Harrington, C.A., and P.J. Courtin. 1994. Evaluation of site quality for red alder. Pages 141-158 *in* Hibbs, D.E., D.S. DeBell, and R.F. Tarrant, eds. The Biology and Management of Red Alder. Corvallis, OR: Oregon State University Press. 256 p.

10

Evaluation of Site Quality for Red Alder

CONSTANCE A. HARRINGTON & PAUL J. COURTIN

Information on the relationships between site quality and tree or stand productivity is needed by foresters to determine the sites where alder can be successfully planted, to predict growth and yield, and to evaluate the potential efficacy of silvicultural practices designed to increase productivity. Although using total yield as a measure of productivity (and thus as a measure of site quality) is intuitively appealing, determining total yield is often complicated and difficult (Carmean 1975). Site index (or height at a specified age) is the most commonly used index of site quality in the United States and Canada. This chapter (1) explains how to determine site index if suitable trees are present on the site, (2) presents information on relationships between alder site index and other measures of productivity, (3) discusses methods to estimate site index when it cannot be measured directly, (4) summarizes information on sensitivity of red alder to edaphic and physiographic factors, and (5) speculates on the potential influences of management activities on site quality.

Determination of Site Index

For red alder, site index has been defined as the mean height of free-to-grow, dominant and codominant trees of seed origin at a specified index age. Based on this definition, site index can only be *directly* measured when stands are at the index age. Site index tables or curves allow site index to be estimated when heights and ages are available from suitable trees. The first curves for red alder (Bishop et al. 1958; Worthington et al. 1960) were anamorphic (i.e., the basic shape of the curves was the same for all sites), used an index age of 50 years, and were based on data from only western Washington; in addition, these publications did not include information on stands below 10 years of age. More recent site estimation curves are available (Harrington and Curtis 1986) that use an index age of 20 years (total age). The new curves have several advantages over previous curves: (1) they are based on a much larger sample of trees covering a greater geographic range, (2) the reference age of 20 years is more appropriate to future short rotation management of the species, and (3) the curves are polymorphic and provide a better expression of observed height growth trends. If a value of site index at 50 years is needed, the curves of Harrington and Curtis (1986) were modified by Mitchell and Polsson (1988) to provide estimates of height, given age and site index at age 50. These height growth curves (or tables) can be used to estimate site quality (given age and height) although the estimates will be somewhat less accurate.

Trees to be measured for site index determination (site trees) should have been in a free-to-grow (non-overtopped) position throughout their life; thus, trees showing evidence of past suppression in their ring pattern should not be measured. Site trees should be in dominant or codominant crown positions. Wide spacing at time of planting has been shown to depress height growth of young red alder (DeBell et al. 1989), but it is not known if early growth depressions will persist to index age or if significant effects will be detectable within the range of densities in managed stands. Site index estimates based on open-grown trees, however, may underestimate potential site index and should be used cautiously.

As a general rule, site trees should not show evidence of past major damage; however, as with any general rule, there are exceptions. Some topographic positions are very susceptible to top damage and may have several episodes of top breakage during a rotation; such positions would include areas where high winds occur (e.g., ridge tops, near mountain passes, by the ocean), or areas that receive wet snow or ice storms. On these sites it may not be possible to select trees that do not exhibit some past top damage. Site index values can be estimated for such sites by using damaged site trees; however, we would expect these estimates to be poorer predictors of (i.e., more poorly correlated with) other measures of site quality than will occur for sites without top damage.

Site index estimates should be based on a minimum of four trees per plot; more are desirable if plot size permits (Curtis 1983). Trees to be measured should represent the area to be sampled; that is, they should be well distributed throughout the plot (Curtis 1983). The greatest uniformity in site index estimates among individual trees occurs when the area is stratified based on site conditions and each stratum (e.g., upper, mid and lower slope positions) is sampled separately. The need for such stratification depends on what uses will be made of the estimate. For example, if future management activities (such as determining rotation length or thinning regimes) will vary based on differences in site index of 2 to 3 m, then areas on the ground should be stratified so that differences of that magnitude are detectable. On the other hand, if management activities will not change unless site index values differ by 10 m, then little stratification is needed. The need for stratification should also consider practical matter, such as what is the smallest area that it is feasible to manage?

Site index estimates will be most accurate when stand age is within ± 10 years of the index age. Estimates are very unreliable for stands below age 5 and become increasing less reliable at older ages. In addition, almost no information beyond age 65 was used in developing the site index curves of Worthington et al. (1960) or Harrington and Curtis (1986).

Unless total age is known (e.g., from stand records), age will commonly be determined by boring at breast height (1.3 m), then adding a correction factor. Harrington and Curtis (1986) recommended a two- or three-year correction factor for the poorest sites (SI_{20} < 15 m), a one-year correction factor for average sites (SI_{20} 15 to 25 m), and no correction factor for the best sites (SI_{20} > 25 m). These recommendations should be modified if local experience indicates other values are more appropriate.

Red alder is a diffuse-porous species; thus, to obtain accurate counts of annual rings, more care is needed in preparing and examining the increment cores or cross sections from red alder than those from temperate-zone conifers or ring-porous hardwoods. Newton and Cole (Chapter 7) refer to unpublished data on alder trees approximately 106 years old that had missing or incomplete rings; however, there is no evidence that missing rings reduce the accuracy of site index estimates for stands within the age range (tree age < 70 years) used in constructing the available red alder site index curves. DeBell et al. (1978) found few abnormal rings (false, partial, or missing) in cross sections from red alder trees ages 29 to 88, especially when sections were examined from breast height rather than root collar locations. They concluded that counts made carefully on increment cores extracted at breast height should provide a reliable assessment of age. They recommended making a smooth razor cut along one or two sides of the freshly extracted core, then counting the rings when the ring boundary darkens (the darkening is caused by oxidation of phenols and occurs in less than 30 minutes).

Relationships Among Measures of Site Productivity

It has long been recognized by mensurationists that many of the stand characteristics used to describe tree stands are interrelated. Thus, mature stands on highly productive sites have fairly high values for site index, basal area, and volume production (if the stands have not been thinned or if the basal area or volume removed in the thinning has been accounted for in some manner) and mature stands on sites of low productivity have correspondingly low values for site index, basal area, and volume production. Many land managers would like to know the current or predicted future wood volume of red alder stands without having to directly measure it. Unfortunately, volume equations for red alder are limited. Chambers (1983) developed predictions for unmanaged red alder stands; these predictions are based on percentage of normal basal area, site index and age, or site index, observed basal area, and average diameter. Earlier tables for normal (i.e., well-stocked) stands predicted basal area or cubic volume as a function of site index and age (Worthington et al. 1960).

We examined the relationships among several stand descriptors by using our unpublished data from naturally regenerated, unmanaged red alder stands in western Oregon, Washington, and British Columbia. Table 1 presents pair-wise correlation coefficients for those stands. For these stands—many of which were less than 35 years—site index was poorly correlated with total basal area or total stand stem volume but was significantly correlated ($R = 0.61$, $p = 0.0001$) with mean annual increment of stem volume (mai). A linear regression equation with site index, age, and basal area accounted for 90 percent of the variation in mai.

Table 1. Pair-wise correlations between stand statistics for unmanaged red alder stands in western Oregon, Washington, and British Columbia (n = 64). Age = mean age of site trees, SI_{20} = site index at base-age 20, BA = basal area, Vol = total stem volume (based on Snell and Little, 1983), MAI = Vol ÷ Age. (Correlation coefficients ≥ 0.24 significant at p = 0.05).

	Age	SI_{20}	BA	Vol	MAI
Age	1.00	-0.45	0.53	0.60	-0.40
SI		1.00	-0.13	0.09	0.61
BA			1.00	0.91	0.45
Vol				1.00	0.47
MAI					1.00

Other Methods for Estimation of Site Index

When no suitable red alder site trees are present, there are several methods that can be used to estimate site index for red alder. The most commonly used methods involve known relationships between alder site index and (a) soil series, soil mapping unit, or soil classification information, (b) site index or other site quality measures for another species, (c) mathematical or biologically based site prediction models, or (d) British Columbian biogeoclimatic zones and related nutrient and moisture regimes. Each of these methods has advantages and disadvantages. The method chosen for a specific situation is probably more dependent on what information is available (and thus, which methods could be used) and which method has been adopted for a given region than on the theoretical advantages and disadvantages of a specific method. Users should be aware, however, of the relative merits of each method.

Estimation Based on Soil Series or Taxonomic Classification

A frustration commonly expressed by foresters is that all categories of soil taxonomy—from soil order down to soil series—seem to encompass a wide range of site quality. Thus, the question has been raised, "What useful information can be gained by knowing the soil series or other level of classification information for a site?" The answer is, "A little or a lot, depending on what is known and how the information is used." No *one* piece of soil-site information (e.g., soil order, soil series, slope position, texture of the A horizon) will ever provide foresters with accurate estimates of site quality for a *wide* range of sites. Combining several pieces, though, can often be effective. We may not have enough information to "complete the puzzle," but often when we fill in some of the pieces, we can see enough of the picture to make a good guess at the result.

Information on site index for red alder on specific soils is limited. Only a fraction of the potential soil series have been examined for alder site relations and the information we have is restricted in terms of geographic spread and soil conditions. In addition, none of these soil series have been subdivided into phases based on characteristics specifically selected to reduce the variability in red alder site index within phases. Many existing or potential alder sites in western Washington and Oregon, however, have been soil surveyed and the resulting soil mapping units or soil series have been classified using the U.S. system (Soil Survey Staff 1975). We present the available soil-site index information within this taxonomic framework in the hope that it will enable managers to make inferences about soils with similar classifications. The relationship between Canadian taxonomy and red alder site productivity is also discussed below.

The following discussion assumes that the soil series or taxonomic classification available for a specific site is accurate. Users should be aware, however, that soil information presented on a map will not be correct for all sites. This occurs because it is not practical to determine or to map all existing soil units. If it is important to know that the mapped soil information is correct, users should verify that the profile description associated with the mapped soil unit is consistent with the soil profile on the site.

We summarized information from soil-site plots for which both red alder site index and soil classification were known. This 200-plot data base was collected by us (Pacific Northwest Research Station and British Columbia Ministry of Forests) or by other organizations (the former Crown Zellerbach Corporation, USDA Soil Conservation Service, and the Washington State Department of Natural Resources). The following discussion emphasizes the *maximum* site index values for each classification unit. This approach has been useful in organizing other types of soil-site data (e.g., Harrington 1991). Emphasizing the maximum values helps screen out the negative effects of factors which are not part of the classification system (and may not occur equally across all classification units).

The first level of classification in U.S. soil taxonomy is soil order; the orders are based on pedogenesis (i.e., soil-forming processes as indicated by presence or absence of major diagnostic horizons). Seven of the eleven soil orders were rep-

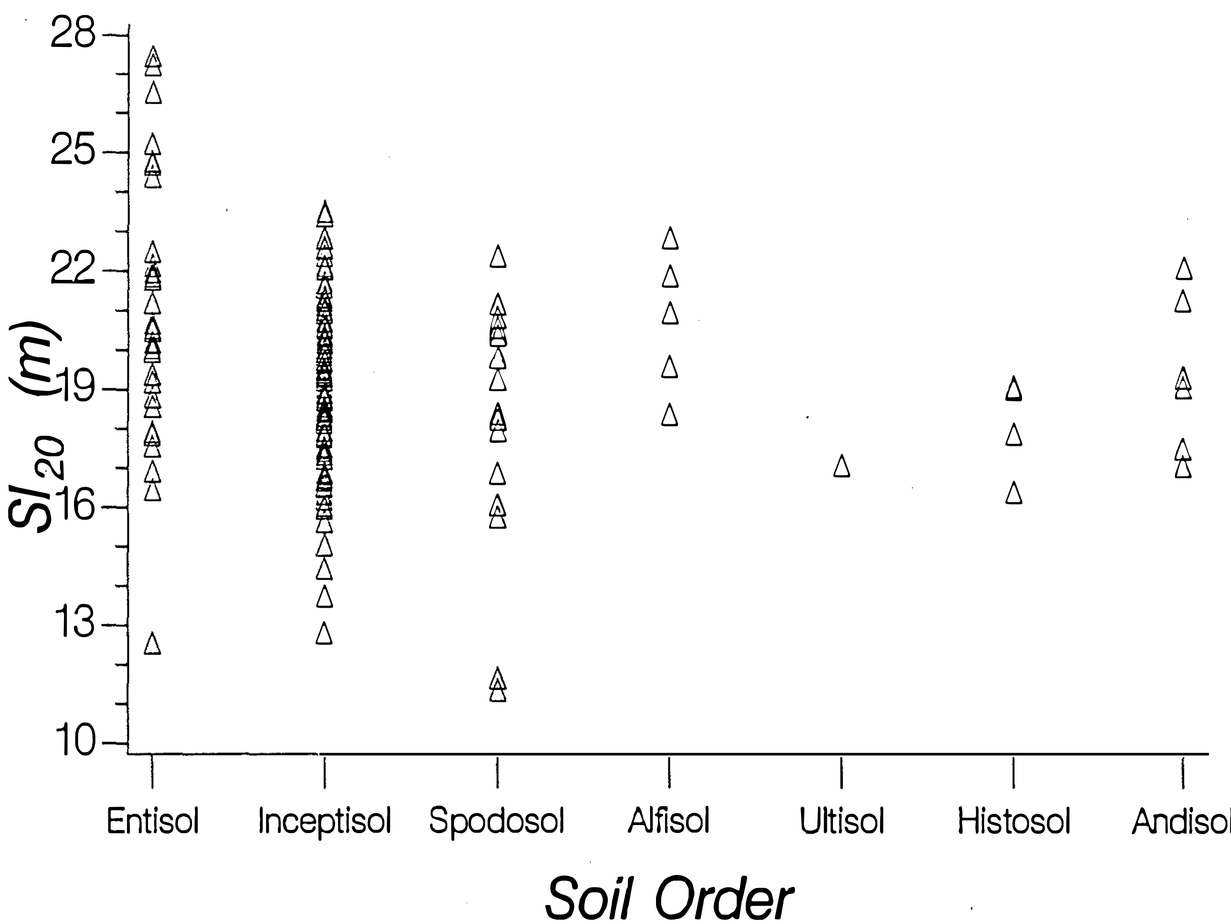

Figure 1. Relationship between red alder site index (base-age 20 years) and soil order for stands in western Oregon, Washington, and British Columbia. Data collected by the authors or from the USDA Soil Conservation Service Soil-Woodland data base. Soil-site index information collected in British Columbia was classified to soil order based on the U.S. system.

resented in the data (Fig. 1, plots from British Columbia were classified to soil order in the U.S. system for this figure). Most of the soils were Entisols or Inceptisols, but four other orders were also represented with 4 to 17 plots. Site quality information is summarized below by order. When available, information is also presented for other levels of classification (suborders, great groups, and subgroups). Site index information for red alder by soil series (or other level of classification) is presented in Table 2 (U.S. information only).

Entisols have little or no evidence of development of pedogenic horizons. All red alder stands sampled on Entisols were on stream terraces or in flood plains. The highest SI_{20} values (> 27 m) were on Entisols but the order encompasses soils with a wide range in productivity (Fig. 1). The best great groups (maximum values for $SI_{20} \geq 24$ m) were Fluvaquents (Typic or Mollic) or Udifluvents with friable or very friable surface horizons containing little or no rock or gravel, and loamy or clayey textures. Xeropsamments (drier, sandy soils) were less productive.

Inceptisols are immature soils with few diagnostic features. Over half of the soils with alder soil-site information are in this order; five suborders are represented—Andepts, Aquepts, Ochrepts, Tropepts, and Umbrepts. Inceptisols are found in all slope positions and cover a wide range in site quality. The highest SI_{20} values for Inceptisols represented good sites (23 to 24 m) but were about 3.5 meters less than the highest values for Entisols.

Some of the highest SI_{20} values for Inceptisols are in the Andept suborder (Typic Dystrandepts). The best Andept sites (SI_{20} > 23 m) are at low elevations, are on flat land or gentle slopes, and have little gravel or rock in surface horizons.

The Ochrept suborder includes a wide range in SI_{20}. The best Ochrepts (SI_{20} > 23 m) are at low elevations, have good rooting volume, are not coarse-textured, and do not contain much gravel or rock. For Durochrepts and Fragiochrepts, the depth to the duripan or fragipan is an important factor influencing site index. For Dystrochrepts and Xerochrepts, the Andic or Aquic subgroups are the most favorable for alder growth. Soils classified as loamy (e.g., fine-silty or coarse-loamy) or medial (amorphous but feels loamy) are more favorable than those classified as skeletal (having 35 percent or more rock fragments).

Umbrepts also include a substantial range in alder-site quality. The poorest sites have low rooting volume (Fragiumbrepts with shallow fragipans or soils with shallow phases) or frigid temperature regimes. The best sites (SI_{20} > 22 m) are Typic or Andic Haplumbrepts with loamy or medial textures and mesic temperature regimes. Within a series, elevation and slope are generally important factors influencing alder site quality.

Aquepts are found on stream terraces, in depressional areas, and on gentle slopes. Shallow Placaquepts (plac = thin pan) and Haplaquepts are less productive than Humaquepts. The poorest Humaquepts have firm horizons at fairly shallow depths, sandy A horizons, and are on southerly aspects.

Tropepts are only represented in the data by Typic and Andic Humitropepts (two series). Values for SI_{20} were low to moderate, but the data were too limited to form any conclusions.

Spodosols have a horizon in which organic matter and aluminum have accumulated. Many people assume that all Spodosols have a thick leached horizon and low productivity, but those assumptions are not necessarily true. Typic or Aqualfic Haplorthods can have SI_{20} values $\geq$ 21 m. Other Haplorthods can also have moderate SI_{20} values if soil textures are not sandy or skeletal. Information on alder productivity on other great groups is limited; however, great groups with fragipans, placic horizons (thin pans), frigid temperature regimes, or thick leached layers are less productive than great groups without those features.

Alfisols have a light-colored (ochric) surface, a clayey horizon, and high base status. Information on alder site quality is limited, but measured SI_{20} values ranged from low to above average. Maximum SI_{20} was 23 m (Ultic Haploxeralf).

Ultisols are geologically old, weathered soils with low base status. Only one plot with site index information was classified as an Ultisol. The site index for that plot was low (SI_{20} = 17.2 m); although other Ultisols may have higher productivity than this plot, most soils in this order would have below-average productivity.

Table 2. Site index information for red alder in western Washington and Oregon by soil classification. Within each soil order soils are listed by the maximum site index value for the series. Soils with three or more site index plots are indicated by an asterisk.

Soil order and other classification information	Max. SI_{20}(m)
Entisols	
Udifluvents (without additional classification information)	27.6*
Rennie: fine, montmorillonitic, nonacid, mesic Mollic Fluvaquent	27.4*
Nuby: fine-silty, mixed, acid, mesic Typic Fluvaquent	26.7*
Coquille: fine-silty, mixed, acid, mesic Typic Fluvaquent	25.4
Hoh: coarse-loamy, mixed, acid, mesic Typic Udifluvent	24.8
Puget: fine-silty, mixed, nonacid, mesic Aeric Fluvaquent	22.6
Juno: sandy-skeletal, mixed, mesic Typic Udifluvent	22.0
Ocosta: fine, mixed, acid, mesic Typic Fluvaquent	21.3
Pilchuck: mixed, mesic Dystric Xeropsamment	19.5
Humptulips: coarse-loamy over sandy/sandy skeletal, mixed, nonacid, mesic Typic Udifluvent	19.0
Inceptisols	
Cathcart: medial, mesic Andic Xerochrept	23.9
Cloquallum: fine-silty, mixed, mesic Aquic Dystrochrept	23.7
Mues: medial over loamy-skeletal, mixed, isomesic Typic Dystrandept	23.6
Montesa: coarse-loamy, mixed, mesic Aquic Dystrochrept	23.0*
Bear Prairie: medial, mesic Typic Dystrandept	22.7*
Blethen: medial-skeletal, mesic Andic Xerochrept	22.7
Alderwood: loamy-skeletal, mixed, mesic Dystric Entic Durochrept	22.7*
Aabab: fine-silty, mixed, mesic Aquic Dystrochrept	22.7*
Bunker: medial, mesic Andic Haplumbrept	22.5
Rinearson: fine-silty, mixed, mesic Typic Haplumbrept	22.3*
Ohop: loamy-skeletal, mixed, frigid Aquic Dystrochrept	22.3
Queets: medial, mesic Andic Dystrochrept	22.2*
Yelm: medial, mesic Aquic Dystric Xerochrept	22.2
Templeton: medial, mesic Andic Haplumbrept	21.7*
Stimson: fine-silty, mixed, acid, mesic Typic Humaquept	21.5*
Everett: sandy-skeletal, mixed, mesic Dystric Xerochrept	21.4
Skamo: medial, mesic Andic Haplumbrept	21.3*
Zenker: medial, mesic Andic Haplumbrept	21.2
Nestucca: fine-silty, mixed, acid, mesic Fluvaquentic Humaquept	20.9
Tealwhit: fine, mixed, acid, mesic Aeric Haplaquept	20.4
Arta: medial, mesic Andic Haplumbrept	20.3*
Cathlamet: medial, mesic Andic Haplumbrept	19.9
Skipanon: fine-loamy, mixed, isomesic Andic Humitropept	19.7
Cinebar: medial, mesic Typic Dystrandept	19.5
Mt. Baker NF MU 22: coarse-silty, mixed, mesic Fragiumbrept	19.1
Siuslaw NF MU 22: fine-silty, mixed, mesic Typic Dystrochrept	19.1
Glohm: fine-silty, mixed, mesic Typic Fragiochrept	19.1
Ecola: fine-silty, mixed, mesic Andic Haplumbrept	19.0
Wishkah: fine, mixed, mesic Aquic Dystrochrept	18.3*
Mt. Baker NF MU 34: fine, mixed, slowly permeable Andic Haplumbrept	18.0
Newaukum: medial, mesic Typic Dystrandept	17.6
Nemah: fine, mixed, acid, mesic Humic Haplaquept	17.4
Grindbrook: fine-silty, mixed, isomesic Typic Humitropept	16.7
Molalla: fine-loamy, mixed, mesic Typic Haplumbrept	16.4
Boistfort: medial, mesic Andic Haplumbrept	16.2
Halbert: loamy, mixed, acid, mesic, shallow Histic Placaquept	16.1
Wilhoit: medial, frigid Andic Haplumbrept	13.0

Table 2 continued.

Soil order and other classification information	Max. SI_{20}(m)
Spodosols	
Sehome: coarse-loamy, mixed, mesic Typic Haplorthod	22.5
Skipopa: fine, mixed, mesic Aqualfic Haplorthod	21.3*
Yaquina: sandy, mixed, mesic Aquic Haplorthod	19.9
Solduc: medial-skeletal, mesic Humic Haplorthod	18.5
Mt. Baker NF MU 81: coarse-loamy, mixed Typic Ferrod	18.1
Alfisols	
Melbourne: fine, mixed, mesic Ultic Haploxeralf	23.0*
Bow: fine, mixed, mesic Aeric Glossaqualf	18.5
Ultisols	
Mayger: clayey, mixed, mesic Aquic Haplohumult	17.2
Histosols	
Mukilteo: dysic, mesic Typic Medihemist	19.2*
Fluvaquentic Borohemist	16.5
Andisols	
Hemcross: medial, mixed, mesic Alic Hapludand	21.4
Necanicum: medial-skeletal, isomesic Alic Fulvudand	20.6
Klistan: medial-skeletal, mesic Alic Hapludand	19.2
Klootchie: medial, isomesic Alic Fulvudand	17.8

Histosols are organic soils; most are saturated or nearly saturated with water most of the year. Productivity for alder is below average on Hemists (maximum SI_{20} = 19.2 m); no information is available for other suborders.

Andisols are derived from volcanic materials. Several series formerly classified as Andepts are now Udands. Alic Fulvudands and Alic Hapludands have average to above-average values for SI_{20} (maximum SI_{20} = 21.4 m). Medial textures, gentle slopes, and low elevations are more favorable than medial-skeletal textures, steep slopes, and higher elevations.

Canadian taxonomy. In British Columbia there has never been an attempt to correlate categories of the Canadian System of Soil Taxonomy (Agriculture Canada 1987) and forest productivity. If there had been such an attempt, it would likely have resulted in poor relationships. Like the U.S. system, the Canadian system stresses pedogenesis in its classification rather than a functional relationship between soil taxonomy and productivity. Of the nine soil orders in the Canadian system, five occur within the range of red alder: Brunisols, Gleysols, Organics, Podzols, and Regosols. Certain generalizations can be made concerning alder growth and certain chemical and morphological features that may relate to soil orders. For example, Organic soils are too wet to give anything but poor growth and often alder is replaced by willow species, Pacific crab apple, or coniferous trees. The same comment generally applies for Gleysols, although some Humic Gleysols with thick A horizons can yield excellent growth. Poor or medium growth of alder is expected on Podzols and Regosols where the degree of eluviation and organic matter accumulation in surface horizons will result in great variability. Brunisols probably have the greatest chance of providing the best growth for alder, especially the Melanic and Sombric subgroups with thick A horizons.

When more information is available, it may be helpful to use the Canadian System of Soil Taxonomy with parent material classification to develop red alder productivity relationships. Even when taxonomic units are subdivided by parent material classes, however, the resulting subunits may still include more variability in particle size and drainage than is desirable for productivity prediction. In addition, such analysis would require fairly expert knowledge or large-scale soils mapping (e.g., 1:100,000).

Estimation Based on Other Species

Prediction of site index for a tree species has been done based on site index of another tree species, height growth of other tree species, or the presence, abundance, or size of understory plant species (Carmean 1975). The accuracy of the prediction is dependent on the ecological similarity of the two species (e.g., red alder and the species on which the prediction is based). In addition, it is important to know the type of data used in developing the prediction equations. General relationships exist between the site index values for geographically associated species; however, species differences in dependence on "growing-season" conditions, tolerance to poor drainage or flooding, need for soil-supplied nitrogen, and geographic and elevational ranges make any predictions of this type unreliable unless they are limited to sites where differences between species in ecological tolerances are not strongly expressed.

Some past predictions have used a two-step estimation process in which the site index values for the species on which the prediction is based have not been directly measured; instead they were based on a second prediction relationship (e.g., the relationship between soil series and Douglas-fir site index). This adds another source of variability to the predicted value.

Red alder site index values from 23 stands did not differ significantly ($p = 0.10$) among Douglas-fir site classes (Harrington and Curtis 1986); that is, in that data set, Douglas-fir site class was not a good predictor of red alder site index. Sites classified as excellent for Douglas-fir consistently had above-average SI_{20} values for red alder; however, some of the highest red alder SI_{20} values were on flood plains classified as unsuitable for Douglas-fir. Compared to Douglas-fir, red alder is more tolerant of occasional flooding, poor soil drainage, and low soil nitrogen (Minore 1979). Douglas-fir, on the other hand, has greater cold hardiness, especially to unseasonable frosts. In addition, because of its ability to photosynthesize during the winter (Waring and Franklin 1979) and its determinate pattern of height growth, Douglas-fir may be able to better utilize sites with deep, well-drained to somewhat excessively drained soils.

Site index predictions for one species based on a value for another species will be most accurate if the range in site conditions is low or kept within specified bounds (e.g., low elevation, well-drained soils without major nutrient deficiencies) and if it is known that both species may be present on those sites. For example, it is probable that within plant association groups in which both species occur fairly accurate prediction equations could be developed. The relationships developed for one plant association group, however, could not be transported and used for other groups without testing. Based on actual measurements of red alder and Douglas-fir trees in low elevation, mixed-species stands or pure-species, adjacent stands in western Washington, an R^2 value of 0.47 ($n = 29$) was reported (Fergerson et al. 1978). Although these sites were geographically associated, it is not known what range in ecological conditions was represented.

Estimation Based on Mathematical or Biologically Based Soil-Site Models

Prediction of site quality from soil and site characteristics has been a goal of many forestry studies over the years (see Carmean 1975). If the area of interest can be defined so that all site characteristics are similar except for a few (e.g., soils in the same area with similar parent material but differing rooting depths), then fairly accurate prediction equations can be developed. This approach to site index prediction requires that equations be developed for each group of interest. For example, McKee (1977) grouped loblolly pine soil-site plots first by soil series, then predicted site index within soil-series group based on soil physical and chemical properties. When regression equations developed from plots that represent a wide range in site conditions are tested with data from new plots, however, the equations have not held up well (i.e., the correlation between measured and predicted site index drops substantially) (see McQuilkin 1976). For red alder, this was demonstrated by Harrington (1984); a regression equation predicting site index had an R^2 value of 0.95 for the 25 plots used in equation development but was worthless in predicting site index for a new set of 15 plots (R^2 = 0.05).

Another approach to predicting site quality is to use a biologically based model. The best-known example of this approach is for southern hardwood species (Baker and Broadfoot 1977). Each part of the model is based on relationships that are consistent with what is known about the silvics of the species rather than on a mathematical fit from a specific data set. Such models require information on many variables, but are more robust in their performance. The model for red alder (Harrington 1986), for example, required information on 14 soil and site properties. It tested well (R^2 = 0.92 and 0.80) with two data sets from western Washington and Oregon (Harrington 1986), but more poorly (R^2 = 0.42) with one from British Columbia (Courtin 1992). The model apparently needs to be modified to function outside the geographic area where it was developed.

Estimation Based on British Columbian Biogeoclimatic Zones

In British Columbia, an approach to determining site quality and, indirectly, site index is the characterization of forest ecosystems using biogeoclimatic ecosystem classification. This system classifies the forest landscape for the purposes of site quality evaluation on the premise that the physical environment of an ecosystem can be simplified into three elements: regional climate, soil moisture regime, and soil nutrient regime (Pojar et al. 1987). Within this classification, the biogeoclimatic subzones delineate those segments of the landscape with similar regional climate and the same zonal climax vegetation development. Then, for the purposes of site classification, units called site series group ecosystems based on similar soil moisture and nutrient regimes with the same regional climate. Site associations are site series that can occur across different regional climates; they are analogous to Daubenmire's habitat type classification or to the plant associations used by the U.S. Forest Service in many western states. Field personnel can determine biogeoclimatic units by using maps and differentiating characteristics and can key out moisture and nutrient regimes from physiographic information, soil physical and morphological criteria, and vegetation (Green et al. 1984).

The link between site quality and site index evaluation for Douglas-fir has been made by developing regression equations using site associations (Green et al. 1989) and soil moisture and nutrient regimes as categorical variables (Green et al. 1989; Klinka and Carter 1990). Ultimately, the goal is to incorporate site index into the biogeoclimatic ecosystem classification system by having a range of site index values for each site association. Some red alder site index information has been collected in British Columbia along with biogeoclimatic ecosystem classifications (data on file, British Columbia Ministry of Forestry, Burnaby), but not enough data are yet available to develop prediction equations.

Relationships Between Site Index and Selected Site Characteristics

Currently many sites exist for which no site quality information is readily available for red alder because there are no suitable trees to measure and there is no information on soil or ecological classification (or if some classification has been made, the relationship between that classification unit and alder site quality is not known or is not known precisely enough). In the following sections we discuss relationships between site index and selected site characteristics. Knowledge of these relationships may provide managers with an approximate indication of site quality or at least with an appreciation for some of the factors that influence it. One useful way to examine the effect of a specific soil or

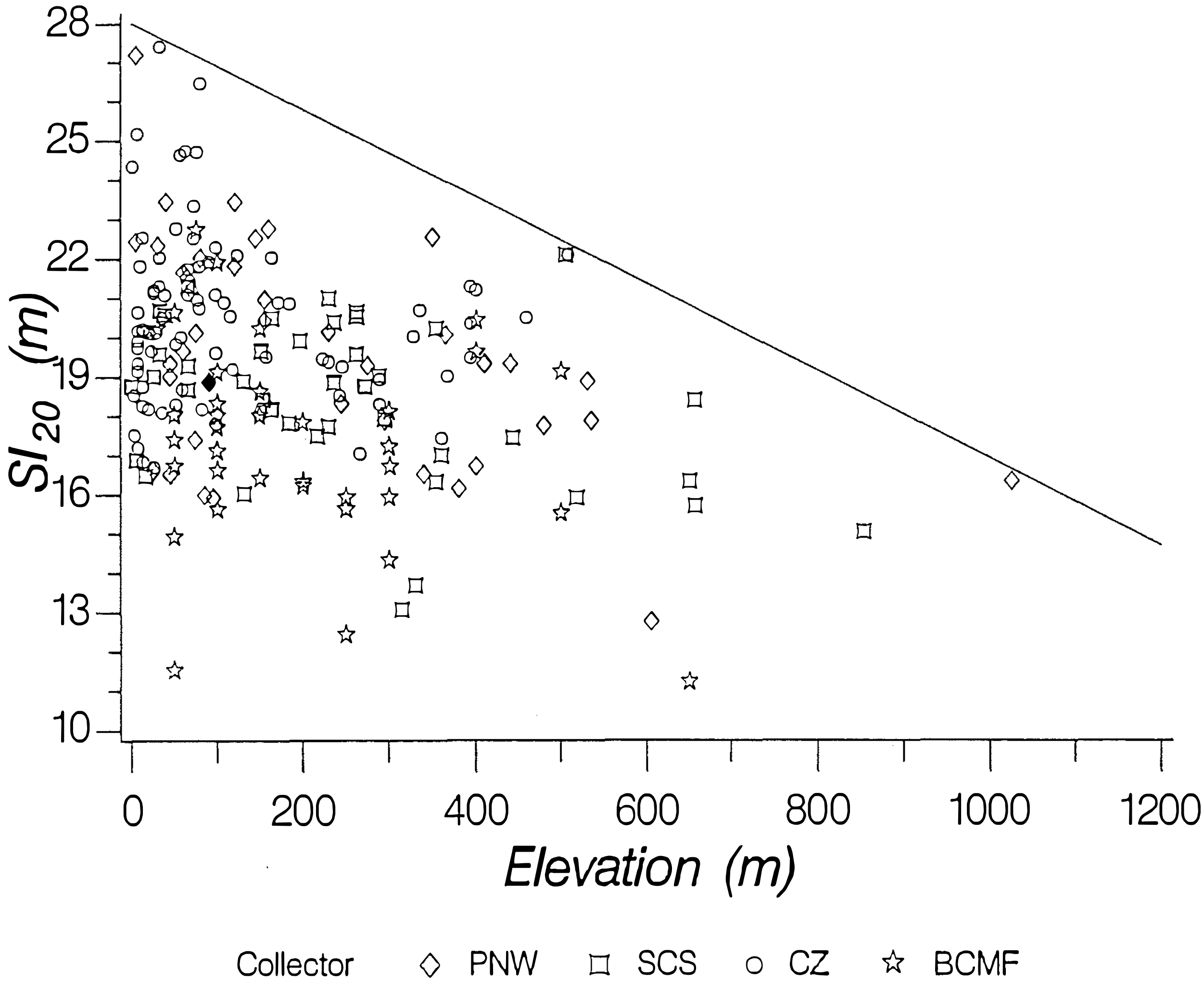

Figure 2. Relationship between red alder site index (base-age 20 years) and stand elevation (mean above sea level) for stands in western Oregon, Washington, and British Columbia. Plotting symbols indicate organization that collected data.

site factor (e.g., elevation) on a variable like site index that is influenced by many factors is to look at the *maximum* values of site index that are associated with each level of that factor. If sufficient data are available, this value will indicate the maximum that can be achieved when all other possible factors are at their optimum levels; this allows the effect of that factor alone to be examined. This technique, called boundary-line analysis, has been used in the analysis of plant-soil relations (see Evanylo and Sumner 1987; Harrington 1991).

Climatic Factors

Very little specific information is directly available on the relationships between red alder and climatic factors; most information is based on observations of height growth or site index in natural stands or on occurrence of natural stands. The variables we would assume to have an influence on site index are temperature (mean, minimum, maximum, length of frost-free period), precipitation (amount and timing, including frequency of ice or heavy snow), wind, and radiation (light levels and photoperiod). Unfortunately, few weather stations are located in or near alder stands for which we have site index information; thus, we usually must rely on correlated variables or estimation. For example, elevation is not a climatic variable but it is correlated with many climatic variables (such as length of the frost-free growing season or minimum and maximum temperatures) and is easily obtainable. For some sites, specific information from adjacent weather stations is available and can be examined.

Elevation is strongly related to red alder site index and to species occurrence. For example, the highest values of red alder site index are at low elevations and the maximum site index value achievable declines as elevation increases (Fig. 2). Elevation alone will not accurately predict site index ($R = -0.36$, $p < 0.01$), but it appears to set the upper limit for site index values. Specific information is not available to test which climatic variables are most closely associated with the observed effects on site index; however, we assume that length of the growing season and air temperature are key factors. Elevation values must be considered in the context of latitude. For example, in northern Oregon or southern Washington, red alder trees are found as high as 1100 m, but in Alaska they generally occur close to sea level. Since alder only occurs at fairly low elevations in the most northerly portion of its range, we would assume that the effect of elevation becomes more negative as latitude increases.

Precipitation during the growing season is an important factor in influencing alder tree growth (and site index). It should be recognized, however, that precipitation does not directly affect growth but is one of the variables that influence soil moisture during the growing season, a factor that directly influences growth (see discussion below). If all other factors are equal, site index increases as growing season precipitation increases up to about 45 cm (1 April through 30 September). On well-drained sites without access to water tables, the species could undoubtedly benefit from additional growing-season precipitation (see the benefits from irrigation reported by DeBell and Giordano, Chapter 8); however, within the natural range of the species, higher precipitation is commonly associated with cooler temperatures, higher elevations, or more northerly latitudes, and does not result in higher values of site index.

Some climatic factors (e.g., high winds, the frequency of ice or heavy snow storms) influence site index for red alder by increasing the chances of top breakage rather than by directly influencing growth rates per se. These factors must be taken into account when evaluating sites near mountain passes, close to the ocean (without intervening topography), at high elevations, or in areas of locally unusual climatic conditions.

Soil Moisture

The availability of soil water during the growing season is a key factor influencing site quality for red alder. The importance of this factor can be seen in both the distribution of the species on the landscape and in its performance (Harrington 1990). Since red alder is deciduous, it is more dependent on favorable growing conditions during the summer months than its evergreen competitors (Waring and Franklin 1979). In most years, precipitation during the summer is insufficient to supply the water required for the species to achieve acceptable growth rates. Soil water available beyond that provided by current precipitation can come from storage in the soil profile, accessing soil moisture perched above temporary or permanent water tables, or from water transported by gravity from uphill positions.

Soil drainage classes used by the USDA Soil Conservation Service indicate how rapidly water applied to the soil surface will move downward through the profile. Plotting red alder site index against drainage class (Fig. 3) indicates that a wide range in site index occurs for all drainage classes. The sites with the very highest site index values were on soils classified as poorly drained. The apparent uniformity of maximum site index values for the other drainage classes, however, is somewhat misleading. Drainage classes do not take into account the availability of soil water from other sources. Thus, the maximum values for site index on well-drained or somewhat excessively drained soils are associated with plots on flood plains or stream terraces, where tree roots have access (at least for part of the growing season) to water tables, or with plots in lower slope positions, where they receive water from uphill locations.

Red alder can tolerate high water tables and flooding. Winter water tables at or close to the soil surface do not appear to reduce growth (Minore 1968; Minore and Smith 1971). The species is not hydrophytic, however, and its survival and growth will be reduced if high, unaerated water tables are

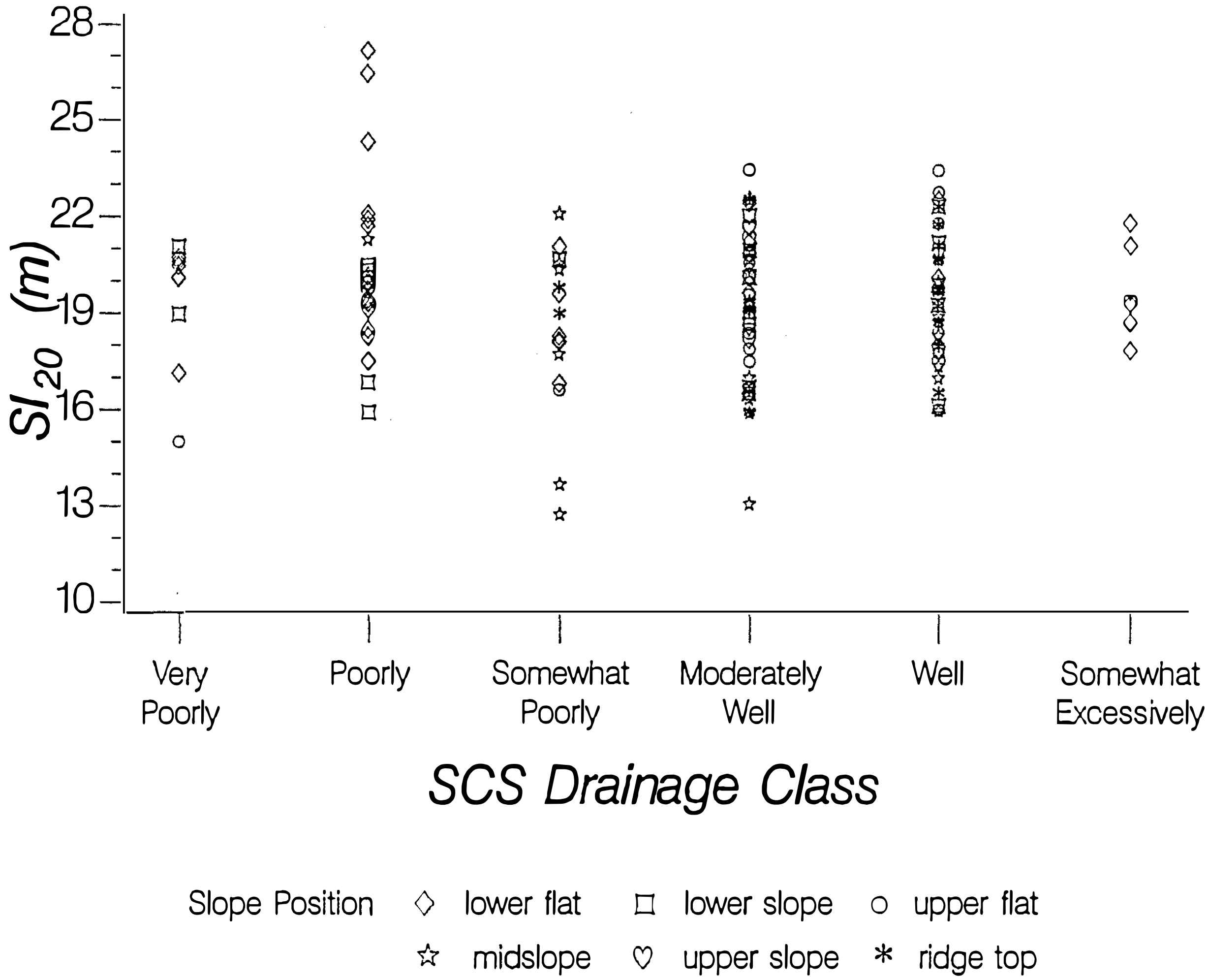

Figure 3. Relationship between red alder site index (base-age 20 years) and soil drainage class for stands in western Oregon and Washington. Data collected by the senior author or from the USDA Soil Conservation Service (SCS) Soil-Woodland data base. Plotting symbols indicate slope position class for each stand.

present during the growing season (for results from artificial flooding experiments, see Minore 1968, 1970; Harrington 1987). Aerated water tables (e.g., those found on sites along rapidly moving rivers and streams) are much more favorable for growth of alder than unaerated or stagnant water tables (e.g., those in bogs). One effect of high water tables (particularly unaerated ones) is to restrict the area where root growth can occur to the uppermost section of the soil profile; this concentrates roots in a low volume of soil and results in high competition for nutrients (and for water when a seasonal water table recedes). Thus the best site index values among the plots classified as very poorly drained (Fig. 3) are those that have some microrelief present. The microrelief increases the soil volume that is suitable for growth of fine roots; this can be a critical factor influencing tree growth. For example, Tiarks and Shoulders (1982) concluded that on phosphorus-deficient soils, uptake of phosphorus and height growth of pines were controlled by the volume of soil available for root exploration. Very poorly drained soils can also be unproductive because some soil nutrients become less available or toxic substances increase under anaerobic conditions.

Soil Physical Condition

Information on the relationship between red alder site quality and soil physical condition is limited. Minore et al. (1969) reported substantial penetration of alder seedling roots *into* as well as growth *along* the sides of soil cores of sandy loam that had been artificially compacted to a medium density of 1.45 g/cm^3 (however, growth was less than at a lower density). At the highest soil density tested, seedling weight and root growth along the sides of the cores was the same as at the medium density, however, depth of root penetration into the cores was sharply reduced. This is consistent with personal observations that tree roots in high bulk density soils often grow along ped faces or at horizon boundaries. It appears that root growth can be somewhat plastic (or opportunistic) if soil structure is strongly developed. Strong soil structure provides channels for growth of roots and for movement of soil solutions and gases.

The presence of soil organic matter improves soil physical condition by promoting favorable soil structure and decreasing soil bulk density. Soil organic matter is also beneficial in increasing or retaining soil water and nutrients (see below). Red alder is a "soil builder." Because it increases soil organic matter more quickly than do many of its associated species, the negative effects of low soil organic matter may be smaller or shorter in duration than those for many other species. Young trees, however, grow more poorly in soils with very low organic matter contents.

Nutrient Availability

Nutrient availability influences site index, but information on how specific levels of a nutrient or groups of nutrients impact site index is not available. Most information on nutrient availability is indirect in nature. For example, the low maximum site index values in some soil orders may indicate that these older weathered (and leached) soils have lower nutrient availability than the younger, less weathered soils present in other orders. Red alder is tolerant of fairly low pH conditions, but maximum site index values are not associated with the most acid soils. The reduction in site index as pH decreases probably is primarily the effect of reduced availability of the macronutrients (and some micronutrients) at low pH and not the effect of hydrogen concentration *per se.* Based on information from 129 sites, SI_{20} values $\geq$ 21 m are on sites with pH values between 4.5 and 5.6 (measured in water) in the 0- to 30-cm surface soil (see discussion below and Fig. 5). This is similar to the optimum range of 4.6 to 5.5 previously reported (Harrington 1986).

One complication in the relationship between alder site quality and nutrient availability is that alder stands may cause changes in soil chemistry. Long-term presence of alder species on sites in the United States and Canada resulted in decreases in soil pH in all studies examined by Bormann et al. (Chapter 3); the decrease was greatest in basic, primary-succession soils and least in acidic, older soils. Van Miegroet and Cole (1988) attributed pH decreases to reduced base saturation resulting from nitrification. Binkley and Sollins (1990) concluded that qualitative changes in soil organic matter other than base saturation are also important factors influencing changes in soil pH. In contrast to the results in North America, Mikola (1966) reported that the presence of gray or black alder trees or the additions of alder leaf litter *increased* soil pH in acidic forest soils (pH < 5.0) or in a nursery soil (pH = 5.4). Thus, the long-term effects of alder on soil pH (and consequently on nutrient availability) may differ depending on initial soil conditions and on climatic or other site conditions. More work is needed to predict the site-specific, long-term effects of alder on soil chemistry—and on site quality.

The macronutrient that seems to be of particular importance to red alder nutrition is phosphorus (Radwan and DeBell, Chapter 15), which becomes less available at low pH. Not only are many red alder stands on soils low in pH, but they are on imperfectly drained sites where soil rooting volume and thus total available soil phosphorus is low. For example, Figure 4 demonstrates that at low levels of available soil phosphorus (defined as phosphorus concentration times rooting depth), maximum SI_{20} increases linearly with increasing available soil phosphorus. Availability of phosphorus, however, can also be important on well-drained sites. In one trial on a sandy, well-drained soil, red alder trees responded to additions of phosphorus or to irrigation, but no additional increases in growth were realized when irrigation and phosphorus were combined (DeBell et al. 1990). Phosphorus is considered important in promoting root growth; under the right conditions high levels of phosphorus may promote enough additional root growth to increase the tree's capacity for water uptake.

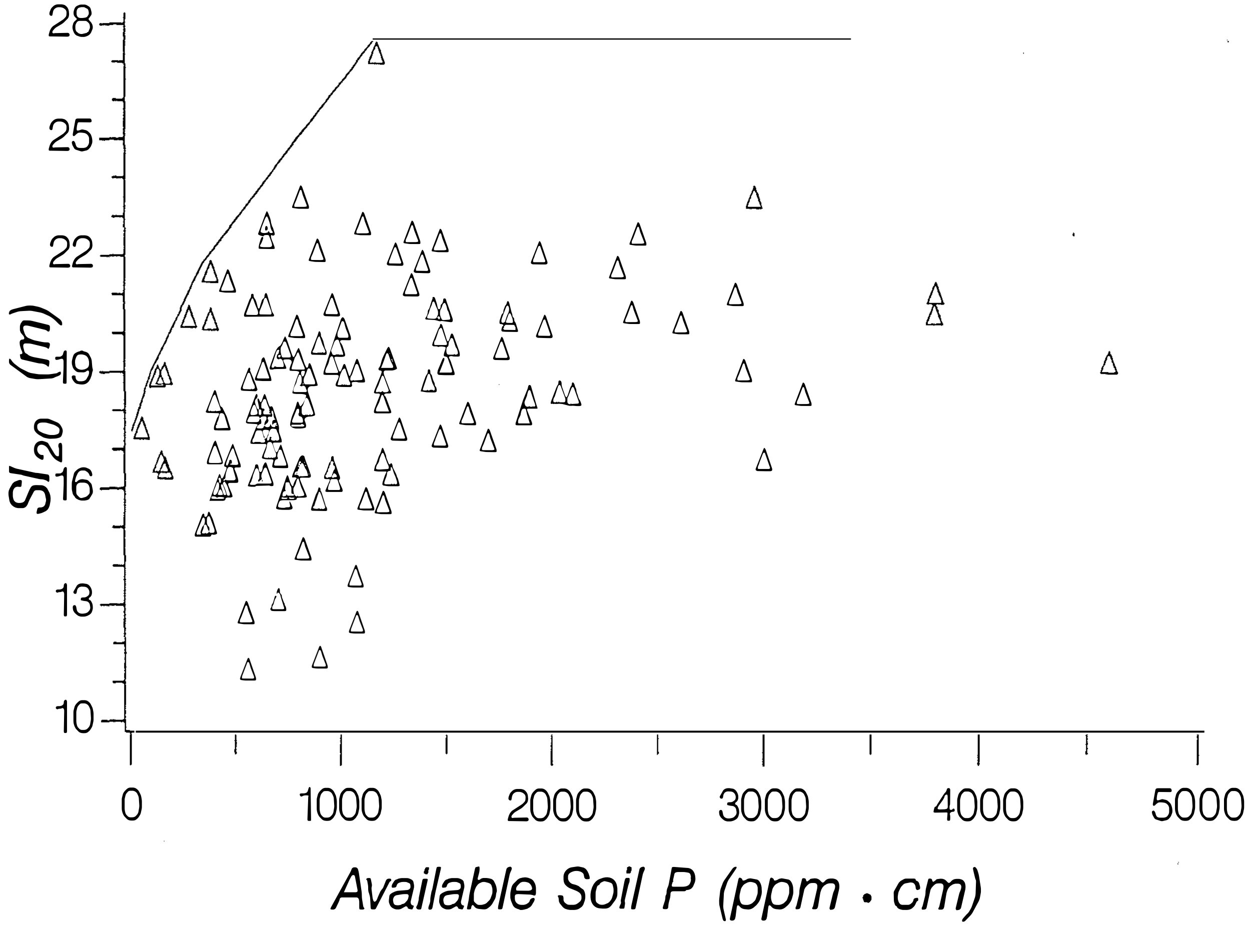

Figure 4. Relationship between red alder site index (base-age 20 years) and available soil phosphorus [defined as (Bray #1-extractable P in 0- to 30-cm layer in ppm) x (rooting depth in centimeters)].

Relationships between red alder site quality and micronutrients are even less well understood than those involving the macronutrients. Generally molybdenum and boron become less available at low pH, while iron, manganese, zinc, copper, and cobalt become more available. Availability of specific micronutrients is also affected by soil oxygen levels. Some poorly drained organic soils may have such low availability of micronutrients (due to both pH and anaerobic effects) that growth is significantly reduced. For example, gray alder planted on a peat bog in Sweden grew very poorly until boron was applied (Rytter et al. 1990).

Hughes et al. (1968) pointed out that red alder seedling growth responses to nutrient amendments must be interpreted carefully as fertilizer additions can alter soil pH and stimulate or depress elements other than those present in the fertilizer amendment. Thus, they attributed some of the beneficial effects of calcium additions to its associated increase in soil pH and decrease in manganese uptake. Similarly, negative effects of nitrogen additions were partially attributed to the associated reduction in soil pH and the stimulation of manganese uptake. In our data, the most productive sites ($SI_{20} \geq 21$ m) have low to moderate values of soil iron or manganese. The data presented in Figure 5 indicate that the most productive sites (SI_{20} > 21 m) have available iron values < 30 ppm in the 0- to 30-cm soil layer. None of the most productive sites were in pH class 1 (4.00 to 4.49), and all the sites with iron values > 60 ppm were in pH class 1.

Red alder seedlings in a growth chamber grew dramatically better on forest floor material from a hemlock stand than on rotten wood (Minore 1972);

this difference was attributed to higher nutrient availability in the forest floor and to observed differences in rooting habit and nodule formation between the two media. Under natural conditions, the presence of very high soil organic matter contents (> 25 percent) is not favorable, as it indicates low organic matter turnover rates (and thus, low nutrient cycling rates) associated with cold temperatures (high elevation or northerly latitude) or low oxygen (very poorly drained soils) (Harrington 1986).

Influences of Management Activities on Site Quality

Silvicultural decisions can influence site quality or apparent site quality (i.e., situations where measured site quality or site index has been altered but no changes have been made to the inherent productive capacity of the site) in several ways. Choice of genotype or planting stock and control of conditions at stand establishment influence early growth of red alder. Under many circumstances, these early gains will probably still be measurable at index age and thus will result in an apparent increase in site quality. For many species, separate site index and height growth curves have been developed for natural and planted stands as field observations indicated differences in growth rates.

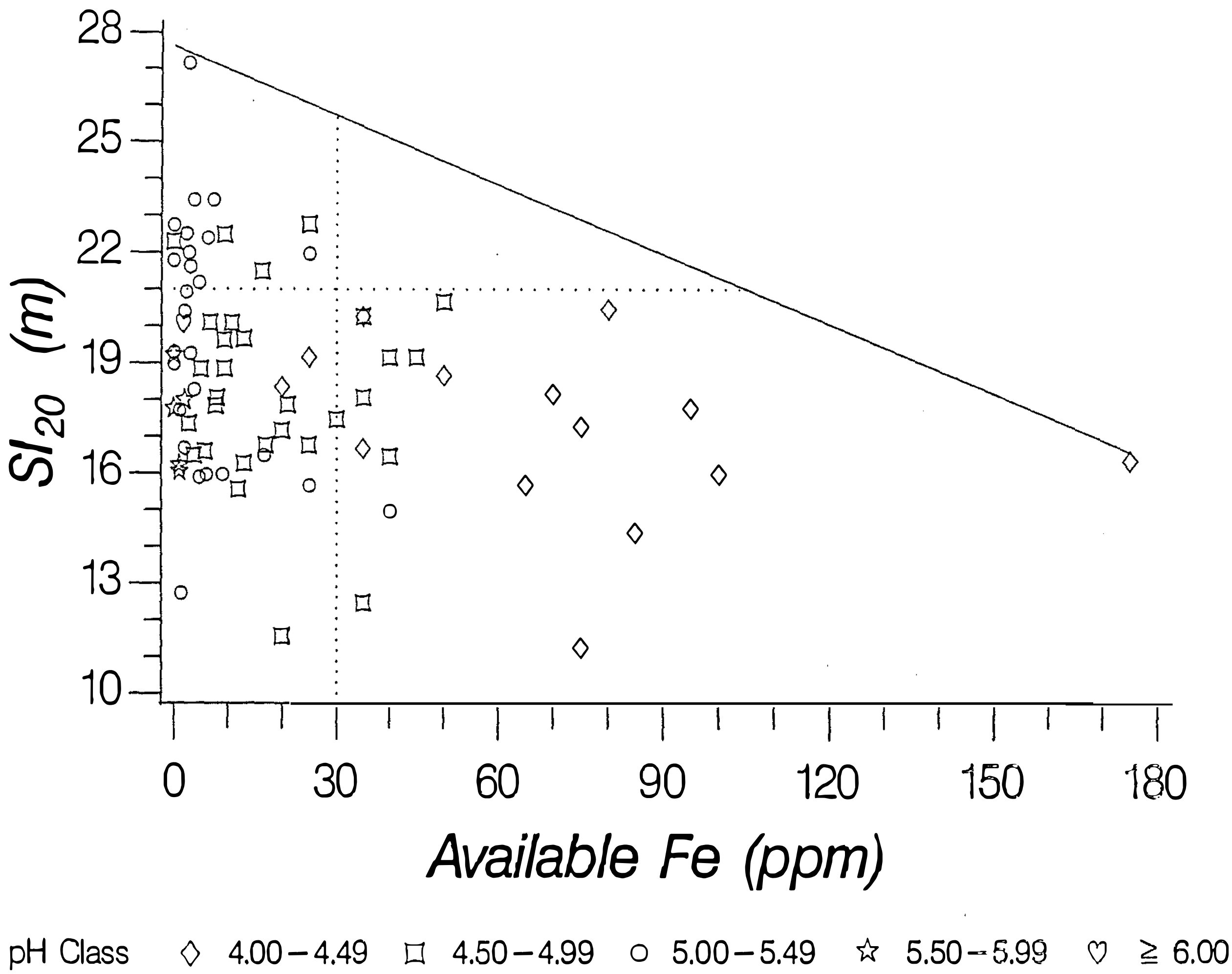

Figure 5. Relationship between red alder site index (base-age 20 years) and available iron concentration in the 0- to 30-cm soil layer. Plotting symbols indicate pH class (pH measured in water) for the same soil layer.

Spacing experiments have indicated that alder height growth is influenced by initial stand spacing with maximum height growth occurring at intermediate spacings (DeBell and Giordano, Chapter 8). It is not yet known how persistent those differences in early height growth will be or how differences in apparent site index will relate to other measures of productivity. In addition, planting specific genotypes with high growth rates or tolerances for specific site conditions may alter apparent site quality. Other management activities actually alter the inherent productive capacity of the site for short or long periods of time. Examples of such activities include drainage, irrigation, fertilization, burning, and treatments that increase or decrease soil compaction. Not enough is known to predict the specific conditions under which these activities influence site quality for red alder or the magnitude or duration of the effects. And, as discussed earlier, we do not know which sites may be degraded (decreased soil pH and increased cation leaching) or under what conditions changes in site quality may occur by growing repeated crops of pure alder (Bormann et al., Chapter 3).

Future Research Needs

Our knowledge base from which to evaluate site quality for red alder is quite limited. Polymorphic site curves for the species (Harrington and Curtis 1986) exist, and this chapter includes recommendations on their use. A research priority should be to determine if planted or managed stands require new curves or adjustments to the existing ones. Alternative methods to evaluate site quality for red alder are in their infancy. Expanded work on biologically based soil-site or biogeoclimatic-site models could help pinpoint areas where our understanding of the underlying biological relationships is weak. This could be coordinated with more basic plant nutrition research to maximize the returns. For example, additional research is needed on the relationships among soil organic matter, pH, aeration, nutrient availability, and growth of alder. Improved understanding of these relationships could pinpoint which soils warrant testing to improve accuracy of site quality estimation. In addition, the general topic of how management activities affect short-term or long-term site quality for red alder stands should also be a high priority for future research.

Acknowledgments

Some of the soil-site data collected in Washington and Oregon was supported by funding from the U.S. Department of Energy, Woody Crops Program, under interagency agreement DE-AI05-810R20914. Data collection for the sites in British Columbia was supported by funding from the Canada-British Columbia Forest Resources Development Agreement, 1985-90 Backlog Reforestation Program, Research and Development Subprogram Project No. 2.54 (red alder component).

Literature Cited

Agriculture Canada Expert Committee on Soil Survey. 1987. The Canadian system of soil classification. 2nd ed. Agric. Canada Pub. 1646.

Baker, J. B., and W. M. Broadfoot. 1977. A practical field method of site evaluation for eight important southern hardwoods. USDA For. Serv., Southern For. Exp. Sta., Gen. Tech. Rep. SO-14.

Binkley, D., and P. Sollins. 1990. Factors determining differences in soil pH in adjacent conifer and alder-conifer stands. Soil Sci. Soc. Am. J. 54:1427-1433.

Bishop, D. M., F. A. Johnson, and G. R. Staebler. 1958. Site curves for red alder. USDA For. Serv., Res. Note PNW-162.

Carmean, W. H. 1975. Forest site quality evaluation in the United States. Advances in Agronomy 27:209-269.

Chambers, C. J. 1983. Empirical yield tables for predominately alder stands in western Washington. 4th print. Washington State Dept. of Natural Resources, DNR Rep. 31. Olympia, WA.

Courtin, P. J. 1992. The relationships between the ecological site quality and the site index and stem form of red alder in southwestern British Columbia. M.S. thesis, Univ. of British Columbia, Vancouver.

Curtis, R. O. 1983. Procedures for establishing and maintaining permanent plots for silvicultural and yield research. USDA For. Serv., Gen. Tech. Rep. PNW-155.

DeBell, D. S., B. C. Wilson, and B. T. Bormann. 1978. The reliability of determining age of red alder by ring counts. USDA For. Serv., Res. Note PNW-318.

DeBell, D. S., M. A. Radwan, D. L. Reukema, J. C. Zasada, W. R. Harms, R. A. Cellarius, G. W. Clendenen, and M. R. McKevlin. 1989. Increasing the productivity of biomass plantations of alder and cottonwood in the Pacific Northwest. Annual technical report submitted to the U.S. Dept. of Energy, Woody Crops Program.

DeBell, D. S., M. A. Radwan, C. A. Harrington, G. W. Clendenen, J. C. Zasada, W. R. Harms, and M. R. McKevlin. 1990. Increasing the productivity of biomass plantations of alder and cottonwood in the Pacific Northwest. Annual technical report submitted to the U.S. Dept. of Energy, Woody Crops Program.

Evanylo, G. K., and M. E. Sumner. 1987. Utilization of the boundary line approach in the development of soil nutrient norms for soybean production. Comm. Soil Sci. Plant Anal. 18:1379-1401.

Fergerson, W., G. Hoyer, M. Newton, and D. R. M. Scott. 1978. A comparison of red alder, Douglas-fir, and western hemlock productivities as related to site: a panel discussion. *In* Utilization and management of alder. *Compiled by* D. G. Briggs, D. S. DeBell, and W. A. Atkinson. USDA For. Serv., Gen. Tech. Rep. PNW-70. 175-182.

Green, R. N., P. J. Courtin, K. Klinka, R. J. Slaco, and C. A. Ray. 1984. Site diagnosis, tree species selection and slashburning guidelines for the Vancouver Forest Region. Land Manage. Handb. 8., British Columbia Ministry of Forests, Victoria.

Green, R. N., P. L. Marshall, and K. Klinka, K. 1989. Estimating site index of Douglas-fir (*Pseudotsuga menziesii* {Mirb.} Franco) from ecological variables in southwestern British Columbia. For. Sci. 35:50-63.

Harrington, C. A. 1984. Site quality prediction for red alder. Agronomy Abstracts 76th annual meeting. 260-261.

———. 1986. A method of site quality evaluation for red alder. USDA For. Serv., Gen. Tech. Rep. PNW-192.

———. 1987. Responses of red alder and black cottonwood seedlings to flooding. Physiol. Plant. 69:35-48.

———. 1990. *Alnus rubra* Bong.—red alder. *In* Silvics of North America, vol. 2, Hardwoods. *Technically coordinated by* R. M. Burns and B. H. Honkala. USDA For. Serv., Agric. Handb. 654. Washington, D.C. 116-123.

———. 1991. PTSITE—a new method of site evaluation for loblolly pine: model development and user's guide. USDA For. Serv., Southern For. Exp. Sta., Gen. Tech. Rep. SO-81.

Harrington, C. A., and R. O. Curtis. 1986. Height growth and site index curves for red alder. USDA For. Serv., Res. Pap. PNW-358.

Hughes, D. R., S. P. Gessel, and R. B. Walker. 1968. Red alder deficiency symptoms and fertilizer trials. *In* Biology of alder. *Edited by* J. M. Trappe, J. F. Franklin, R. F. Tarrant, and G. M. Hansen. USDA For. Serv., PNW For. Range Exp. Sta., Portland, OR. 225-237.

Klinka, K. and R. E. Carter. 1990. Relationships between site index and synoptic environmental factors in immature Douglas-fir stands. For. Sci. 36:815-830.

McKee, W. H., Jr. 1977. Soil-site relationships for loblolly pine on selected soils. *In* Proceedings 6th Southern Forest Soils Workshop, 19-21 October 1976, Charleston, SC. USDA For. Serv., State and Private Forestry, Southeastern Area, Atlanta, GA. 115-120.

McQuilkin, R. A. 1976. The necessity of independent testing of soil-site equations. Soil Sci. Soc. Amer. J. 40:783-785.

Mikola, P. 1966. The value of alder in adding nitrogen in forest soils. Final Report for Project E8-FS-46, grant EG-Fi-131 under P.L. 480. Dept. of Silviculture, Univ. of Helsinki, Finland.

Minore, D. 1968. Effects of artificial flooding on seedling survival and growth of six northwestern tree species. USDA For. Serv., Res. Note PNW-92.

———. 1970. Seedling growth of eight northwestern tree species over three water tables. USDA For. Serv., Res. Note PNW-115.

———. 1972. Germination and early growth of coastal tree species on organic seed beds. USDA For. Serv., Res. Pap. PNW-135.

———. 1979. Comparative autecological characteristics of northwestern tree species—a literature review. USDA For. Serv., Gen. Tech. Rep. PNW-87.

Minore, D., and C. E. Smith. 1971. Occurrence and growth of four northwestern tree species over shallow water tables. USDA For. Serv., Res. Note PNW-160.

Minore, D., C. E. Smith, and R. F. Woollard. 1969. Effects of high soil density on seedling root growth of seven northwestern tree species. USDA For. Serv., Res. Note PNW-112.

Mitchell, K. J., and K. R. Polsson. 1988. Site index curves and tables for British Columbia: coastal species. Canadian Forestry Service and British Columbia Ministry of Forests, FRDA Rep. 37.

Pojar, J., K. Klinka, and D. V. Meidinger. 1987. Biogeoclimatic ecosystem classification in British Columbia. For. Ecol. Manage. 22:119-154.

Rytter, L., U. Granhall, and A. S. Arveby. 1990. Experiences of grey alder plantations on a peat bog. *In* Fast growing and nitrogen fixing trees. 8-12 October 1989, Marburg. *Edited by* D. Werner and P. Muller. Gustav Fischer Verlag, Stuttgart. 112-114.

Snell, J. A. K., and S. N. Little. 1983. Predicting crown weight and bole volume of five western hardwoods. USDA For. Serv., Gen. Tech. Rep. PNW-151.

Soil Survey Staff. 1975. Soil taxonomy. USDA Soil Conservation Serv., Agric. Handb. 436. Washington, D.C.

Tiarks, A. E., and E. Shoulders. 1982. Effects of shallow water tables on height growth and phosphorus uptake by loblolly and slash pines. USDA For. Serv., Southern For. Exp. Sta., Res. Note SO-285.

Van Miegroet, H., and D. W. Cole. 1988. Influence of nitrogen-fixing alder on acidification and cation leaching in a forest soil. *In* Forest site evaluation and long-term productivity. *Edited by* D. W. Cole and S. P. Gessel. Univ. of Washington Press, Seattle.

Waring, R. H., and J. F. Franklin. 1979. Evergreen coniferous forests of the Pacific Northwest. Science 204:1380-1386.

Worthington, N. P. 1965. Red alder. *In* Silvics of forest trees of the United States. *Compiled by* H. A. Fowells. USDA For. Serv., Agric. Handb. 271. Washington, D.C. 83-88.

Worthington, N. P., F. A. Johnson, G. R. Staebler, and W. J. Lloyd. 1960. Normal yield tables for red alder. USDA For. Serv., Res. Pap. PNW-36.