1975). The results can be used to determine which variables are good at discriminating the groups, how well these variables discriminate the groups, and how the groups are spatially related as defined by these variables (Morrison 1969).

Discriminant analysis was performed for site index classes 1 through 3 using all 24 plots and the following key soil variables; TN, D2ROOTS, VMC, and MINPH. The canonical correlations of the two derived discriminant functions were 0.90 and 0.55, indicating that the first function is strongly correlated with the site index classes while the second function is only moderately correlated. Standardized discriminant function coefficients are presented in Table 12. The first discriminant function is largely influenced by D2ROOTS and to a lesser extent, VMC which is negatively correlated. TN and MINPH appear to contribute little. The second discriminant function is primarily a reflection of TN and VMC, while D2ROOTS and MINPH contribute essentially nothing.

Table 12. Standardized discriminant function coefficients for dependent variables.

Variable	Function 1	Function 2
VMC	-0.579	0.636
TN	0.376	0.725
D2ROOTS	0.662	-0.132
MINPH	0.331	0.165

The adequacy of the discriminant functions was tested by classifying the original set of plots using the probability of a plot's class membership calculated from discriminant scores (Klecka 1975). Table 13 summarizes the classification success by comparing predicted and actual class memberships. The classification routine was able to identify correctly 92% of the plots as members of the class they actually belonged to. This large proportion of successful classifications suggests that the soil properties are good discriminators of the three site index

Table 13. Frequency of plots according to actual and predicted site index class membership, based on discriminant analysis

Actual SI Class	n	Predicted SI Class 1	2	3	Classification Success (%)
1	8	8	0	0	100
2	8	0	8	0	100
3	8	0	2	6	75
Total					92

classes. Two class 3 plots (#01 and #12) were misclassified into class 2 by a narrow margin of probability. The combined effect of slightly shallower D2ROOTS, higher VMC, and lower TN values relative to class 3 plots contributed to the misclassification of plot 1, while slightly lower TN, MINPH, and shallower D2ROOTS influenced plot 12.

Spatial relationships among the groups were examined by plotting discriminant scores for the 24 plots in the space defined by the two discriminant functions (Figure 17). Site index classes 1 and 2 are clearly separated with very minor overlap, with class 1 plots forming a relatively tight group. Classes 2 and 3 are also clearly distinguished; however, some overlap occurs with two class 3 plots showing similarity to class 2. Class 3 appears to have more variability than the other classes, as indicated by its greater dispersion among plots. Based on the discriminant function coefficients, VMC decreases while D2ROOTS increases from class 1 through to class 3. The increasing TN along factor 2 is primarily reflecting plots 23 and 24 which are located at the top right portion of the ordination and which had the highest TN contents for the class.

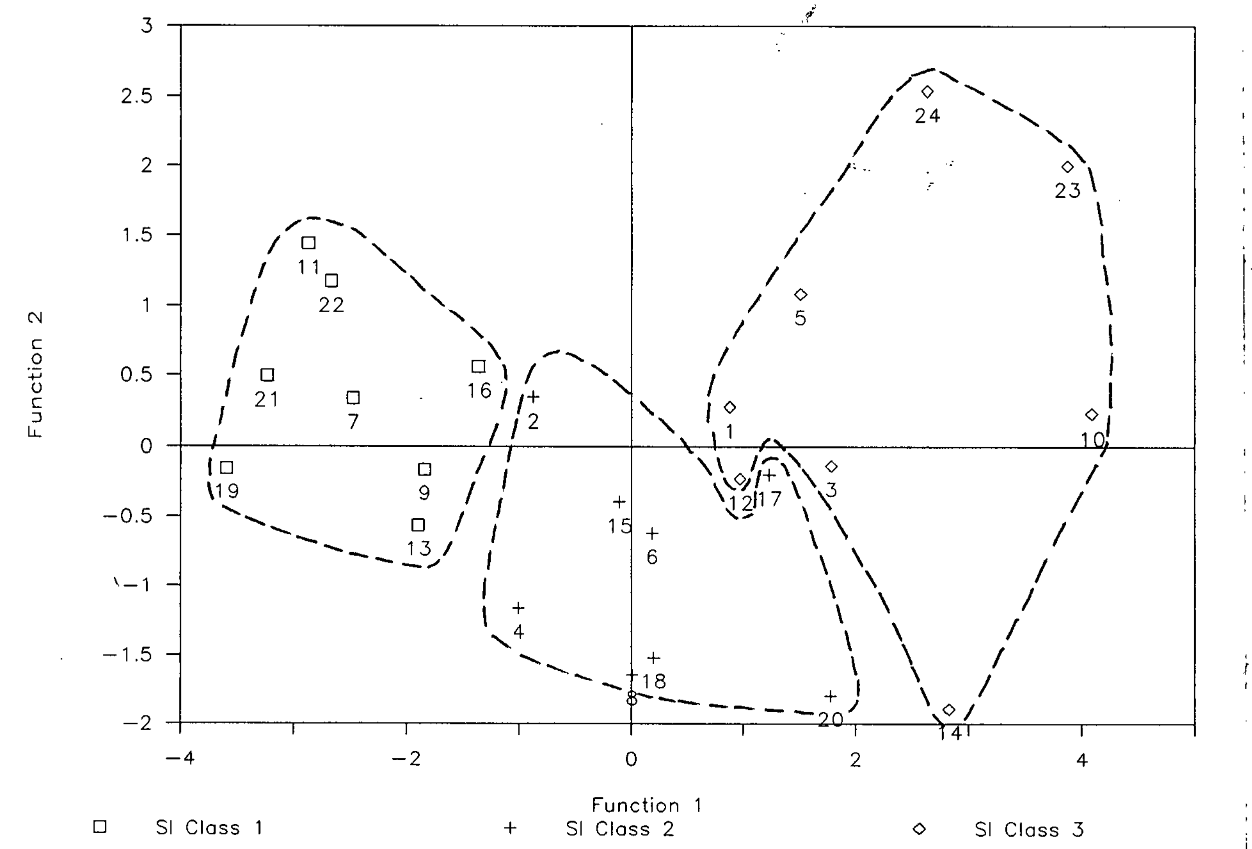

Figure 17. Plot of discriminant scores for 24 plots in relation to discriminant functions 1 and 2. Plots displayed according to site index class.

The classification success described above may be biased upwards since the classification was undertaken on the same sample plots that were used to derive the discriminant functions. One method of avoiding this is to fit a discriminant function to part of the data and test this function by classifying the remaining data (Morrison 1969). The data set was therefore randomly divided in half, with each site index class split into two sets of four plots. Discriminant analysis was performed on the "training" set of plots using the same four key soil variables. The discriminant functions derived from these data were then used to classify the remaining 12 plots. This "chance" model correctly classified 83% of the plots, with one plot being misclassified in each of site index classes 2 and 3, and all class 1 plots correctly classified. This is good classification success, particularly considering the small sample size of the training and test data sets. This verifies the interpretation of the original model which suggests the soil properties are relatively good discriminators of the three site index classes. Ordinations of the test plots and training plots in relation to the discriminant functions showed similar spatial relationships among site index classes to the original analysis of all plots.

5.3.2 Vegetation

The frequency and mean cover of understory species found in the three site index classes are shown in Table 14. Several species showed a definite affinity to class 1, particularly *Sphagnum girgensohnii*, *Blechnum spicant*, and *Bazzania denudata*. These species are all indicators of moist to wet soils which were characteristic of these sites (Klinka *et al.* 1989). *Gaultheria shallon* was also associated with class 1 sites, although it also occurred in other site index classes under openings in the canopy. *Hylocomium splendens* and *Rhytidiadelphus loreus* showed a greater affinity to class 1, as indicated by their higher cover. This contrasts with *Kindbergia oregana*, which showed a lower affinity with class 1 .

Table 14. Species composition of the three site index classes

Site Index Class	1		2		3	
n	8		8		8	
Species	Presence class and mean percent cover[1]					
Bazzania denudata	III	.6				
Blechnum spicant	V	2.5			II	.5
Blepharostoma trichophyllum	II	.3	II	.3	II	.3
Calypogeja muelleriana	II	.8	IV	.9	II	.6
Calypogeja trichomanis	I	.6	II	.8	II	.6
Carex anthoxanthea	I	.3				
Cephalozia bicuspidata	I	.1				
Cephalozia lunulifolia	I	.1	II	.4	II	.4
Coptis asplenifolia	I	.3				
Dicranum fuscescens	II	.4	I	.1	II	.3
Dicranum scoparium	I	.1	II	.5	II	.8
Dryopteris expansa					I	.1
Gaultheria shallon	III	1.9				
Gyrothyra underwoodiana			I	.3	I	.3
Hookeria lucens	I	.4	I	.3	III	2.5
Hylocomium splendens	V	36.3	V	15.6	V	9.1
Hypnum circinale	III	1.0	II	1.3	II	.4
Kindbergia oregana	IV	12.2	V	44.1	V	35.9
Lepidozia reptans	IV	1.3	IV	2.5	IV	1.4
Listera caurina	II	.3	II	1.1		
Listera cordata	IV	1.4	III	1.3	II	.4
Lobaria oregana			II	.3	II	.4
Lophozia incisa			I	.1	I	.1
Luzula parviflora					I	.1
Lysichitum americanum	II	.9				
Maianthemum dilatatum	I	.3	I	.1	II	.3
Malus fusca	II	.9				
Menziesia ferruginea	IV	1.4	II	.4		
Moneses uniflora	I	.1			I	.1
Pellia neesiana	I	.1				
Peltigera aphthosa					I	.1
Plagiochila porelloides	III	1.8	II	.6	III	1.4
Plagiothecium undulatum	III	4.3	V	9.1	V	10.9
Pteridium aquilinum			I	.1		
Rhizomnium glabrescens	V	6.3	V	9.5	V	13.8
Rhytidiadelphus loreus	V	28.1	V	7.7	V	12.0
Riccardia multifida	I	.3	II	.4	I	.1
Scapania bolanderi	V	9.8	V	14.4	V	5.6
Sphagnum girgensohnii	IV	5.0				
Sphagnum squarrosum	I	.4				
Streptopus amplexifolius	II	.3				
Vaccinium alaskaense	I	.3				
Vaccinium parvifolium	V	2.8	IV	2.5	IV	1.1
Veratrum viride	I	.0				

[1] Presence classes express percentage frequency: I = 1-20%, II = 21-40%, III = 41-60%, IV = 61-80%, V = 81-100%.

relative to the remaining two classes, although it was generally present on most sites. This is likely a reflection of the more humid microclimate of forest floors in the wetter class 1 sites. *Hylocomium splendens* and *Rhytidiadelphus loreus* are known to show greater preference than *Kindbergia oregana* for forest floors with greater water holding capacity and therefore, a more humid microclimate (Klinka and Krajina 1986). *Hookeria lucens* occurred more commonly in class 3, which likely reflects the higher pH, lower C/N ratio, and greater nutrient content of these sites (Klinka *et al.* 1989).

The vegetation data were transformed and expressed in the form of spectra of five soil moisture and three soil nutrient indicator species groups (ISG) according to Klinka *et al.* (1989). Spectral values for each sample plot were calculated from the sum of percent cover of all species included in an ISG (eg. nutrient-poor ISG), divided by the sum of percent cover of all ISGs for that attribute (eg. all soil nutrient ISGs), multiplied by 100. These values give the relative frequencies of ISGs present in a sample plot. Mean spectral frequencies were calculated for each site index class from the component plot's ISG frequency data. Figure 18 shows the soil moisture spectra for the three site index classes. The very dry to moderately dry ISG is poorly represented in all classes, which reflects the lack of water deficits in these sites. Site index class 1 has a lower frequency of moderately dry to fresh indicator species, but had more fresh to very moist and slightly more very moist to wet species relative to other classes. Again this reflects its wetter soils. Generally classes 2 and 3 were quite similar, although class 3 did show a very slight tendency towards moister soils.

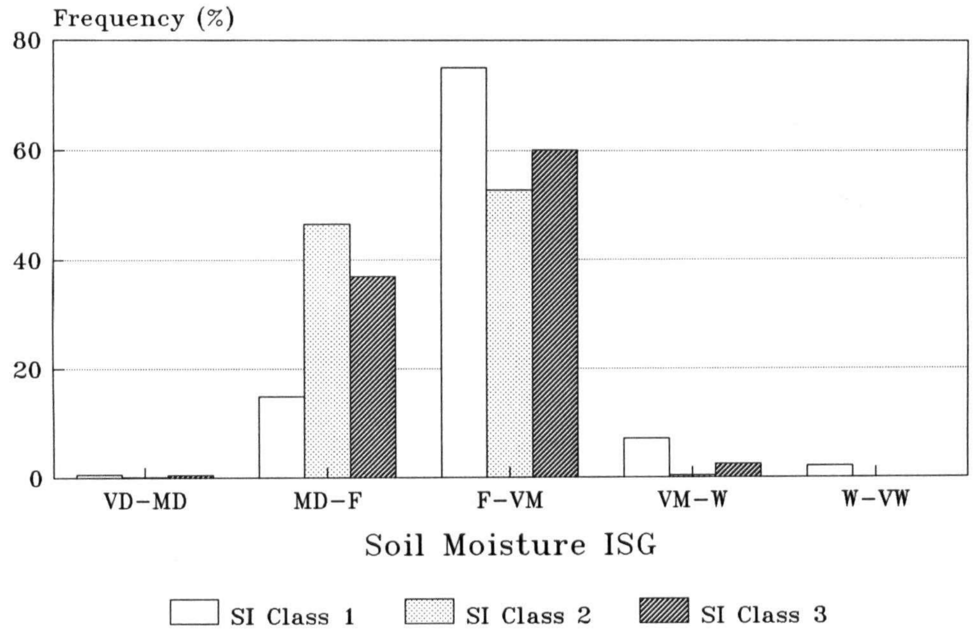

Figure 18. Soil moisture spectra for the three site index classes (VD-MD: very dry to moderately dry; MD-F: moderately dry to fresh; F-VM: fresh to very moist; VM- W : very moist to wet; W-VW: wet to very wet).

Figure 19 shows the soil nutrient spectra for the three site index classes. There is a clear trend of decreasing frequency of the nutrient poor ISG and increasing frequency of the nutrient medium ISG from site index class 1 through 3. This is consistent with the trend observed in soil properties. Similar relationships between soil ISGs and soil nutrient status have been observed by Kabzems (1985) and Green *et al.* (1989). All sites are, however, dominated by the nutrient-poor ISG which reflects the thick, acid Mor humus forms commonly occurring in most plots. The occurrence of a few nutrient-rich species in site index class 1 is associated with one plot (#11) which was atypical in the occurrence of several wet, nutrient-rich indicator species such as *Veratrum viride, Lysichitum americanum, and Maianthemum dilatatum*.

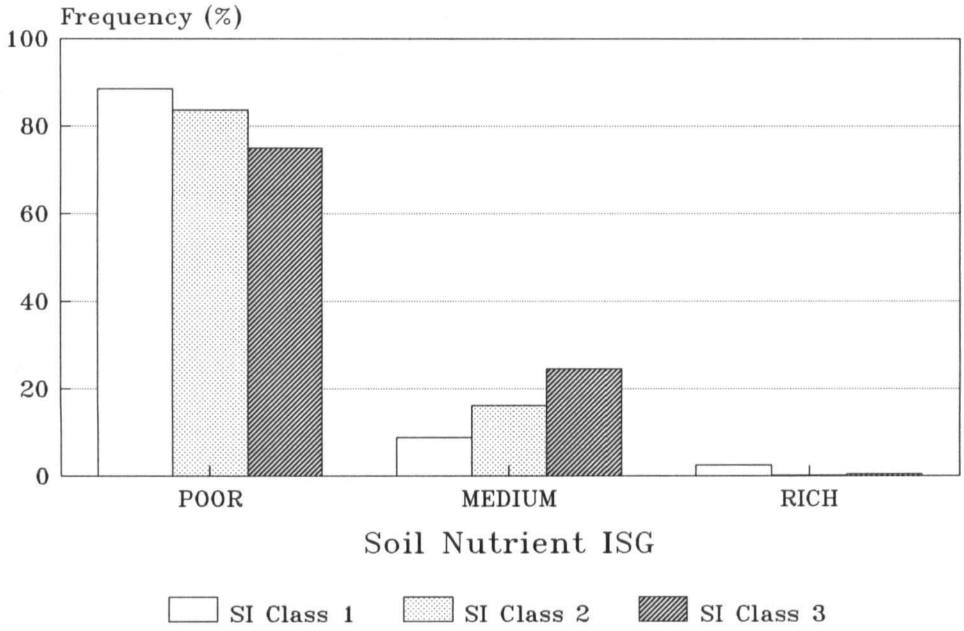

Figure 19. Soil nutrient spectra for the three site index classes.

5.4 Natural Structure in the Data

In the previous section, predetermined site index classes were characterized and analyzed in relation to soil and vegetation properties. This section assesses the natural structure which may exist in the soil and vegetation data, and the underlying factors which contribute to these observed relationships. The consistency of any natural groupings with the original site index classes is also examined as a further test of how well these classes reflect meaningful ecological patterns in the study area.

5.4.1 Soil properties

Soil properties were examined using principal components analysis and cluster analysis. These are both exploratory multivariate techniques which can be used to uncover natural groupings or structure in the data. While principal components analysis produces a geometrical ordination of sample plots which can be visually assessed for natural patterns, cluster analysis imposes a more objective classification on the data. As the relative strengths and weaknesses of these two methods are complementary, it is profitable to combine them in analyses to examine whether partitioning the data using clustering indicates similar structure as the geometrical representation (Gordon 1981).

Principal components analysis was undertaken on the data set defined by the 14 selected soil variables described in section 5.1.1. The analysis was done on a correlation matrix of all 24 plots using the MIDAS statistical package (Fox and Guire 1977). Only the first three axes were extracted since axes beyond the first three or four are generally not readily interpretable (Nichols 1977). A single outlier (plot 23) severely distorted the ordination so it was removed and the analysis repeated. To assist in the interpretation of components, component scores were correlated with the original variables.

Cluster analysis was undertaken on the data set defined by the same 14 soil variables. Euclidean distance was used as a measure of proximity between cases. All data were standardized to Z-scores[3], as Euclidean distance is greatly affected by different variable scales (Everitt 1980). Clusters were identified using Ward's method (also known as sum-of-squares method). This is a hierarchical clustering algorithm which aims to partition the set of cases into a number of groups so as to minimize the total within-group sum-of-squares about group centroids. Ward's method is widely used, and is an intuitively reasonable approach to deriving compact clusters which avoids the "chaining" problem common to some of the other methods (Gordon 1981). The output includes a dendrogram of cases displaying hierarchically arranged groups, with branches lined up so that similar cases are closest to each other in their order. The relative branch lengths reflect the joining distance between pairs of clusters (Wilkinson 1987).

The three extracted principal components accounted for 75% of the variation in the data (Table 15). The majority of this was in the first component. Component correlations with the original variables are shown on Table 16.

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[3] Z scores are calculated by subtracting the sample mean from a case, then dividing by the standard deviation. The mean of a set of Z scores is 0, and the variance is 1 (Zar 1984).

Table 15. Eigenvalue and variance extracted by the first three principal components.

Component	Eigenvalue	% Variance[1]	Cumulative % variance
1	6.50	46.4	46.4
2	2.34	16.7	63.2
3	1.62	11.6	74.8

[1] percent variance explained by a component is the proportion of its eigenvalue in relation to the sum of all component eigenvalues (14.02 in this case)

Table 16. Component correlations with original soil variables. Values are r.

Variable	Component 1	2	3
VMC	-.77	.43	-.22
AIR	.62	-.25	.22
DH2OS	.66	-.40	.19
D2ROOTS	.88	.03	-.00
TC	.80	-.03	-.46
TN	.79	.31	-.47
HUMPH	.39	.42	.64
HUMCN	-.05	-.85	.10
MINPH	.39	.63	.52
MINCN	-.24	-.59	.21
MINN	.75	.09	-.40
CA	.81	.11	.19
MG	.88	.11	.01
K	.82	-.41	-.08

All variables except pH and C/N of both the forest floor and mineral soil show high loadings on the first component. All variables are positively correlated with the exception of VMC. The quantity of nutrients in the root zone, the rooting depth, and the root zone aeration as inferred by moisture content, clearly characterize this component. The second component is interesting in that the only variables loading highly are pH and C/N ratio, the same variables that load weakly on the first component. This component could be interpreted as an index of nutrient mineralization rates, with higher pH values and lower C/N ratios associated with higher positions along the component. Figure 20 shows an ordination of samples in relation to the first two components.

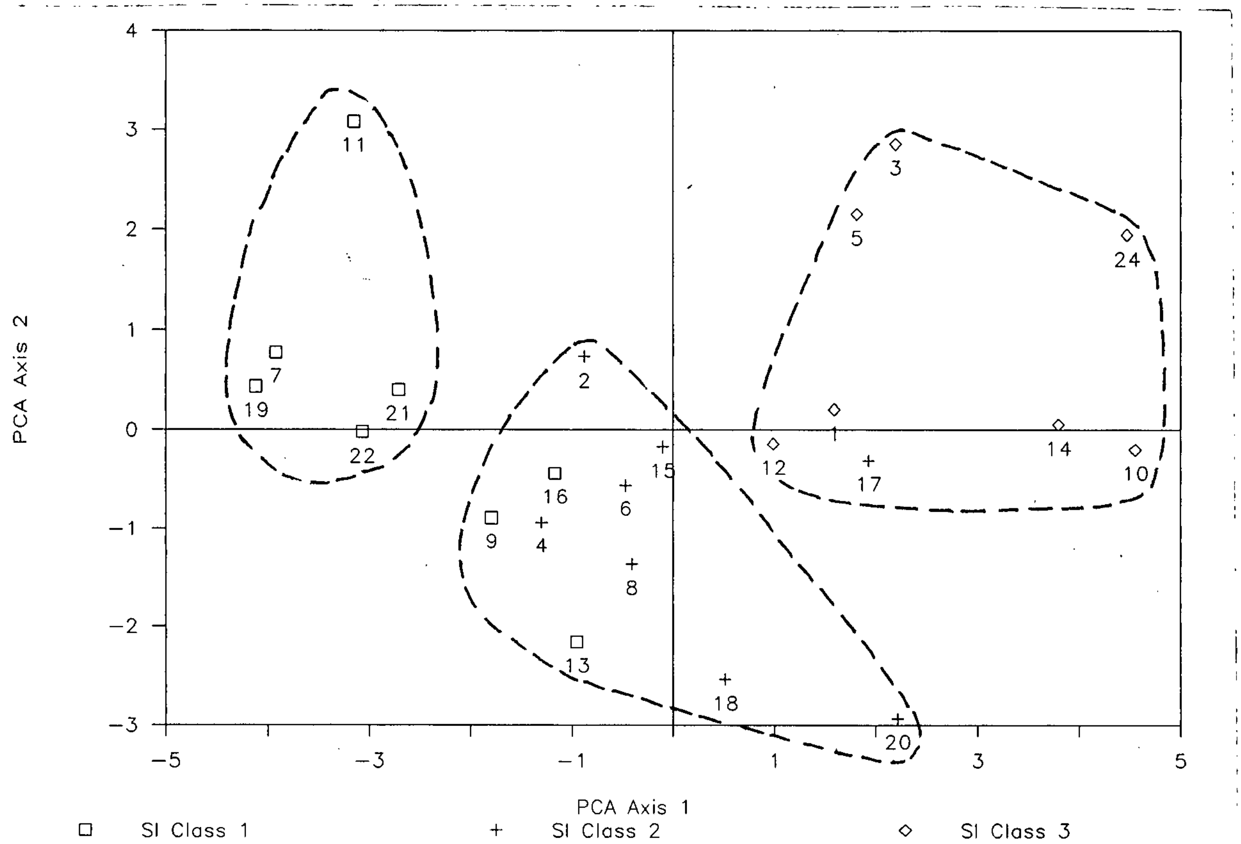

Figure 20. Ordination of sample plots in relation to soil PCA axes 1 and 2 (plot 23 deleted). Dashed lines show the three main clusters identified in cluster analysis.

Plots are arranged along the first component according to a trend of increasing site index from the lower to upper range of the axis. Site index class 1 plots are generally restricted to the lower range while site index class 3 plots occur in the upper range. Some overlap occurs in the central area of the ordination, with three plots from site index class 1 occurring together with plots from site index class 2. The outlier deleted from the analysis (plot 23) would be associated with the extreme upper right range of the ordination. Plots 3, 5, 24, and 11 stand apart in the upper range of the second axis because of their higher pH and lower C/N values. Presumably these soils could be interpreted to have slightly more active mineralization rates. Plot 11 appears to represent a slightly better quality soil than the other low productivity sites, based on its higher pH and lower C/N ratio. This is reflected to some extent in the vegetation which contains more herbaceous species, including several nutrient-medium to rich indicator species such as *Lysichitum americanum*, *Maianthemum dilatatum,* and *Veratrum viride* (Klinka *et al.* 1989). Plots 13, 18, and 20 tend to stand apart from the main body of data along the lower range of the second axis, a result of their higher C/N and lower pH values.

Cluster analysis identified two groups at the highest level, one representing plots from site index classes 1 and 2, the other containing predominantly site index class 3 plots (Figure 21). An important secondary division occurred in the first group, where five plots from SI class 1 were split into a separate cluster from remaining plots. A similar secondary division of the second main group identified plot 23 as an outlier. The cluster analysis has identified three principal clusters which very closely match the structure revealed in the principal components analysis ordination (Figure 20), including the single outlier. This "agreement" would suggest the structure uncovered in both analyses could be considered a reasonable reflection of actual structure present in the soils data.

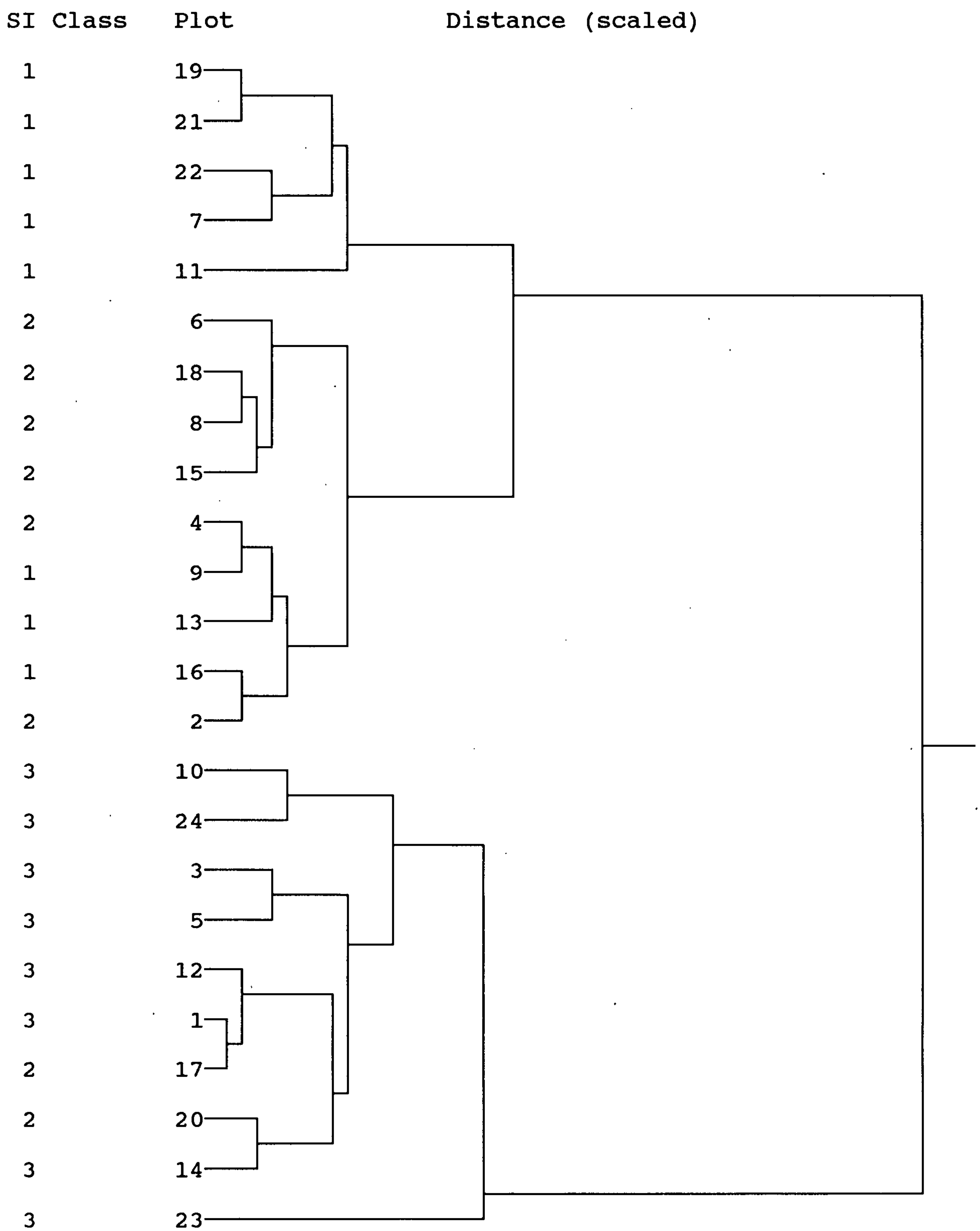

Figure 21. Cluster analysis on the 14 soil variables

These three "natural" groups identified on the basis of soil properties reflect quite well the three site index classes. Only 17% of cases could be considered "misclassified" in relation to the site index classes. The exceptions are site index class 1 plots 9, 13, and 16 which are edaphically more closely related to site index class 2 because of their relatively lower VMC values, and plot 16's higher TN value. Site index class 2 plot 17 appears more closely related to class 3 because of its relatively deeper rooting depth, and higher TN content. Plot 23 stands out from site index class 3 to which it is most closely related because of its high MINN content and high mineral soil pH.

One means of checking how useful natural clusters are is to assess whether they convey information about other related variables which were not used in the analysis. The Tukey HSD multiple comparison test was used to compare all possible pairs of the three soil-derived clusters in relation to the complete set of 14 soil variables as well as CWSI, HWSI, PLSI, SSSI, MAI, SAND, SILT, CLAY, HUMDEP, and SLOPE (Table 17). All three clusters differ significantly in relation to MAI, while clusters 1 and 3, and 2 and 3 differ in CWSI, HWSI, PLSI, and SSSI. As expected, clusters show an increasing trend in productivity from 1 through to 3.

VMC was important in differentiating cluster 1 from 2 and 3, with cluster 1 having more limited aeration. Clusters 2 and 3 were similar in this property. AIR only differed significantly between clusters 1 and 3. Rooting depth (D2ROOTS) differed between clusters 1 and 3, and 2 and 3, but not 1 and 2. DH2OS was important only between the extreme clusters (1 and 3), although the trend was one of greater depths with increasing productivity. Cluster 1 had significantly less sand in the fine fraction of upper mineral soil than the other clusters, while cluster 3 had significantly greater slope than cluster 1.

Table 17. Means and standard deviations of soil and productivity variables for soil-derived clusters.

Variable	Soil-Derived Cluster 1		2		3	
n	5		10		9	
	Mean	SD	Mean	SD	Mean	SD
MAI ($m^3ha^{-1}yr^{-1}$)	4.9[a][1]	0.9	7.5[b]	2.2	12.5[c]	2.0
CWSI (m/50yrs)	14.4[a]	0.8	16.4[a]	2.6	21.8[b]	1.9
HWSI (m/50yrs)	12.2[a]	1.0	15.2[a]	3.1	21.1[b]	3.5
PLSI (m/50yrs)	13.6[a]	1.5	17.0[a]	3.3	21.8[b]	1.9
SSSI (m/50yrs)	10.3[a]	1.8	13.7[a]	4.8	24.5[b]	5.1
VMC (%/100)	.79[a]	.05	.58[b]	.08	.54[b]	.08
AIR (%/100)	.09[a]	.02	.14[ab]	.04	.16[b]	.07
DH2OS (%/100)	31[a]	8	50[ab]	27	71[b]	31
D2ROOTS (%/100)	25[a]	6	32[a]	5	41[b]	5
TC (kg/ha)	108253[a]	29522	151495[b]	21510	188593[c]	39492
TN (kg/ha)	2234[a]	572	2849[a]	449	4718[b]	1273
MINN (kg/ha)	40[a]	10	55[a]	15	95[b]	50
P (kg/ha)	9[a]	3	16[b]	5	14[ab]	6
CA (kg/ha)	272[a]	71	377[a]	72	527[b]	104
MG (kg/ha)	174[a]	38	307[b]	75	451[c]	94
K (kg/ha)	99[a]	13	176[b]	30	204[b]	34
HUMPH	3.3[a]	.1	3.2[a]	.1	3.4[a]	.2
HUMCN	51.5[a]	1.7	59.6[b]	5.3	49.9[a]	7.1
MINPH	3.4[a]	.2	3.3[a]	.1	3.6[a]	.2
MINCN	45.5[a]	6.2	47.9[a]	9.6	35.8[b]	5.6
SAND	16.9[a]	6.6	32.8[b]	10.5	30.6[ab]	13.5
SILT	48.1[a]	12.6	48.7[a]	7.4	46.3[a]	9.7
CLAY	29.7[a]	9.0	18.6[b]	4.0	23.1[ab]	5.2
HUMDEP	12[a]	2	16[a]	2	15[a]	5
SLOPE[2]	0[a]	0	2[a]	2	5[ab]	4

[1] classes not followed by a common letter are significantly different using the Tukey HSD test ($P \leq 0.05$). See Appendix N for procedure used to check test assumptions

[2] class differences using to a non-parametric analogue of the Tukey HSD test (Zar 1984)

In relation to soil chemical properties, all three clusters differed in TC and MG, with a strong increasing trend from cluster 1 through to 3. A similar trend occurred for other nutrients, with TN, MINN, and CA showing a strong difference between clusters 2 and 3, and 1 and 3. P was significantly lower in cluster 1 than the others. HUMPH and MINPH did not differ significantly amongst clusters. MINCN is significantly lower in cluster 3, than 1 and 2, while HUMCN is highest in cluster 2.

In general, the three clusters identified in the soil data reflect distinctly different forest productivities. The first and least productive cluster appears particularly limited in soil aeration, as reflected in moisture content and air-filled porosity. Base content is important in differentiating all three clusters, and nitrogen differences are particularly strong between the last two clusters. The overall trend is one of greater nutrient reserves in more productive clusters. Depth of rooting is an important differentiating property, but particularly so between clusters 2 and 3 where soil aeration is not as strongly limiting as in the first cluster.

Properties of the soil-derived clusters did not differ substantially from the site index classes because of the similarity in their component plots (see section 5.3.1). In general, productivity indices were more variable within soil-derived clusters than site index classes, as expected. The exception was the first soil-derived cluster which was smaller and more uniform than its counterpart site index class. Variability of soil physical and chemical properties was slightly lower overall within soil-derived clusters since these properties were the basis for stratification. There were some minor changes in properties which significantly differed between soil-derived clusters compared to site index classes. In the latter, all productivity indices but only one soil chemical property (MG) differed between all classes because of the relative shifts in within-group variability comparing the two classifications. D2ROOTS differed significantly between site index classes 1 and 2, but not 2 and 3, whereas clusters 2 and 3 differed, but not 1 and 2. This reflects the inclusion of site index class 1 plots into cluster 2. Aside from some minor differences in pH and C/N ratios, the two classifications were otherwise quite similar.

5.4.2 Vegetation

An objective examination of natural structure in the vegetation data was undertaken using reciprocal averaging (RA). RA ("correspondence analysis") may be considered a doubly standardized, non-centered eigenvector analysis (Noy-Meir and Whittaker 1978). The algorithm iteratively calculates sample scores from the weighted average of species scores and vice versa, beginning with species which are weighted along a rough initial gradient, according to percent cover. This continues until a stable solution is reached (Gauch *et al.* 1977, Pielou 1984). Although similar to principal components analysis, RA differs in its double standardization of the initial data matrix, and its use of chi-square rather than covariance or correlation matrices (Noy-Meir and Whittaker 1978). RA has been shown by many authors to be a superior technique to principal components analysis for indirect ordination of vegetation data (Hill 1973, Gauch *et al.* 1977, and Whittaker 1978). It is particularly good at extracting the first major axis of vegetation and environment variation from a data set (Whittaker 1978).

The vegetation data matrix was trimmed of rare species (species present in fewer than 5% of sample plots) and submitted to reciprocal averaging analysis in the ORDIFLEX statistical package (Gauch 1977). Sample and species scores for the first two RA axes were used to plot samples in species space. The initial analysis using all plots was strongly affected by a single outlier (# 11). This plot had atypical cover of nutrient-rich indicator species (see Section 5.3.1). Since outliers cause severe distortion in the ordination, it was removed and the RA analysis repeated (Whittaker and Gauch 1978). The first three RA axes resulting from this analysis accounted for 58% of the variance in the data (Table 18). The proportion of variance extracted drops off substantially in subsequent axes. Most of the variance is accounted for by the first axis.

Table 18. Variance extracted by RA axes 1 - 3.

Axis	Eigenvalue	% Variance[1]	Cumulative % variance
1	0.29	32.2	32.2
2	0.13	13.9	46.1
3	0.11	11.9	58.0

[1] percent variance explained by an axis is the proportion of its eigenvalue in relation to the sum of eigenvalues for all axes (0.90 in this case).

A species by sample matrix with both species and samples ranked by the first RA axis scores reveals much information about the floristic structure in the data (Table 19). The most obvious feature of this matrix is that all but one plot from site index class 1 (plot # 13) are ranked at the low end of the axis, where they are characterized by higher coverage of *Hylocomium splendens, Rhytidiadelphus loreus,* the nearly unique occurrence of *Sphagnum girgensohnii, Gaultheria shallon, Blechnum spicant,* and *Menziesii ferruginia,* and lower coverage of *Kindbergia oregana* and to a lesser extent, *Plagiothecium undulatum.*

Table 19. Species by sample matrix, ranked according to the first RA axis scores. Matrix values are deciles, scaled by the matrix maximum (code 9 = 45% cover)

Site index: class	1	1	1	1	1	1	3	2	2	2	3	2	3	1	3	2	2	3	3	2	3	2	3
Plot number:	19	16	22	09	07	21	23	15	04	06	05	18	01	13	03	02	08	12	24	17	14	20	10
LYSIAME [1]	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SPHAGIR	1	+	+	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
GAULSHA	-	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
STREAMP	+	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
BAZZDEN	-	+	+	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
BLECSPI	+	+	+	+	+	+	+	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-
MENZFER	+	+	-	-	+	+	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	+	-
HYLOSPL	5	7	5	7	5	4	2	3	1	2	2	1	+	1	+	1	1	1	1	+	+	1	-
RHYTLOR	5	5	3	4	3	2	3	1	2	1	1	1	3	1	2	1	+	1	+	+	+	-	-
MALUFUS	+	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
MONEUNI	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PLAGPOR	+	-	+	-	+	+	-	-	+	+	+	-	+	-	+	+	-	-	+	-	-	-	-
VACCPAR	+	+	+	+	+	-	+	+	-	-	-	+	+	+	+	+	+	+	-	+	+	+	+
HYPNCIR	+	+	+	-	+	-	-	+	-	-	-	+	-	-	-	-	-	-	-	+	+	-	+
DICRFUS	-	-	-	+	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	+	+	-	-
LISTCOR	+	-	-	+	+	+	-	-	-	+	+	+	-	+	+	-	+	+	-	-	-	+	-
HOOKLUC	-	-	-	-	-	+	1	-	+	-	-	-	+	-	+	-	-	+	-	-	-	-	-
SCAPBOL	+	1	1	1	+	1	+	1	1	2	1	1	+	1	1	1	1	+	+	1	+	1	+
LEPIREP	+	+	+	-	+	+	+	+	+	+	+	+	-	-	-	-	+	-	+	+	+	-	+
BLEPTRI	-	-	+	-	-	-	-	-	+	+	+	-	-	-	-	-	-	-	-	-	-	-	+
DICRSCO	-	-	-	-	-	-	+	-	+	+	-	-	-	-	-	+	-	+	-	-	-	-	-
RHIZGLA	+	-	+	1	+	+	1	+	3	1	1	+	3	1	2	2	+	1	1	+	1	1	+
CALYMUE	-	-	-	-	+	+	-	-	+	+	+	+	+	-	-	+	-	-	-	+	-	-	+
LOPHINC	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	+	-	-	-	-	-	-
KINDORE	1	1	1	-	-	3	3	6	3	4	5	5	5	5	5	5	6	5	9	9	+	5	+
GYROUND	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	+	-	-	-	-	-	-	-
LISTCAU	-	+	-	+	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	+	-	+	-
PLAGUND	-	+	-	-	1	1	1	1	1	1	1	1	+	1	+	+	+	1	1	1	3	3	2
LOBAORE	-	-	-	-	-	-	-	-	-	+	-	-	-	-	+	-	-	+	-	+	-	-	-
MAIADIL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	-	-	+	-	-	-	-
CALYTRI	-	-	-	-	-	-	-	-	+	-	+	-	-	+	-	-	-	-	+	-	+	+	-
CEPHLUN	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	+	-	-	-	-	-	+	+

[1] see Appendix A for species names.

There does not appear to be a distinct floristic trend among site index class 2 and 3 plots. An ordination of samples in relation to the first two RA axes (Figure 22) shows the general structure in the data.

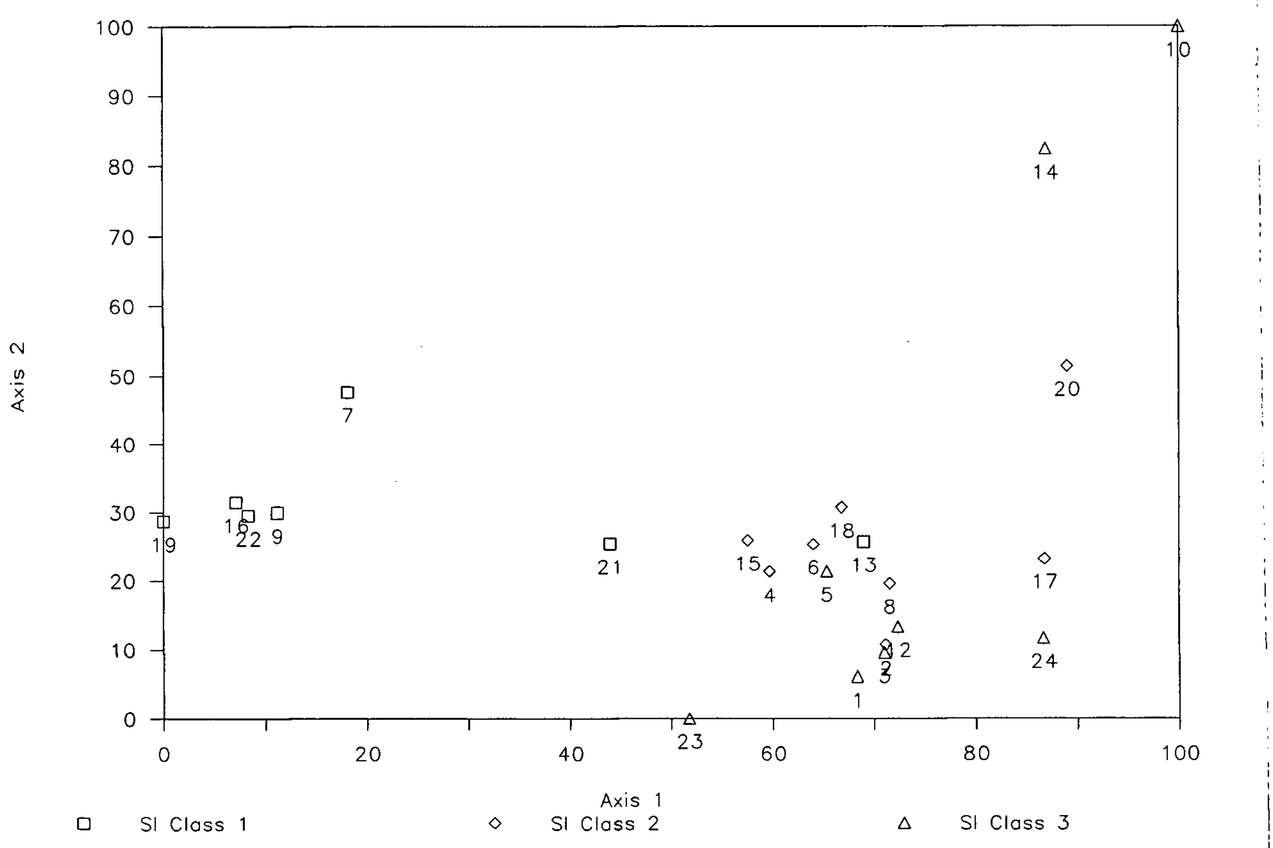

Figure 22. Ordination of samples in relation to RA axes 1 and 2 (plot 11 deleted).

The differentiation of the majority of site index class 1 plots from the rest of the data is evident. The outlier plot which was excluded from the analysis (# 11) is closely associated with site index class 1 based on other characteristics. Plot 21 has floristic affinities to the growth class 2 and 3 plots due to its lower and higher cover of *Hylocomium splendens* and *Kindbergia oregana* respectively (Table 19). Plots 10, 14, 20, 17, and 24 stand out somewhat from the bulk of the data because of the high cover of *Plagiothecium undulatum* in the first three, and very high cover of *Kindbergia oregana* in the latter two. They are separated from each other due to this difference. Two anomalies stand out. Plot 13 is floristically similar to the bulk of site index class 2 and 3 plots; yet it has distinctly poorer productivity and soil properties. On the other hand, plot 23 appears floristically related to the poorer sites with its relatively high cover of *Hylocomium splendens* and *Rhytidiadelphus loreus*, yet it has the highest productivity and the most favourable soil properties of all plots. In these cases, floristic features do not appear to reflect site properties.

In general, the patterns revealed in the RA analysis were similar to those discussed in Section 5.3.1. Site index class 1 plots appear to stand out as having the most distinct floristic characteristics which reflect the wetter soils of these sites. Site index class 2 and 3 plots feature greater cover of *Kindbergia oregana* but cannot be easily differentiated floristically.

5.5 Functional Relationships Between Site Index and Ecological Properties

In the previous sections, examination of relationships between redcedar site index and ecological properties has focussed on data structure and classes of sample plots defined by site index. In order to better understand the underlying ecological process influencing tree growth on these sites, the functional relationships between site index and selected ecological variables were investigated using multiple linear regression. The principle of model selection was to choose the smallest number of meaningful independent variables that explains the most substantial part of the variation in redcedar site index (Chatterjee and Price 1977).

The procedure for model selection followed the methods for evaluating regression models outlined by Chatterjee and Price (1977) and Zar (1984). Initially, a model using all selected variables in the particular example is fit to the data. The adequacy of fit is assessed using the coefficient of multiple determination (R^2) and the residual mean square (RMS). The model assumptions are then evaluated for serious violations using graphical examination of residuals. A plot of residuals which shows a random scatter is indicative of a well specified model (Chatterjee and Price 1977). If serious violations are evident, variable transformations may be undertaken to improve the model. The partial regression coefficients are then evaluated to identify non-essential variables. Non-essential variables are those which are not significantly different from 0 using a student's t test ($P \leq 0.05$). Including these variables in a model leads to a loss of precision in estimation and prediction (Chatterjee and Price 1977). Non-essential variables are dropped and the model refit to the data, with the new model being assessed as described above. Since all models evaluated had relatively few predictor variables, all combinations of meaningful variables were evaluated for a given example.

5.5.1 Site index/soil relationships

5.5.1.1 Soil chemical and physical properties

Figures 23 to 25 show scatterplots for the initial set of 14 soil variables. All variables show positive linear relationships with CWSI except VMC, HUMCN, and MINCN which are negatively related. TN displays a potentially curvilinear relationship which is addressed in the following discussion on model selection. The influence of each case on the correlation between a variable and CWSI was assessed using influence plots (Wilkinson 1988). All variables except MINPH, MINCN, HUMCN, and HUMPH showed no single case(s) having undue influence on the relationship. One plot (#23) stood out from the rest in terms of MINN content yet it did not influence the correlation coefficient. This plot did however have undue influence on the pH and C/N ratio of the forest floor and mineral soil, being atypically high and low in pH and C/N ratio, respectively. These atypical properties of plot 23 are consistent with its humus form which was the only Moder encountered in the study area, and which reflected greater biological activity and nutrient mineralization rates. An additional plot (#11) had an atypically high MINPH for its CWSI value, which influenced the correlation. This was also reflected in its atypical vegetation

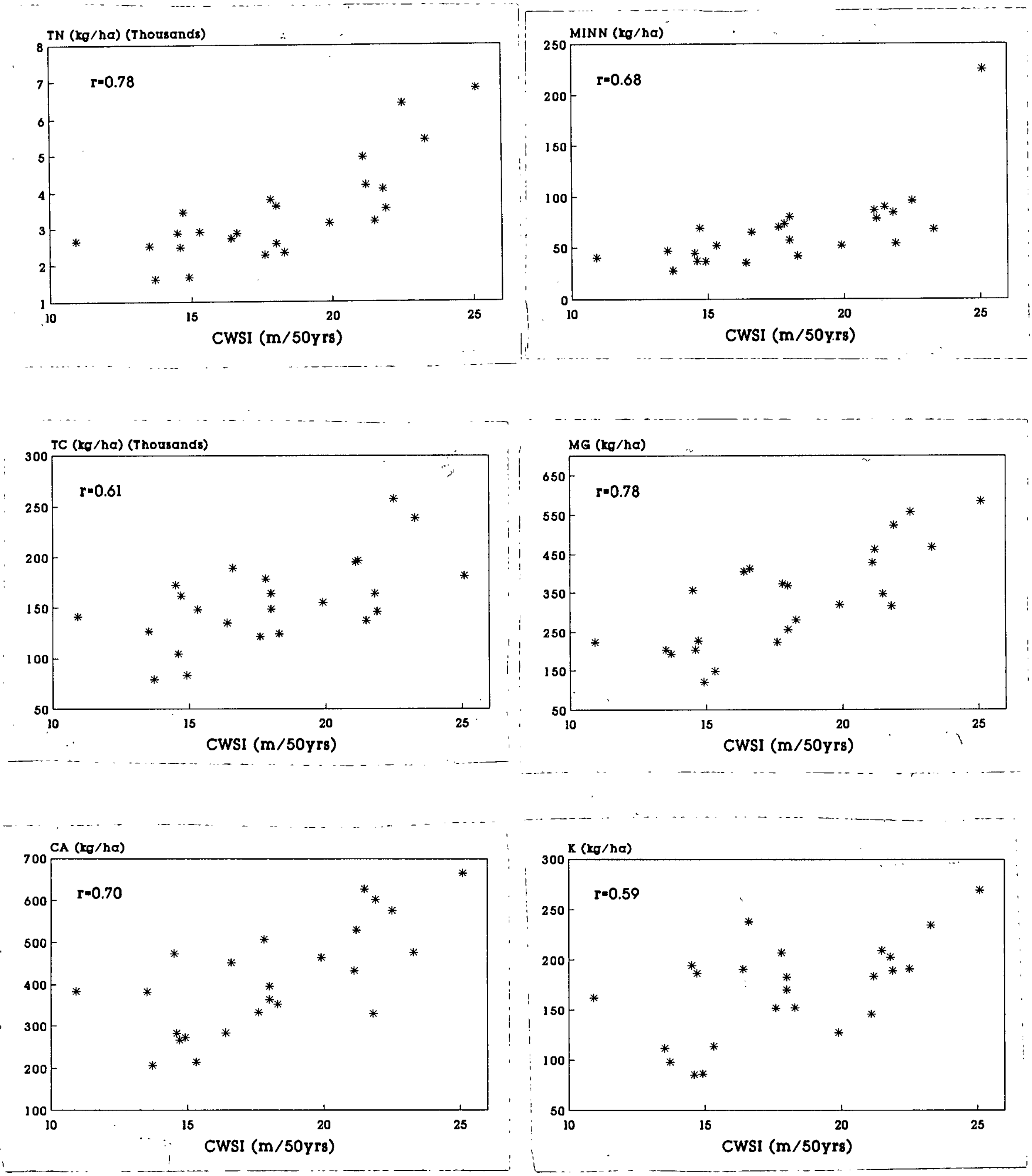

Figure 23. Relationships between soil nutrient contents and Cw site index.

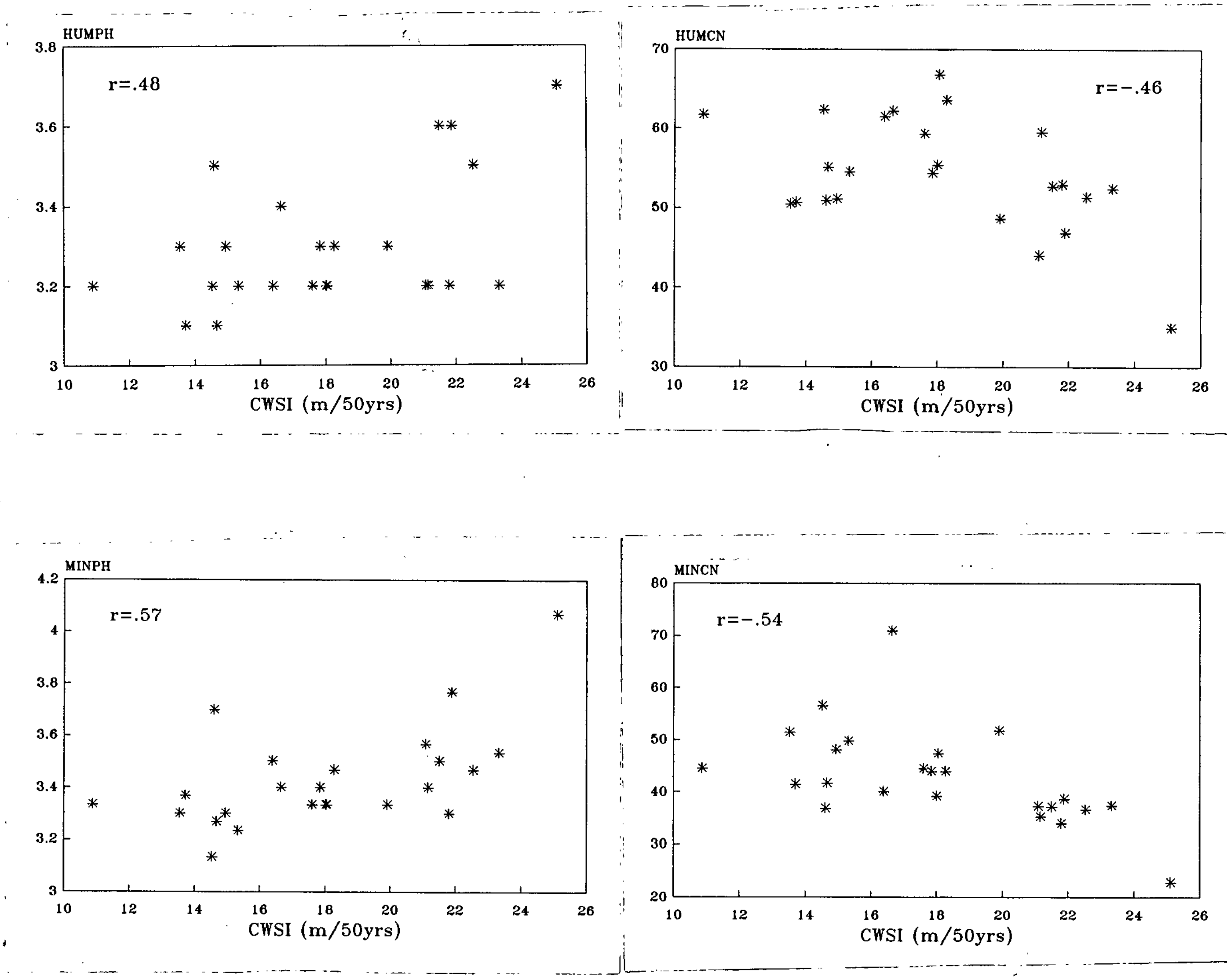

Figure 24. Relationships between pH and C/N ratios of the forest floor and mineral soil, and Cw site index.

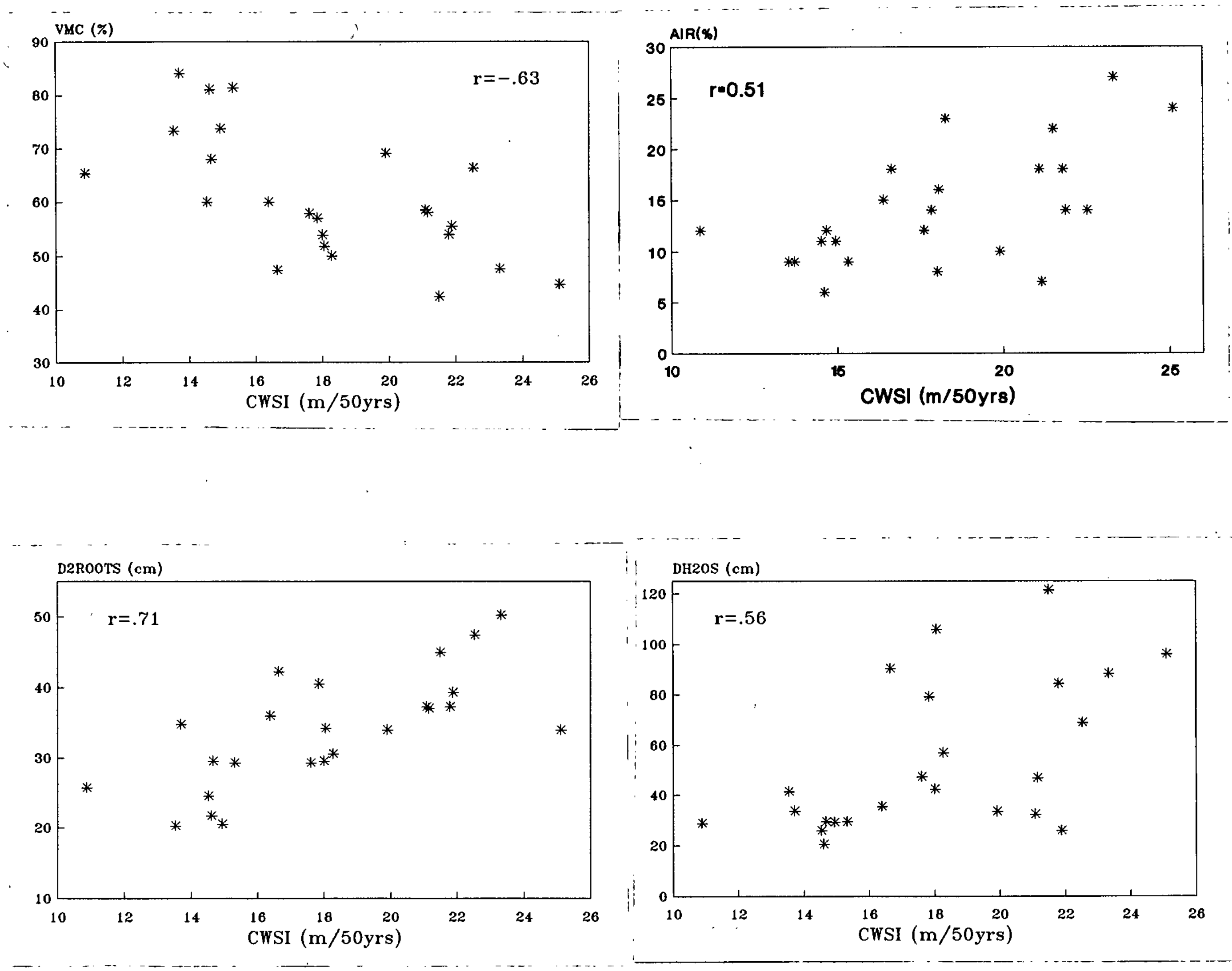

Figure 25. Relationships between soil physical properties and Cw site index.

which contained several nutrient-rich indicator species not present in other plots with similar site index values (see section 5.3.1). Because of the influence of these cases, a certain amount of caution must be used in interpreting the correlations, although the degree of influence was low (10 - 19%) in all cases.

Only the four key variables (TN, D2ROOTS, MINPH, VMC) were selected to represent soil properties in the regression analysis because of the problems associated with multicollinearity. A number of combinations of these independent variables were fit to the data. Three models were identified in which all coefficients were significant - CWSI as a function of 1) VMC and TN; 2) VMC and D2ROOTS; and 3) D2ROOTS and TN. The first model was the most promising based on the above assessments. A single outlier (#09) was identified based on its high studentized residual (Wilkinson 1988). This plot was deleted and the model refit to the remaining 23 plots. The new model showed an improved fit with very minor change in the coefficients, indicating the model is stable and not sensitive to the one outlier. Plot 09 represents a 150 year old stand on outwash sand in the northern study area. It may be considered atypical from the bulk of the population because it has the lowest CWSI encountered, it is in the northern extremity of the study area, and it is the only plot on this parent material. On this basis, its deletion from the data for purposes of this model may be justified. An evaluation of residuals from this model revealed no distinct pattern, indicating serious departures from the assumptions did not occur.

Two logarithmic transformations of TN were tested to determine if a real curvilinear relationship existed between TN and CWSI. No obvious changes occurred in the fit or form of residuals using the transformed variables, therefore, TN was left in its original form in the final model. The form of the final model is:

[1] CWSI = 19.47 - 11.02VMC + 0.002TN

R^2=0.780 Se[4]=1.69 m

where VMC is volumetric moisture content expressed as a proportion, and TN is total N content in the forest floor plus root zone mineral soil expressed as kg/ha.

Model [1] effectively summarizes the important soil properties associated with redcedar height growth, accounting for 78% of the variation in CWSI. TN is representative of the total nutrient reserve potentially available to trees. It is strongly correlated with most other nutrients, particulary MINN and MG, and incorporates soil physical properties (bulk density) and rooting depth which influence soil nutrient content. While other nutrients show a similar trend in relation to CWSI, TN is the best overall expression, with every 1000 kg/ha increase in TN associated with a 2 m increase in site index (with VMC remaining constant). VMC on the other hand, reflects the soil aeration status in the mineral soil rooting zone. It affects productivity in a negative manner, with each 11% increase in moisture content associated with a 1m drop in site index (with TN remaining constant). In essence, this model indicates that the quantity of root zone nutrient reserve and root zone quality in terms of aeration, are most important to forest productivity in the study area.

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[4] standard error of the estimate

The two other models fitted to the the same data set are:

[2] CWSI = 18.247 - 11.284VMC + 0.202D2ROOTS

$R^2=0.600$ Se=2.26 m

where D2ROOTS is the secondary rooting depth measured from the ground surface, expressed in cm.

[3] CWSI = 8.097 + 0.002TN + 0.147D2ROOTS

$R^2=0.740$ Se=1.84 m

An examination of residuals indicated that no serious departures from the assumptions occurred in either model. These models essentially reflect the importance of rooting depth to variation in Cw site index. Model [2] emphasizes rooting depth and aeration status in the root zone, as reflected by moisture content. Model [3], which explains nearly as much variation in CWSI as model [1], emphasizes the combined importance of rooting depth and soil nutrient content. While TN content partly reflects the available rooting depth, these two variables were not strongly correlated and therefore, do not create multicollinearity problems in the model.

5.5.1.2 Field-recognizable properties

The above relationship provides insight into the major processes influencing site index; however, it has limited utility for site index prediction because of difficulties in measuring the independent variables. Therefore, regression analysis was applied to a set of variables which can be readily identified in the field. Because field description of forest ecosystems frequently requires qualitative assessment, a mix of both continuous and categorical variables was initially considered for analysis (Table 20).

Table 20. Continuous and categorical variables which are readily described in the field.

Symbol	Property
D2ROOTS	secondary rooting depth from ground surface (cm)
DH2OS	depth to free water from ground surface (cm)
SLOPE	slope (%)
H2OST	free water status (absent, slow, moderate, rapid)
ROOT	rooting density in the soil root zone (very few, few, plentiful, abundant)
TEXPM	field texture of parent material (C, SC, CL, SCL, SIL, SIL+, SL, LS[1])
CONS	consistence of root zone soil (soft, firm-friable)
CEM	presence of cemented horizon (present, absent)
HUE	hue of root zone soil (Munsell colour notation)
CHROMA	chroma of mineral soil (Munsell colour notation)

Table 20. Continued.

Symbol	Property
SHAPE	surface shape (depression, level, sloping, convex, receiving)
PM	parent material (alluvial, fluvial veneer over morainal, lacustrine veneer over morainal, morainal, glaciofluvial)

[1] texture codes from CSSC (1987). SIL+ denotes a high clay content within the range for silt loam.

The categorical variables were initially screened to identify those which were most promising in relation to CWSI. This was done by examining plot frequencies according to site index class and categorical variable class using contingency tables. Only H2OST, CONS, ROOT1, and SHAPE, showed any apparent association with site index class (Table 21). Most site index class 1 plots had free water moving rapidly or moderately into the soil pits, with no plots lacking free water. On the other hand, none of the class 2 or 3 plots featured rapid input of free water. Several plots from these classes showing moderate flow of free water were located in the Lawn Hill area where seepage water seemed to be more prevalent, particularly in class 3 sites. The majority of class 1 plots featured a soft, buttery-like consistence in the upper mineral soil because of prolonged saturation. All class 2 and 3 plots had upper mineral soil with a firm or friable consistence and subangular blocky structure. Most class 2 and 3 plots had abundant or plentiful root density within the root zone, while only one class 1 plot had abundant roots, reflecting the better soil aeration conditions of the more productive sites. Site index class 1 plots were predominantly located in depressional terrain which contributes to their stagnant soil water regimes. Due to the subdued topography characteristic of the study area, these surface shapes are rather subtle.

However, since slowly permeable soil layers tend to be close to the surface, a relatively minor change in surface topography can impact the available aerated root zone

Table 21. Contingency tables for selected categorical variables showing frequency by site index class

Variable	Category		Site Index Class		
			1	2	3
		n	8	8	8
H2OST	absent		0	3	3
	slow		1	3	2
	moderate		4	2	3
	rapid		3	0	0
CONS	soft		6	0	0
	firm-friable		2	8	8
ROOT	very few		1	0	0
	few		3	0	0
	plentiful		3	3	3
	abundant		1	5	5
SHAPE	depression		7	0	1
	level		1	2	1
	sloping		0	3	2
	convex		0	3	0
	receiving		0	0	4

sufficiently to affect tree growth. Many site index class 1 sites occurred in subdued depressions only a few decimeters lower than adjacent sites with 3 - 4 m greater site index (Cw). Boggie (1972) also found that minor variation in microtopography strongly influenced lodgepole pine growth on waterlogged soils. While parent material texture wasn't included, there was one interesting trend. Site index class 3 plots tended to have coarser textured soils (5 plots SL or coarser), while 88% of class 1 and 2 plots had SCL or heavier textures. This may reflect improved porosity, aeration, and permeability of the coarser underlying soils.

This set of continuous and categorical variables were fitted to a series of multiple regression models to determine the best expression of CWSI. Categorical variables were expressed as dummy variables where x-1 variables of 0 or 1 value were used to distinguish x categories of each variable. In this manner, dummy variables only influence the intercept in the regression (Chatterjee and Price 1977). Fifteen models incorporating various combinations of the above categorical variables plus D2ROOTS, DH2OS, and SLOPE were evaluated using previously described procedures. The SHAPE variable consistently showed only the depression category having any significant influence therefore this variable was changed to DEP with two categories; depressional, and not depressional.

The only variables which showed any significant influence in the various models were D2ROOTS, SLOPE, CONS, and DEP. The most promising models based on these variables were:

[4] $$CWSI = 11.589 + 0.214D2ROOTS - 3.212CONS$$

$R^2 = 0.61$ $Se = 2.40$ m

where CONS takes a value of 1 for soft and 0 for friable-firm.

[5] $$CWSI = 10.174 + 0.257D2ROOTS - 2.528DEP$$

$R^2 = 0.60$ $Se = 2.41$ m

where DEP takes a value of 1 for depressional and 0 otherwise.

[6] $$CWSI = 8.565 + 0.232D2ROOTS + 0.565SLOPE$$

$R^2 = 0.73$ $Se = 1.98$ m

Models 4 and 5 are very similar in fit, and in what they represent, since plots which have soft soil consistence often are in depressional terrain. These models reduce CWSI by

3.2 m and 2.5 m, respectively, for sites with soft consistency and depressional terrain, reflecting the negative effect of high soil water content and reduced aeration on tree growth. The model which explains most of the variation in CWSI (73%) is that based on rooting depth and slope. Each of the categorical variables (CONS and DEP) were separately added to this model; however, neither contributed significantly when combined with D2ROOTS and SLOPE. One plot (#23) was identified as having high leverage in model 4 because of its relatively greater slope (12%). Based on a refitting of the model with plot 23 deleted, this case appears to have minimal effect on the model except for pulling up the SLOPE coefficient slightly and improving the fit slightly. It was decided not to delete this case as the relationship between tree growth and the steeper slopes it expresses is important in the study area. It appears that rather minor changes in slope can influence tree growth, likely a reflection of improved soil water movement and subsequent enhanced soil aeration. In effect, this model indicates that CWSI increases 2.3 m for every 10 cm increase in D2ROOTS, if SLOPE is held constant, while a 2% increase in SLOPE is associated with a 1 m increase in CWSI while holding D2ROOTS constant. This relationship has to be interpreted with some caution, however. Slopes were small and did not vary a great deal over the sample. There is some measurement error at such small slopes, which may influence the model and its application. Intuitively, steeper slopes should be associated with better tree growth because of improved soil drainage and aeration. There is some question as to whether the relationship described in the model is realistic for the whole study area.

5.5.2 Site index/vegetation relationships

To examine functional relationships between CWSI and understory vegetation, the original data set containing 46 species had to be reduced to a manageable size for regression analysis, which was done in two ways. The first method used the three reciprocal averaging axes as new variables to summarize the information contained in the original data set. Each plot is characterized for each plot by 3 scores for the 3 axes, rather than by cover of individual species. This, in effect, is a linear transformation of the original species into 3 new variables. The second method used the five soil moisture and three soil nutrient indicator species groups to summarize the vegetation. Each plot is characterized by a frequency value for each of the 8 ISGs.

The plot scores of the three RA axes were regressed against CWSI. Only the first RA axis (RA1) had significant coefficients in any of the models, therefore a simple linear model of CWSI as a function of RA1 was used to represent the relationship. The form of the model was:

[7] $$CWSI = 13.355 + 0.083RA1$$

$R^2 = 0.44$ $\quad$ $Se = 2.81$ m

where RA1 is the plot's score along the first RA axis. A plot of this relationship is shown in Figure 26. Based on the results from Section 5.4.2, model 7 actually represents a relationship between two groups of plots - those with low site index dominated by *Hylocomium splendens, Rhytidiadelphus loreus,* and the remaining, floristically indistinguishable plots dominated by *Kindbergia oregana*. Although the regression represents a significant relationship ($P \leq 0.05$) it explains only 44% of the variation in CWSI, and does not really reflect a continuous linear function.

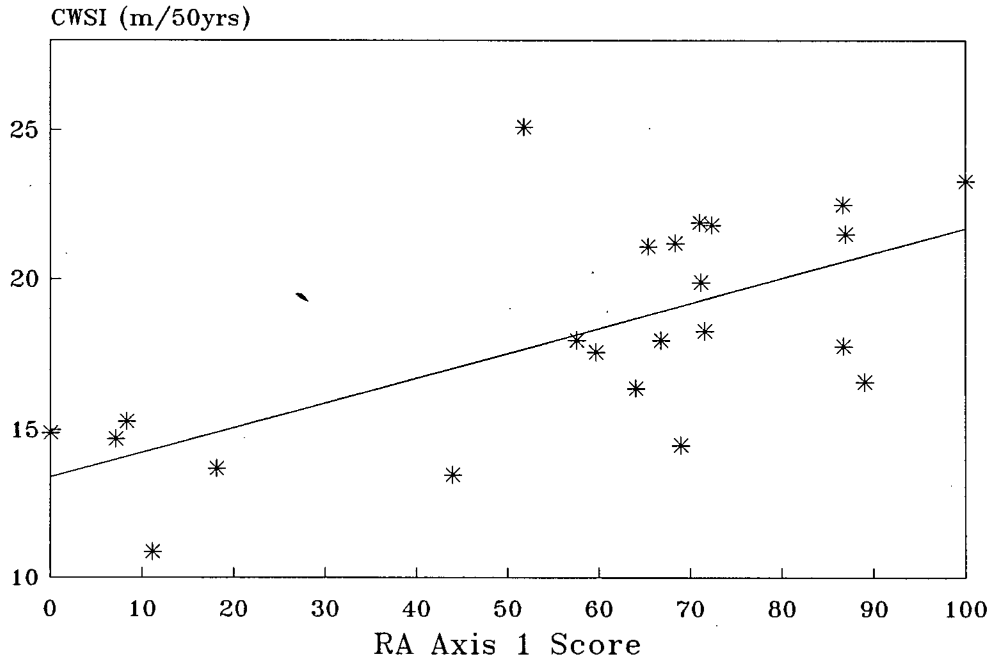


Figure 26. Relationship between Cw site index and RA axis 1.

Various combinations of the 8 ISG variables were regressed against CWSI and it was quickly apparent that only the nutrient-poor (NP), nutrient-medium (NM), and moisture-fresh to very moist (FVM) ISG's showed a significant ($P \leq 0.05$) effect on CWSI. This effect was only expressed singularly, with no combinations of two or more variables having more than one significant coefficient. The best model expressed CWSI as a function of the NM group. The form of the model is:

[8] $$CWSI = 14.806 + 19.363NM$$

$R^2 = 0.31$ $\quad$ $Se = 3.03$ m

where NM is the frequency of the nutrient-medium ISG present in a plot. A plot of this relationship is shown in Figure 27.

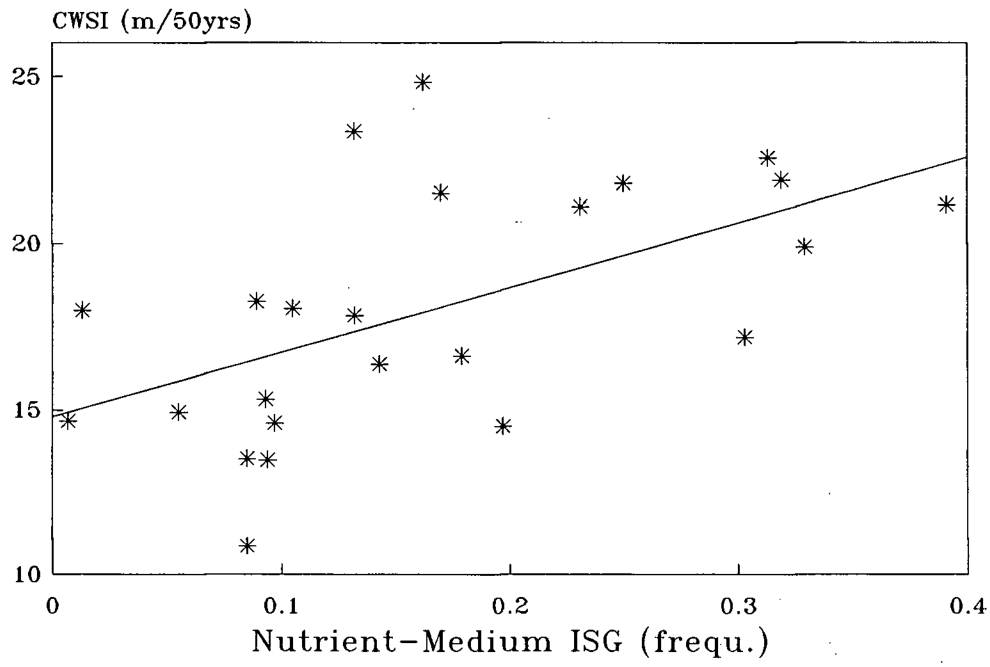


Figure 27. Relationship between CWSI and the nutrient-medium ISG.

As expected, CWSI increases with increasing frequency of nutrient-medium indicator species, which is consistent with the trend of improving soil nutrient status. Although the relationship is more continuous than that with RA1 scores, it is weaker, explaining only 31% of the variation in CWSI. In neither case does vegetation show a strong functional relationship with CWSI. The composition and cover of understory vegetation present on a site depend to some extent on non-site features such as disturbance, overstory density and composition, and chance. High stand density characteristic of these stands severely limits light reaching the understory, resulting in low floristic diversity, often dominated by shade-tolerant mosses. Overbrowsing by Sitka black-tailed deer (*Odocoileus hemionus sitkensis*) has also apparently altered the floristic structure of many ecosystems in the study area (Banner *et al.* 1987). Such "non-site" variation in understory vegetation development masks its ability to clearly reflect changes in site quality.

5.6 Soil Water Quality

Soil water represents an important property of ecosystems, potentially influencing their function and productivity. In most sites in the study area, the presence of soil water near the surface at various times during the year has a potentially negative impact on site productivity. While factors such as the depth, timing, and duration of this excess soil water are important in determining its impact, so too is the quality of the water. Dissolved oxygen in soil water can prevent hypoxia if present in sufficient concentration. Moving soil water tends to be well mixed and contains more dissolved oxygen than stagnant water. As a result, "aeration-stress" in trees is offset and roots can still function within the saturated zone (Zaerr 1983, Kozlowski 1984, Pritchett and Fisher 1987). This is believed to be a major factor in determining productivity of Sitka spruce in soils affected by excess soil water (Blyth and McLeod 1981a, 1981b).

The dissolved chemical loading in soil water has an important influence on ecosystem productivity as it contributes to the available nutrient pool. Supplemental inputs of dissolved nutrients in seepage water have been associated with improved tree growth (Bourgeois 1969).

5.6.1 Specific conductivity

Specific conductivity (electrical conductivity) is a numerical expression of the ability of a water sample to carry an electric current, which is dependent on the concentration of dissolved ions in the water and its temperature (Franson 1976). It is an index of the total loading of soluble salts and has been found to correlate well with the sum of cations (Ca^{++}, Mg^{++}, Na^{+}, K^{+}) and anions (HCO_3^-, SO_4^-, Cl^-) determined chemically (Richards 1954, Bourgeois 1969, Feller and Kimmins 1979).

Specific conductivity values for the 18 measured plots are shown in Appendix I. Values averaged 0.151 dS/m and ranged from 0.081 to 0.312. The coefficient of variation across all plots was 39%. Stream water sampled from Lawn Creek which drains the southern portion of the study area had a conductivity of 0.160 dS/m which is similal to the study plots in the vicinity. From the limited data available on conductivity in south coastal ecosystems, the soil water in the study area appears to have above normal concentrations of dissolved ions. Data from several small streams in the Malcolm Knapp Research Forest in Haney showed average conductivities of approximately 0.020 dS/m (Feller and Kimmins 1979). Soil leachate from C horizons of tills in the southern part of the Research Forest had similar conductivity values (Bourgeois 1969), as did soil seepage water sampled from mature stands throughout the research forest (Klinka *et al.* 1986).

The supply of elements to soil water depends on a number of factors, including mineralogy of the parent material, weathering rate, organic matter decomposition, precipitation, and movement of water through the soil. However, the main source of several ions to the soil solution is the weathering of soil minerals (Richards 1954, Slavinski 1977). Thus the dissolved chemical load in soil water is a direct function of the soil material with which the water has been in contact (Walmsley 1974). The rate of water moving through the soil can also affect ion concentration with fast moving water creating a shorter equilibrium time of the soil-water system, thus lowering ion concentration (Dreibelbis and McGuinness 1957). Lower ion concentration in soil water can therefore be expected in Haney ecosystems because of the base-poor granitic bedrock from which parent materials are derived, and the relatively fast moving subsurface seepage associated with the characteristic steep slopes. In the east Graham Island lowlands, soils are derived primarily from volcanic and sedimentary lithology which yield a relatively greater quantity of bases upon weathering compared to grantic material. Also, because of the subdued topography, water accumulates and moves slowly if at all through the soil, maximizing the equilibrium of the soil-water system.

The relationship between specific conductivity and tree growth (CWSI) was poor ($r=0.237$). Apparently the concentration of dissolved ions in the soil water is not as important as the total soil nutrient reserve potentially available to plants. However, variation in non-nutrient, or luxury-consumption nutrient ions may contribute to this poor correlation with tree growth. There was some evidence of a distributional pattern in specific conductance within the study area. Most (4 out of 6) plots from the Lawn Hill area had relatively high conductivities, averaging 0.200 dS/m. An isolated area of Masset Formation bedrock outcrops in the Lawn Hill area and is characterized by base-rich basalt (Sutherland-Brown 1968). This may influence the mineralogical composition of the local surficial materials and in turn, soil water quality. Other plots between Lawn Hill and Mayer Lake also tended to have high conductivities (above 0.140 dS/m), while all plots located north of Port Clements had "low" conductivities (below 0.110 dS/m). These differences may also reflect variation within the mineralogical composition of the parent materials which would have mixed lithologies depending on the source bedrock. Plots in the Miller Ck. area tended to have lower conductivities which may reflect the relatively base-poor granodiorite pluton that outcrops in this vicinity (Sutherland-Brown 1968).

Specific conductivity values were correlated against all soil chemical variables (both content and concentrations), and plotted against all categorical soil and physiographic variables. Only Mg concentration in the forest floor showed a significant ($P \leq 0.05$) although weak relationship to conductivity ($r = 0.463$). The likely reason for this correlation is uncertain.

5.6.2 Dissolved oxygen

Dissolved oxygen (DO) values averaged 4.7 ppm and ranged from 3.2 to 8.4 ppm (Appendix I). The coefficient of variation across all measured plots was 30%. To put these in perspective, fast and slow moving stream water from Lawn Creek had values of 9.2 and 8.3 ppm respectively, reflecting the degree of aeration due to mixing and stirring of flowing water. Other researchers have recorded DO values of 10.2-10.6 ppm (Walmsley 1974), 10-11 ppm (Baker 1974), and 9-13 ppm (Feller and Kimmins 1979) in flowing streams. No comparative data are available on DO measurements of saturation zone soil water.

While DO in the soil water was clearly lower than that of well-mixed flowing water, no relationship between tree growth and DO was evident. Also, no significant relationships were evident with any of the soil chemical properties (contents and concentrations), or the categorical soil and physiographic variables. This reflects the inherent variability of dissolved oxygen in soil water, or problems in the measurement technique. In the latter case, a number of factors affect precision and repeatability of measurements. One of the more significant potential problems is the disruption of the natural equilibrium by inserting the stand pipe into the saturation zone. By disturbing the water in the presence of air, diffusion of atmospheric oxygen into the sample may change the actual gas content (Walmsley 1974, Franson 1976). This is logistically difficult to overcome when sampling ground water, and generally requires complex techniques employing sealed sample extraction equipment (W.H. Black 1987, pers. comm.). Another factor potentially contributing to variability is that the volume of free water and the rate at which the stand pipe filled varied between sites. This may affect the quality of the DO measurement, particularly in cases where smaller volumes of water were present in the stand pipe. Finally, point samples of dissolved water may not be meaningful in relation to forest productivity. The duration and timing of oxygen supply is important to tree growth. For example, the duration and magnitude of a growing season depression in DO may be a better indication of growing conditions (H. Schreier 1989, pers. comm.). Monitoring dissolved oxygen in soil water over a full year, particularly in relation to water table level, may reveal more physiologically meaningful trends in oxygen availability.

One sample plot was of particular interest, however. Plot 03 showed the highest dissolved oxygen value recorded (8.4 ppm). The measurement was repeated for verification with the same result. The soil profile contained a 17 cm thick layer of porous gravelly loamy sand (30% coarse fragments), over a slowly permeable layer of clayey till. The sand layer was saturated with a perched water table above the dense till. As the site was on a uniformly gentle slope, the seepage water likely moves easily within the coarse layer because of its high hydraulic conductivity. This would result in higher dissolved oxygen content because of the mixing effect. This was reflected in the live roots present within this saturated layer. This site supported one of the more productive stands in the study area.

5.7 Soil Oxidation Zone Index

Initial attempts to measure the oxidized zone of steel rods revealed that iron oxidation was manifested in different morphological features related to the degree of oxidation. A single zone of "rusted" steel was lacking on all but the wettest sites. Two methods of distinguishing zones of oxidation were therefore tested. The first method focussed on the presence of rust accumulations on the rod surface. Three zones of oxidation were recognized:

zone 1 - many patches of bright orange to shiny red accumulations of oxidized material creating a rough surface; surface of metal shiny; soil material often adheres to accumulations. Assumed to reflect good aeration.

zone 2 - patches of oxidized accumulations fewer, with dull dark reddish colours rather than bright orange or shiny red as in zone 1; surface of metal generally shiny but may be dull; soil material adheres to accumulations. Assumed to reflect moderate aeration.

zone 3 - no reddish oxidized accumulations; patches of dark (black) discoloured material present but not accumulated to any appreciable thickness; surface of metal dull. Assumed to reflect poor aeration.

Below zone 3 the metal surface is dull and free of any discolouration, due to the more-or-less complete lack of oxygen.

The second method focussed on the presence of the shiny surface on the steel rod. Two zones were recognized:

zone 1 - surface of metal bright and shiny; reddish oxidized accumulations often present. Assumed to reflect moderate to well aerated conditions.

zone 2 - surface of metal dull; no reddish oxidized accumulations; patches of dark (black) discoloured material present but not accumulated to any appreciable thickness. Assumed to reflect poor aeration. (Like zone 3 above).

Measurements were made according to the two methods, with the depths recorded from the ground surface to the bottom of each zone. Using the first method, zone 1 was generally easy to distinguish, having a sharp lower boundary. The lower boundary of zone 3 was also easily recognized. The boundary between zone 2 and 3 was somewhat more difficult as it often represented a transition associated with decreasing oxygen supply. In the second method of measurement, the lower boundaries of both zones were relatively easy to distinguish. In 26 of the 144 rods measured, a lower boundary of the last zone using both methods was not reached within the depth of rod inserted in the ground. In these cases, the maximum depth reached by the rod was recorded. Data representing this lower zone must be interpreted with caution. Table 22 shows the Pearson correlation matrix of the depth of oxidized zones with CWSI and selected soil properties.

Table 22. Pearson correlation matrix for oxidized zones and CWSI plus selected soil properties.

Zone	CWSI	VMC	AIR	DH2OS	D2ROOTS	DUFF
Method 1:						
AZ1[1]	0.355	-0.421	0.413	0.439	0.652	0.871
AZ2	0.581	-0.710	0.575	0.561	0.791	0.510
AZ3	0.563	-0.794	0.682	0.589	0.721	0.383
Method 2:						
BZ1	0.627	-0.833	0.808	0.829	0.708	0.350
BZ2	0.563	-0.793	0.683	0.589	0.721	0.384

[1] AZ1, AZ2, AZ3: method 1, zones 1 to 3 respectively
BZ1, BZ2: method 2, zones 1 and 2.

According to method 1 measurements, the depth to the bottom of all three zones was relatively weakly correlated with CWSI, with AZ2 and AZ3 showing the stronger relationships. Increasing site index is associated with increasing thickness of "oxidized" soil.

The first zone was highly correlated with the forest floor thickness measured where the rods were inserted. This was obvious in the field, and reflects the much greater porosity of the forest floor relative to mineral soil, and its closer proximity to the atmosphere. The greatest density of rooting also occurs within this well-aerated zone on all sites, reflecting the importance of good aeration to root development (Brady 1974). VMC was well correlated with both AZ2 and AZ3, while AIR was correlated with AZ3 only. Greater moisture content and lower air-filled porosity associated with shallower depths of "oxidized" soil. The depth to the bottom of AZ3 showed the strongest correlation because it usually had a very abrupt, shallow lower boundary on sites featuring saturated soils. AZ2 and AZ3 were also well correlated with D2ROOTS, showing that shallower rooting is associated with thinner zones of "oxidized" soil.

In the second measurement method, the lower zone is the same as AZ3 therefore relationships are identical (except for rounding). The upper zone (BZ1) generally shows stronger correlations with most properties than either AZ1 or AZ2 from the first method. It is also highly correlated with DH2OS, indicating shallow water tables are associated with shallow zones of "oxidized" soil. Nearly 40% of the variation in CWSI is associated with BZ1. It thus appears that measuring the depth of a "shiny" metal surface on steel rods provides the most meaningful index of the thickness of "oxidized" soil. It shows the best correlation to tree growth, and to soil properties which are affected by, or which directly influence the depth of aerated soil. Finally, it is relatively easy to identify the lower boundary of this zone. The mean depths to the bottom of the oxidized zones for the three site index classes are shown in Table 23.

Table 23. Means (and standard deviations) of oxidized zones on steel rods for site index classes.

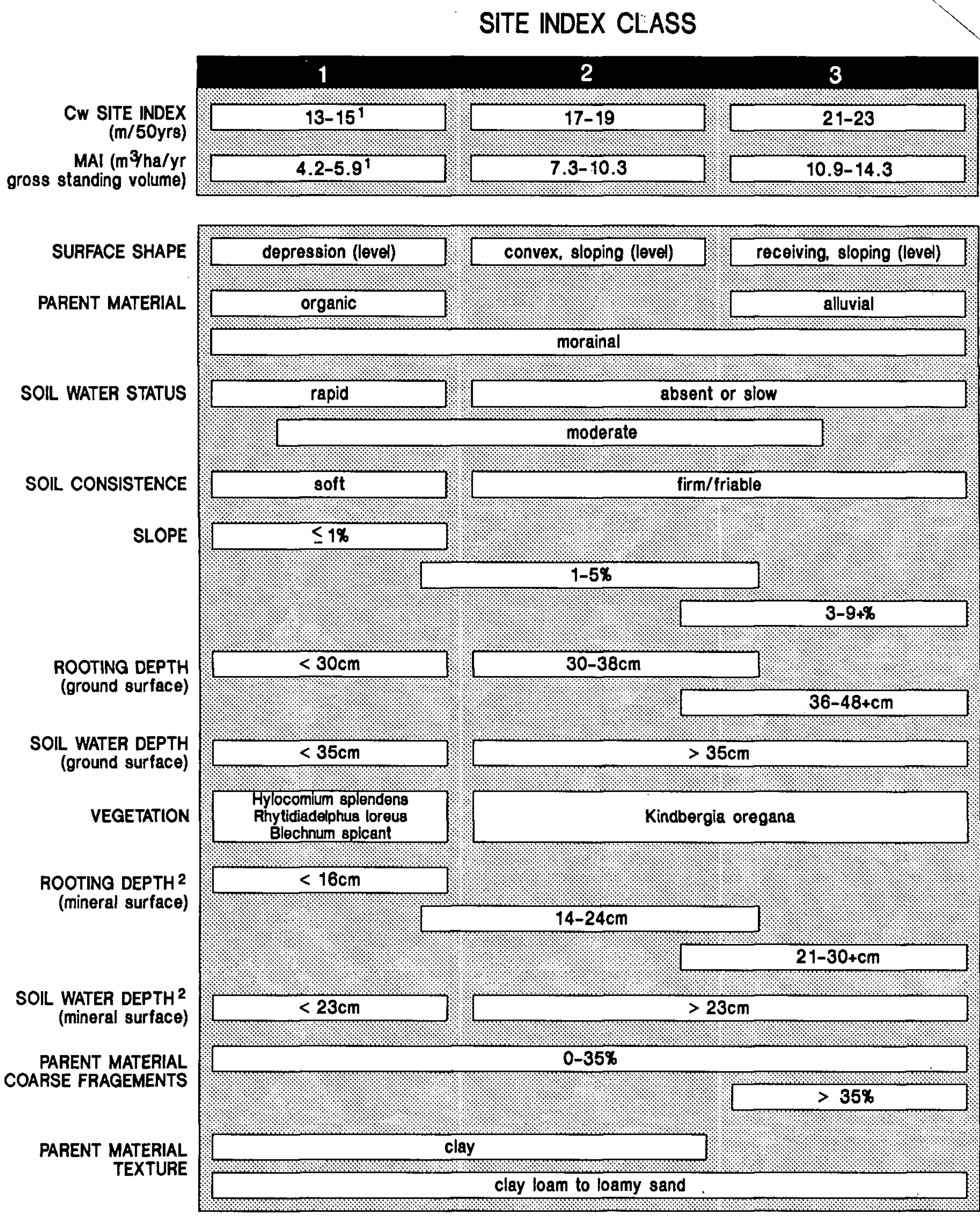
	Site Index Class		
Zone	1	2	3
n	8	8	8
AZ1	10[a1] (2)	14[a] (2)	14[a] (5)
AZ2	22[a] (6)	33[b] (6)	38[b] (6)
AZ3	31[a] (9)	45[b] (9)	50[b] (6)
BZ1	20[a] (6)	33[b] (10)	38[b] (10)
BZ2	31[a] (9)	45[b] (9)	50[b] (6)

[1] classes not followed by a common letter are significantly different using the Tukey HSD test ($P \leq 0.05$)

Site index classes 1 and 2 differ significantly for all measured oxidized zones except AZ1, while classes 2 and 3 do not differ. The class 1 and 2 differences reflect the abrupt change to non-oxidized steel at shallow depths in the class 1 sites featuring saturated surface soils. Soil properties which influence this, VMC and DH2OS, also differ significantly between class 1 and 2 but not between classes 2 and 3 (Table 11). While class 2 and 3 do not differ significantly, there is a trend of increasing thickness of oxidized soil from class 2 to 3. The mean depths of BZ1, considered the most useful of the measurements, are similar but slightly less than the mean rooting depths (D2ROOTS) for the site index classes. This would suggest that this simple measurement is a reasonable index of the zone of soil receiving sufficient aeration for root development.

5.6 A Simplified Model for Field Recognition of Site Index Classes

While the model previously described in Sec. 5.5.1 and based on field-recognizable properties showed a reasonably good relationship to CWSI, there were some potential limitations in its application associated with the SLOPE variable. In light of this, an attempt was made to synthesize all relevant, field-recognizable information revealed in the analysis into a simple system for characterizing and differentiating the three site index classes. This would provide field staff with a method for estimating the expected range in productivity indices for a given site based on important and easily measured or described ecological features. This system is summarized in Figure 28.



[1]95% confidence interval
[2]potentially applicable in old-growth stands

Figure 28. Summary of field-recognizable ecological properties in relation to site index classes

A number of site properties can interact in a variety of ways to affect the principal factors influencing variation in productivity - the depth and quality of the aerated root zone. Thus the best way to apply this information in identifying a site index class is to describe the appropriate site properties, assess where these fit on the summary figure, and determine which class is most strongly reflected.

Class 1 is easy to identify because of the persistent water table, saturated upper soil, and very shallow rooting. Sites from class 1 occur commonly throughout the lowlands, often grading into adjacent poorer bog forests. Classes 2 and 3 are more difficult to differentiate, and emphasis should be placed on rooting depth, slope, surface shape, and to some extent coarse fragment content in the parent material. However, it should be noted that sites from class 3 were relatively uncommon in the lowlands, occurring mainly in the Lawn Creek and Miller Creek areas. Even in Lawn Creek, they were fairly localized. Because of the fluctuations in water tables in relation to high rainfall periods, properties relating to soil free water characteristics are most relevant during the mid-late summer when the water tables have dropped and more-or-less stabilized. The data were collected from June 24 to July 17, 1987, a period when precipitation was infrequent. Rooting depth and depth to soil free water should be measured in several soil pits in an area and averaged. There is considerable variation in these properties on many sites.

To apply this information in identifying sites supporting old-growth stands, some adjustments must be made. Understory species composition is substantially different from second-growth stands and the forest floor is usually thicker, thus affecting total depths measured from the ground surface. Rooting depth and free water depth measured from the mineral soil surface should be used. These properties showed slightly weaker relationship to Cw site index and therefore show more overlap between productivity classes in the summary. The vegetation characteristics shown in the summary for second growth stands do not apply in old-growth. The relationships shown in the summary have not been tested in old-growth stands aside from cursory observations, and should be the subject of future research.

Terms used in Figure 28 are explained in the following:

SURFACE SHAPE: the general topographic expression of the site in question. Because of the subdued topography characteristic of the lowlands, surface shapes tend to be rather subtle, yet they can have a significant impact on productivity. Since water tables tend to be close to the surface, minor changes in surface topography can result in enough change in available aerated root zone to affect tree growth.

Depression: concave, depressional topography relative to surrounding area. While generally localized, depressional terrain can also be on a somewhat broader scale. It is associated with poor drainage and persistently high water tables.

Level: flat topography.

Sloping: sloping topography. In the lowlands, slopes are typically less than 10% except for localized stronger slopes (eg. gulleys, creeks, etc.), and the more sloping terrain rising to the Skidegate Plateau in the south (eg. Miller Ck., Lawn Hill).

Convex: somewhat "elevated" convex topography relative to the surrounding area. Again this tends to be a subtle expression, often representing less that 1 m elevation difference from an adjacent depressional area.

Receiving: generally concave shaped, lower positions of gentle slopes which receive additional inputs of seepage water. Often the moving water is better oxygenated than stagnant soil water resulting in better productivity. Such sites were found at Lawn Hill and Miller Cr.

PARENT MATERIAL: the unweathered material from which soils are derived (below the upper "developed" horizons).

Organic: parent material comprised of organic sediments. These are poorly to well decomposed "peat" or "muck" type materials that are saturated with water. Typically these are more than 40cm thick below the forest floor but thinner layers may be considered under this category. Organic soils were not sampled in the study but were observed under low productivity stands during reconnaissance.

Alluvial: older, usually inactive post-glacial alluvial sediments associated with creeks and rivers.

Morainal: glacial till, generally fine-textured and dense in lowland ecosystems.

PARENT MATERIAL COARSE FRAGMENTS: estimated volumetric content of gravel, cobbles and stones in the parent material.

SOIL WATER STATUS: characteristics of "free water" present in the soil profile.

Absent: none visible in the soil pit.

Slow: very slow seepage into pit; no appreciable standing water.

Moderate: seepage water moving slowly but steadily into pit; standing water present but does not accumulate quickly to appreciable depth.

Rapid: seepage water moving rapidly into pit, accumulating quickly to appreciable depth (bailing bucket required).

SOIL CONSISTENCE: the apparent consistency or structure of soil in the root zone.

Soft: a soft, "squishy" consistency similar to soft butter.

Firm-friable: soil is firm and/or friable; appears to have some structure.

ROOTING DEPTH (ground surface): depth from the ground surface to the bottom of the zone of visible living roots.

SOIL WATER DEPTH (ground surface): depth from the ground surface to the presence of free water in the soil profile.

VEGETATION: predominant understory species, the principal differentiating ones being *Hylocomium splendens, Kindbergia oregana, Rhytidiadelphus loreus,* and *Blechnum spicant.*

ROOTING DEPTH AND SOIL WATER DEPTH (mineral surface): as above but measured from the surface of the mineral soil (below forest floor).

5.9 General Discussion

Several approaches have been used to examine the data, from the perspective of site index-defined classes, classes recognized in the data structure itself, to functional relationships among various properties. In all the analyses, essentially the same key features were revealed regarding the important ecological variables associated with variation in tree growth. Site index of redcedar is associated with the quantity and to some extent, availability of root zone nutrient reserves, the aeration status of the available rooting zone, and the effective rooting depth. This conforms to the majority of previous site/productivity studies where forest productivity is largely correlated with soil properties that reflect the status of soil moisture, soil nutrients, and soil aeration (given a uniform climate) (Ralston 1964, Broadfoot 1969, Carmean 1975, Pritchett and Fisher 1987). However, the precise nature of these relationships varies with the tree species, soil, physiography, climate, and region under investigation.

5.9.1 Soil nutrient status

In this study, soil nutrient content, expressed on a kg/ha basis, particularly total N and exchangeable Mg, was found to be strongly associated with tree growth. Similar results have been observed in other studies relating soil properties to tree growth. For example, total N in the forest floor was found to have the highest and most consistent correlation of all site variables with growth of Sitka spruce on a range of soils in northeast Scotland (Blyth and MacLeod 1981a, 1981b). Because rooting was confined mainly to the forest floor in these sites, N content of the mineral soil did not contribute much to the relationship. In contrast to the Graham Island sites, extractable (by acetic acid) Mg showed a significant although weak negative correlation with Ss growth in these Scottish soils. It was believed this reflected the influence of drainage on growth as Glentworth and Muir (1963, as cited by Blyth and MacLeod 1981a) found that exchangeable Mg increased in the subsoil as drainage deteriorates.

Total N and exchangeable Mg content in the mineral soil (Kabzems 1985) and mineral soil plus forest floor (Roy 1984) were found to correlate strongly with Douglas-fir site index in ecosystems of south coastal B.C. In both these studies, however, mineralizeable N accounted for the greatest variation in Fd site index. This contrasts with the Graham Island study area where mineralizable N showed a positive but less pronounced trend with Cw site index. Most of these sites featured well-developed, acid Mor humus forms which are known to be associated with slow decomposition and mineralization rates (Wilde 1958, Klinka *et al.* 1981). Given these conditions, a more subdued trend with increasing site quality can be expected in comparison to the Douglas-fir ecosystems described by Roy (1984) and Kabzems (1985) where humus forms varied through Mors, Moders, to Mulls from low to high productivity, respectively. In fact, the one plot featuring a Moder humus form in the Graham Island sample also had the highest level of mineralizable N.

Mineral soil and forest floor pH and C/N ratios showed an increasing and decreasing trend respectively in relation to tree growth. These trends, particularly the latter, are generally associated with improving mineralization rates (Powers 1980, Pritchett and Fisher

1987) and do in fact coincide with increasing mineralizable N content in the study plots. However, C/N ratios are high and pH levels very acid in most plots, indicating a relatively low availability of N in these soils (Heilman 1979). This again explains the more subdued relationship between mineralizable N and tree growth relative to Douglas-fir ecosystems.

An interesting feature of the Graham Island sites was the lack of any relationship between phosphorus and tree growth. In Britain, total P is one of the most frequent nutrients found important for tree growth (White 1982). In northeast Scotland, total P content in the forest floor was consistently correlated with Sitka spruce growth (Blyth and MacLeod 1981a). Phosphorus deficiencies, manifested as retarded growth, are widespread in conifer plantations on poorly drained soils. Reactions between P and soluble Fe, Al, and Mn in strongly acid and poorly aerated soils form hydroxyphosphates which render P insoluble and unavailable to plants (Pritchett and Fisher 1987).This is particularly true of soils featuring large amounts of extractable aluminum (James *et al.* 1978). In the Graham Island sites, soils are very acid with high (>1%) extractable Al concentrations, and most are poorly aerated for varying durations, therefore available P levels are likely to be low across most of the study area. In addition, the lack of any relationships which have been shown in other studies may reflect the form in which P was expressed. Blyth and MacLeod (1981a) found available P to be poorly correlated with Ss growth while total P was consistently correlated over a wide range of soils in Scotland. Similar findings have been reported by Adams *et al.* (1970) and James *et al.* (1978). While total P content may be high, the majority of it is not available to plants, being bound in organic form in the forest floor and high organic matter content characteristic of these mineral soils (James *et al.* 1978). The lack of correlation between available P and Cw site index in the Graham Island sites is consistent with these findings.

To place the Graham Island soils into perspective with other coastal B.C. soils, they were assessed in relation to the quantitative classification of soil nutrient regimes proposed by Courtin *et al.* (1985). This classification is based on a population of mesothermal soils from coastal southwestern B.C., and uses C/N ratio and pH of the forest floor, and total N and the sum of exchangeable bases in the mineral soil root zone (in kg/ha) to characterize classes. Soils from site index classes 1 and 2 were most similar to the "poor" nutrient regime, while site index class 3 soils were within the range of the "medium, N low" nutrient regime. The C/N ratios in the Graham Island soils tended to be higher than those characterizing the nutrient regime classes, likely reflecting slower forest floor decomposition in the cooler soils in the study area. The sum of exchangeable bases tended to be slightly lower in the Graham Island sites which may reflect greater leaching losses from these soils. In soils featuring poor aeration, Fe and Mn in reduced form displaces cations from exchange sites rendering them more susceptible to leaching, particularly in high precipitation climates (Ponnamperuma 1984).

5.9.2 Soil aeration

Poor soil aeration, reflected in moisture content, air-filled porosity, and oxidation of iron rods was consistently associated with poorer tree growth in the Graham Island sites.

Similar relationships have been found in other areas where soils feature periodic or seasonal saturation. Armstrong *et al.* (1976) found improved growth of Sitka spruce associated with better soil aeration indicated by soil oxygen flux measured in the profile of peaty gley soils in Scotland. Moisture content of the surface 15 cm of soil, a reflection of aeration, was significant in regression models using soil physical and morphological properties to predict Sitka spruce growth in Britain (Page 1970). Blyth and MacLeod (1981a, 1981b) found depth to mottling to be highly correlated with Sitka spruce yield in forests of Scotland where poor drainage and soil aeration are important. Growth of loblolly pine and other tree species has been found to be associated with soil properties related to aeration status such as depth to a water table and mottling in coastal lowland ecosystems of the southeast U.S. (Klawitter 1978). In general, soil aeration "stress" can have a profound effect on forest productivity as a good supply of oxygen is necessary for root growth and function (Pritchett and Fisher 1987). Poor aeration affects soil chemical properties by setting in motion a series of "redox" reactions according to the degree of anaerobism. Denitrification of nitrate takes place, which may lead to net loss of N. As previously mentioned, Fe and Mn become soluble in their reduced forms, displacing cations from exchange sites where they may be subject to increased leaching losses (Ponnamperuma 1984). Ethylene, an important plant growth regulator, is produced in oxygen-deficient soils, and may reach concentrations which are injurious to plant growth (Smith and Renstall 1971).

Poor soil aeration also directly affects the plant. Reduced root respiration in an oxygen-deficient environment is believed to stimulate abcissic acid (ABA) production in leaves which causes stomata to close and photosynthesis to drop (Ray 1972). This has been shown to occur in Sitka spruce (Coutts 1980). Other plant growth regulators are affected by signals from aeration- stressed roots, with the general trend being lower production of gibberellic acids and cytokinins, and increased contents of auxins and ethylene in above-ground plant parts (Reid and Bradford 1984). The exact nature of the physiological effects of these changes is poorly understood, although ethylene accumulation has been shown to accelerate leaf abscission and senescence (Sexton 1985) and is associated with several morphological adaptations for tolerating poorly aerated soils such as formation of adventitious roots (Hook 1984) and enhanced internal oxygen transport (Jackson 1985).

Nutrient uptake is reduced in plants influenced by poor soil aeration, largely due to reduced root respiration. This inhibits active transport of nutrients, particularly N, P, and K. Magnesium and Ca are less affected as they rely more on passive uptake (Kozlowski and Pallardy 1984). Lower transpirational demand associated with reduced plant vigour also contributes to lower rates of nutrient uptake. Lower nutrient uptake, particularly P, is exacerbated by reduced mycorrhizal development on roots in poorly aerated soil (Jackson and Drew 1985). Since most mycorrhizae are strongly aerobic, they are inhibited in poorly aerated soil. This has been demonstrated in many tree species, including Douglas-fir (Gadgil 1971), lodgepole pine (Boggie 1972, Coutts and Philipson 1978b) and Sitka spruce (Coutts and Philipson 1978b).

The above physiological effects of poor soil aeration generally interfere with providing adequate supplies of water, nutrients, and balanced plant growth regulators to the crowns of plants. The obvious result is reduced growth of the entire plant. Root growth not only slows or stops entirely, but dieback of major portions of the root network may occur. This results in development of a shallow root system, limited to the zone of adequate aeration. The extent to which these effects take place in a given ecosystem depends on the nature of soil saturation, including its depth, its duration, its timing during the year, and the quality of the water. Water quality, particularly dissolved oxygen content is believed to play an important role in the impact of soil saturation. Moving soil water contains higher concentrations of oxygen because of mixing and can offset aeration stress in trees (Pritchett and Fisher 1987). The dissolved oxygen data from the Graham Island sites did not show a definite relationship with tree growth, largely a result of measurement limitations. However, one plot did demonstrate enhanced dissolved oxygen content in what appeared to be a moving perched water table. It is likely that this factor plays a role in other site index class 3 sites featuring periodic soil saturation which are located on gentle slopes or adjacent to streams.

Perhaps the most important of soil saturation conditions is the timing of saturation events. Trees are most sensitive to soil saturation during the growing season when respiratory demand for oxygen is high and oxygen solubility is low due to higher temperatures (Gill 1970). For example, Coutts and Philipson (1978a) found substantially higher survival of lodgepole pine and Sitka spruce roots that were dormant when waterlogged, compared to those that were active. It was also observed that initially dormant roots resumed growth shortly after aeration was reestablished, while initially active roots took considerably longer to regenerate new growth. The point samples of indices of soil aeration used in this study are somewhat limited in that they do not provide any information on temporal variation in soil saturation activity over the range of sites, although they do address relative differences between sites during the mid-growing season. During my three years experience in the area, there has been considerable variation in the state of water tables on different sites, depending on the season, the precipitation events in the days preceding inspection, and in the growing season precipitation patterns. Obvious evidence of dieback of well-established roots in several soil pits indicates that the nature of soil saturation varies over the years, and that annual growth likely varies according to these conditions.

In addition to soil saturation conditions, the effects of poor soil aeration on tree growth also vary with the species. Different species have different capabilities for tolerating poor aeration. In general, angiosperms are more tolerant than gymnosperms. Western redcedar, lodgepole pine, and black spruce (*Picea mariana*) are examples of B.C. gymnosperms with relatively high tolerance. Since the principal limitation of saturated soil is oxygen deficiency, trees can follow two adaptation strategies. They can improve the internal supply of oxygen to the roots by way of morphological adaptations, or they can improve the ability of root cells to function in periods of low oxygen through metabolic adaptation. Usually a combination of these is adopted by most tolerant species (Tripepi and Mitchell 1984). Examples of morphological adaptations are the formation of hypertrophied lenticels to enhance gas exchange into the phloem (Hook and Scholtens 1978), formation of adventitious roots above the poorly aerated zone, and formation of special "water adapted" roots which feature enhanced internal transport of oxygen to the active root tips. Such roots develop in lodgepole pine in response to soil saturation and feature large stelar cavities which allow oxygen to move from aerated regions to root tips within poorly aerated environments (Coutts and Philipson 1978a, 1978b).

5.9.3 Rooting depth

The effective rooting depth was associated with tree growth in the Graham Island study (accounting for 51% of CWSI variation), with perched water tables and dense, heavy-textured, and/or strongly cemented soil layers limiting total rooting depth from the ground surface to under 50 cm for most sites. Root growing space, measured as the depth of rooted soil, has been used as an indicator of site productivity more often than most soil physical properties in other site/productivity studies. It can be measured with some accuracy, particularly if a distinct restricting layer occurs, and it integrates many other factors important to tree growth such as water storage capacity and nutrient reserve (Pritchett and Fisher 1987).

Rooting depth has been correlated with tree growth in a wide range of studies in North America (Carmean 1975) and specifically for Sitka spruce in Britain (Worrel 1987). Effective rooting depth in the study area, while restrictive in itself because of limitations in the volume of soil exploitable by trees, becomes more critical when periodic soil saturation reduces the quality of the already limited root zone. These root zone limitations will likely affect the long term productivity of stands on these sites. As stands develop, root systems extend and more fully exploit the fixed volume of soil. Thus the effective "quantity" of soil decreases in relation to the supply to trees (Armson 1977). Day (1963) suggested these factors would lead to eventual decline in stand volume and quality as stands age on lowland ecosystems of east Graham Island. He speculated that as stands age, they may reach a point where the demand for growing space and nutrients exceeds the supply capacity of these soils featuring shallow root zones. This would lead to decline in height growth, die-back of root systems, opening of the canopy due to death of the least tolerant trees (Sitka spruce), and invasion of understory shrub species such as salal, *Vaccinium* spp., and *Menziesia ferruginea*. A steady, slow decline in standing volume would follow, resulting in decadent old-growth stands such as those common in the study area. While his observations were based on limited data, Day's (1957, 1963) theories were intuitively logical and hold up in view of closer examination of these ecosystems.

5.10 Management Implications

Understanding some of the important ecological factors associated with tree growth provides a basis for developing management strategies which take advantage of these factors to improve forest productivity or prevent its degradation (Stone 1977). In the Graham Island study area, analysis of ecological relationships has provided some insight into what may be considered appropriate silvicultural practices, particularly regarding tree species selection and site amelioration.

5.10.1 Tree species selection

One of the most important, and least expensive silvicultural decisions to make is selecting suitable tree species to manage on a site. In the study area, the choice is limited to only four commercial species, however considerable variation was observed in relative species performance between different sites. The species of most concern is Sitka spruce. Not only is it the most sensitive species to degrading site conditions, but it is also the most preferred from a management perspective. Because of generally higher volumes and value of stands containing greater spruce components, managers favour spruce wherever possible (Farr and Harris 1983). In the study area, spruce showed the greatest sensitivity of all species to poor soil aeration, and decreasing soil nutrient content. In light of this it is unsuitable for site index class 1 ecosystems. In site index class 2 sites, soil aeration improves sufficiently so that spruce can form a component of mixed species stands. Based on existing stand conditions, it should be limited to less than 10 to 15% of the stand composition. One of the factors which enables spruce to perform reasonably well on these sites, in spite of their limitations in aerated rooting zone depths, may be the presence of lodgepole pine in the stand composition. It has been commonly observed in Britain that the performance of Sitka spruce on poorly aerated gley soils is enhanced significantly when grown together with lodgepole pine rather than in pure stands. While the mechanism for this synergistic effect is not clear, it is believed to be related to N supply (Carlyle and Malcolm 1985). The ability of lodgepole pine to aerate its rhizosphere in poorly aerated soil is one possible factor contributing to this effect. As previously discussed, pine can adapt to limited soil aeration by forming special "water adapted" roots which contain large cavities in the stele to allow enhanced internal transport of oxygen to the growing root tips (Coutts and Philipson 1978a, 1978b). This enables pine roots to function and, in fact, grow down to 20 cm and more into an anaerobic soil. This enhanced oxygen transport system was found to be absent in Sitka spruce roots, thus explaining its lower tolerance to aeration stress. Sitka spruce root systems would conceivably benefit from improved rhizosphere aeration in intimate association with lodgepole pine root systems in mixed stands.

Soil conditions improve sufficiently in site index class 3 ecosystems that spruce can be managed as a major component of mixed species stands. In such stands it generally achieves dominance in the canopy, with individual trees having large diameters relative to other species. However, it should not be managed as a monoculture on these sites as the soils may still be sufficiently limited, and unable to meet the demands of such stands.

Lodgepole pine plays an interesting role in these ecosystems as it is unusual to find it forming a major component of second-growth stands within wet maritime climates of B.C. Its establishment, no doubt, is a reflection of the fire history. Because of pine's high tolerance of poorly aerated soil, it has an important role in the management of these ecosystems. Specifically, it can be managed as a component in mixed species stands on site index class 1 and 2 sites. It is not well suited to long term production on site index class 3 sites as it is unable to successfully compete with Sitka spruce. Careful selection of planting stock is important for successful management of pine on these sites. The stock must be selected from local provenances adapted to the ecological conditions of Graham Island and it must also be capable of developing well-formed roots which can readily exploit the shallow rooting zones. To ensure good lateral root development from the root collar down, copper-coated containers should be used.

Redcedar and western hemlock appear suited to the full range of site conditions encountered and form components of all stands, although cedar is more tolerant of very poorly aerated soils (Hook and Scholtens 1978). A summary of the recommended species composition for management of these sites is shown in Table 24.

Table 24. Recommended tree species composition for sites on east Graham Island.

Site index class	Species composition
1	Cw (leading), Pl, Hw
2	Cw, Hw, Pl, (Ss)
3	Hw, Ss, Cw

5.10.2 Site amelioration

Since the major factor limiting productivity in these sites is the shallow depth of well aerated root zones, one method of improving productivity potential is to increase the available rooting space. Two approaches to this problem are to reduce the effects of perched water tables on the root zone through forest drainage, or to raise the level of aerated soil above the restricting layer through mounding. Drainage of poorly drained soils for forestry has been widely used in the U.S. Southeast and Gulf coastal plains, as well as

Britain, and European and Scandinavian countries. Substantial increases in stand yield have been realized on many sites through this practice, with the major benefits being derived from increased rooting depth, improved soil aeration, and reduced windthrow (Pritchett and Fisher 1987). However the effectiveness of surface water draining varies considerably depending on the conditions of the site, the design and construction of the drainage system, and the follow-up maintenance.

Soil hydraulic conductivity is of prime importance as it affects the draw-down effect of ditches. In heavy textured soils with slow conductivity, the draw-down of the water table may only extend a few meters from the ditch. Substantially greater density of drainage ditches is required in such cases to effectively remove water from the site (Boelter 1978, Pritchett and Fisher 1987). Drainage systems must be engineered with a continuous ditch grade to prevent ponding. Therefore, uniform, gently sloping topography is most suitable. To be effective, the drainage system must have an outlet which will allow water to move off the site in a short period of time (Terry and Hughes 1978). Drainage systems must also be maintained for long-term effectiveness, to prevent ditches from plugging and allowing the site to revert to its original condition (Thomasson 1975). Another form of drainage involves ripping strongly cemented soil horizons which impede water movement. Such techniques are only applicable where subsoils are deep and freely drained. Rapid reconsolidation of ripped trenches may limit long-term effectiveness.

In the Graham Island study area, drainage has relatively limited application. The majority of soils are heavy textured tills with low hydraulic conductivity. Limited draw-down of surface water would require high drainage density. Because of the dense subsurface layers, root development would still remain limited to a shallow zone. However, successful drainage would improve the aeration conditions within this limited root zone. Drainage design would pose problems over much of the area due to a lack of continuous slope. Also, natural drainage systems are infrequent, making it difficult to construct effective drainage outlets. There is some potential for drainage in the northern portion of the area on glaciofluvial sand deposits. Portions of this area feature gently sloping terrain suitable for drainage systems. The occurrence of deep, coarse textured, freely-drained sand below the impermeable layer in some areas provides an outlet for drainage, however maintenance of such an outlet is essential to prevent build up of finer-textured sediments with lower hydraulic conductivity. Because of the strongly cemented horizons common in these soils, the increased volume of aerated soil provided by drainage will remain limited.

An alternative to surface water drainage is mounding. Row mounding (bedding) has been used in the U.S. Southeast coastal plain to improve growth of slash pine (*Pinus elliottii*) on water logged soils (Pritchett and Fisher 1987). Haines and Haines (1978) observed improved soil conditions from bedding, resulting in substantially larger and more extensive slash pine root systems compared to untreated soils. The density of branching and frequency of mycorrhizal associations was particularly improved through bedding. One of the limitations of this form of bedding is that the early advantages from the treatment may not persist through the rotation. The mounds are created by bedding harrows or ploughs, and represent a relatively small volume of "raised" soil. While such volumes enhance early stand performance, trees would fully exploit the improved rooting medium well before they reached maturity.

Mounding offers the most promise as a site modification treatment in the Graham Island area, however a specific form of mound is required to achieve the greatest long term benefits. Based on the results of this study, a relatively modest increase in the depth of aerated soil is associated with substantial increases in tree growth. Therefore mounds can be relatively low (eg. 50 cm). Mounds should, however, be wide (eg. 2-3 m) to provide a large volume of aerated soil for root systems to exploit as the trees age. Such mounds would closely mimic the type of blowdown disturbance which is associated with productive tree growth within the study area. To accelerate the weathering and amelioration of recently overturned subsoils, a cover of grasses and legumes can be established on the mounds following planting. This type of mounding treatment can be undertaken with medium-sized excavators, and has been found to be operationally feasible in a trial area north of Port Clements. While costs are relatively high, expected long term gains should be substantial, both in terms of stand yield and value, and in expanding the forest land base by incorporating land currently excluded from the yield analysis.

6.0 SUMMARY

Twenty-four sample plots were established in fire regenerated second-growth stands on the east side of Graham Island, Queen Charlotte Islands. These were distributed over a range of site productivities as indicated by site index of western redcedar, and represented a number of imperfectly to poorly drained mineral soils characteristic of the coastal lowland ecosystems. Soil chemical and physical properties, soil water quality, floristic composition, mensuration characteristics, and site index of major tree species were determined for each plot. The available data were screened to select the most promising variables for examining site/productivity relationships. Three classes defined by site index of cedar were characterized according to stand properties and ecological properties. Discriminant analysis was used to test objectively the validity of these classes in relation to soil properties. Inherent structure in the soils data was assessed using a combination of principal components analysis and cluster analysis. Reciprocal averaging was used to examine structure present in the vegetation data. Inherent data structure was compared with the three site index classes to assess how well these classes reflect ecological patterns in the study area. Functional relationships between cedar site index and ecological properties were investigated using multiple linear regression. Relevant information revealed in all the analyses was incorporated into a simplified model for field recognition of site index classes to assist practitioners. Results of the study were interpreted in relation to suggested silvicultural practices for these ecosystems.

The main results of the study are summarized as follows:

1. Tree growth, as expressed by cedar site index, was correlated with nutrient content in the available root zone, the depth of this root zone, and the mineral soil root zone aeration, as reflected by moisture content, air-filled porosity, and oxidation of iron rods. Of the nutrients examined, total nitrogen and exchangeable magnesium showed the strongest relationships. A simple model using total N content and volumetric moisture content in the mineral soil root zone summarized the relationship between site index and soil properties, accounting for 78% of the site index variation. This model indicates that the quantity of root zone nutrient reserve available to trees, and the aeration status of the root zone, as reflected by moisture content, are most important to tree growth. Using field-recognizable variables alone, 73% of the variation in site index could be accounted for in a simple model using total rooting depth from the ground surface and slope. There is, however, some question as to whether this relationship is realistic for the whole study area because of some limitations in the slope variable. Rooting depth alone accounted for 51% of site index variability.

2. The effectiveness of understory vegetation showed some limitation in accurately reflecting site conditions due to non-site related variation. While the wettest, lowest productivity sites clearly differed from remaining sites largely on the basis of moss cover, the site index class 2 and 3 sites could not be floristically differentiated. In spite of their similar understory development, these sites ranged considerably in productivity (7 to 14 m^3 ha^{-1} yr^{-1} MAI), and soil properties. In such dense stands with poor floristic diversity, emphasis on soil and physiographic features is required to effectively recognize important differences in site quality.

3. Three site index classes were originally designed as sampling strata to obtain a balanced distribution of plots. However, these classes appeared to reflect natural groupings occurring in the study area. Cedar site index observed in second-growth stands tended to cluster within the ranges of each class, with 13-14 m, 17-18 m, and 21 m/50yrs b.h. age being the most frequent site indices encountered. These site index classes are reasonably well discriminated by soil properties using discriminant analysis, and are also reflected, with minor overlap, in the natural structure present in the soil data. Site index classes and soil-defined clusters do not differ substantially in terms of stand and soil variables.

4. Subtle differences in topography can have a big impact on tree growth. Many of the study sites could be considered sensitive in relation to changing environmental conditions. Soils have limiting conditions in the form of slowly permeable, root restricting layers close to the surface. Minor physiographic variation can increase or decrease the volume of well-aerated rooting zone sufficiently to affect productivity. Tree growth is sensitive to relatively minor changes in the major limiting factor, as on most ecologically "limiting" sites.

5. Sitka spruce is the most sensitive of the tree species present in these stands to deteriorating site quality. Hemlock, lodgepole pine, and cedar followed similar height growth patterns based on site index, although Hw tends to have slightly slower growth than cedar on the poorest sites. Spruce exhibits substantially poorer growth than cedar

on the poorer sites, but as site conditions improve, its performance exceeds that of cedar. This reflects spruce's ability to grow very rapidly when site conditions become adequate for its requirements.

These relative differences in tree species tolerance to site conditions are reflected to some extent in stand composition. Poorest sites support Cw, with slightly less Hw, and Pl proportions; intermediate sites support approximately equal proportions of Cw, Hw, and Pl, with a minor component of Ss; the better sites support equal proportions of Cw, Hw, and Ss, with Pl dropping out because of its inability to compete with the dominant Ss.

6. Some management strategies were recommended on the basis of the ecological relationships observed in the study, . Tree species selection generally follows the patterns of species composition observed above. The recommended mixtures are: for site index class 1 - Cw, Pl, and Hw; for site index class 2 - Cw, Hw, Pl, (Ss); for site index class 3 - Hw, Ss, Cw.

Site modification treatments aimed at increasing the depth of aerated root zone have good potential for improving productivity of these ecosystems. Creating relatively low but wide mounds would provide a reasonable volume of aerated soil which can be exploited as trees age. Such mounds would closely mimic the type of blowdown disturbance associated with productive tree growth within the study area. To accelerate the weathering and amelioration of recently overturned subsoils, a cover of grasses and legumes may be established on mounds following planting.

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APPENDIX A. Alphabetical list of plant species.

BAZZDEN	Bazzania denudata	(Torrey ex Gott. *et al.*)
BLECSPI	Blechnum spicant	(L.) Roth
BLEPTRI	Blepharostoma trichophyllum	(L.) Dum.
CALYMU	Calypogeja muelleriana	(Schiffn.) K. Mull.
CALYTRI	Calypogeja trichomanis	(L.) Corda
CAREANT	Carex anthoxanthea	(Presl)
CEPHBIC	Cephalozia bicuspidata	(L.) Dum.
CEPHLUN	Cephalozia lunulifolia	(Dum.) Dum.
COPTASP	Coptis aspleniifolia	Salisb.
CYSTFRA	Cystopteris fragilis	(L.) Bernh. in Scrad.
DICRFUS	Dicranum fuscescens	Turn.
DICRSCO	Dicranum scoparium	Hedw.
DRYOEXP	Dryopteris expansa	(Presl) Fraser-Jenkins
EQUARV	Equisetum arvense	L.
GAULSHA	Gaultheria shallon	Pursh
GYROUND	Gyrothyra underwoodiana	M.A. Howe
HOOKLUC	Hookeria lucens	(Hedw.) Sm.
HYLOSPL	Hylocomium splendens	(Hedw.) B.S.G.
HYPNCIR	Hypnum circinale	Hook.
KINDBER	Kindbergia oregana	(Sull.) Ochyra
LEPIREP	Lepidozia reptans	(L.) Dum.
LISTCAU	Listera caurina	Piper
LISTCOR	Listera cordata	(L.) R. Br. in Ait.
LOBAORE	Lobaria oregana	(Tuck.) Mull. Arg.
LOPHINC	Lophozia incisa	(Schrad.) Dum.
LUZUPAR	Luzula parviflora	(Ehrh.) Desv.
LYSIAME	Lysichitum americanum	Hult. & St. John
MAIADIL	Maianthemum dilitatum	(How.) Nels. & Macbr.
MALUFUS	Malus fusca	(Raf.) Schneid.
MENZFER	Menziesia ferruginea	Sm.
MONEUNI	Moneses uniflora	(L.) Gray
PELLNEE	Pellia neesiana	(Gott.) Limpr.
PELTAPH	Peltigera aphthosa	(L.) Willd.
PLAGPOR	Plagiochila porelloides	(Torrey ex Ness) Lindenb
PLAGUND	Plagiothecium undulatum	(Hedw.) B.S.G.
PTERAQU	Pteridium aquilinum	(L.) Kuhn in Decken
RHIZGLA	Rhizomnium glabrescens	(Kindb.) Kop.
RHYTLOR	Rhytidiadelphus loreus	(Hedw.) Warnst.
SCAPBOL	Scapania bolanderi	Aust.
SPHAGIR	Sphagnum girgensohnii	Russ.
SPHASQU	Sphagnum squarrosum	Crome
STREAMP	Streptopus amplexifolius	(L.) DC.
VACCALA	Vaccinium alaskaense	How.
VACCPAR	Vaccinium parvifolium	Sm. in Rees
VERAVIR	Veratrum viride	Ait.

APPENDIX B. Conversions from nutrient concentration to kg/ha (modified from Kabzems (1985).

To convert soil nutrients expressed as concentrations (percent, ppm, meq/100g) to weight (kg) per hectare for a given soil layer. To calculate total nutrient content for a site, combine the kg/ha calculated for the forest floor, with that calculated for the mineral soil to the appropriate rooting depth.

1. Determine the proportion (P) of soil (<2mm fraction) consisting of nutrient "N":

i) for ppm: $P = \text{ppm N} \times 10^{6}$

ii) for %: $P = \%\text{ N} \times 10^{-2}$

iii) for meq/100g: $P = (\text{meq N}/100) \times 10^{3} \times \text{equivalent wt.} \times 10^{6}$

2. Determine the weight of soil (<2 mm fraction) in 1 hectare for the thickness of the soil layer.

$\text{kg soil/ha} = \text{BDcff} \times 10^{-3} \times 10^{8} \times \text{TH} \times (1\text{-CF})$

where BDcff is coarse-fragment-free bulk density (Mg/m^3), TH is layer thickness (cm) and CF is the proportion of coarse fragments, by volume.

3. Calculate the weight of nutrient "N" in the soil layer.

$\text{kg/ha N} = \text{P} \times \text{kg soil/ha}$

These calculation steps can be reduced as follows:

For nutrient N:

i) expressed in %: $\text{kg/ha N} = 10^{3} \times \%\text{N} \times \text{BDcff} \times \text{TH} \times (1\text{-CF})$

ii) expressed in ppm: $\text{kg/ha N} = 10^{-1} \times \text{ppmN} \times \text{BDcff} \times \text{TH} \times (1\text{-CF})$

For exchangeable bases (expressed in meq/100g):

kg/ha CA: $\text{kg/ha CA} = 20.04 \times \text{meqCA} \times \text{BDcff} \times \text{TH} \times (1\text{-CF})$

kg/ha MG: $\text{kg/ha MG} = 12.16 \times \text{meqMG} \times \text{BDcff} \times \text{TH} \times (1\text{-CF})$

kg/ha K: $\text{kg/ha K} = 39.096 \times \text{meqK} \times \text{BDcff} \times \text{TH} \times (1\text{-CF})$

APPENDIX C. Soil chemical data - kg/ha nutrients in the forest floor.

Note: See page xii for explanation of codes. Class refers to site index class.

PLOT	CWSI	Class	TC	TN	MINN	P	CA	MG	K
1	21	3	119685	2023	48	18	407	245	113
2	20	2	87814	1819	31	12	391	231	88
3	22	3	51566	1102	28	13	333	136	70
4	18	2	82737	1403	53	17	304	166	111
5	21	3	79679	1814	36	10	290	198	68
6	16	2	76057	1242	23	13	229	206	119
7	14	1	74368	1496	26	12	203	188	96
8	18	2	70881	1116	28	7	273	172	96
9	11	1	86391	1411	27	11	347	181	124
10	23	3	123831	2366	37	10	449	285	137
11	15	1	46701	920	14	5	205	117	52
12	22	3	75248	1438	34	11	276	159	82
13	15	1	108284	1739	32	21	435	238	139
14	22	3	66242	1265	45	7	413	120	117
15	18	2	75153	1364	44	8	296	142	107
16	15	1	74951	1364	36	11	216	146	116
17	18	2	65824	1213	41	10	283	113	98
18	18	2	93380	1401	37	8	361	226	110
19	15	1	46751	916	27	6	242	85	68
20	17	2	72912	1178	36	12	343	173	129
21	14	1	65797	1305	31	11	355	156	78
22	15	1	48503	892	17	6	190	88	66
23	25	3	78222	2240	64	5	605	192	70
24	23	3	93491	1831	39	6	429	292	109

APPENDIX D. Soil chemical data - kg/ha nutrients in the mineral soil to the secondary rooting depth

Note: See page xii for explanation of codes. Class refers to site index class.

Plot	CWSI	Class	TC	TN	MINN	P	CA	MG	K
1	21.2	3	77207	2167	30	8	122	217	70
2	19.9	2	67607	1333	21	5	74	87	39
3	21.9	3	94956	2457	25	5	269	388	119
4	17.6	2	38945	856	17	5	29	57	41
5	21.1	3	115713	3135	51	8	144	229	77
6	16.4	2	59097	1477	12	5	54	200	72
7	13.7	1	4493	109	2	0	3	4	2
8	18.3	2	53761	1213	14	3	81	108	57
9	10.9	1	54650	1228	14	4	36	42	39
10	23.3	3	114915	3075	30	2	28	184	97
11	14.6	1	57596	1558	23	1	77	87	33
12	21.8	3	88978	2650	50	2	54	156	121
13	14.5	1	64318	1130	12	3	39	118	55
14	21.5	3	71273	1944	45	4	214	227	92
15	18.0	2	88901	2263	37	5	69	115	76
16	14.7	1	86950	2090	32	5	50	81	71
17	17.8	2	112852	2590	32	8	224	260	109
18	18.0	2	55571	1179	19	3	35	143	60
19	14.9	1	36052	751	9	1	30	35	18
20	16.6	2	116591	1683	29	5	108	239	109
21	13.5	1	61133	1210	15	2	28	48	33
22	15.3	1	99877	2014	34	2	25	60	48
23	25.1	3	103762	4573	161	2	60	392	199
24	22.5	3	163894	4583	57	3	147	266	82

APPENDIX E. Soil chemical data - kg/ha nutrients in the combined forest floor plus mineral soil to the secondary rooting depth.

Note: See page xii for explanation of codes. Class refers to site index class.

PLOT	CWSI	Class	TC	TN	MINN	P	CA	MG	K
1	21	3	196892	4190	78	25	529	462	184
2	20	2	155421	3152	52	17	465	319	127
3	22	3	146523	3559	54	18	602	524	189
4	18	2	121682	2259	70	22	333	223	152
5	21	3	195392	4949	86	18	433	427	146
6	16	2	135154	2719	35	18	283	405	191
7	14	1	78861	1604	28	12	207	193	98
8	18	2	124642	2329	41	10	354	280	152
9	11	1	141041	2639	40	15	384	223	162
10	23	3	238746	5441	68	12	477	468	234
11	15	1	104297	2478	37	6	282	203	85
12	22	3	164227	4088	84	13	331	315	203
13	15	1	172601	2869	44	25	473	357	194
14	22	3	137515	3209	90	11	627	347	209
15	18	2	164054	3627	80	13	365	256	183
16	15	1	161901	3455	69	16	266	227	187
17	18	2	178677	3804	73	18	507	374	207
18	18	2	148951	2580	57	11	396	368	170
19	15	1	82803	1667	36	7	272	120	86
20	17	2	189503	2862	65	16	452	412	238
21	14	1	126929	2515	47	13	383	204	111
22	15	1	148379	2906	52	8	215	148	113
23	25	3	181984	6813	225	6	665	584	269
24	23	3	257385	6413	96	9	576	558	191

APPENDIX F. Soil chemical data - pH and C/N ratios for the forest floor and root zone mineral soil.

Note: See page xii for explanation of codes. Class refers to site index class.

PLOT	CWSI	CLASS	HUMPH	HUMCN	MINPH	MINCN
1	21.2	3	3.2	59.5	3.4	35.2
2	19.9	2	3.3	48.6	3.3	51.8
3	21.9	3	3.6	46.9	3.8	38.6
4	17.6	2	3.2	59.3	3.3	44.4
5	21.1	3	3.2	44.1	3.6	37.2
6	16.4	2	3.2	61.5	3.5	40.0
7	13.7	1	3.1	50.7	3.4	41.3
8	18.3	2	3.3	63.6	3.5	43.9
9	10.9	1	3.2	61.7	3.3	44.4
10	23.3	3	3.2	52.4	3.5	37.3
11	14.6	1	3.5	50.9	3.7	36.8
12	21.8	3	3.2	52.9	3.3	33.9
13	14.5	1	3.2	62.4	3.1	56.5
14	21.5	3	3.6	52.7	3.5	37.1
15	18.0	2	3.2	55.3	3.3	39.2
16	14.7	1	3.1	55.0	3.3	41.6
17	17.8	2	3.3	54.3	3.4	43.9
18	18.1	2	3.2	66.8	3.3	47.3
19	14.9	1	3.3	51.1	3.3	48.0
20	16.6	2	3.4	62.2	3.4	70.9
21	13.5	1	3.3	50.5	3.3	51.4
22	15.3	1	3.2	54.4	3.2	49.7
23	25.1	3	3.7	34.9	4.1	22.7
24	22.5	3	3.5	51.3	3.5	36.6

APPENDIX G. Soil physical properties.

Note: See page xii for explanation of codes. Class refers to site index class; BDMIN and BDFF refer to bulk density of root zone mineral soil and forest floor respectively, expressed in Mg/m^3. VMC and AIR are expressed as proportions; DH2OS, D2ROOTS, FFDEP, and CAP in cm; and SAND, SILT, CLAY in percent.

PLOT	GC	CWSI	VMC	AIR	BDMIN	BDFF	DH2OS	D2ROOTS	FFDEP	CAP	SAND	SILT	CLAY
1	3	21.2	0.58	0.07	0.90	0.12	47	37	22		40.8	34.0	25.2
2	2	19.9	0.69	0.10	0.51	0.11	34	34	18	18	25.2	53.7	21.1
3	3	21.9	0.56	0.14	0.77	0.12	26	39	10	12	26.6	53.2	20.2
4	2	17.6	0.58	0.12	0.78	0.12	47	29	16	21	52.4	32.6	15.0
5	3	21.1	0.59	0.18	0.59	0.14	32	37	13	17	18.5	55.2	26.3
6	2	16.4	0.60	0.15	0.65	0.10	36	36	16	19	25.8	51.4	22.8
7	1	13.7	0.84	0.09	0.14	0.11	34	35	15	42	9.9	51.8	38.3
8	2	18.3	0.50	0.23	0.70	0.12	57	31	13	13	48.3	39.2	12.5
9	1	10.9	0.65	0.12	0.55	0.11	29	26	18	12	30.0	50.2	19.8
10	3	23.3	0.48	0.27	0.63	0.13	88	50	21	15	24.3	48.9	26.8
11	1	14.6	0.81	0.06	0.31	0.11	21	22	10	15	15.2	53.1	31.7
12	3	21.8	0.54	0.18	0.99	0.13	84	37	14	13	26.9	50.2	22.9
13	1	14.5	0.60	0.11	0.72	0.14	26	25	18	12	24.6	55.2	20.2
14	3	21.5	0.42	0.22	0.92	0.13	121	45	12		62.7	26.8	10.5
15	2	18.0	0.54	0.08	0.97	0.12	42	30	14	11	23.9	53.4	22.7
16	1	14.7	0.68	0.12	0.50	0.13	30	30	13	16	24.5	53.2	22.3
17	2	17.8	0.57	0.14	0.74	0.10	79	41	14	13	21.9	54.7	23.4
18	2	18.1	0.52	0.16	0.83	0.11	106	34	19	9	39.3	45.6	15.1
19	1	14.9	0.74	0.11	0.38	0.09	29	21	11	18	26.5	26.5	20.0
20	2	16.6	0.47	0.18	0.88	0.11	90	42	15	13	34.0	52.0	14.0
21	1	13.5	0.73	0.09	0.42	0.12	42	20	12	17	20.3	59.2	20.5
22	1	15.3	0.81	0.09	0.22	0.11	30	29	10	19	12.4	49.7	37.9
23	3	25.1	0.45	0.24	0.84	0.21	96	34	9	15	28.2	45.6	26.2
24	3	22.5	0.66	0.14	0.46	0.11	69	48	19	20	25.2	47.8	27.0

APPENDIX H. Categorical variables.

Note: See page xii for explanation of codes. CLASS refers to site index class. Categories are as follows: H2OST - 1=absent, 2=slow, 3=moderate, 4=rapid; ROOT - 1=very few, 2=few, 3=plentiful, 4=abundant; CONS - 0=firm or friable, 1=soft; CEM - 0=strongly cemented horizon absent, 1=cemented horizon present; TEXPM - 1=C, 2=SC, 3=CL, 4=SCL, 6=SIL, 7=SIL+ (high clay), 8=SL, 9=LS; SHAPE - 1=depression, 2=level, 3=sloping, 4=convex, 5=receiving; PM - 1=alluvial, 2=fluvial veneer over morainal, 3=lacustrine veneer over morainal, 4=glaciofluvial, 5=morainal; HUE and CHROMA according to Munsell notation.

PLOT	CWSI	CLASS	H2OST	ROOT	CONS	CEM	TEXPM	SHAPE	PM	HUE	CHROMA
1	21.2	3	2	3	0	0	6	1	1	2.5	2
2	19.9	2	2	3	0	0	4	4	5	3.5	2
3	21.9	3	2	3	0	0	4	5	5	3.5	2
4	17.2	2	1	3	0	0	3	1	2	4.5	2
5	21.1	3	2	4	0	0	8	5	5	3.5	2
6	16.4	2	2	4	0	0	4	1	3	3.0	2
7	13.7	1	3	1	1	0	4	2	2	3.0	2
8	18.3	2	1	4	0	0	8	3	5	4.5	1
9	10.9	1	2	3	1	1	7	2	4	4.0	1
10	23.3	3	1	4	0	0	7	2	5	3.0	2
11	14.6	1	3	2	1	0	1	2	5	4.0	2
12	21.8	3	0	3	0	1	9	4	5	3.5	2
13	14.5	1	2	4	0	0	2	1	5	4.0	1
14	21.5	3	0	4	0	1	8	4	5	5.0	2
15	18.0	2	1	4	0	1	3	4	5	4.0	2
16	14.7	1	2	3	0	1	4	2	5	4.0	2
17	17.8	2	0	3	0	0	1	4	5	4.0	2
18	18.1	2	0	4	0	1	4	3	5	5.0	1
19	14.9	1	2	2	1	1	4	2	5	4.0	1
20	16.6	2	0	4	0	1	4	3	5	5.0	2
21	13.5	1	1	3	1	1	4	2	5	4.0	1
22	15.3	1	3	2	1	1	4	2	5	3.0	2
23	24.8	3	0	4	0	1	9	5	2	3.0	2
24	22.5	3	1	4	0	0	4	5	5	3.5	2

APPENDIX I. Soil oxidation zone index and soil water quality.

Note: See page xii for explanation of codes. CLASS refers to site index class. DO in ppm, and SC in mS/m

PLOT	CWSI	CLASS	AZ1	AZ2	BZ1	BZ2	BZ3	DO	SC
1	21.2	3	25	45	16	36	45	3.2	0.194
2	19.9	2	30	40	17	35	39	4.3	0.191
3	21.9	3	29	53	8	39	53	8.4	0.144
4	17.6	2	24	34	12	25	34	4.5	0.095
5	21.1	3	29	47	12	35	47	3.4	0.191
6	16.4	2	31	48	14	38	48	4.7	0.194
7	13.7	1	13	18	9	15	18	3.5	0.113
8	18.3	2	34	44	11	30	44	6.7	0.312
9	10.9	1	27	50	14	35	50	3.6	0.081
10	23.3	3	50	63	24	45	63		
11	14.6	1	17	28	8	21	28	3.6	0.113
12	21.8	3	38	45	17	32	45		
13	14.5	1	29	39	10	24	39	4.6	0.207
14	21.5	3	49	51	14	44	51		
15	18.0	2	24	37	10	28	37	4.3	0.081
16	14.7	1	17	30	10	23	30	4.9	0.084
17	17.8	2	29	49	14	33	49	5.9	0.102
18	18.1	2	40	49	13	34	49		
19	14.9	1	16	28	9	18	28	4.9	0.162
20	16.6	2	54	62	17	45	62		
21	13.5	1	21	29	8	23	29	7.2	0.178
22	15.3	1	17	28	10	19	28	3.4	0.145
23	25.1	3	45	47	7	29	47	4.3	0.132
24	22.5	3	39	50	14	42	50		

APPENDIX J. Site index data.

Note: See page xii for explanation of codes. CLASS refers to site index class.

PLOT	CLASS	CWSI	HWSI	SSSI	PLSI
1	3	21.2	22.5	27.0	
2	2	19.9	20.2	19.1	22.7
3	3	21.9	13.7	20.8	23.2
4	2	17.2	17.1	16.5	19.7
5	3	21.1	21.2	21.9	23.2
6	2	16.4	15.7		18.1
7	1	13.5	13.4		13.6
8	2	18.3	16.7		17.7
9	1	10.9	8.8	5.2	11.0
10	3	23.3	25.5	30.7	23.7
11	1	14.6	13.0	11.4	16.2
12	3	21.8	22.7	20.5	22.2
13	1	14.5	12.9		14.3
14	3	21.5	23.5	24.5	20.5
15	2	18.0	17.5	15.7	18.8
16	1	14.7	13.3	9.4	14.1
17	2	17.8	17.6	15.7	18.4
18	2	18.1	15.5	14.0	16.3
19	1	14.9	11.5	8.3	12.5
20	2	16.6	14.0	15.8	17.1
21	1	13.5	11.5		12.8
22	1	15.3	11.5	11.3	12.8
23	3	24.8	22.1	28.0	22.9
24	3	22.5	22.0	31.0	20.0

APPENDIX K. Mensuration data - combined for all species.

Note: See page xii for explanation of codes. CLASS refers to site index class. MAI in $m^3ha^{-1}yr^{-1}$; VOL (volume) in m^3/ha; BA (basal area) in m^2/ha; QMD (quadratic mean diameter) in cm; STHA (stems/ha). All volumes are total standing volume > 7.5cm dbh of live trees.

PLOT	CLASS	CWSI	AGE	MAI	VOL	BA	QMD	STHA
1	3	21.2	123	9.9	1216	92	38.9	775
2	2	19.9	107	10.6	1136	99	37.4	900
3	3	21.9	129	14.3	1849	149	44.1	975
4	2	17.6	98	8.2	808	75	27.6	1250
5	3	21.1	103	11.7	1203	99	40.4	825
6	2	16.4	102	10.9	1112	102	25.5	2000
7	1	13.7	111	4.6	507	60	20.3	1900
8	2	18.3	99	7.3	727	69	24.5	1475
9	1	10.9	165	3.9	643	88	22.2	2275
10	3	23.3	75	14.3	1073	85	29.7	1225
11	1	14.6	73	6.5	472	58	19.9	1875
12	3	21.8	78	11.5	899	80	26.5	1500
13	1	14.5	103	5.4	561	67	20.0	2125
14	3	21.5	78	13.0	1013	81	35.3	825
15	2	18.0	113	7.0	796	71	27.2	1225
16	1	14.7	111	6.5	723	86	20.9	2500
17	2	17.8	110	11.2	1234	111	28.5	1750
18	2	18.0	103	8.8	907	85	24.9	1750
19	1	14.9	98	4.0	396	53	17.3	2225
20	2	16.6	106	6.3	670	65	22.5	1625
21	1	13.5	107	4.8	514	62	20.3	1925
22	1	15.3	106	4.4	461	57	18.4	2150
23	3	25.1	75	11.8	886	77	35.7	775
24	3	22.5	104	12.9	1340	103	41.1	775

APPENDIX L. Mensuration data - by species.

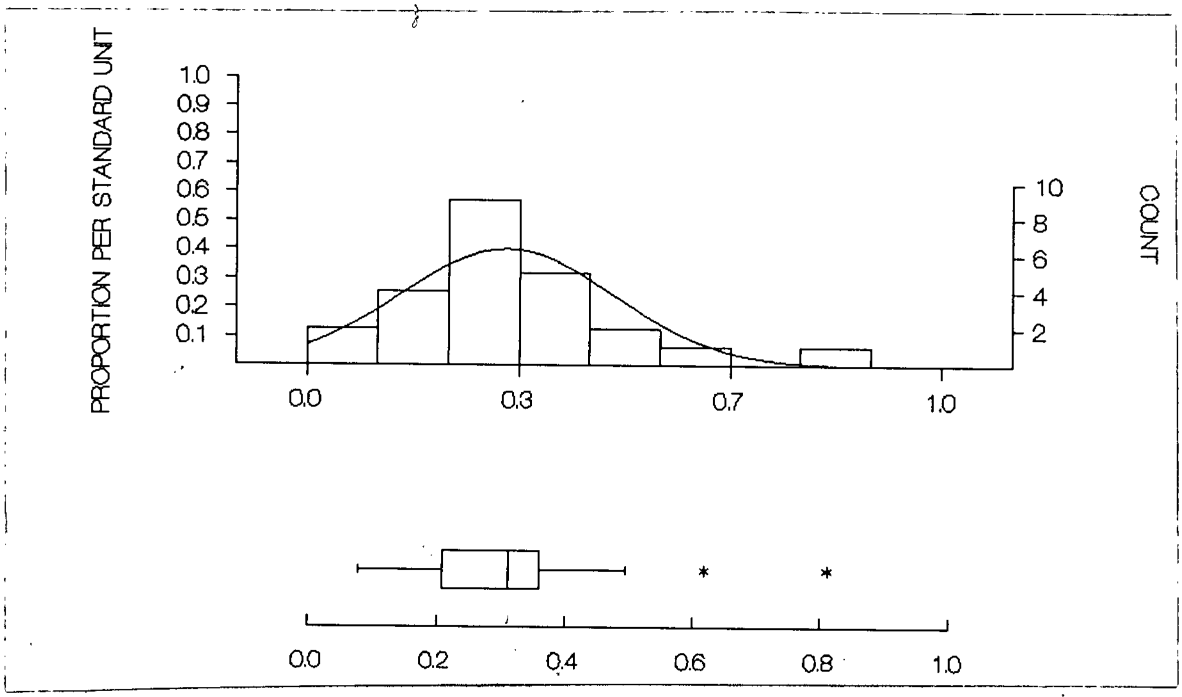
Note: See page xii for explanation of codes. CLASS refers to site index class. VOL, BA, QMD, STHA as above for each species indicated by preceding two letter code.

PLOT	CLASS	CWVOL	CWBA	CWQMD	CWSTHA	HWVOL	HWBA	HWQMD	HWSTHA	PLVOL	PLBA	PLQMD	PLSTHA	SSVOL	SSBA	SSQMD	SSSTHA
1	3	141	13	40.9	100	609	44	34.5	475	0	0	0.0	0	466	35	46.9	200
2	2	457	45	40.6	350	500	40	32.1	500	0	0	0.0	0	179	13	57.5	50
3	3	708	64	45.3	400	151	11	30.8	150	297	24	39.0	200	694	50	53.0	225
4	2	318	32	26.8	575	261	24	25.2	475	220	18	36.2	175	9	1	21.0	25
5	3	463	44	36.2	425	92	7	33.1	75	320	25	46.1	150	327	24	49.3	125
6	2	376	38	25.0	775	282	28	19.4	950	455	36	40.9	275	0	0	0.0	0
7	1	191	23	20.6	700	181	22	18.1	850	135	15	25.0	300	0	0	0.0	0
8	2	324	33	24.5	700	263	24	24.0	525	139	13	25.2	250	0	0	0.0	0
9	1	259	43	26.5	775	227	28	16.9	1250	157	17	29.5	250	0	0	0.0	0
10	3	88	9	21.6	250	463	37	25.8	700	15	1	26.2	25	506	38	43.8	250
11	1	266	33	20.7	975	39	6	11.5	575	154	18	31.8	225	12	1	13.3	100
12	3	409	41	27.7	675	421	33	26.0	625	30	3	21.6	75	39	4	24.8	75
13	1	237	29	20.6	875	105	15	14.5	875	216	23	29.0	350	2	0	12.0	25
14	3	152	16	25.6	300	347	25	35.8	250	49	4	32.5	50	466	36	45.1	225
15	2	145	15	27.4	250	443	39	25.7	750	121	10	32.2	125	86	7	30.2	100
16	1	304	38	20.4	1150	188	23	18.0	900	232	25	26.6	450	0	0	0.0	0
17	2	352	36	28.1	575	363	32	25.5	625	439	37	31.6	475	78	7	33.3	75
18	2	286	29	25.5	575	152	16	18.6	575	413	36	28.2	575	56	4	46.8	25
19	1	243	33	19.9	1050	94	13	13.4	925	59	7	18.6	250	0	0	0.0	0
20	2	194	20	23.1	475	294	29	20.4	875	158	14	27.9	225	24	2	23.5	50
21	1	266	32	22.7	800	154	20	16.0	975	95	10	29.3	150	0	0	0.0	0
22	1	285	35	19.7	1150	69	10	12.7	800	108	12	27.1	200	0	0	0.0	0
23	3	430	41	36.2	400	147	12	29.0	175	77	6	39.6	50	232	19	39.6	150
24	3	305	29	35.1	300	400	29	36.4	275	58	5	35.1	50	577	41	58.7	150

APPENDIX M. Explanation of boxplots.

A boxplot is a simple graphical summary of a batch of data. Based on the median and other percentiles of data distribution, boxplots provide more information about the nature of one or several data sets than traditional summary statistics such as the mean and standard deviation. (Titus 1987).

The following figure compares a histogram and boxplot for within-plot CVs for exchangeable Ca in the mineral soil, across the 24 plots. In the boxplot, the vertical line within the box represents the median. The left and right sides of the box represent the 25 and 75 quartiles, respectively. The lower (left) and upper (right) whiskers extend to the lower and upper 1/5 percentiles respectively, or to extreme values. Values outside the inner fence (the 25 quartile minus 1.5 times the interquartile range, and the 75 quartile plus 1.5 times the interquartile range) are plotted with an asterisk. Empty circles represent values beyond three times the interquartile range on either side of the box (Wilkinson 1987).



APPENDIX M. Procedure for checking assumptions of parametric multiple comparison test.

The Tukey HSD test is relatively robust to violations of the basic assumptions for parametric analysis, however substantial departures from the assumptions can affect its performance (Zar 1984). Examination of residuals from a one-way ANOVA was the basic method used to detect potentially serious problems of heteroscedasticity (Wilkinson 1987). The following procedure was used to check the assumptions.

1. If residuals do not display a problematic pattern, use the parametric test.

2. If residuals show a problematic pattern, transform the data. If transformation improves the residuals, and yields the same outcome as the untransformed data, assume the test is robust, and use the untransformed data with the parametric test.

3. If transformation improves the residuals but yields a different result from the untransformed data, assume the test is not robust, and use the transformed data with the parametric test.

4. If transformation does not improve the residuals, use a nonparametric test on the original data. If this yields the same result as the parametric test, assume the original test is robust, and use the parametric test on the untransformed data.

5. If transformation does not improve the residuals, and the nonparametric test results on the original data differ from the parametric test, assume the parametric test is not robust, and use the nonparametric test.