Estimating Site Quality from Early Height Growth of White Spruce and Red Pine Plantations in the Thunder Bay area

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ABSTRACT

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Key Words: early height growth, growth intercepts, *Picea glauca, Pinus resinosa,* plantations, red pine, site index curves, site quality, Thunder Bay, white spruce.

Growth intercepts and breast height-age height growth curves were developed for estimating the site quality using early height growth in white spruce (*Picea glauca* (Moench) Voss) and red pine (*Pinus resinosa* Ait.) plantations in the Thunder Bay, Ontario area. These methods for estimating site quality were developed from height growth data obtained using annual node measurements and stem analyses of three dominant, undamaged, trees in each of 46 white spruce and 25 red pine plots located throughout the Thunder Bay area.

White spruce growth intercepts were computed using series of one through seven internodes from eight starting heights between 0 and 3.0 m. Red pine growth intercepts were computed using series of one through 10 internodes from the same eight starting heights. The best estimates of white spruce and red pine site quality were obtained from the average length of the first three, four, and five internodes above 2.0 m, and the first three, four, and five internodes above 1.5 m, respectively.

Both white spruce and red pine height growth patterns were best described by an expanded Chapman-Richards function capable of expressing polymorphic height growth patterns. These height growth patterns compared well with those of eastern Ontario and the Lake States. Height growth below breast height for both species was very erratic and was not related to site quality. Consequently, total height-age height growth curves that included this early erratic height growth did not provide accurate estimates of site quality in these white spruce and red pine plantations. Growth intercepts provided accurate estimates of site quality in early years. However, breast height-age height growth curves provided more accurate estimates of site quality when plantations exceeded the ages required for these growth intercepts.

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INTRODUCTION

Planting trees is now the most commonly used method for regenerating forest cutovers in the Ontario Ministry of Natural Resources (OMNR) Thunder Bay District (Towill, pers. comm., 15 Jan 86). There are now approximately 57 000 ha of forest plantations in the Thunder Bay District. This total area is increasing rapidly as the annual rate of planting has increased from approximately 2 000 ha in 1982 to approximately 7 000 ha in 1985 (Figure 1). This present rate of planting in the Thunder Bay District is expected to continue under the

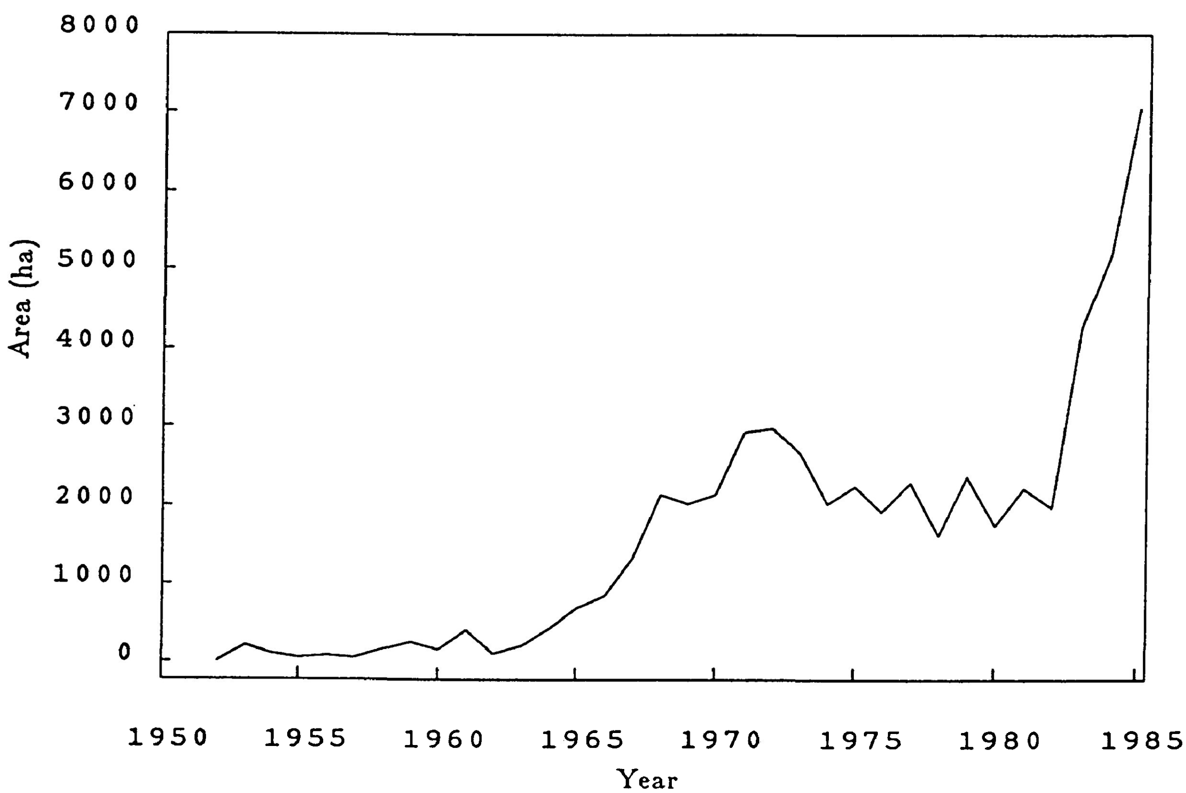

Figure 1. Forest cutover area planted in the OMNR Thunder Bay District from 1952 to 1985. Area includes bareroot and transplant stock of all species.

recently signed Forest Management Agreements with Abitibi-Price Inc. and Great Lakes Forest Products Ltd. Consequently, a significant portion of the productive forest land in the Thunder Bay District will ultimately be under plantation management.

The social and economic welfare of northwestern Ontario depends on a strong, competitive, viable forest products industry. This industry can only be maintained through biologically and economically responsible intensive forest management. In other words, the long term stability of the forest industry in northwestern Ontario can only be maintained by intensive forest management aimed at producing sufficient quantities of high quality wood, from the least area of land, and at the lowest possible cost.

Accordingly, intensive management of the vast areas of forest plantations should be concentrated in the plantations growing on the most productive sites. These productive sites not only produce a larger quantity and better quality of wood, but respond to silvicultural treatments with greater increases in yield than do less productive sites. Consequently, the economic return on intensive forest plantation management is maximized on the most productive sites.

Prior to 1968, only small areas of forest cutover were regenerated by planting. As a result, most forest plantations in the Thunder Bay area are less than about 20 years of age. However, several white spruce (*Picea glauca* (Moench) Voss) and red pine (*Pinus resinosa* Ait.) plantations are greater than 20 years of age. Some of these older plantations are approaching the 30-40 year age class where intermediate silvicultural treatments such as thinning and pruning should be considered. However, there are currently no quantitative methods for assessing the site quality and productivity of these plantations. Therefore, there is currently no quantitative basis for the allocation of intensive forest plantation management funds. Forest managers presently rely on their experience and general knowledge of local forest and land conditions to assess relative productivity. Economically and biologically responsible intensive forest management requires that these qualitative procedures be replaced by quantitative methods that provide accurate estimates of site quality based on actual tree growth.

The ultimate measure of site quality in forest plantations is the total volume of wood produced under a given management regime at rotation. However, forest managers require estimates of forest plantation site quality very early in the rotation. The height growth of free growing, uninjured, dominant trees in fully stocked even-aged stands is more closely related to volume growth than any other single measure. Height growth is relatively unaffected over a wide range of stocking for most tree species. Thus, height growth provides a good estimate of site quality that is relatively independent of stocking. This accounts for the wide spread use of height growth (site index) as a measure of site quality in North America and Europe (Carmean, 1975; Hägglund, 1981).

Accordingly, the objective of this study was to develop simple, accurate methods for estimating site quality from early height growth in white spruce and red pine plantations in the Thunder Bay area. These methods involve growth intercepts and height growth curves based on height growth measurements from local plantations. The growth intercepts and height growth curves from this study can then be used to predict later height growth, and thus site quality for white spruce and red pine plantations in the Thunder Bay area.

Growth intercepts were developed with the objective of identifying the best possible combination of internodes to provide the most accurate estimates of site quality for white spruce and red pine plantations. This objective involved computing growth intercepts using various numbers of internodes from various starting heights. In addition, the conventional method of computing growth intercepts from a continuous sequence of internodes was modified by the systematic elimination of certain internodes in attempts to provide even more accurate estimates of site quality.

Height growth curves were developed with the objective of providing the best quantitative description of height growth patterns in these white spruce and red pine plantations. These height growth curves were then used to estimate site quality. These height growth curves also were compared to height growth curves from eastern Ontario and the Lake States.

LITERATURE REVIEW

FOREST SITE QUALITY

The Society of American Foresters (1958) defines site as: "An area considered as to its ecological factors with reference to capacity to produce forests or other vegetation; the combination of biotic, climatic and soil conditions of an area". Davis (1966) interprets this as: "How good is the land; how much wood will it grow?" Site can also be considered as a combination of both land and forest (Hills, 1960). Barnes (1985) simply defines site as a "place" in the forest. Sammi (1965) states that forest site can be variously defined, but is essentially the classification of an area with respect to its wood producing capacity.

Carmean (1982) defines forest site quality as the ability of forest land to grow timber. Spurr and Barnes (1980) define forest site quality as the sum total of all the factors affecting the capacity to produce forests or other vegetation; climatic, edaphic, and biological. Spurr (1952) earlier noted that site quality is the sum total of all the interacting factors that determine the productive capacity of an area. He stated that the task of isolating a single decisive index of this quality is extremely complex and difficult, if not impossible.

An Historical Perspective

The classification of forest sites by productivity in Germany was at first by ocular estimation and was very subjective (Hartig, 1795). The graphical "strip method" of classifying forest sites by volume and age, originally introduced in France by DePerthuis (1788), was introduced into general use in Germany by Baur (1877). Realizing that the volume of a stand was influenced by factors other than the productive capacity of the site, Baur proposed the mean height of a stand as a measure of site quality (Assmann, 1970; Cajander, 1926, 1949).

He proposed using the same graphical strip method used for classifying stands by volume and age as a means for classifying forest stands into five height quality classes based on total height and total age.

The Central European Forest Research Institutes used the same graphical technique, but employed the "directing curve method" (Heyer, 1846, 1857) of portraying height growth from periodic measurements of permanent sample plots (Cajander, 1926). The "index method" (Cajander, 1926, 1949) or the "indicator method" (Assmann, 1970) invented by Huber (1824) and introduced by Hartig (1868) was also used to portray height growth. This method used stem analyses to reconstruct height growth patterns of dominant trees from sample plots. Weise (1880) presents the first height-age curves showing the development of dominant height.

In 1888, the German Silvicultural Experimental Stations at Ulm, decided to accept the gross volume in m^3 per ha at 100 years of age as the standard definition of quality class (Cajander, 1949; Roth, 1916). However, height growth was still considered a more useful measure of site quality where stand conditions were not "normal" (Schwappach, 1908).

The need for a standard system of site classification in North America had become apparent in the early 1900's (Carmean, 1975). European influence had introduced three schools of thought regarding forest site classification: 1) those influenced by Cajander, advocating the site-type concept (Zon, 1913); 2) those advocating the use of volume, as was accepted earlier in Germany (Bates, 1918); and 3) and the largest group, those advocating the use of height (Frothingham, 1918, 1921a, 1921b; Graves, 1906; Parker, 1916; Roth, 1916, 1918; Sterrett, 1921; Watson, 1917). All agreed that volume was the ultimate measure of site quality, but the effects of species mixture and stocking made volume impossible to use for classifying site quality in the natural forest. The Society of American Foresters appointed a committee "To consider the various suggestions for site standardization with reference to their practicability for adoption by the profession" (Sparhawk *et al.*, 1923). This committee did not recommend any one system, but did favour the use of height growth because of its simplicity and relative accuracy.

Height Growth as a Measure of Site Quality

The height of free-grown trees of a given species is more closely related to the capacity of a given site to produce wood than any single measure (Spurr and Barnes, 1980). The relationship between height and age provides a good estimate of site quality in fully stocked, even-aged stands because height growth is closely related to volume growth, height and age are easily measured, and the height of most species is relatively unaffected by stand density (Husch *et al.*, 1982). Bates (1918) states that height is one of the most important attributes of a site, but does not sum up all of the qualities that a forester is interested in when attempting to express site quality.

Site index is the most widely accepted method of estimating site quality in North America (Carmean, 1975) and in Europe (Hägglund, 1981). The relationship of tree height and age, commonly called site index, is defined as the height of the dominant portion of a forest stand at a specified standard age (Spurr and Barnes, 1980). Index age is usually 100 years for the long lived species of western North America, 50 years for the shorter lived species of eastern North America, and 25 years or less for young plantations or species managed on short rotations (Carmean, 1975). The advantages and disadvantages of using site index as an estimate of site quality are discussed by Avery and Burkhart (1983), Carmean (1975), Heiberg and White (1956), Jones (1969), Sammi (1965), Vincent (1961), and many others.

Estimates of site index are most often obtained using measurements of height and age with a height-over-age growth curve to estimate height at a standard age (Spurr and Barnes, 1980). These height-over-age growth curves are commonly referred to as site index curves (Carmean, 1975). Site index curves are primarily used for classification purposes, however, site index curves may also be used to predict the future height of trees (Strand, 1964). Strand points out that these two uses are different and that curves efficient for one use are not necessarily efficient for the other use. Curtis *et al.* (1974) state that the traditional type of height-over-age "site index curve" does not provide optimum estimates of site index. They recommend that curves intended to be used for estimating site index should equate site index as a function of height and age, instead of the traditional approach of equating height as a function of site index and age as is done with height growth curves.

Volume Growth as a Measure of Site Quality

The ultimate measure of site quality is the maximum volume of timber a given area of land can produce in a given period of time (Daniel *et al.*, 1979; Husch, 1963). However, evaluating site quality by volume production is of limited practical use (Husch, 1963). Actual yield is conditioned not only by site factors, but also by genetic factors, stand density, and the biotic history of the stand (Spurr and Barnes, 1980). The influence of these non-site factors render volume growth of limited value as a measure of site quality because of the difficulty in the development and application of such a technique (Husch *et al.*, 1982).

Volume growth is considered to be more sensitive to environmental factors than height growth (Mader, 1963). Van Eck and Whiteside (1963) state that volume is a better measure of site quality that is capable of revealing real differences in site productivity. Diameter growth seems considerably more sensitive to environmental conditions than shoot growth (Kramer and Kozlowski, 1960). Height growth occurs early in the growing season, thus is less likely to be affected by drought than is diameter growth that occurs throughout the growing season (Hoyle and Mader, 1964). Sammi (1965) suggests that site index is not a true index of site because heights of trees taken for site index are not necessarily a valid index of volume for a given area. This hypothesis is supported in results given by Assmann (1970) showing 20 % differences in volume between stands of Norway spruce (*Picea abies* (L.) Karst.) with similar site index values and under similar management regimes. Alban (1985b) also gives results supporting this hypothesis, showing two red pine stands on different soils with different site index values, but having similar volume growth rates.

EARLY HEIGHT GROWTH AS A MEASURE OF SITE QUALITY

Growth Intercepts

When stands are too young to estimate site index by the conventional height-age approach, early height growth can be a useful measure of site quality (Alban, 1979). The growth intercept method uses a selected period of early height growth as an indicator of site quality rather than the long term height growth portrayed in site index curves (Carmean, 1975). Alban (1972) lists the advantages of the growth intercept method as: 1) it can be used in stands too young to be evaluated with standard site index curves; 2) it eliminates the need to measure tree age and height, either of which can be a major source of error; 3) it can be measured easily and rapidly; and 4) by measuring internode lengths above breast height many of the variables associated with the establishment period can be reduced or eliminated. The major disadvantages of the growth intercept method are: 1) early height growth patterns may not reflect later height growth patterns, especially in areas where soil and site conditions differ from those of the study area (Carmean, 1975); and 2) short term climatic variation affecting annual height growth can influence estimates of site quality obtained by this method (Alban, 1972, 1979).

Bull (1931) was the first to test a growth intercept method for estimating site quality. He found the number of years for planted red pine trees to grow from three to 14 feet (0.91 to 4.27 m) to be an unsatisfactory estimate of site quality. Wakeley proposed a similar growth intercept method in 1937 for estimating site quality of young pine plantations in the southern United States (Wakeley and Marrero, 1958). This method used the height increment for a five year period during which the first year of which the tree attained breast height. Marrero tested this "five-year intercept" method in 1946 in southern pine plantations (loblolly pine (*Pinus taeda* L.), slash pine (*P. elliotti* Engelm.), shortleaf pine (*P. echinata* Mill), and longleaf pine (*P. palustris* Mill)). Wakeley and Marrero (1958) reported the results of these tests and showed the five-year intercept was significantly related to the total height of these plantations.

Wakeley and Marrero are considered the pioneers of the five-year intercept method (Day *et al.*, 1960). However, a similar method developed independently by Wylie (1951) multiplied the average length of internodes above breast height, in inches, by a factor of six to estimate the 100 year site index of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in British Columbia (Smith and Ker, 1956). Further development of Wylie's method found the length of three and five internodes above breast height to be significantly related to the 100 year site index of Douglas-fir (Warrack and Fraser, 1955).

Five-year growth intercepts taken from breast height were significantly related to the estimated 50 year site index of red pine (Day *et al.*, 1960; Ferree *et al.*, 1958; Richards *et al.*, 1962), and to the estimated 100 year site index of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) (Gregory, 1960). Ferree *et al.* (1958) also stated that height growth above breast height is closely related to the respective five-year growth intercept of white pine (*Pinus strobus* L.), Norway spruce, and Scots pine (*P. sylvestris* L.). A ratio of the total height of planted red pine trees to the five-year intercept above breast height was found a useful indicator of both soil and site conditions, revealing the productive capacity of different soils and the growth depressing effects of competing vegetation (Wilde, 1964, 1965).

Growth intercept is commonly defined as the total length of the first five internodes above breast height (Alban, 1972). However, five-year growth intercept measurements starting two internodes above breast height (Brown and Stires, 1981), at 2.5 m (Alban, 1972, 1979; Hägglund, 1976), and at 3.0 m (Blyth, 1974) provided better estimates of the 50 year site index of white pine, red pine, Scots pine, Norway spruce, and Sitka spruce, than when internode measurements were started from breast height. Gunter (1968) used five-year intercepts beginning one year after release to estimate the 50 year site index of suppressed red pine.

Warrack and Fraser (1955) found the 100 year site index of Douglas-fir estimated from the length of the first three internodes above breast height was not significantly different from using the first five internodes above breast height. The length of one through five internodes above breast height were all significantly related to the 25 year site index of Douglas-fir (Smith and Ker, 1956). Schallau and Miller (1966) found no significant differences among the 50 year site indices of red pine estimated from the length of one through five internodes above breast height. Beck (1971) found estimates of the 50 year site index of white pine using five internodes above breast height were only slightly more accurate than estimates using only three internodes above breast height. Oliver (1972) used one through six internodes above breast height to estimate the 100 year site index of Ponderosa pine (*Pinus ponderosa* Laws.) and found only little improvement from using more than four internodes.

The length of five internodes measured from 2.5 m was the best compromise between ease of measurement and accuracy when three, five, 10, and 15 internodes were used to estimate the 50 year site index of red pine (Alban, 1972). This growth intercept method was developed for the Lake States, but works well for both plantations and natural stands throughout the range of red pine (Alban, 1985a). Alban (1979) compared the site indices estimated using three and five internodes above breast height and one through four internodes above 2.5 m. He found the first two internodes above 2.5 m would predict the 50 year site index of red pine as accurately as five internodes above breast height. He concluded that the 50 year site index of red pine cannot be reliably estimated earlier than about two years after the trees reach 2.5 m. Brown and Stires (1981) used three, five, and 10 internodes measured at various starting points on the bole to estimate the 50 year site index of white pine. The accuracy of the estimate increased with the number of internodes measured and the height of the starting point. However, no appreciable increase in accuracy resulted when intercept measurements began more than two years above breast height.

Height Growth Curves

White Spruce

Anamorphic height growth curves based on 40 year old planted white spruce near Petawawa, Ontario are presented by Stiell and Berry (1967). Polymorphic height growth curves based on the same plantations at 50 years of age are given by Stiell and Berry (1973b); the metric equivalent of these updated curves are given by Berry (1978). Polymorphic height growth curves for planted white spruce in Quebec (Bolghari, 1977) are very similar to height growth in the 15 to 21 m range of site index given for planted white spruce near Petawawa (Berry, 1978). No site index or height growth curves are available for plantation-grown white spruce in the Lake States (Nienstaedt, 1982).

Red Pine

The anamorphic height growth curves for natural red pine given by Gevorkiantz (1957) are considered adequate to describe the height growth of both natural stands and plantations throughout the Lake States (Alban, 1976, 1979; Alban and Prettyman, 1984; Shetron, 1972; Van Eck and Whiteside, 1963). Stiell and Berry (1973a) used a number of techniques to construct height growth curves for planted red pine at Petawawa. They found that anamorphic curves produced by the method detailed by Husch (1963) conformed most closely to actual height growth patterns. Anamorphic height growth curves are given for planted red pine by four site groups (McCormack, 1956), by a classification age of 50 years from planting (Alban, 1976; Berry, 1984; Shetron, 1972; Stiell and Berry, 1973a; Wilde *et al.*, 1965), by a classification age of 20 years from breast height (Richards *et al.*, 1962), and by five-year growth intercepts above breast height (Ferree *et al.*, 1958). Van Eck and Whiteside (1963) also give height growth curves for red pine planted on soils with free carbonates, on soils having compact horizons at shallow depths, and for coarse textured soils.

Bull (1931) used internode measurements to construct polymorphic height growth curves for planted red pine for age from planting and age from a height of three feet (0.91 m). Richards *et al.* (1962) used total and periodic height measurements to construct polymorphic height growth curves for planted red pine based on age from breast height.

HEIGHT GROWTH PATTERNS

White Spruce

White spruce is considered a slow-starting species, seedlings often take several years to assume a rapid or even reasonable rate of height growth (Stiell, 1976). After about 15 years of age, height growth of planted white spruce is fairly uniform until it begins to decline between 25 and 35 years of age (Stiell, 1976; Stiell and Berry, 1973b).

White spruce commonly suffers a period of post-planting depression known as "check" (Stiell, 1976). Mullin (1963) describes this as a prolonged period of reduced height growth that occurs after planting. Typical symptoms of check are short, greenish yellow needles, poor retention of needles that are two or more years old, small buds, and very slow growth (Sutton, 1975). Suggested causes of planting check in white spruce include bunching of roots at planting, competition from heavy sod, removal of surface mineral soil, planting when roots are actively growing, planting when roots are dormant, and planting too deep (Stiell, 1976). Vyse (1981) lists possible causes of planting check in white spruce as partial root system loss during planting, the slow development of a fine root system after planting, competition from other vegetation, frost, or a combination of these factors. Sutton (1968) concluded through experimental evidence that planting check in white spruce is not a direct result of physical damage, but is caused by the trees inability to exploit the rooting zone. Rauscher (1984) cites personal communication with Hans Nienstaedt stating that check is not an inherent characteristic of white spruce, but rather is a management problem.

The duration of planting check in white spruce varies from two and three years (Burdett *et al.*, 1984; Vyse, 1981) to 10 and 15 years (Mullin, 1963, 1964b, 1966; Stiell, 1976). This duration depends largely on the time required for the trees to rebuild a root system in sufficient proportion to the top to provide the needs of water and nutrients from the soil (Mullin, 1963). Mullin (1970) reports that even with irrigation and fertilization, planted white spruce were in check for three years.

Planted white spruce took six to 12 years to reach breast height near Petawawa (Stiell and Berry, 1967). White spruce planted near Thunder Bay took seven to eight years to reach breast height where surface soil was left intact, and 12 to 16 years where surface soil was removed (Thrower, 1984). Mullin (1978a) reports the average time required for planted white spruce to reach breast height is about eight to 10 years in Ontario. Natural white spruce seeded on mineral soils took 10 to 15 years to reach breast height in Manitoba and Saskatchewan (Rowe, 1955), and 13 to 20 years in British Columbia (Eis, 1967).

The 25 year site index of planted white spruce in Quebec varies from six to 12 m (Bolghari, 1977). The 50 year site index of planted white spruce near Petawawa varies from 15 to 24 m (Stiell and Berry, 1973b). Bolghari (1977) reports that although a 50 year site index of 24 m is rare for planted white spruce in Quebec, height growth patterns are very similar to planted white spruce near Petawawa (Stiell and Berry, 1973b). Harding (1982) studied 56 white spruce plantations in northern Minnesota. He found the height of dominant, uninjured, free-to-grow trees to vary from 5.32 to 10.59 m at 15 years from breast height, and from 10.62 to 21.09 m at 30 years from breast height.

Red Pine

Red pine height growth patterns are remarkably similar throughout the species range (Alban, 1976). Spurr (1955) used a single set of site index curves for both natural stands and plantations throughout the range of red pine. Alban (1972) found that height growth patterns in both natural stands and plantations of red pine in Minnesota were similar to height growth patterns for red pine plantations in Connecticut (Bull, 1931) and New York (Richards *et al.*, 1962). Alban (1972) suggests that differences in early height growth patterns observed between plantations and natural stands should diminish by 25 years of age, and that later height growth should be similar for both plantations and natural stands.

Despite the similarity of red pine height growth patterns over a wide geographic range, the time required to reach breast height is quite variable and is not related to site quality or soil type (Alban, 1972, 1979; Alban and Prettyman, 1984; Day *et al.*, 1960; Ferree *et al.*, 1958; Richards *et al.*, 1962; Wilde, 1964). Alban (1972) also states that natural stands and plantations require about the same time to reach breast height. Table 1 gives the number of years for red pine to reach breast height from planting reported for various locations.

Polymorphic height growth patterns appear to be uncommon in red pine (Alban, 1985a; Alban and Prettyman, 1984). However, polymorphic height growth patterns have been

Table 1. Number of years for red pine to reach breast height from planting in various locations.

Reference	Location	Years to Breast Height	Comments
Kotar and Coffman, 1982	Michigan	4 7	machine scalped soil hand scalped soil
Wilde, 1964	Wisconsin	5 - 6	
Mullin, 1978b	Ontario	7 - 8	
Alban and Prettyman, 1984	Minnesota	8	fine textured soil
Alban, 1972	Minnesota	8.3	none less than 6 years
Van Eck and Whiteside, 1963	Michigan	9 16	cultivated soil uncultivated soil
Richards *et al.*, 1962	New York	4 - 13	
Day *et al.*, 1960	Michigan	4 - 14	
Ferree *et al.*, 1958	New York	4 - 14	

shown on poorly drained soils (Richards *et al.*, 1962; DeMent and Stone, 1968; Stone *et al.*, 1954; Wilde *et al.*, 1964), soils of restricted rooting depth (Alban, 1979; Van Eck and Whiteside, 1963), and sub-irrigated soils (Wilde, 1964, 1965; Wilde *et al.*, 1965). Alban (1985a) suggests that early suppression may be the cause of the polymorphic height growth of red pine reported by Bull (1931) and Hannah (1967).

The maximum site index (50 years from planting) of red pine plantations is reported as 22, 23, and 24 m in Michigan (Kotar and Coffman, 1982; Van Eck and Whiteside, 1963; and Coffman, 1976, respectively), 23 to 24 m in Minnesota (Alban, 1976), and 22 m in Wisconsin (Wilde *et al.*, 1965). The maximum site index (50 years from seed) of natural stands of red pine in Minnesota is about 21 m (Alban, 1976). Bull (1931) reports the site index (15 years from planting) of red pine plantations in Connecticut to range from 2.1 to 6.7 m. Richards *et al.* (1962) report the maximum site index (20 years from breast height) to be 14.3 m in New York.

Bull (1931) reported the maximum height growth of red pine in Connecticut was attained between 10 and 15 years of age on poor sites, and 20 to 25 years on good sites. Ferree *et al.* (1958) reported the maximum height growth of red pine was achieved in the five-year growth period after breast height was reached.

NON-SITE FACTORS AFFECTED BY FOREST MANAGEMENT

Early height growth of forest plantations may be greatly affected by non-site factors such as planting stock quality, planting technique, vegetative competition, allelopathic compounds, frost damage, animal and insect damage, genetics, and stand density (Alban, 1979; Day *et al.*, 1960; Ferree *et al.*, 1958; Heiberg and White, 1956; Jones, 1969; Perala, 1982; Richards *et al.*, 1962; Spurr, 1952; Vincent, 1961; Wakeley and Marrero, 1958). Using breast height-age for determining site index will reduce much of the random variation associated with these factors (Alban, 1979; Carmean, 1975, 1982; Day *et al.*, 1960; Ferree *et al.*, 1958; Husch, 1956; Jones, 1969; Richards *et al.*, 1962). However, erratic early height growth after breast height is reported in red pine and Sitka spruce (Alban, 1979; Blyth, 1974; Kotar and Coffman, 1982; Wilde, 1964).

Stand Density

Tree height is usually considered to be relatively independent of stand density for most tree species (Braathe, 1957; Husch *et al.*, 1983; Spurr, 1952; Spurr and Barnes, 1980). However, Carmean (1975) lists studies showing the height growth of upland oaks (*Quercus spp.*), lodgepole pine (*Pinus contorta* Dougl.), Ponderosa pine, and slash pine to be affected by varying stand density. Carmean (1975) concluded that reductions in height growth seems particularly serious for densely stocked stands on poor sites. Evert (1971) reviewed North American and European literature on tree spacing. He concluded that height growth is likely to be restricted by close spacing for plantations on poor to medium sites, whereas spacing appears to have little or no affect on height growth on good sites. Smith (1962) states that increased branching in very open stands is at the expense of height growth. Spurr (1952) concludes that height growth is not affected by the variation of density commonly found in managed forests, or in natural stands of moderate density.

White Spruce

No differences in dominant height growth were observed 10 and 20 years after thinning a 35 year old white spruce plantation near Petawawa (Stiell, 1970, 1980). Likewise, height growth was unaffected 15 years after thinning a 23 year old white spruce plantation in northeastern Wisconsin (Wambach and Cooley, 1969). Early results of spacing trials from 10 to 15 years of age have failed to show any effects of spacing on the height growth of white spruce (Bella and DeFranceschi, 1980; Gillespie, 1971; Herring, 1981).

Red pine

Height growth of red pine is unaffected by density except for poor sites, or extremely open or dense stands (Baker, 1950; Buckman, 1962; Spurr, 1952; Stiell, 1978, 1985). Ralston (1954) states that height growth of red pine can be reduced on poor sites because of the intense competition for soil moisture at close spacing.

Height growth of red pine was unaffected by density over a wide range of spacings (Allison and Cole, 1956; Bella and DeFranceschi, 1980; Bramble *et al.*, 1949; Richards *et al.*, 1962; Stiell, 1964, 1982). However, height growth of red pine was retarded at very close spacings on poor sites (Adams and Chapman, 1942; Byrnes and Bramble, 1955; Ralston, 1954; Schantz-Hansen, 1945). Day and Borczon (1971) report that height growth of planted red pine also was retarded at wide spacings. Stiell and Berry (1977) report that red pine planted at wider spacings consistently grew more in average height than at close spacings, however, the dominant height (tallest 10 % of the stand) was not significantly related to spacing.

No difference in height growth was observed after thinning red pine plantations (Althen and Stiell, 1965; Morrow, 1974; Wilson, 1946) or natural stands (Smithers, 1954). However, Engle and Smith (1951) report that height growth of red pine on poor sites was accelerated from thinning both an overstocked natural stand and an overstocked 42 year old plantation in lower Michigan. No change in height growth was evident five years after thinning a 14 year old red pine plantation near Petawawa (Bickerstaff, 1946). However, subsequent analyses at 20 and 30 years after thinning did show a slight, but insignificant reduction in height growth in the five year period immediately following thinning (Berry, 1965, 1971).

Competition

A heavy cover of weeds is the most frequent and critical factor responsible for depressed growth of forest plantations in many regions (Wilde, 1965, 1970; Wilde *et al.*, 1965).

The success of conifer plantations depends primarily on the adverse effects of subordinate vegetation, particularly root competition (Shirley, 1945). Forest weeds compete with conifer seedlings for light, water, and nutrients, and may inhibit growth directly by releasing allelopathic chemicals (Perala, 1982). In addition to ultimate reductions in timber yield, the presence of ground or overstory vegetation during the establishment period may inhibit early height growth of trees which subsequently may be used for estimating site quality (Ralston, 1964).

White Spruce

Weed competition is one of the main factors affecting early height growth of white spruce plantations (Jarvis *et al.*, 1966; Rowe, 1955; Shirley, 1945). The degree that white spruce suffers depends on the density and relative size of competitors (Stiell, 1976). Stiell also notes that a light or moderate ground cover may give protection from exposure. However, dense low vegetation, especially grasses, offers severe competition to newly planted white spruce seedlings that can have a lasting effect on their development.

Height growth of planted white spruce is much better in the open than in the shade (Jarvis *et al.*, 1966; Moore, 1926). Shirley (1945) found that white spruce seedlings required at least 45 % of full sunlight for optimum height growth. Gustafson (1943) reports that after seven years, the maximum height growth of white spruce transplants was attained under 75 % full sunlight. Logan (1969) found that after nine years, optimum height growth of white spruce seedlings was attained under 45 and 100 % sunlight. Eis (1967) found that height growth of seeded white spruce increased with light up to about 60 %. Stiell (1976) states that juvenile white spruce will retain optimum growth in somewhat less than 50 % light, but full sunlight is required for optimum height growth from about 10 years of age.

Height growth of white spruce outplants is significantly increased by controlling competing woody and herbaceous weed vegetation (Althen, 1970; Baskerville, 1961; Dobbs, 1976; McMinn, 1974; Mullin, 1974; Stephens, 1965; Sutton, 1968, 1969b; Wang and Horton, 1968). Waldron (1959) found that white spruce seedlings were 43 cm in height four years after planting where beaked hazel (*Corylus cornuta*) was removed, but were only 30 cm in height where the hazel was not removed. Likewise, Rowe (1961) found that 14 year old white spruce seedlings grown in the open were 112 to 120 cm in height, but were only 18 to 36 cm in height under an overhead canopy. Sutton (1972) found that after seven years the height growth of white spruce did not respond to fertilization or irrigation, but increased significantly from 114 cm on plots without weed control to 155 cm on plots with weed control. Sutton (1975) considered improved fertility resulting from reduced weed competition as the principal cause for a significant increase in the second and third years height growth of white spruce outplants.

Fisher (1980) found that leachates from bog laurel (*Kalmia polifolia* Wang.) and large-leaf aster (*Aster macrophyllus* L.) contain allelopathic compounds that inhibited the early growth of white spruce seedlings. White spruce transplants and seedlings mulched with reindeer moss (*Cladonia rangiferina* and *C. alpestris*) also were stunted after 17 weeks growth (Fisher, 1979).

Red Pine

Red pine may survive shading for the first few years, but cannot grow satisfactorily under even moderate overhead cover (Stiell, 1978), and serious growth losses will occur with even a light overstory (Benzie, 1977; Horton and Bedell, 1960; Rudolph, 1957). Logan (1966) found that red pine can achieve full height growth at 43 % of full sunlight until age five, but requires full sunlight to attain maximum height after six years of age. Height growth of red pine seedlings was found to increase with sunlight up to 63 % of full sunlight (Fraser, 1959; Mitchell and Rosendahl, 1939; Shirley, 1932). Four years after planting, red pine transplants attained maximum height growth in 43 % light (Shirley, 1945). Red pine seedlings grown under the shade of hazel (*Corylus spp.*) grew only four cm in height in the second year from outplanting, while seedlings not shaded grew 15 cm in height (Strothmann, 1967). In contrast, Wilde (1965) states that light plays a small part in the early growth of red pine and that height growth usually reflects edaphic and biotic influences.

The consumption of water by weeds is the primary cause of reduced early height growth of red pine plantations in Wisconsin (Shaw *et al.*, 1968; Wilde, 1970; Wilde *et al.*, 1968 Wittenkamp and Wilde, 1964). Increased water availability in a seven year old red pine plantation resulted in a 13 % increase in height growth one year following the removal of weed competition (Lambert *et al.*, 1972). Weed competition was given as the reason for a reduction in estimated site index from 65 to 50 feet (19.81 to 15.24 m) in a 27 year old red pine plantation (Wittenkamp and Wilde, 1964). Kotar and Coffman (1982) also report higher estimated site index values for parts of a red pine plantation where weed competition was reduced. Water extracts containing allelopathic compounds from six common weed species found in a red pine plantation variously inhibited the height growth of seven week old red pine seedlings (Norby and Kozlowski, 1980).

Planting and Stock Quality

A plantation that develops from variable stock will almost inevitably be variable in growth rate (Sutton, 1982a). Segaran *et al.* (1979) state that it is reasonable to assume that a well spread out root system will provide better support, nutrient uptake, and water uptake than an unevenly distributed root system. However, the relationship between root system form and the growth of coniferous trees is not clearly understood (Sutton, 1969a). There is no consensus in the literature on the nature of the relationship between root system form and other aspects of tree performance (Owston and Stein, 1978). Some workers believe that root configuration will not have a harmful effect on long term growth and yield (Armson, 1978; Jansson, 1972; Van Eerden and Arnott, 1974). Tinus (1978) discusses the nature of the problem and asks: "What does root configuration do for or to a tree ?" He identifies this as a very important but complex problem because of the difficulty of separating the effects of root form from that of weather, soil, nutrients, seed origin, disease, etc. Many studies concerning the root development of coniferous outplants are given by Sutton (1969a) and Van Eerden and Kinghorn (1978).

White Spruce

White spruce transplants were significantly taller than seedlings at five, 10, and 15 years after outplanting, with 15 year results showing transplants to be 38 % taller than seedlings (Mullin, 1968, 1980b; Mullin and Howard, 1973). White spruce transplants also were significantly taller than seedlings three to seven years after outplanting (Hall, 1979; Mullin, 1970, 1980a; Wang and Horton, 1968). White spruce plug stock grew more rapidly in the first year than did bareroot stock types, thus recovering from an initial size disadvantage (Thompson, 1980; Vyse, 1981). Burdett (1981) reports that larger white spruce container stock grew 14 cm in height in the first year after outplanting, while smaller seedling stock grew only five cm in height. Burdett *et al.* (1983) found the first season shoot extension of white spruce seedlings was linearly related to the root growth capacity.

In contrast, no significant differences in height growth were found among white spruce stock types after outplanting (Dobbs, 1976; Vyse, 1981). Ten years after outplanting, no significant differences in height growth were found among different ages of white spruce transplant stock (Waldron, 1964). Alm (1983) reports that the height of white spruce seedling stock was not significantly different from transplant stock, but bareroot stock was significantly taller than container-grown stock four years after outplanting.

Height growth of white spruce 10 years after outplanting was directly related to the height of the stock at time of planting (Brace, 1964; Jarvis *et al.*, 1966; Mullin and Svaton, 1969). Eis (1967) found that seedlings dominant at two years of age usually retain their dominance in later years. Hall (1979) found similar results and reports that the average height of white spruce outplants after five years reflected the heights of the trees when planted, with larger trees maintaining their advantage over smaller ones. White spruce tube seedling quality and size after two growing seasons were related to the size at planting (Scarratt, 1972). Dobbs (1976) found that large white spruce stock outperformed small stock three years after planting. White spruce transplant stock selected for superior height growth in the nursery continued to express superiority seven years after outplanting (King *et al.*, 1965). After 18 years, these same trees showed a 30 % advantage in height over average trees (Nienstaedt, 1981).

White spruce planted on the top of the plough furrow were significantly taller than those planted in the bottom of the furrow (Armson, 1958; Stoeckeler and Limstrom, 1950). Stiell (1960) found the method of planting had a significant affect on the height of three year old white spruce. In contrast, Mullin (1966) found no significant differences in the height of white spruce 10 years after planting by four different methods. Armit (1970) found only slight differences in height growth four years after planting white spruce by five different methods. Nine years after outplanting, height growth of white spruce with roots placed horizontally were not significantly different from outplants with roots placed vertically (Brace, 1964).

After five years, the current annual height growth of white spruce was still affected by the month of planting (Ackerman and Johnson, 1962). Mullin (1971) also found the height growth of white spruce in the second year following planting was related to time of planting. Differences in height growth of white spruce due to time of planting were highly significant five and 10 years after planting (Mullin, 1973). Four years after outplanting, the height of white spruce planted from July through October declined with subsequent plantings (Sutton, 1982b). Vyse (1983) found that first year height growth of white spruce was significantly affected by season of planting, but not by handling technique. In contrast, Jarvis *et al.* (1966) found that time of planting had no effect on the height growth of white spruce transplants after 10 growing seasons.

Mullin (1967) reports the height growth of white spruce outplants was reduced by excessive exposure before planting. White spruce stock dipped in water immediately after lifting were significantly taller two years after outplanting than stock not dipped in water (Mullin, 1971). Mullin (1973) reports the effect of packing material was still evident in the height growth of white spruce outplants 10 and 15 years after planting. Burgar and Lyon (1968) found the height growth of white spruce transplants two years after planting was affected by the length of cold storage time.

Red Pine

Red pine transplants usually have a faster initial growth rate than seedlings (Horton and Bedell, 1960). Red pine transplants were significantly taller than seedlings at two, five, 10, and 15 years after outplanting (Mullin, 1968, 1980a, 1980b; Mullin and Howard, 1973). Wright *et al.* (1972) found the height growth of two age-classes of red pine seedling stock was significantly different after 11 years. Paterson and Fayle (1984) report that red pine outplants tallest two years after planting also were tallest five years years after planting.

Pierpoint *et al.* (1981) report handling and planting technique to be the cause of a significant reduction in height growth in several red pine plantations detected five years after outplanting. Rudolph (1939) found that young red pine trees with roots placed in a single plane showed about a 20 % reduction in height growth compared with those with a more even root distribution. In contrast, Mullin (1974) found no significant difference in the height growth of red pine among planting methods or types of packaging material after 20 years. Mullin (1964a) reports the height growth of 10 year old red pine was significantly affected by the depth of planting, but not by the planting method.

Genetics

Success in planting ultimately depends on the genetic suitability of the planting stock to the climate and site where the trees are planted (Yeatman, 1976). Moving seed too far from its place of origin can result in adverse effects such as reduced height growth, increased mortality, increased susceptibility to frost, and increased susceptibility to pests (Rauter, n.d.). The first step for controlling the collection of seed, and the distribution of seed and seedlings for regeneration is the designation and application of seed zones (Yeatman, 1976).

Ontario Seed Zones

Skeates (1979) gives the following historical review of the development of seed zones in Ontario. For many years seed collections were made or arranged by the staff at the OMNR tree seed plant at Angus, Ontario. At this time seed was used primarily for private forestry in southern Ontario. In 1952, the Ontario Department of Lands and Forests, Division of Reforestation adopted seed zones based on Hills (1952) seven Site Regions (Figure 2). These seed zones were numbered one in the south to five in the north, and six and seven in the northwest. Seed movement was restricted to within these zones whenever possible. These seed zones were renumbered in 1961 to correspond with the 13 revised Site Regions of Hills (1960) (Figure 3). In 1977, these seed zones were subdivided by administrative districts.

Ontario seed zones have not been tested adequately through provenance trials, but preliminary results indicate that sufficient genetic variation exists for many species within these zones to justify further delineation (Morgenstern, 1979). Yeatman (1976) points outs that seed zones are not biological realities, and the present Ontario Site Regions often bear little relationship to the response of some species.

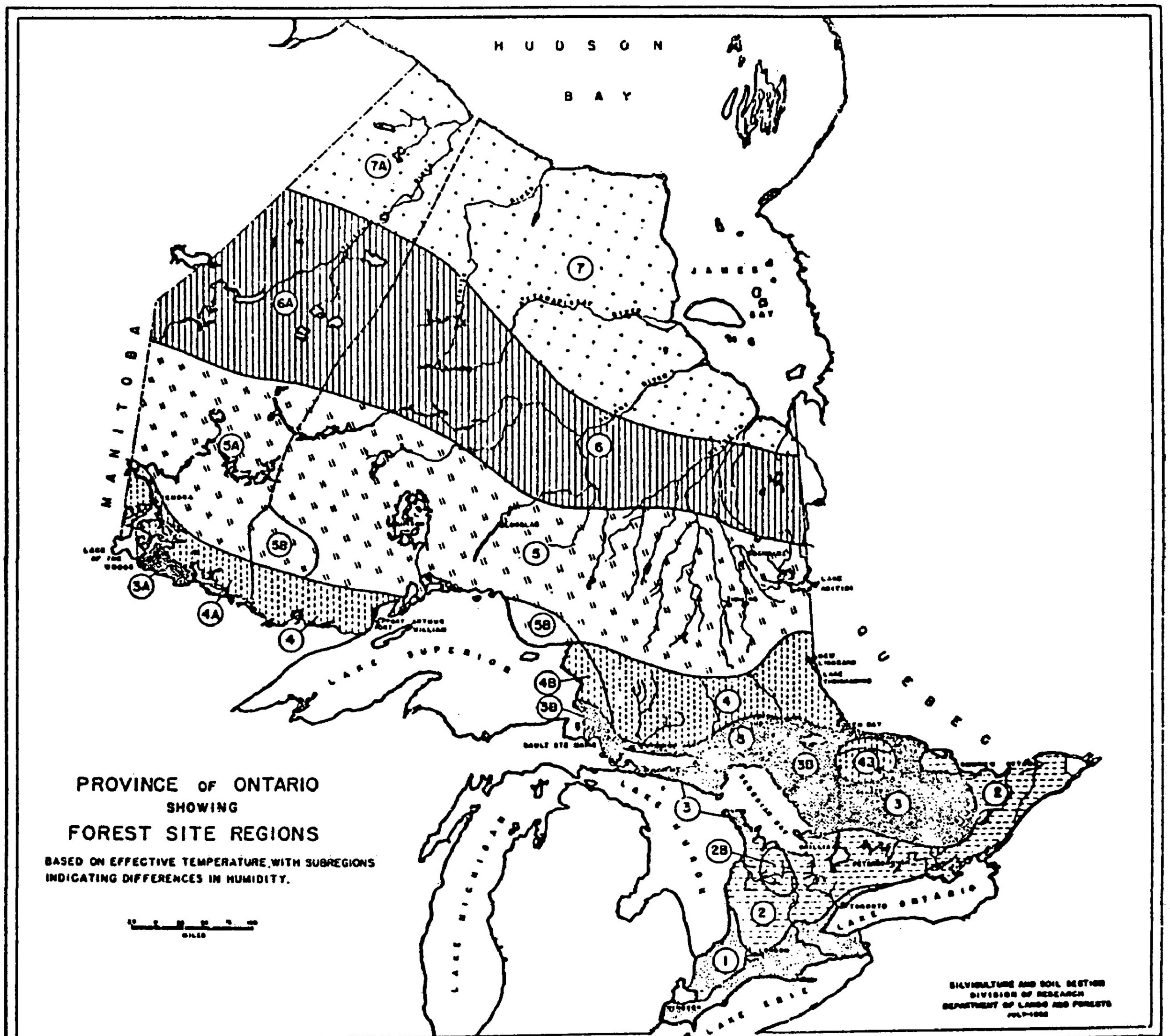

Figure 2. Hills (1952) Site Regions.

Variation in Height Growth of White Spruce

White spruce is a highly variable species (Nienstaedt and Teich, 1972). The pattern of variation generally follows latitudinal and longitudinal gradients (Nienstaedt, 1969, 1982; Radsliff *et al.*, 1983; Wright, 1976). Separate eastern and western populations (Nienstaedt and Teich, 1972) and limestone ecotypes (Teich and Holst, 1974) are also reported. Range-wide

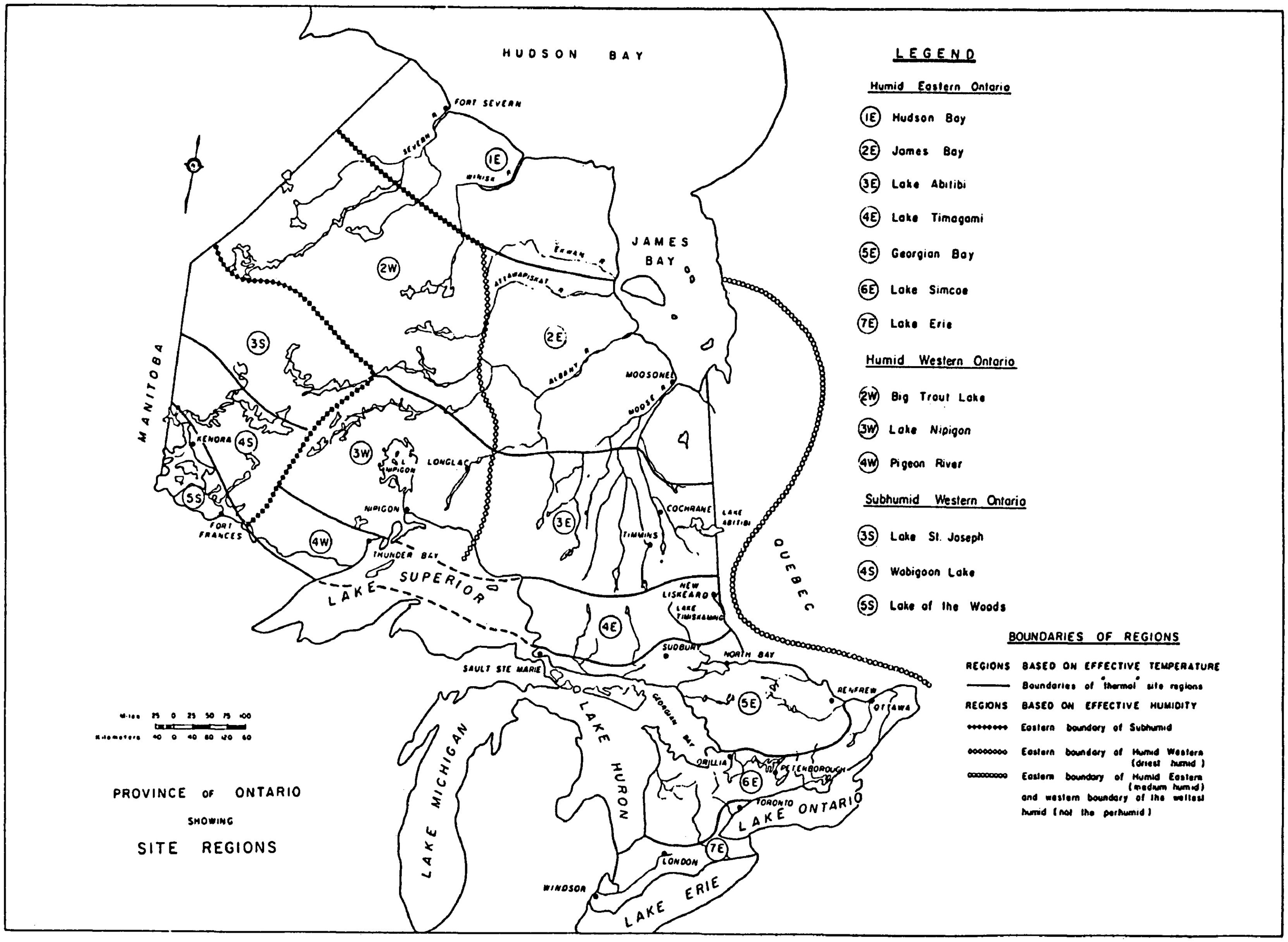

Figure 3. Hills (1960) Site Regions.

and regional provenance trials show the height growth of white spruce to vary significantly among provenances (King and Rudolph, 1969; Mohn *et al.*, 1976; Nienstaedt, 1969; Stellrecht *et al.*, 1974) and within provenances (Holst and Teich, 1966; Jeffers, 1969; Nienstaedt, 1969, 1982; Pollard and Teich, 1972).

Thirteen trials were established in the late 1950's throughout Ontario, Quebec, New Brunswick, and Newfoundland to identify superior seed sources of white spruce for planting in eastern and central Canada (Teich, 1973). At six locations in Ontario, superior provenances from eastern Ontario and western Quebec grew 19 to 26 % taller than plantation averages. Provenances from southeastern Ontario grew 18 to 20 % taller than the plantation average in New Brunswick, and 13 to 19 % taller than the plantation average in Newfoundland (Nicholson, 1970). These same provenances are also reported among the best in Newfoundland at 15 and 20 years of age (Khalil, 1974, 1979). Local provenances were among the tallest in Quebec, showing 14 to 30 % superiority over plantation averages (Corriveau et Boudoux, 1971).

Ninety-one white spruce provenances were established in 11 experimental plantations in five Ontario Site Regions between 1958 and 1965 (Teich *et al.*, 1975). The variation in height growth among provenances of plantations 13 to 20 years from seed was significant. All locations considered, the most rapidly growing provenances were 22 % taller than the mean of all provenances studied and 21 % taller than the provenance closest in origin to the plantation site.

Forty-nine of these white spruce provenances were established in a trial in Pearson Township near Thunder Bay. The local provenance was among the poorest in height growth at 13 years of age, achieving only 80 % of the plantation average (Teich *et al.*, 1975). Provenances from the Beachburg-Cobourg corridor grew well, averaging 117 % of the plantation average. These provenances from southeastern Ontario and provenances from western Quebec have shown superior height growth in many range-wide and regional provenance trials (Corriveau et Boudoux, 1971; Dhir, 1975; Genys, 1965; King and Rudolph, 1969; Nicholson, 1970; Nienstaedt, 1969; Nienstaedt and Kang, 1983; Nienstaedt and Teich, 1972; Radsliff *et al.*, 1983; Rauter and Ying, 1979; Stellrecht *et al.*, 1974; Teich, 1973; Teich *et al.*, 1975; Wright *et al.*, 1977).

White spruce is especially susceptible to late spring frosts that can delay the normal growth of young seedlings by damaging newly flushed buds (Fraser, 1965). Damage by frost is avoided or greatly reduced in trees with late budbreak (Wilkinson, 1977; Yeatman and Venkatesh, 1974). The date of budbreak in white spruce varies as much as 21 days among trees in a stand (Nienstaedt and Teich, 1972; Wilkinson, 1977) and is under strong genetic control (Nienstaedt, 1972; Nienstaedt and King, 1969; Nienstaedt and Teich, 1972; Wilkinson, 1977; Yeatman and Venkatesh, 1974). Individual trees within a provenance also differ in their sensitivity to frost (Logan and Pollard, 1975). Nienstaedt and King (1969) report a strong positive correlation between late budbreak and rapid height growth. Conversely, Wilkinson (1977) reports a weak negative correlation between these attributes. Wilkinson suggests that until the relationship is further clarified, a negative correlation or no correlation between these two traits should be assumed.

Variation in Height Growth of Red Pine

Red pine is one of the least variable species among those intensively studied (Fowler and Heimburger, 1969; Fowler and Lester, 1970). Variation among progenies and provenances is as great as variation between regions (Fowler and Lester, 1970). The only apparent genetic variation in red pine is in growth rate (Wright, 1976; Wright and Yao, 1972). However, Fowler and Morris (1977) report no variation in any of seven enzyme systems examined through electrophoresis of 297 red pine seed sources from five widely separate geographic regions.

Variation in height growth between the overall mean and the best provenance or progeny is often about 10 % for red pine up to about 20 years of age (Fowler and Lester, 1970; Morgenstern *et al.*, 1975). Early results of several range-wide and regional provenance trials from three to 12 years of age concur with this estimate, showing the variation in height growth among provenances to be approximately 10 % (Holst, 1975; Lester and Barr, 1965; Sprackling and Read, 1975; Sweet, 1963; Wright and Yao, 1972; Wright *et al.*, 1963, 1972; Yao *et al.*, 1971). Some older regional provenance trials have also shown significant differences in height among provenances at 25 to 30 years of age (Hough, 1967; Nienstaedt, 1964). In contrast, Buckman and Buchman (1962) report no significant differences among provenances of a 27 year old regional provenance trial.

Significant differences found in height growth among red pine provenances are strongly influenced by environmental factors (Benzie, 1982; Fowler and Heimburger, 1969; Fowler and Lester, 1970; Park and Fowler; 1981). The narrow range of genetic variation in red pine suggests that a genetic interpretation of common-environment studies may be more subject to uncertainties associated with non-genetic differences than in most species (Fowler and Lester, 1970). They also note that many studies were established using unreplicated nursery stock and often no information is given on seed weight and seedling growth prior to planting. Fowler and Lester state that the amount of genetic and non-genetic variation observed in red pine is not clear, and until these can be identified, genetic interpretation of provenance and progeny tests will not be conclusive.

These concerns are shown by a red pine seed source exhibiting the poorest height growth in one trial (Rudolph, 1948), and later showing the best height growth in another trial (Nienstaedt, 1964). Red pine seed sources showing outstanding height growth in the nursery (Wright *et al.*, 1963) were later found only slightly better than average (Wright, 1980; Wright *et al.*, 1972). Park and Fowler (1981) report that small significant differences in height growth in a regional provenance trial diminished between 17 and 21 years of age.

Most of the variation in the height of a range-wide red pine provenance trial at three years of age was accounted for by seedbed density (Wright *et al.*, 1963). In contrast, Armson (1968) found that seedbed density did not affect the height growth of one year old red pine seedlings. The dry weight of red pine seedlings was correlated with seed weight (Hough, 1952), and green weight of seedlings was correlated with height at five and 10 years of age (Hough, 1957). Height growth of 11 year old red pine was significantly correlated with the height at outplanting (Lester and Barr, 1966; Wright *et al.*, 1972).

METHODS

ESTABLISHING THE DATA BASE

Plantation and Study Plot Selection

All white spruce and red pine plantations 20 years of age and older located in the Thunder Bay and Nipigon administrative Districts were identified from OMNR silvicultural ledgers. Details including planting season, stock type, seed source, and post planting treatments were obtained for each of these plantations from OMNR project files. All of these plantations were inspected in the field except where poor road conditions prevented access to the plantation, or where project files indicated severe competition, very poor stocking, or repeated release treatments. Forty-six white spruce study plots and 25 red pine study plots were subsequently located in 41 of the approximately 75 plantations identified from OMNR records. Thirty-eight white spruce and 18 red pine study plots were located in Hills (1960) Site Region 4w, and eight white spruce and seven red pine study plots were located in Site Region 3w. Figure 4 shows the location of these 46 white spruce and 25 red pine study plots.

The age, stock type, seed zone, location by Site Region, and soil type of white spruce and red pine study plots are given in Appendix I. White spruce study plots were located in somewhat younger plantations than were red pine study plots (Figure 5). The average age of white spruce and red pine study plots was 25.7 and 29.5 years from planting, respectively. Three white spruce study plots were located in plantations established in the spring of 1964. As a result, these plantations were only 19 years of age when sampled. However, these study plots were retained in the analyses.

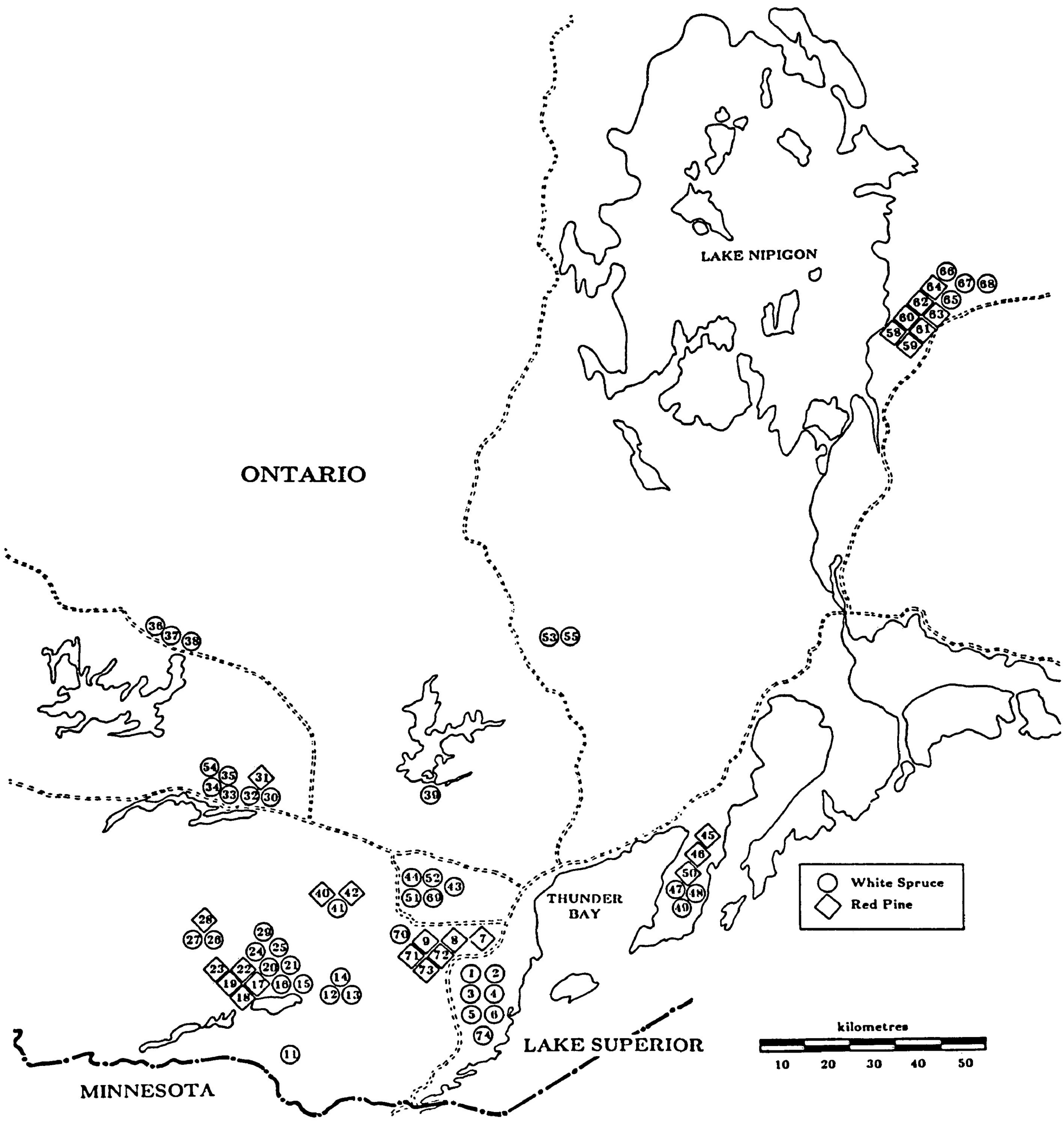

Figure 4. Location of white spruce and red pine study plots.

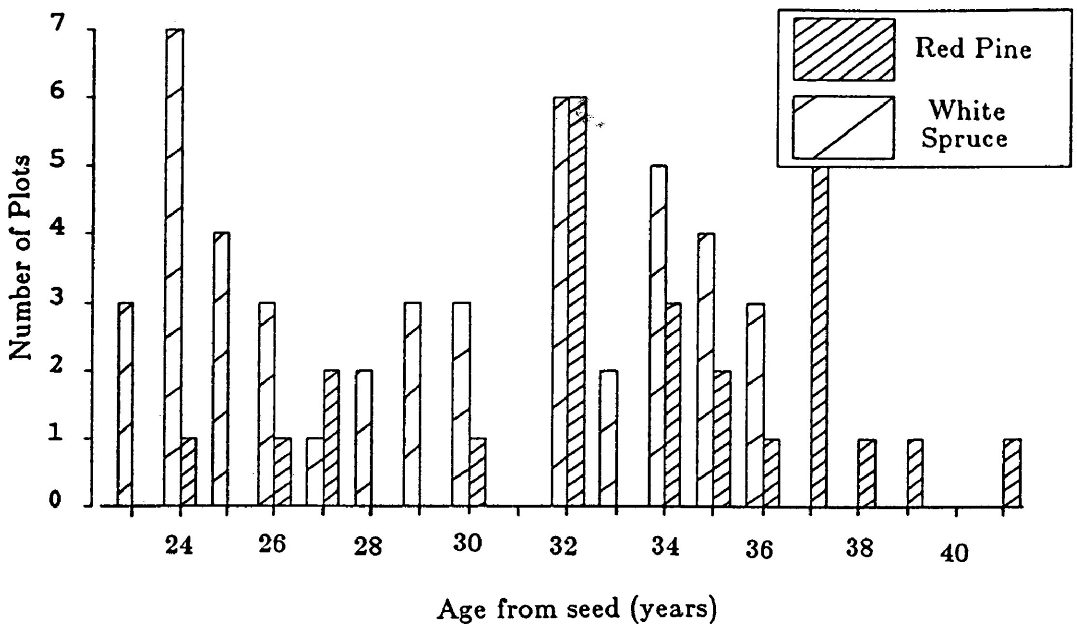

Figure 5. Age distribution of white spruce and red pine study plots.

Most study plots were located in plantations using seed from zone four (seed zone four remained relatively unchanged when the seed zones were revised in 1961). However, several study plots were located in plantations using seed from both the original seed zones (Figure 2) and the revised seed zones (Figure 3) numbered three, four, five, and six. All red pine and almost all white spruce study plots were located in plantations using 2+2 transplant stock. The only exceptions were three white spruce study plots located in plantations using 2+1 transplant stock.

White spruce study plots were located primarily on sandy soils, but some were on fine textured soils (Appendix I). All red pine study plots were located on sandy soils. Nine white spruce and eight red pine study plots were in plantations located on previously abandoned agricultural fields; all other study plots were in plantations located on former cutovers. All plantations were established at approximately 1.8 m^2 spacing. Appendix II gives tree height statistics for both white spruce and red pine study plots, including total height and the number of years to reach breast height (from seed) for each sample tree.

Inspection and sampling of these white spruce and red pine plantations was conducted during the summer of 1984. A ground reconnaissance was made of each plantation noting stocking, vegetative competition, topography, and variations in site quality as expressed by dominant tree height. Each plantation was then delineated into broad site types based on dominant tree height, soil, and topographic conditions. One study plot approximately 10 m in radius was located to represent the height growth potential of each site type. These study plots were located away from frost pockets in well stocked areas of the plantations that were free of competition, and where soil and topographic conditions appeared relatively homogeneous.

A qualitative description was made of each study plot noting approximate spacing of trees, stand condition, weed competition, slope, aspect, and general site conditions. A shallow soil pit was dug noting general soil textural class and other general soil characteristics. Geographic features and landmarks were noted on a sketch map showing each study plot location.

Three dominant trees showing no visible evidence of damage or suppression were chosen to represent the maximum height growth potential of each study plot. These trees were felled, limbed, and the stump cut at ground level. Total tree height and the height at each annual node were measured to the nearest 5.0 cm from ground level. Shoot elongation was not completed when sample trees were felled, thus the total height of sample trees was taken at the height of the annual node corresponding to the end of the 1983 growing season.

Radial sections were cut from each tree at 0.25 m intervals for the first 1.0 m above ground level, and at 0.50 m intervals thereafter. Tree sections were then transported to Lakehead University and stored at 2° C. Subsequent laboratory analysis of tree sections was conducted during the summer and fall of 1984.

Height-age Data

The age of each tree section was determined by counting annual growth rings to the end of the last full growing season (1983). Tree section ages were confirmed through two independent counts of the growth rings. The age of each tree section was then compared to section ages immediately above and below to ensure that tree sections were recorded in the correct order.

The age of each sample tree (from seed) at the height of a particular tree section was determined by subtracting the age of the tree section (from growth ring counts) from the total age of the sample tree (from seed, at the end of the 1983 growing season). The actual height of the sample tree at the end of the growing season corresponding with the age determined for each tree section, is always lower using this procedure than the height where the tree section was taken. This positive bias in height is a result of section points not corresponding exactly with the tree height at the end of a growing season. Accordingly, Equation 1 was used to remove this bias by lowering the height where each tree section was taken by an amount equal to one-half of the estimated current annual height increment.

$$Ht_i = ht_i - \frac{1}{2}\left[\frac{ht_i - ht_{i-1}}{age_{i-1} - age_i}\right] \qquad [1]$$

where: Ht_i = adjusted height of tree section i
ht_i = height where tree section i was taken
age_i = age of tree section i (from ring counts)

The height-age data for individual sample trees determined from annual node height measurements were then compared with adjusted height-age data determined from growth ring counts of tree sections. This comparison confirmed annual node height measurements taken in the field, and also identified the occasional annual node that was missed during field measurements. The heights of annual nodes missed in field measurements were subsequently estimated from adjusted height-age data determined from growth ring counts of tree sections. The resulting height-age data, based almost exclusively on annual node height measurements, were used for all subsequent analyses.

Height versus age curves were plotted for individual sample trees and examined for abnormal height growth patterns. All data and field notes were re-examined for several sample trees suspected of damage or suppression. However, no reason was found to remove any sample tree from the analysis. Thus, all study plots and all sample trees were retained in the analysis and all study plots include three dominant, undamaged, free-to-grow sample trees.

The average height growth of the three sample trees in each study plot was represented by plot average total height-age data and plot average breast height-age data. Plot average total height-age data were computed as the average height of the three sample trees in each study plot at each year from seed. Plot average breast height-age data were computed as the average height of the three sample trees in each study plot at each year from breast height. Only full years height growth above breast height were used for computing breast height-age data. The height at a breast height-age of zero was not taken as breast height (1.30 m), but was taken as the height at the end of the year in which the tree attained breast height, i.e. the height at the beginning of the first full years height growth above breast height. For example, the height at a breast height-age of zero would be 1.75 m for a tree with annual nodes occurring at 1.25 and 1.75 m.

Estimated Site Quality

The estimated site quality of white spruce and red pine study plots was represented by the average height of the three sample trees in each study plot at 15 and 20 years from breast height, respectively (hereafter referred to as breast height site index: $BHSI_{15}$ and $BHSI_{20}$). However, one or more sample trees in 15 of the 46 white spruce study plots and in six of the 25 red pine study plots did not achieve the appropriate index age (Appendix III). Therefore, the height of each of the three individual sample trees in each of these study plots was extrapolated to achieve the appropriate breast height-age used to estimate site quality; 15 years for white spruce and 20 years for red pine. This extrapolation of the height of sample trees was considered necessary so the height at the oldest possible age could be used as the estimate of site quality. This procedure avoided the loss of valuable older height-age data, thus provided for better estimates of site quality.

To achieve more realistic extrapolations of individual tree height growth, asymptotic height was first defined by fitting the expanded Chapman-Richards function presented by Ek (1971) (Eq. 2) to plot average total height-age data.

$$Ht = b_1 SI^{b_2} \left(1 - e^{-b_3 Age}\right)^{b_4 SI^{-b_5}} \qquad [2]$$

where: Ht = predicted total height
SI = site index
Age = total age
b_i = model coefficients
e = base of the natural logarithms

The resulting coefficients estimating model parameters b_1 and b_2 (that define asymptotic height as a function of site index) were reentered in Equation 2 as constants. Equation 3 was then used to extrapolate the total height-age height growth curve of each of the three individual sample trees in the 15 white spruce study plots to a total age corresponding with a breast height-age of 15 years. Likewise, Equation 4 was used to extrapolate the total height-age height growth curve of each of the three individual sample trees in the six red pine study plots to a total age corresponding with a breast height-age of 20 years. Site index in Equations 2, 3, and 4 was taken as the plot average height at the oldest total age common to all study plots of each species; 23 years for white spruce and 24 years for red pine.

$$Ht = 14.5346 \ SI^{\ 0.322463} \left(1 - e^{-b_1 Age}\right)^{b_2 SI^{-b_3}} \qquad [3]$$

$$Ht = 8.03181\ SI^{\ 0.510861} \left(1 - e^{-b_1 Age}\right)^{b_2 SI^{-b_3}} \qquad [4]$$

From one to five years were required to extrapolate the height growth curves of the three individual sample trees in the 15 white spruce study plots to achieve a breast height-age of 15 years. The individual height growth curves of the three sample trees in the six red pine study plots were extrapolated from one to seven years to achieve a breast height-age of 20 years. These extrapolations averaged 2.67 years for white spruce and 3.33 years for red pine. Appendix III gives the number of years the total height-age height growth curves of the three individual sample trees in the 15 white spruce and the six red pine study plots were extrapolated to achieve a breast height-age of 15 and 20 years, respectively, and the standard error of the estimate of the equations used for these extrapolations.

GROWTH INTERCEPTS

Various growth intercepts were tested to determine the best number of internodes and the best starting height for estimating site quality of these white spruce and red pine study plots. The average length of the internodes used for each growth intercept was computed for each sample tree and expressed as an average of the three sample trees in each study plot, hereafter referred to as the growth intercept length. Thus, a growth intercept length represents the average length (m) of the various internodes comprising the particular growth intercept, for all three sample trees in each study plot.

One hundred, ninety-two different growth intercepts were used to estimate site quality for the 46 white spruce study plots, and 288 different growth intercepts were used to estimate site quality for the 25 red pine study plots. Each white spruce growth intercept consisted of a different combination of internodes selected by one of four methods from eight different series of one to seven internodes. Likewise, each red pine growth intercept consisted of a different combination of internodes selected using the same four internode selection methods and eight starting heights. However, the slightly older age of the red pine study plots allowed using series of one to 10 internodes. Internode selection began from series starting with the first internode above: 0, 0.5, 1.0, 1.3, 1.5, 2.0, 2.5, and 3.0 m above ground level. The four methods of selecting internodes from a series were: 1) all internodes included in a series; 2) the smallest internode removed from a series; 3) the largest internode removed from a series; and 4) both the smallest and the largest internodes removed from a series. Table 2 gives the number of growth intercepts computed by species and internode selection method.

The lengths computed for these various growth intercepts were then related to estimated site quality ($BHSI_{15}$ for white spruce and $BHSI_{20}$ for red pine) using Equation 5. This was achieved using the regression procedure of SPSS^x (Nie, 1983) on the VAX-11/780 computer at Lakehead University. The resulting coefficients of determination (R^2) were then

Table 2. Number of growth intercepts computed by species and internode selection method.

Species and Internode Selection Method[1]	Maximum Number of Internodes in a Series	× 8 starting heights[2]
White Spruce		
1	7	56
2	6	48
3	6	48
4	5	40
		192
Red Pine		
1	10	80
2	9	72
3	9	72
4	8	64
		288
Total		480

[1]1 = all internodes included in a series
2 = smallest internode removed from a series
3 = largest internode removed from a series
4 = both the smallest and largest internodes removed from a series
[2] starting heights are: 0, 0.5, 1.0, 1.3, 1.5, 2.0, 2.5, and 3.0 m above ground level

compared among the four different internode selection methods. Only the internode selection method explaining the most variation in $BHSI_x$ was retained for further analyses.

$$BHSI_x = b_0 + b_1GI + b_2GI^2 \qquad [5]$$

where: $BHSI_x$ = predicted $BHSI_x$
GI = growth intercept length (average internode length (m))

Further attempts were made to increase the amount of variation in $BHSI_x$ explained by Equation 5 using the lengths of the various growth intercepts of the remaining internode selection method. Additional models involving transformations that would account for any further curvilinearity or heteroscedasticity in the data were fit to $BHSI_x$ and the lengths of the various growth intercepts (Table 3). The model ultimately used to describe the data explained the most variation in $BHSI_x$, involved the fewest transformations, and had normally

Table 3. Models used in attempts to increase the amount of variation in $BHSI_x$ explained by Equation 5.

Model	Eq.
$BHSI_x = b_0 + b_1GI^{-1}$	[6]
$BHSI_x = b_0 + b_1GI^{-2}$	[7]
$BHSI_x = b_0 + b_1GI^{-3}$	[8]
$BHSI_x = b_0 + b_1GI^{-½}$	[9]
$BHSI_x = b_0 + b_1GI^{½}$	[10]
$BHSI_x = b_0 + b_1GI^2$	[11]
$BHSI_x = b_0 + b_1GI^3$	[12]
$BHSI_x = b_0 + b_1GI + b_2GI^{-1}$	[13]
$BHSI_x = b_0 + b_1GI + b_2GI^{-2}$	[14]
$BHSI_x = b_0 + b_1GI + b_2GI^{-½}$	[15]
$BHSI_x = b_0 + b_1GI + b_2GI^3$	[16]
$BHSI_x = b_0 + b_1GI + b_2GI^2 + b_3GI^3$	[17]
$BHSI_x = b_0 + b_1ln(GI)$	[18]
$ln(BHSI_x) = b_0 + b_1ln(GI)$	[19]

distributed residuals with a mean of zero and constant variance (i.e. $\epsilon \sim$ NID (0, σ^2)).

Three growth intercepts for each species were subsequently chosen to provide accurate estimates of $BHSI_{15}$ for white spruce and $BHSI_{20}$ for red pine. These growth intercepts were selected to provide accurate estimates of $BHSI_x$ using the fewest number of internodes from the lowest possible starting height. The coefficients for the equation describing these chosen growth intercepts were then compared by predicting $BHSI_x$ using common growth intercept lengths (5.0 cm intervals over the observed range of growth intercept lengths). The chosen growth intercepts were then compared by the reduction in the mean squared error (MSE) of prediction using an F ratio and tabulated F values. The 95 % confidence interval (CI) for the true mean value of Y (BHSI) was then computed for each chosen growth intercept using Equation 20 (Draper and Smith, 1981:211).

$$CI(Y) = Y \pm t_{(0.025,(n-p-1))}\, s\, \left[\mathbf{X'}_0 \,(\mathbf{X'X})^{-1}\, \mathbf{X}_0\right]^{1/2} \qquad [20]$$

where: Y = predicted value of $BHSI_x$
s = standard error of the estimate
$\mathbf{X'}_0$ = 1 × (p+1) vector $[1, X_1, X_2, \ldots, X_p]$
$\mathbf{X}$ = n × (p+1) matrix of X values
n = number of observations (study plots)
p = number of independent variables in the regression equation

HEIGHT GROWTH PATTERNS

Formulated Height Growth Curves

Non-linear functions were used to describe plot average total height-age height growth patterns, and both linear and non-linear functions were used to describe plot average breast height-age height growth patterns. Figures 6 and 7 show the plot average total height-age height growth curves and the plot average breast height-age height growth curves, respectively, portraying the height growth patterns of the 46 white spruce and the 25 red pine study plots. The origin of both non-linear and linear functions fit to the plot average breast

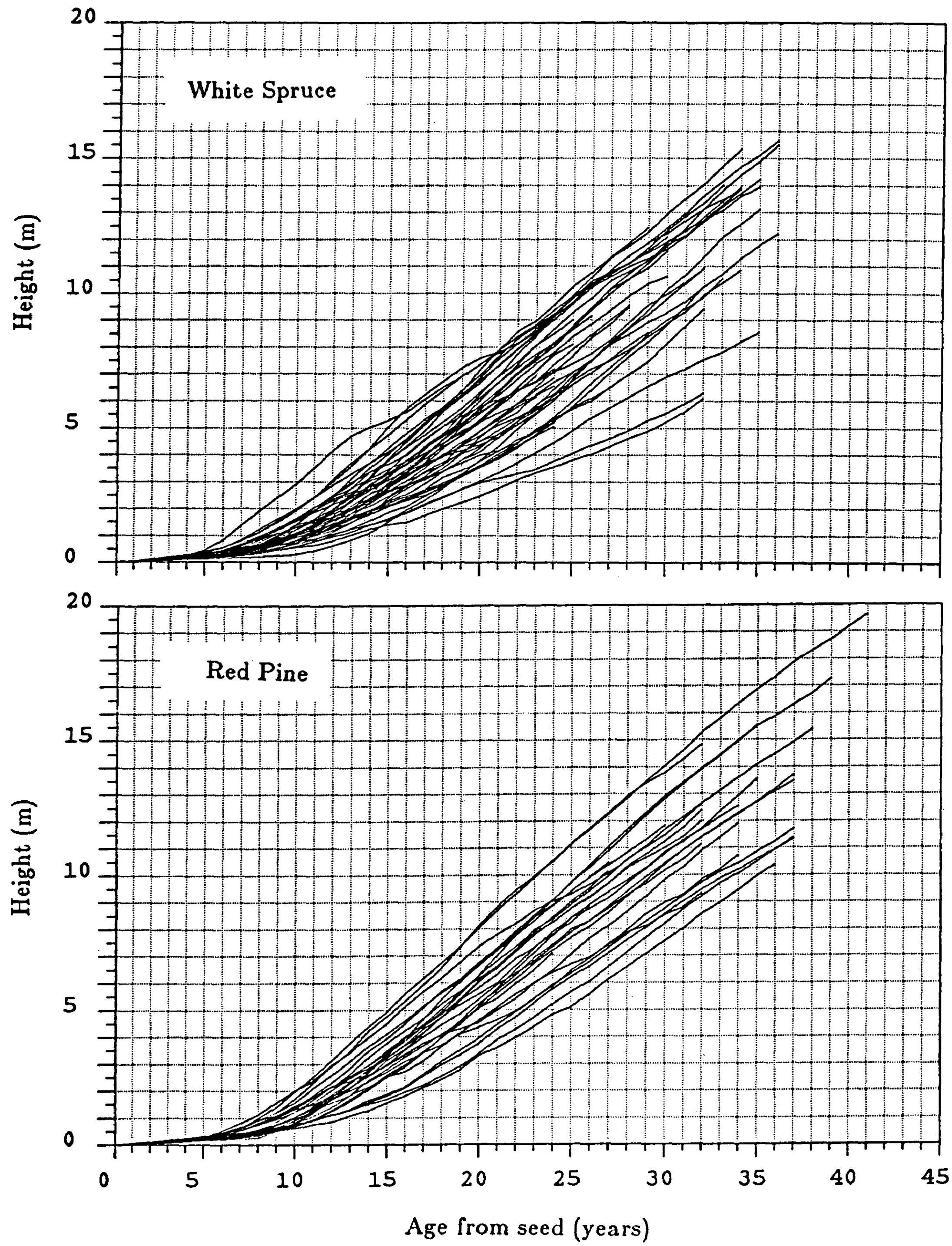

Figure 6. Plot average total height-age height growth curves for the 46 white spruce and 25 red pine study plots.

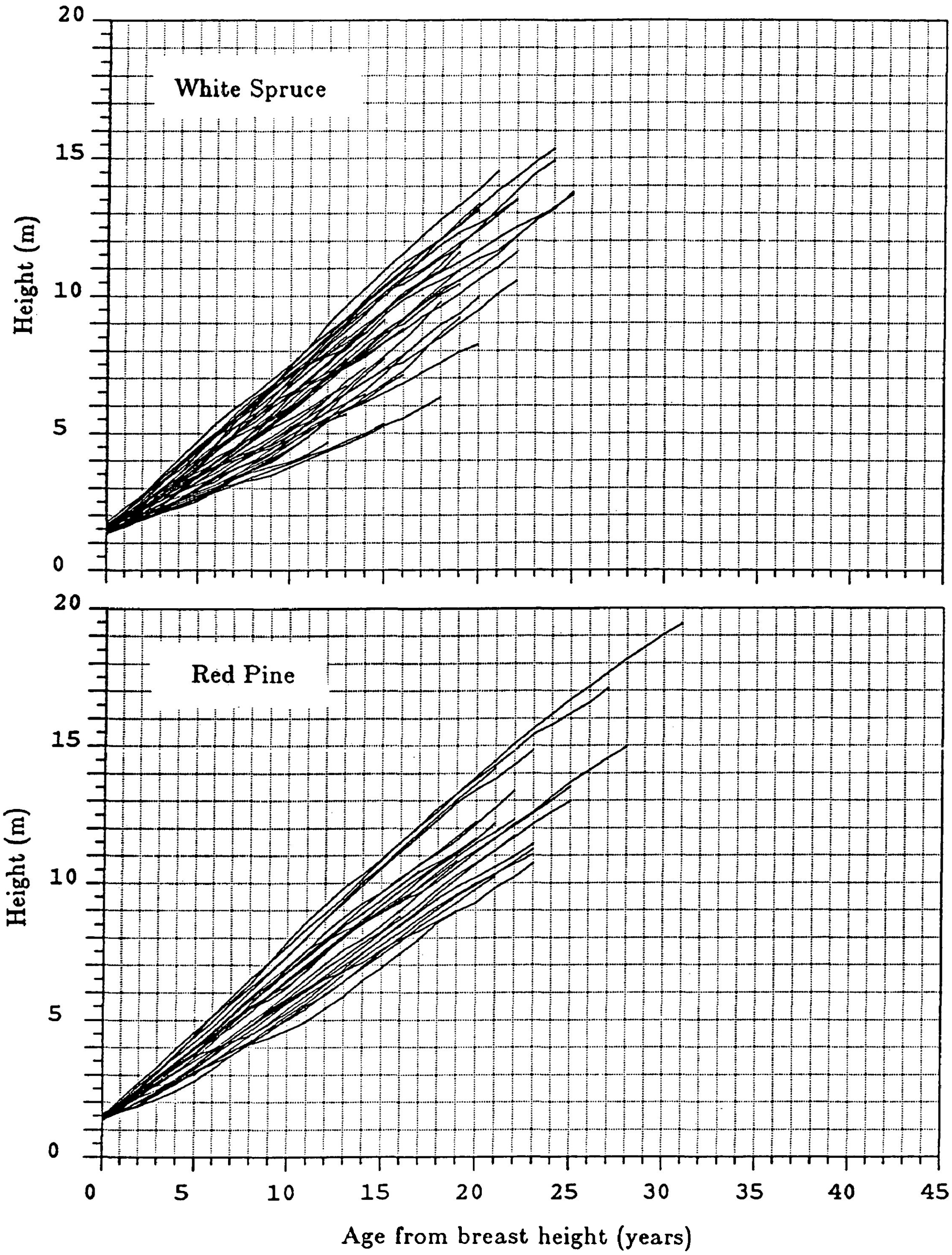

Figure 7. Plot average breast height-age height growth curves for the 46 white spruce and 25 red pine study plots.

height-age data was adjusted to 1.46 m (the average height of both white spruce and red pine sample trees at a breast height-age of zero). Site index was defined as the plot average height at a total age of 25 years for the non-linear models fit to both white spruce and red pine plot average total height-age height growth data. Site index for both non-linear and linear models fit to plot average breast height-age height growth data was defined as $BHSI_{15}$ and $BHSI_{20}$ for white spruce and red pine, respectively.

Non-linear functions fit to plot average total height-age height growth data and plot average breast height-age height growth data include the original Chapman-Richards function (Eq. 21) and the two expanded Chapman-Richards functions (Eq. 22 and Eq. 23) given in Table 4. These non-linear functions were fit to plot average height growth data using NONLINWOOD (Daniel and Wood, 1980), adapted by the author to run on the VAX-11/750 computer with a UNIX 4.2 BSD operating system at Lakehead University. NONLINWOOD is a modification of the University of Wisconsin's GAUSHAUS non-linear least-squares curve fitting FORTRAN program (Meeter, 1966) that utilizes Marquardt's maximum neighbourhood non-linear estimation technique (Marquardt, 1963).

Table 4. Non-linear models fit to plot average total height-age height growth data and plot average breast height-age height growth data.

Model	Reference	Eq.
$Ht = b_1 (1 - e^{-b_2 Age})^{b_3}$	Pienaar and Turnbull (1973)	[21]
$Ht = b_1 SI (1 - e^{-b_2 Age})^{b_3}$	Lundgren and Dolid (1970)	[22]
$Ht = b_1 SI^{b_2} (1 - e^{-b_3 Age})^{b_4 SI^{-b_5}}$	Ek (1971)	[23]

Predicted heights estimated with the expanded Chapman-Richards functions (Eq. 22 and Eq. 23) vary with site index and age. The original Chapman-Richards function (Eq. 21) does not use site index as an independent variable, thus is not capable of expressing varying levels of site index. Therefore, the harmonizing procedure detailed by Husch (1963) was used to force a Chapman-Richards function (Eq. 21) guiding curve through the height at the site index age of each plot average height growth curve. These guiding curves were computed with the coefficients given in Table 5 resulting from fitting the Chapman-Richards function to plot average height growth data. Each guiding curve was adjusted proportionally to each plot average height growth curve by the distance between the height of the guiding curve at index age, and the actual plot average height at index age (Eq. 24). Residuals were computed as predicted heights minus the actual heights, and were then compared with residuals computed from fitting Equations 22 and 23 to plot average height growth data.

$$Ht = Ht_g + \left[Ht_g \left(\frac{SI_p - SI_g}{SI_g} \right) \right] \qquad [24]$$

where: Ht = predicted height
Ht_g = height of the guiding curve (Eq. 21)
SI_g = height of the guiding curve at index age
SI_p = plot average height at index age

Table 5. Coefficients of the Chapman-Richards function (Eq. 21) guiding curves.

Species and Data Type	Index Age	b_1	b_2	b_3
White Spruce				
total height-age	25	41.9253	0.02840	2.52325
breast height-age	15	74.0568	0.01190	1.29329
Red Pine				
total height-age	25	40.8703	0.02848	2.41972
breast height-age	20	76.7641	0.01039	1.19411

Various linear functions (Table 6) also were fit to plot average breast height-age height growth data using the regression procedure of SPSS^x (Nie, 1983). The linear model explaining the most variation in plot average breast height-age height growth data was then compared with the non-linear models describing plot average breast height-age height growth data.

Both linear and non-linear models describing plot average height growth data were compared with an F statistic computed as a variance ratio (Freese, 1964). The most appropriate model for describing the plot average total height-age and plot average breast height-age height growth patterns of each species was chosen as the one explaining the most variation in the data, i.e. the one achieving the lowest error sum of squares (SSE).

Comparison with Published Height Growth Curves

Plot average total height-age height growth patterns (Figure 6) and plot average breast height-age height growth patterns (Figure 7) were visually compared to the height growth patterns of white spruce and red pine plantations of other areas as portrayed in published height growth curves (Table 7). These published height growth curves were superimposed on study plot average height growth curves, as well as the formulated height growth curves describing these height growth patterns.

Table 6. Linear models fit to plot average breast height-age height growth data.

Model	Eq.
$Ht = b_0 + b_1 AGE + b_2 SI + b_3(AGE \times SI)$	[25]
$Ht = b_0 + b_1 AGE + b_2 SI + b_3(AGE \times SI) + b_4 AGE^2$	[26]
$Ht = b_0 + b_1(AGE \times SI)$	[27]
$Ht = b_0 + b_1(AGE \times SI) + b_2 AGE^2$	[28]
$Ht = b_0 + b_1(AGE \times SI) + b_2(AGE \times SI)^2$	[29]

Table 7. Published height growth curves compared with height growth patterns of white spruce and red pine study plots.

Species and Data Type	Classification Age	Location	Reference
White Spruce			
total height-age	50 years from planting	Petawawa	Berry, 1978
Red Pine			
total height-age	50 years from planting	Petawawa	Berry, 1984
total height-age	50 years from planting	Wisconsin	Wilde *et al.*, 1965
breast height-age	20 years from breast height	New York	Richards *et al.*, 1962

Published height growth curves given for age from planting were adjusted to age from seed by adding four years to account for the age of the planting stock used in these study plots. Height-age data describing Berry's (1978) white spruce height growth curves and the red pine height growth curves given by Wilde *et al.* (1965) and Richards *et al.* (1962) were read directly from enlargements of the curves given in the publications. Height-age data describing Berry's (1984) red pine height growth curves were generated with the linear equation given in the publication. The total age height growth curves for natural red pine given by Gevorkiantz (1957) are very similar in shape to Berry's (1984) curves for planted red pine, therefore, only Berry's curves were included in these comparisons.

Predicting Site Index from Height and Age

Attempts were made to describe $BHSI_x$ as a function of total height and age from breast height using Equations 30 and 31. Ek's expanded Chapman-Richards function (Eq. 23) cannot be solved for site index, thus Payandeh (1974) gives Equation 30 as an analogue. Equation 31 is based on Ek's model with the independent variables rearranged according to the authors interpretation of the theoretical distribution of $BHSI_x$ by height and age. These non-linear Equations also were fit to height growth data using NONLINWOOD on the VAX-

11/750 computer at Lakehead University.

The ability of Equations 30 and 31 to describe $BHSI_x$ as a function of total height and age from breast height was first tested by fitting these equations to height growth data generated by the model best describing breast height-age height growth data. Equations 30 and 31 were fit to plot average breast height-age height growth data only if they adequately fit the height growth data generated by the height growth model. In addition, Equation 32 was used to estimate $BHSI_x$ from total height and age from breast height by linearly interpolating between formulated breast height-age height growth curves. The most accurate estimates of $BHSI_x$ were then compared with estimates of $BHSI_x$ obtained from growth intercepts using the same total height and age from breast height data.

$$SI = b_1\, Ht^{b_2}\left(1 - e^{-b_3 Age}\right)^{-b_4 Ht^{-b_5}} \qquad [30]$$

$$SI = b_1\, Age^{-b_2}\left(1 - e^{-b_3 Ht}\right)^{b_4 Age^{b_5}} \qquad [31]$$

$$Est(BHSI_x) = LSI_{age_i} + \left[\frac{Ht_{age_i} - LSI_{age_i}}{USI_{age_i} - LSI_{age_i}}\right] \qquad [32]$$

where: SI = site index ($BHSI_x$)
$Est(BHSI_x)$ = estimated $BHSI_x$
Ht_{age_i} = observed height at age i
LSI_{age_i} = height of site index curve immediately below Ht_{age_i} (lower)
USI_{age_i} = height of site index curve immediately above Ht_{age_i} (upper)

Years to Reach Breast Height

The relationship between height growth above breast height to height growth below breast height was examined by regressing $BHSI_x$ on the number of years from planting for sample trees to reach breast height (Eq. 33).

$$BHSI_x = b_0 + b_1 YRBH \qquad [33]$$

where: $YRBH$ = average number of years from planting for sample trees in each study plot to reach breast height

The number of years for sample trees in white spruce study plots to reach breast height was then compared with the number of years for sample trees in red pine study plots to reach breast height using a t test (Steel and Torrie, 1980:96). Similarly, the number of years for sample trees in study plots located in plantations on abandoned agricultural fields to reach breast height was compared with the number of years for sample trees in study plots located in plantations on cutovers to reach breast height for each species.

Relating Estimated Site Quality to Height at 50 Years

Formulated breast height-age height growth curves were projected to an age approximating the height of dominant trees at 50 years from seed and 50 years from planting. The breast height-age approximating 50 years from seed was estimated by subtracting the average number of years for sample trees to reach breast height from seed, from a breast height-age of 50 years. Likewise, the breast height-age approximating 50 years from planting was estimated by subtracting the average number of years for sample trees to reach breast height from planting, from a breast height-age of 50 years. Estimated heights computed at 0.10 m intervals for the range of height observed at $BHSI_x$ index age were then regressed on the corresponding estimated heights at the appropriate ages estimating heights at 50 years from seed and 50 years from planting (Eq. 34).

$$Ht_{50} = b_0 + b_1 BHSI_x + b_2 BHSI_x^2 \qquad [34]$$

where: Ht_{50} = height at 50 years from planting and 50 years from seed.

RESULTS

ESTIMATED SITE QUALITY

The $BHSI_{15}$ of the white spruce study plots averaged 8.31 m with a range of 5.28 to 10.97 m, and the $BHSI_{20}$ of the red pine study plots averaged 11.35 m with a range of 9.30 to 13.90 m. Figure 8 shows the distribution of the $BHSI_{15}$ observed for the white spruce study plots, and Figure 9 shows the $BHSI_{20}$ observed for red pine study plots by 1.0 m classes. Table 8 gives the range of $BHSI_x$ for both white spruce and red pine study plots divided evenly into good, medium, and poor site classes, and the number of plots falling in each of these classes (actual values are rounded to the nearest 10 cm).

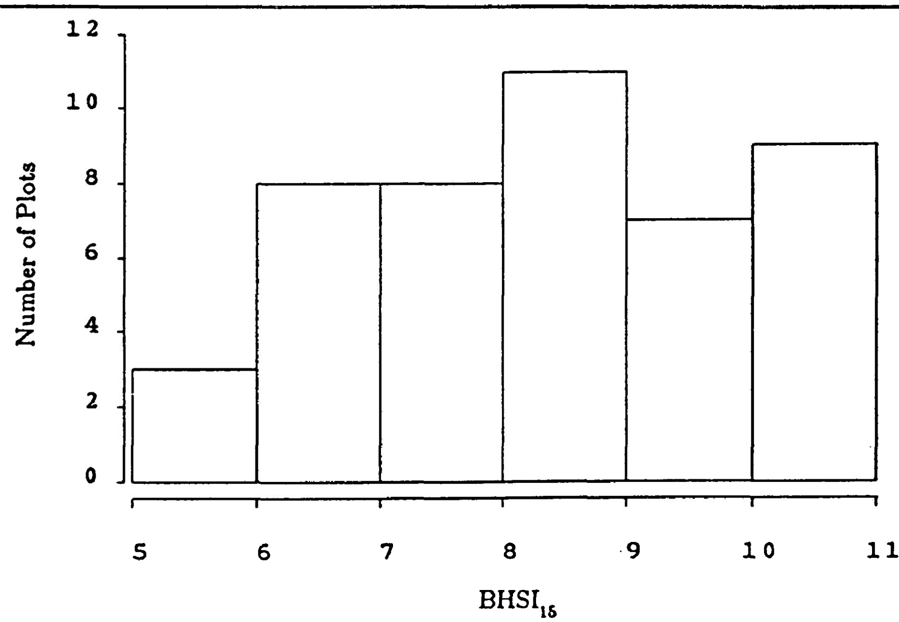

Figure 8. Distribution of the $BHSI_{15}$ of white spruce study plots by 1.0 m classes.

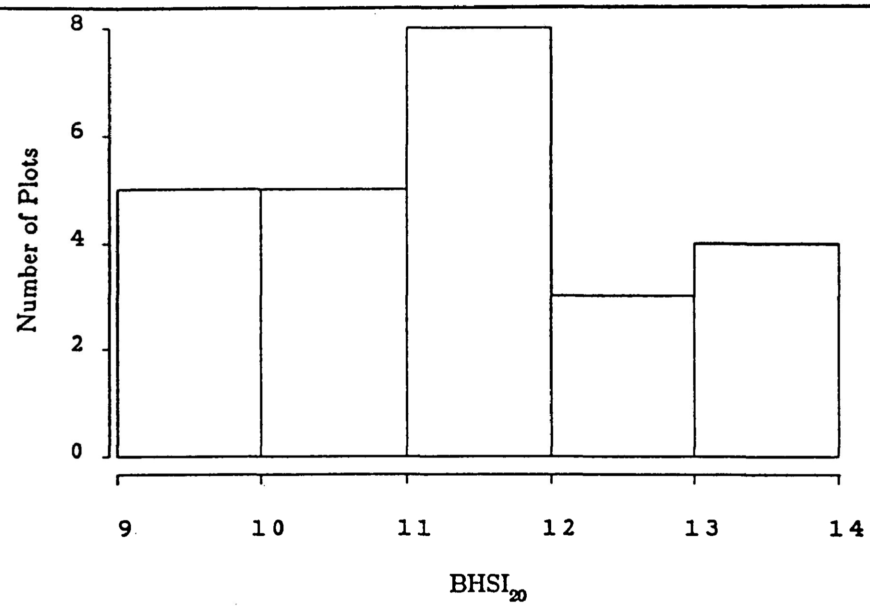

Figure 9. **Distribution of the $BHSI_{20}$ of red pine study plots by 1.0 m classes.**

Table 8. **Good, medium, and poor site classes for white spruce and red pine study plots.**

Species	Site Class		
	Good	Medium	Poor
White Spruce			
$BHSI_{15}$	11.00 - 9.11 m	9.10 - 7.21 m	7.20 - 5.30 m
Number of Plots	16 (35%)	18 (39%)	12 (26%)
Red Pine			
$BHSI_{20}$	13.90 - 12.41 m	12.40 - 10.81 m	10.80 - 9.30m
Number of Plots	4 (16%)	11 (44%)	10 (40%)

GROWTH INTERCEPTS

Internode Selection Methods

Growth intercept lengths computed using the first internode selection method (all internodes included in a series) explained the most variation in the $BHSI_{15}$ of white spruce above 2.0 m and in the $BHSI_{20}$ of red pine above 1.5 m using Equation 5. Growth intercept lengths computed using the second internode selection method (the smallest internode removed from a series) explained the most variation below these starting heights using Equation 5. Growth intercept lengths computed using the third internode selection method (the largest internode removed from a series) and the fourth internode selection method (both the smallest and the largest internodes removed from a series) explained less variation in $BHSI_x$ than either the first or second internode selection methods, regardless of starting height. No advantage was obtained from computing growth intercept lengths using the three modified internode selection methods (the second, third, and fourth internode selection methods). Therefore, only the growth intercept lengths computed using all internodes in a series (the first internode selection method) were used for further analyses. Unless specifically stated, all further reference to growth intercept lengths will imply the first internode selection method. Appendix IV gives the coefficients of determination (R^2) computed using Equation 5 and the lengths of the various growth intercepts of the four internode selection methods for both white spruce and red pine study plots.

White Spruce

The relationship between the $BHSI_{15}$ of white spruce and the length of the various growth intercepts computed using the first internode selection method was best described by Equation 5. Equations 6 through 12 explained slightly less variation in the $BHSI_{15}$ of white spruce, Equations 13 through 19 explained virtually the same amount of variation, and none of these Equations explained more variation than Equation 5. The coefficients of determination (R^2) computed from fitting Equation 5 to $BHSI_{15}$ and the lengths of the various white spruce growth intercepts are given in section A of Appendix IV. Figure 10 is a graphical presentation of these values that illustrates the amount of variation (R^2) explained when the $BHSI_{15}$ of white spruce is estimated using Equation 5 and the length of the various growth intercepts computed from series of one to seven internodes from the eight starting heights between 0 and 3.0 m.

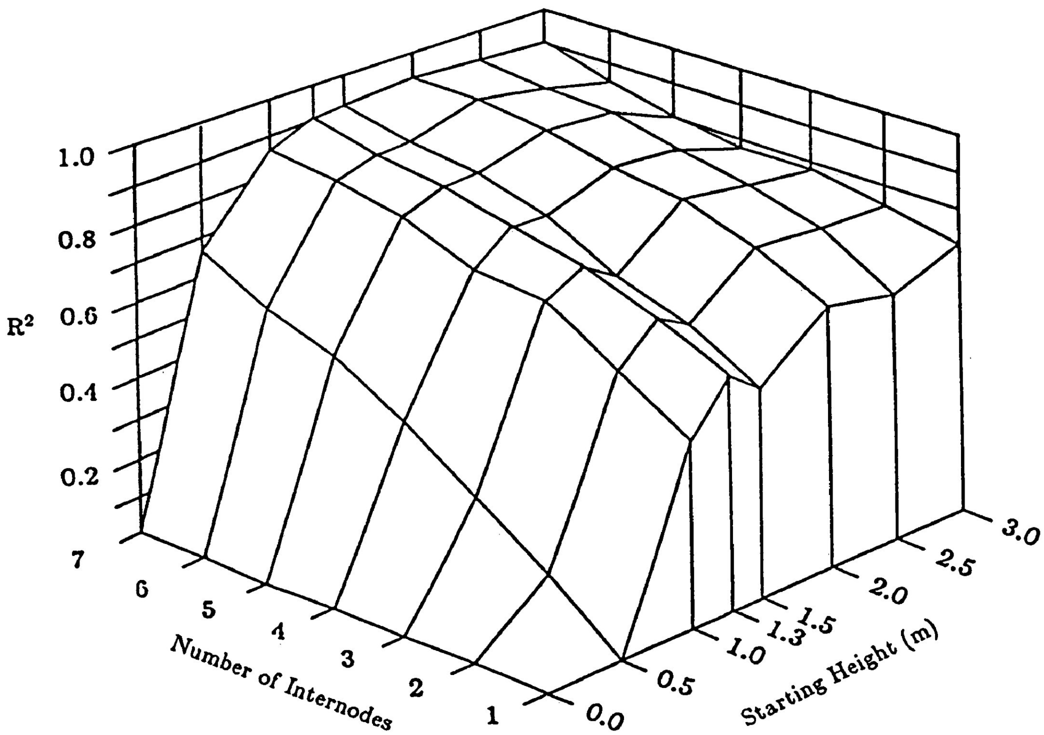

Figure 10. Explained variation (R^2) in the regression of the $BHSI_{15}$ of white spruce on growth intercept lengths computed from series of one to seven internodes from eight starting heights between 0 and 3.0 m.

White spruce growth intercepts using three, four, and five internodes starting from 2.0 m provided the best estimates of $BHSI_{15}$ with the fewest number of internodes at the lowest starting height. The first annual white spruce node above 2.0 m usually corresponded with the third annual node above breast height (1.30 m), i.e. at a breast height-age of two years. Thus, these growth intercepts use the height of white spruce trees from a breast height-age of approximately two to five, two to six, and two to seven years.

The length of these three growth intercepts explained 83, 85, and 89 % of the variation in the $BHSI_{15}$ of the 46 white spruce study plots using Equation 5, respectively (Figure 10, Appendix IV). Using less than three internodes starting from 2.0 m did not provide as good an estimate of $BHSI_{15}$, explaining only 76 % of the variation. Using more than five internodes starting from 2.0 m provided only a marginal increase in the explained variation. Six or more internodes starting from 1.0 m, and five or more internodes starting from 1.3 m and 1.5 m were required to explain more than 80 % of the variation in $BHSI_{15}$. Using internodes starting from heights greater than 2.0 m explained less variation than internodes starting from 2.0 m.

The regressions of the $BHSI_{15}$ of white spruce on the length of growth intercepts computed from three, four, and five internodes starting from 2.0 m are very similar (Figure 11). Table 9 shows the $BHSI_{15}$ predicted by these three regression equations (Eq. 5 and the coefficients given in Table 10) over the observed range of growth intercept lengths.

The reduction in the mean squared error (MSE) of $BHSI_{15}$ was not significant when growth intercept lengths were computed from three and four, or four and five internodes above 2.0 m. However, the reduction in the MSE was significant at the 90 % level of confidence when growth intercept lengths were computed from three and five internodes above 2.0 m. The 95 % confidence interval about the $BHSI_{15}$ predicted by white spruce growth intercept lengths range from: ± 0.27 to 0.63 m using three internodes; ± 0.26 to 0.59 m using four internodes; and ± 0.15 to 0.36 m using five internodes starting from 2.0 m (Figure 11). Appendix V gives the statistics for the computation of these 95 % confidence intervals.

Red Pine

The linear term in Equation 5 did not account for a significant amount of variation in the $BHSI_{20}$ of red pine. Thus, Equation 11 (including only the quadratic term) was used to describe the relationship between the $BHSI_{20}$ of red pine and the lengths of the various growth intercepts based on the first internode selection method. Equations 6 through 10, 12, and 15 explained slightly less variation in the $BHSI_{20}$ of red pine, Equation 11 explained exactly the

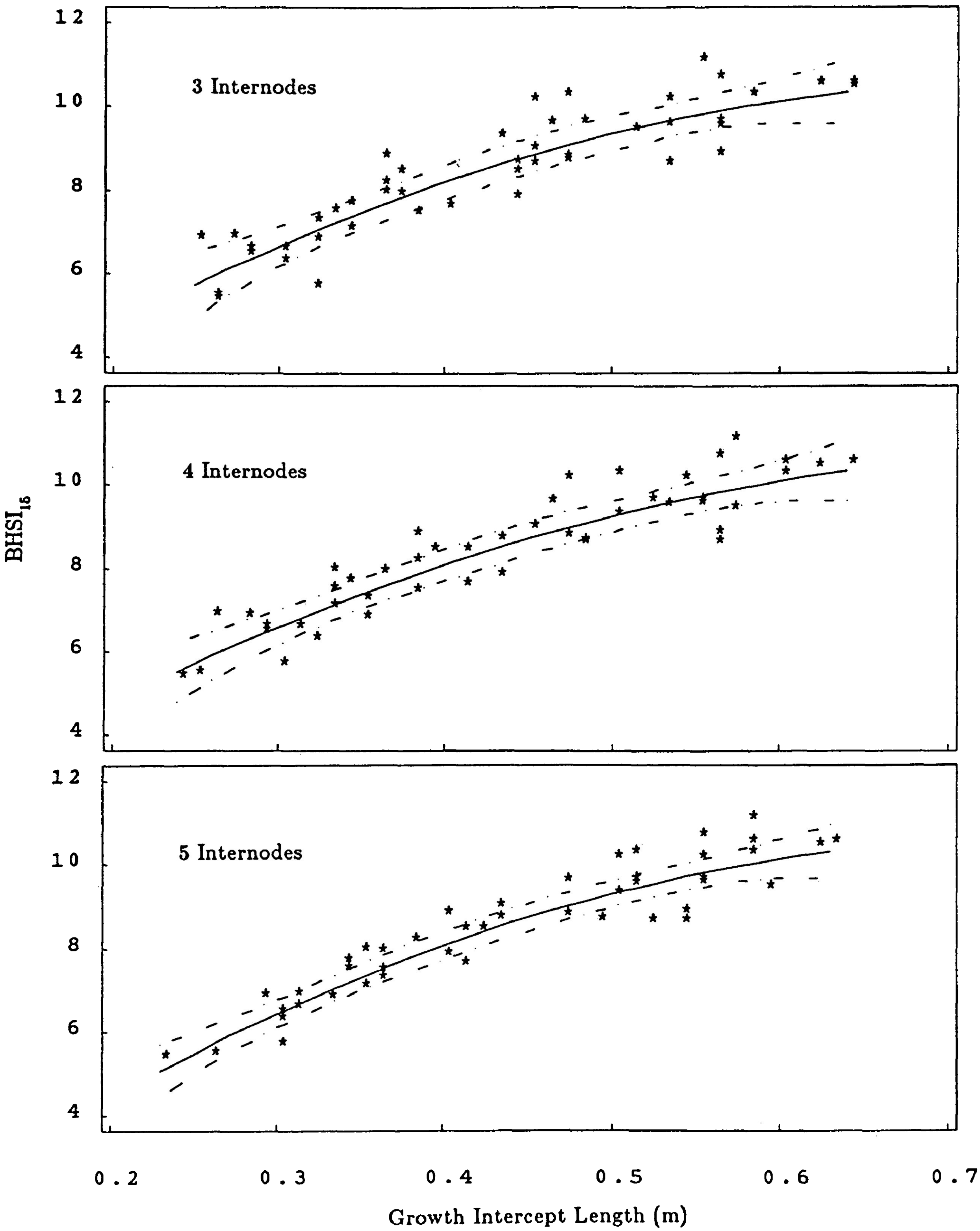

Figure 11. Regressions and 95 % confidence intervals of prediction of the $BHSI_{15}$ of white spruce and growth intercept lengths computed from three, four, and five internodes starting from 2.0 m.

Table 9. White spruce $BHSI_{15}$ values predicted using Equation 5 and the coefficients given in Table 10.

Growth Intercept Length (m)	3 Internodes	4 Internodes	5 Internodes
0.25	5.74	5.71	5.47
0.30	6.66	6.59	6.43
0.35	7.48	7.38	7.29
0.40	8.20	8.09	8.06
0.45	8.83	8.72	8.72
0.50	9.36	9.26	9.29
0.55	9.80	9.72	9.76
0.60	10.14	10.10	10.13
0.65	10.38	10.40	10.41

Table 10. White spruce growth intercept regression statistics using Equation 5 with growth intercept lengths computed from three, four, and five internodes starting from 2.0 m.

Number of Internodes	Parameter	Estimate	95 % CI		SEE	R^2
			Lower	Upper		
	b_0	-0.273	-3.240	2.694		
3	b_1	28.853	14.679	43.027	0.636	0.829
	b_2	-19.165	-35.305	-3.024		
	b_0	0.075	-2.809	2.958		
4	b_1	26.697	12.869	40.525	0.589	0.853
	b_2	-16.643	-32.406	-0.880		
	b_0	-0.8166	-3.5474	1.9141		
5	b_1	30.0412	17.0019	43.0806	0.510	0.890
	b_2	-19.6528	-34.5000	-4.8057		

same amount of variation, and Equations 13, 14, 16, and 17 explained virtually the same amount of variation as Equation 5. The coefficients of determination (R^2) computed from fitting Equation 11 to the lengths of the various red pine growth intercepts are given in Appendix VI. Figure 12 is a graphical presentation of these values that illustrates the amount of variation (R^2) explained when the $BHSI_{20}$ of red pine is estimated using Equation 11 and the length of growth intercepts computed from series of one to 10 internodes from the eight

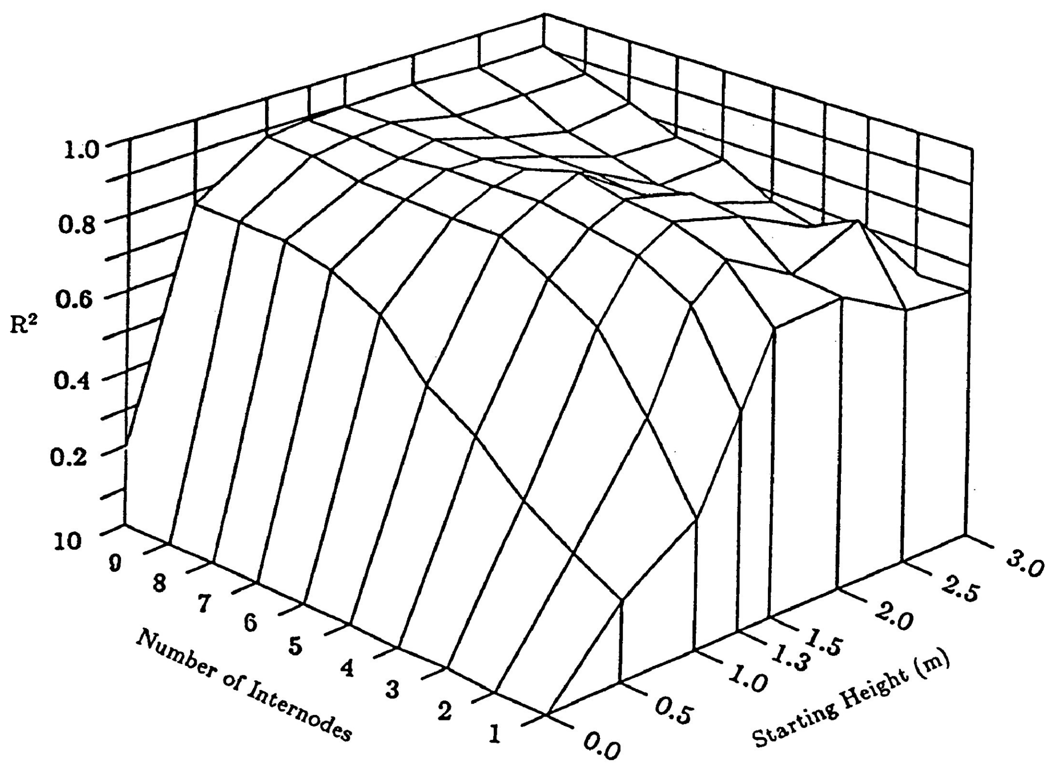

Figure 12. Explained variation (R^2) in the regression of the $BHSI_{20}$ of red pine on growth intercept lengths computed from series of one to 10 internodes starting from eight starting heights between 0 and 3.0 m.

starting heights between 0 and 3.0 m.

Red pine growth intercepts using three, four, and five internodes starting from 1.5 m provided the best estimates of $BHSI_{20}$ using the fewest internodes at the lowest starting height. The first annual red pine node above 1.5 m usually corresponded with the first or second node above breast height (1.30 m), i.e. at a breast height-age of zero or one year. Thus, these growth intercepts use the height of red pine trees from a breast height-age of approximately zero to three, zero to four, and zero to five years; or from a breast height-age of approximately one to four, one to five, and one to six years.

The length of these three growth intercepts explained 90, 92, and 94 % of the variation in the $BHSI_{20}$ of the 25 red pine study plots using Equation 11, respectively (Figure 12, Appendix VI). Using two internodes starting from 1.5 m provided a satisfactory, but somewhat less precise estimate explaining 87 % of the variation in $BHSI_{20}$. More than five internodes starting from 1.5 m, or any number of internodes starting from heights greater than 1.5 m resulted in a decrease in explained variation. Five or more internodes starting from 1.0 m and three or more internodes starting from 1.3 m were required to explain more than 80 % of the variation in the $BHSI_{20}$ of red pine. Growth intercept lengths computed from internodes starting from 0 and 0.5 m did not provide satisfactory estimates of the $BHSI_{20}$ of red pine.

The regressions of the $BHSI_{20}$ of red pine on the length of growth intercepts computed from three, four, and five internodes starting from 1.5 m are also very similar (Figure 13). Table 11 shows the $BHSI_{20}$ predicted by these three regression equations (Eq. 11 and the coefficients given in Table 12) over the observed range of growth intercept lengths.

As with white spruce, the reduction in the MSE of predicting $BHSI_{20}$ was not significant when growth intercept lengths were computed from three and four, or four and five internodes above 1.5 m. Again, the reduction in the MSE was significant at the 90 % level of confidence when growth intercept lengths were computed from three and five internodes above 1.5 m (Figure 13). The 95 % confidence interval about the $BHSI_{20}$ predicted by red pine growth intercept lengths range from: $\pm$ 0.18 to 0.39 m using three internodes; $\pm$ 0.16 to 0.39 m using four internodes; and $\pm$ 0.14 to 0.31 m using five internodes above 1.5 m. Appendix V gives the statistics for the computation of these 95 % confidence intervals.

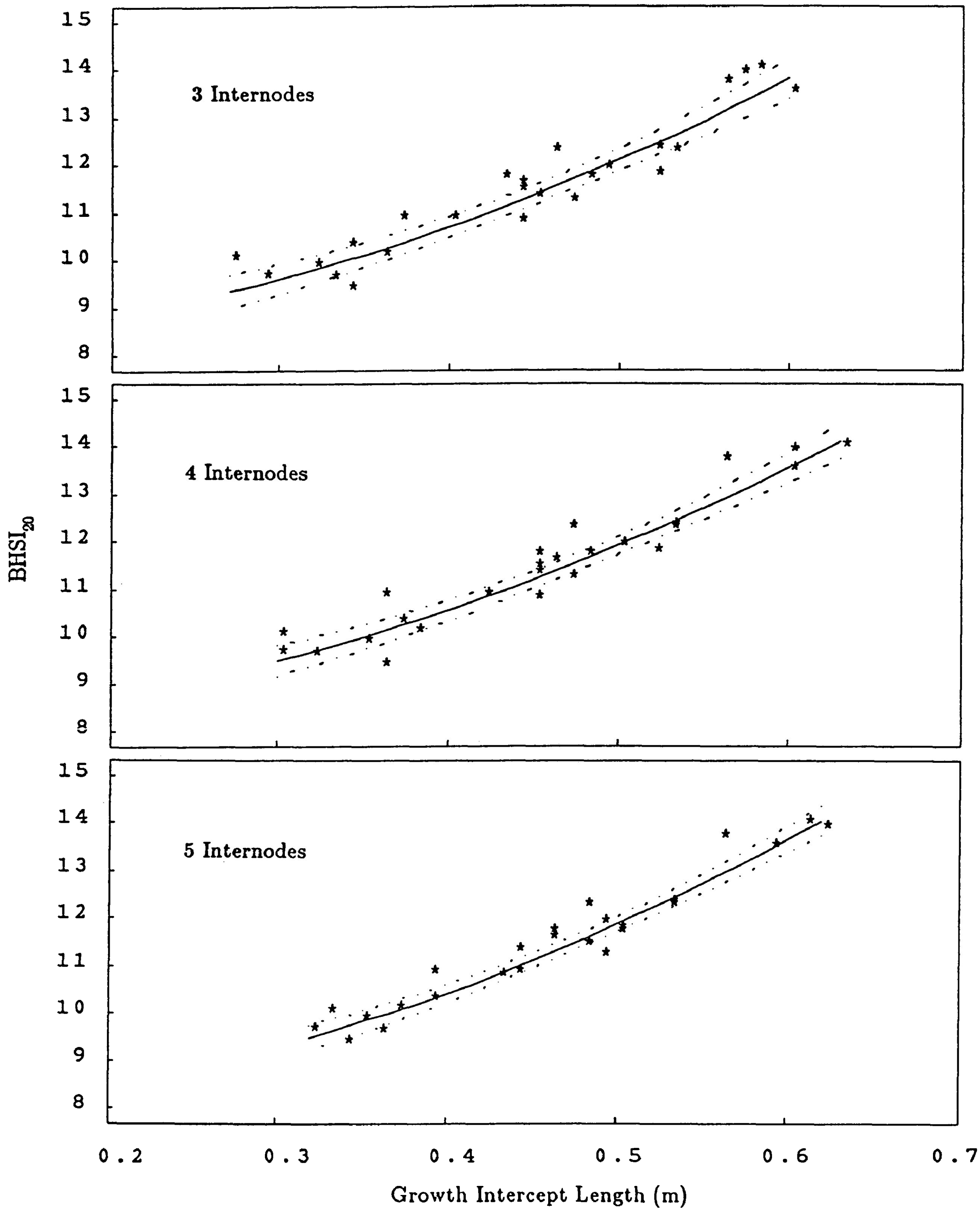

Figure 13. Regressions and 95 % confidence intervals of prediction of the $BHSI_{20}$ of red pine and growth intercept lengths computed from three, four, and five internodes starting from 1.5 m.

Table 11. **Red pine $BHSI_{20}$ values predicted using Equation 11 and the coefficients given in Table 12.**

Growth Intercept Length (m)	3 Internodes	4 Internodes	5 Internodes
0.25	9.18	9.08	8.84
0.30	9.61	9.49	9.29
0.35	10.11	9.98	9.29
0.40	10.69	10.55	10.42
0.45	11.35	11.19	11.11
0.50	12.09	11.91	11.88
0.55	12.91	12.70	12.73
0.60	13.80	13.56	13.66
0.65	14.77	14.51	14.62

Table 12. **Red pine growth intercept regression statistics using Equation 11 with growth intercept lengths computed from three, four, and five internodes starting from 1.5 m.**

Number of Internodes	Parameter	Estimate	95 % CI		SEE	R^2
			Lower	Upper		
3	b_0	8.208	7.725	8.690	0.435	0.901
	b_1	15.540	13.325	17.755		
4	b_0	8.135	7.693	8.576	0.393	0.920
	b_1	15.083	13.159	17.007		
5	b_0	7.830	7.437	8.222	0.327	0.944
	b_1	16.185	14.491	17.880		

HEIGHT GROWTH PATTERNS

Formulated Height Growth Curves

Total Height-Age

Both white spruce and red pine plot average total height-age height growth patterns are best described, in decreasing order, by Ek's model (Eq. 23), Lundgren and Dolid's model (Eq. 22), and the harmonized Chapman-Richards function (Eq. 24) (Table 13). Ek's model (Eq. 23) achieved a significant reduction in the SSE at the 99 % level of confidence over the next best model of Lundgren and Dolid (Eq. 22) with F values of 182.48 for white spruce and 384.43

Table 13. Residual statistics of the non-linear models fit to plot average total height-age height growth data.

Species and Model	SSE	df_e	MSE	Eq.
White Spruce				
Ek	171.757	1386	0.124	[23]
Lundgren and Dolid	216.983	1388	0.156	[22]
Chapman-Richards[1]	256.788	1388	0.191	[24]
Red Pine				
Ek	63.071	852	0.074	[23]
Lundgren and Dolid	119.987	854	0.140	[22]
Chapman-Richards[1]	196.327	854	0.230	[24]

[1] Harmonized

for red pine. Figure 14 shows the white spruce and red pine total height-age height growth curves formulated with Ek's model. The coefficients of these regressions are given in Table 14 and 15 for white spruce and red pine, respectively. A visual inspection of Figure 15 confirms the close association between these formulated height growth curves and the white spruce and red pine plot average total height-age height growth curves. Figure 15 shows these same formulated height growth curves superimposed on the plot average total height-age height

Table 14. Regression coefficients describing white spruce plot average total height-age height growth data using Ek's model (Eq. 23).

Parameter	Estimate	s_{b_i}	t	95 % CI Lower	95 % CI Upper
b_1	13.6701	1.24	11.0	11.2	16.1
b_2	0.354493	0.0317	11.2	0.292	0.417
b_3	0.0413103	0.00167	24.8	0.0380	0.0446
b_4	7.14160	0.379	18.8	6.40	7.88
b_5	0.436406	0.0208	21.0	0.396	0.477

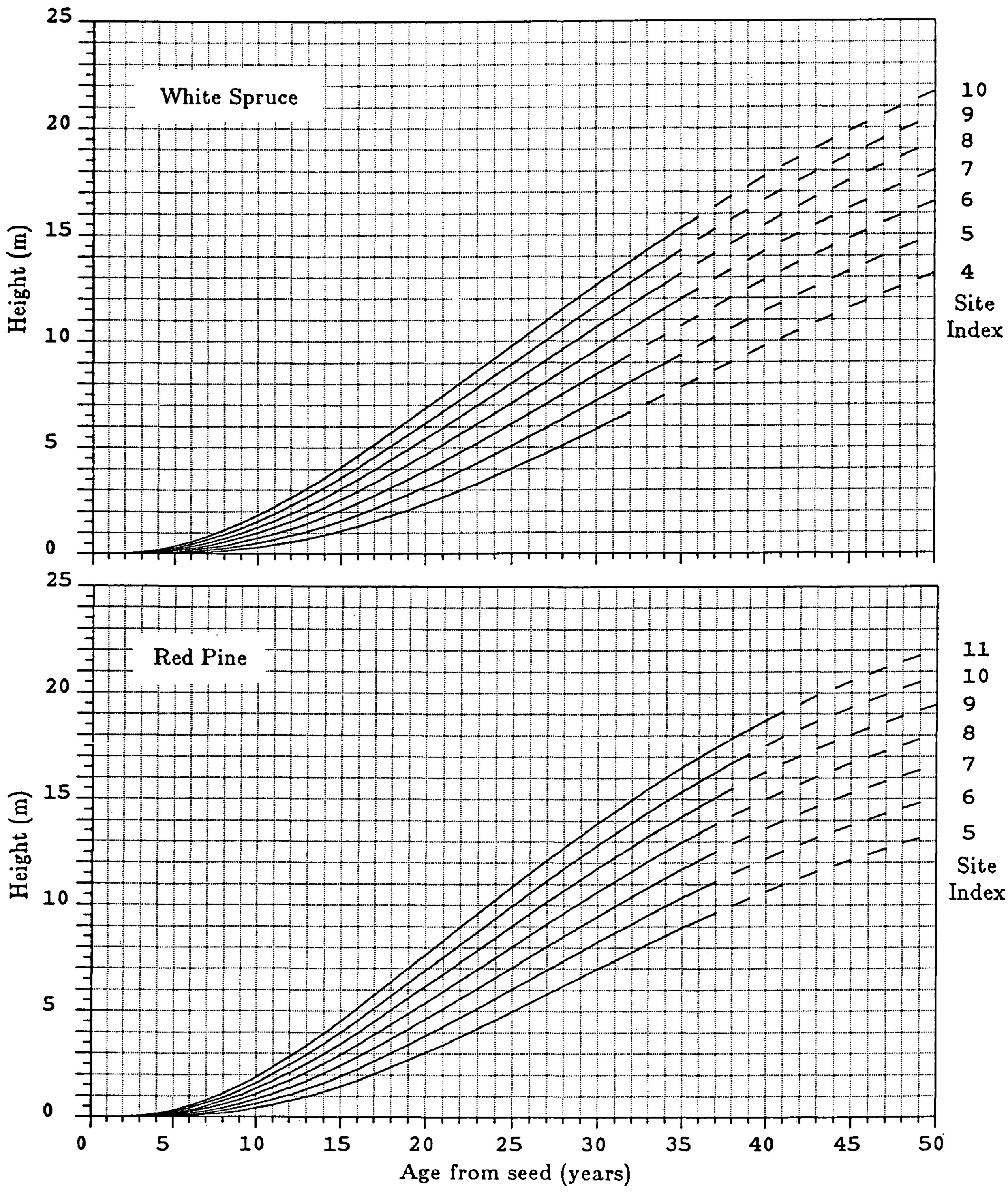

Figure 14. **Formulated white spruce and red pine total height-age height growth curves. Site index is total height of dominant trees at 25 years from seed. Dashed curves represent extrapolation beyond the range of observed data.**

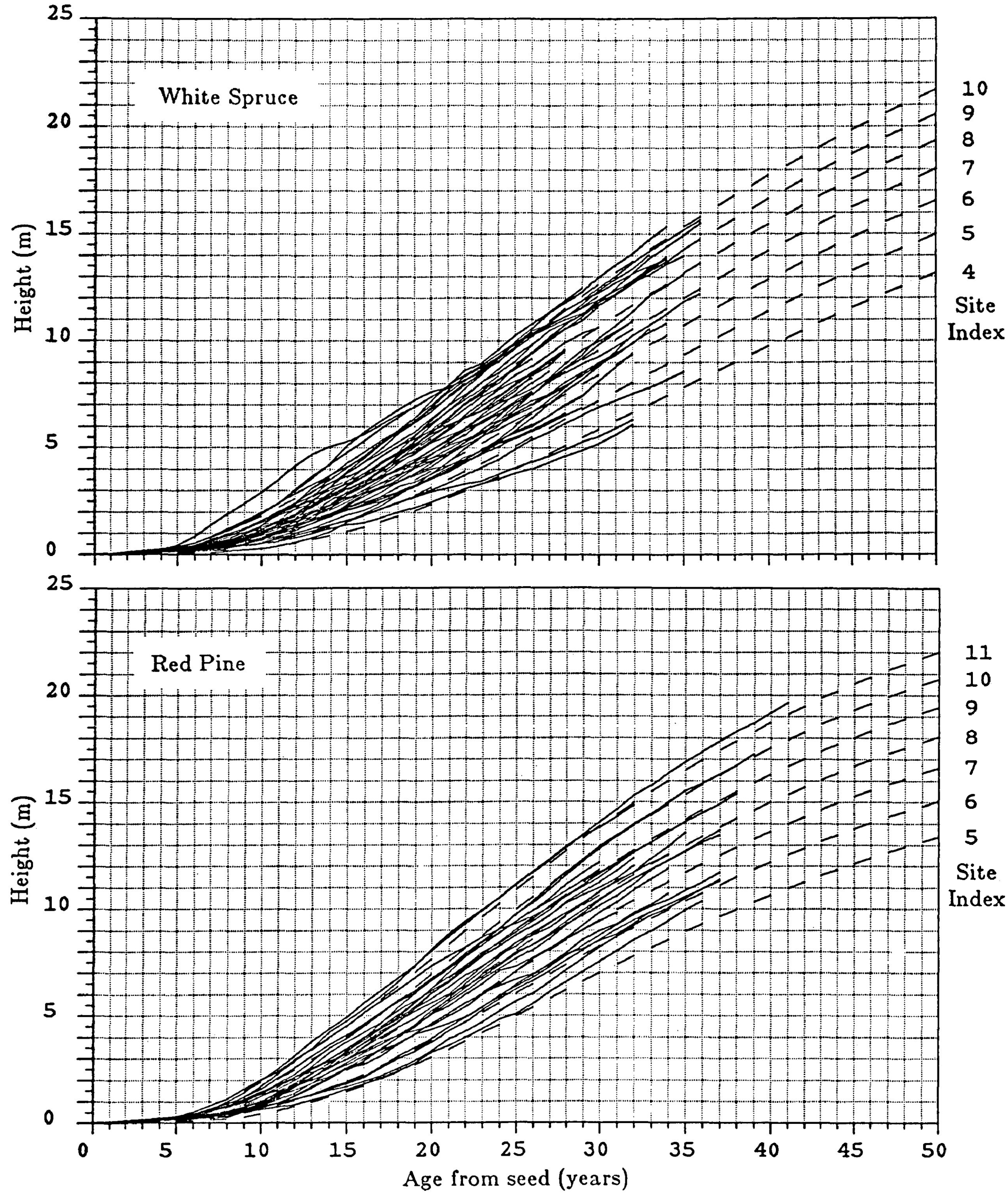

Figure 15. Formulated height growth curves superimposed on white spruce and red pine plot average total height-age height growth curves.

Table 15. Regression coefficients describing red pine plot average total height-age height growth data using Ek's model (Eq. 23).

Parameter	Estimate	s_{b_i}	t	95 % CI Lower	95 % CI Upper
b_1	7.80525	0.397	19.7	7.03	8.58
b_2	0.522405	0.0192	27.2	0.485	0.560
b_3	0.0535547	0.00123	43.6	0.0511	0.0560
b_4	8.44261	0.406	20.8	7.65	9.24
b_5	0.428243	0.0195	22.0	0.390	0.466

growth curves.

Breast Height-Age

Equation 26 explained the most variation of the five linear models fit to both white spruce and red pine plot average breast height-age height growth data (Table 16). The addition of a quadratic term to Equation 25 (Eq. 26) resulted in a very small, but significant reduction in the SSE at the 99 % level of confidence for both white spruce and red pine. Residual statistics using Equations 25 through 29 to describe white spruce and red pine plot average breast height-age height growth data are given in Table 16.

Both white spruce and red pine plot average breast height-age height growth data were best described by Ek's model (Table 17). The linear model (Eq. 26) achieved the next best fit, followed by Lundgren and Dolid's model (Eq. 22) and the harmonized Chapman-Richards function (Eq. 24). Figure 16 shows the white spruce and red pine breast height-age height growth curves formulated with Ek's model. The coefficients of these regressions are given in Tables 18 and 19 for white spruce and red pine, respectively. Figure 17 shows these same formulated height growth curves superimposed on the plot average breast height-age height growth curves. A visual inspection of Figure 17 confirms the close association between these formulated height growth curves and the white spruce and red pine plot average breast

Table 16. Residual statistics of the linear models fit to plot average breast height-age height growth data.

Species and Model	SSE	df_e	MSE	R^2	Eq.
White Spruce					
$Ht = b_0 + b_1AGE + b_2SI + b_3(AGE \times SI) + b_4AGE^2$	59.4593	824	0.0722	0.9927	[26]
$Ht = b_0 + b_1AGE + b_2SI + b_3(AGE \times SI)$	60.1504	825	0.0729	0.9926	[25]
$Ht = b_0 + b_1(AGE \times SI) + b_2AGE^2$	70.6940	826	0.0856	0.9913	[28]
$Ht = b_0 + b_1(AGE \times SI) + b_2(AGE \times SI)^2$	72.7908	826	0.0881	0.9910	[29]
$Ht = b_0 + b_1(AGE \times SI)$	73.7922	827	0.0892	0.9910	[27]
Red Pine					
$Ht = b_0 + b_1AGE + b_2SI + b_3(AGE \times SI) + b_4AGE^2$	27.1927	555	0.0490	0.9965	[26]
$Ht = b_0 + b_1AGE + b_2SI + b_3(AGE \times SI)$	28.2523	556	0.0508	0.9963	[25]
$Ht = b_0 + b_1(AGE \times SI) + b_2AGE^2$	34.5042	557	0.0620	0.9955	[28]
$Ht = b_0 + b_1(AGE \times SI) + b_2(AGE \times SI)^2$	40.2599	557	0.0723	0.9948	[29]
$Ht = b_0 + b_1(AGE \times SI)$	41.1288	558	0.0737	0.9947	[27]

Table 17. Residual statistics of the regressions describing plot average breast height-age height growth data.

Species and Model	SSE	df_e	MSE	Eq.
White Spruce				
Ek	57.4871	824	0.070	[23]
Linear	59.4593	824	0.072	[26]
Lundgren and Dolid	84.0897	826	0.102	[22]
Chapman-Richards[1]	124.196	826	0.150	[24]
Red Pine				
Ek	22.873	555	0.041	[23]
Linear	27.193	555	0.049	[26]
Lundgren and Dolid	43.567	557	0.078	[22]
Chapman-Richards[1]	47.728	557	0.086	[24]

[1] Harmonized

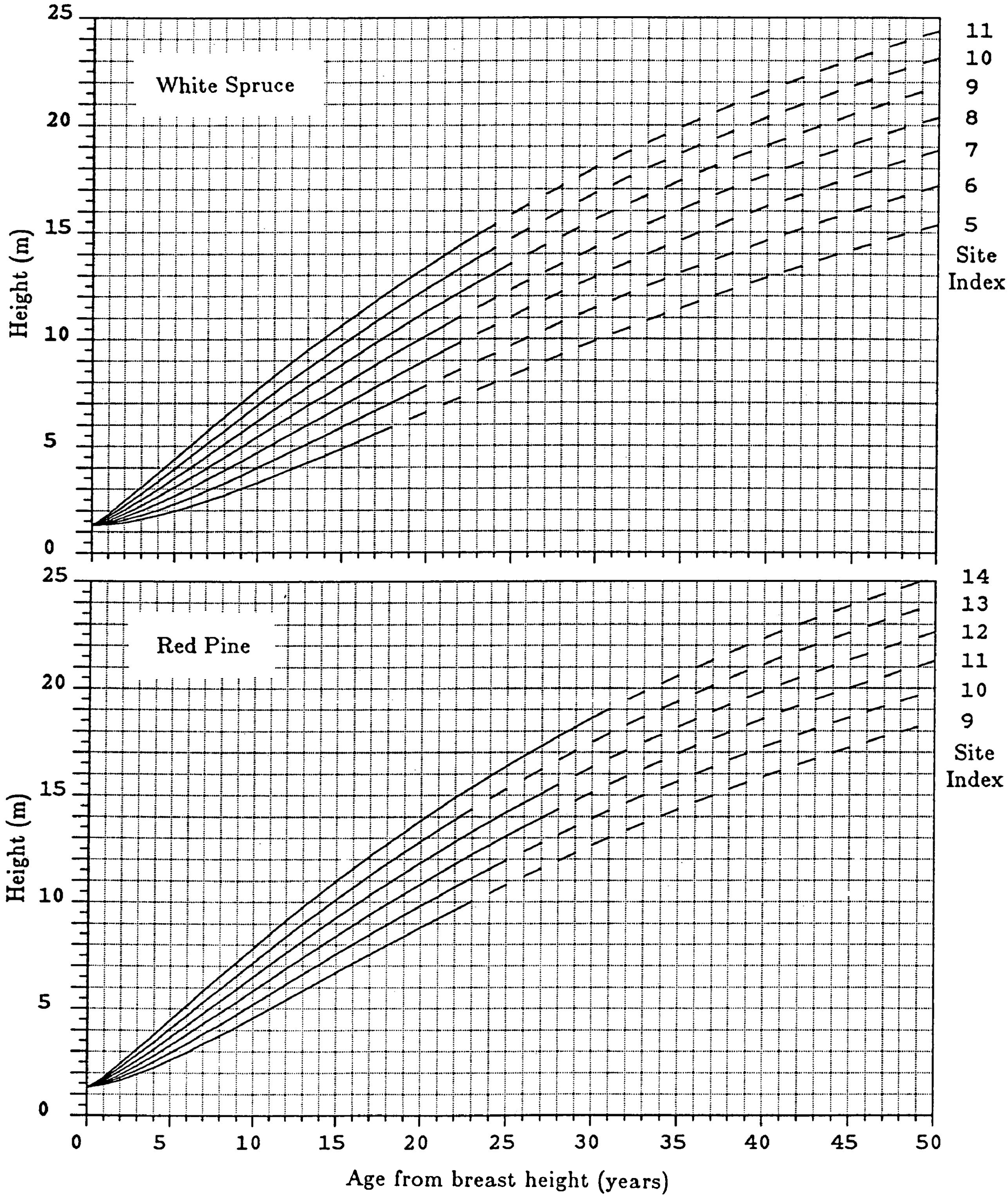

Figure 16. Formulated white spruce and red pine breast height-age height growth curves. Site index is height of trees at 15 and 20 years breast height-age for white spruce and red pine, respectively. Dashed curves represent extrapolation beyond the range of observed data.

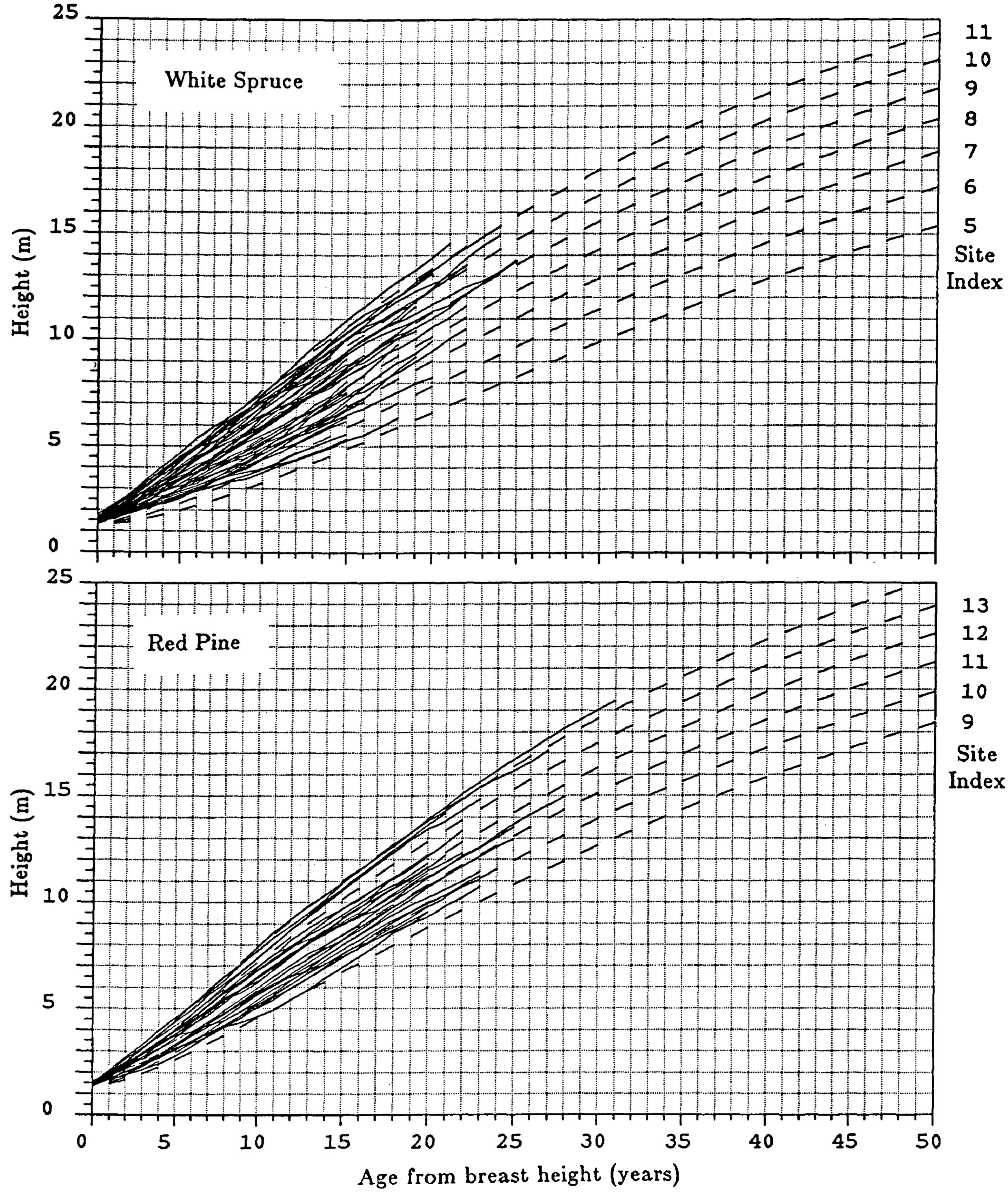

Figure 17. Formulated height growth curves superimposed on white spruce and red pine plot average breast height-age height growth curves.

Table 18. Regression coefficients describing white spruce plot average breast height-age height growth data using Ek's model (Eq. 23).

Parameter	Estimate	s_{b_i}	t	95 % CI Lower	95 % CI Upper
b_1	11.9403	2.04	5.9	7.95	15.90
b_2	0.412608	0.0555	7.4	0.304	0.521
b_3	0.0276888	0.00241	11.5	0.023	0.0324
b_4	4.0323	0.274	14.7	3.49	4.573
b_5	0.526281	0.0281	18.7	0.471	0.581

Table 19. Regression coefficients describing red pine plot average breast height-age height growth data using Ek's model (Eq. 23).

Parameter	Estimate	s_{b_i}	t	95 % CI Lower	95 % CI Upper
b_1	7.62328	1.04	7.3	5.58	9.67
b_2	0.552179	0.0435	12.7	0.467	0.637
b_3	0.0287362	0.00162	17.7	0.0256	0.0319
b_4	5.06122	0.371	13.6	4.33	5.79
b_5	0.558397	0.0284	19.7	0.503	0.614

height-age height growth curves.

Comparison with Published Height Growth Curves

The plot average total height-age height growth patterns of these white spruce study plots appear to follow closely Berry's (1978) white spruce height growth curves (Figure 18A). However, the range of height growth portrayed in Berry's curves is slightly higher than was observed in these white spruce study plots. Differences are more apparent when Berry's height growth curves are compared with the height growth curves formulated from the plot average total height-age growth data of these white spruce study plots (Figure 18B). Height growth patterns of Berry's upper height growth curves for good sites are similar to the height growth

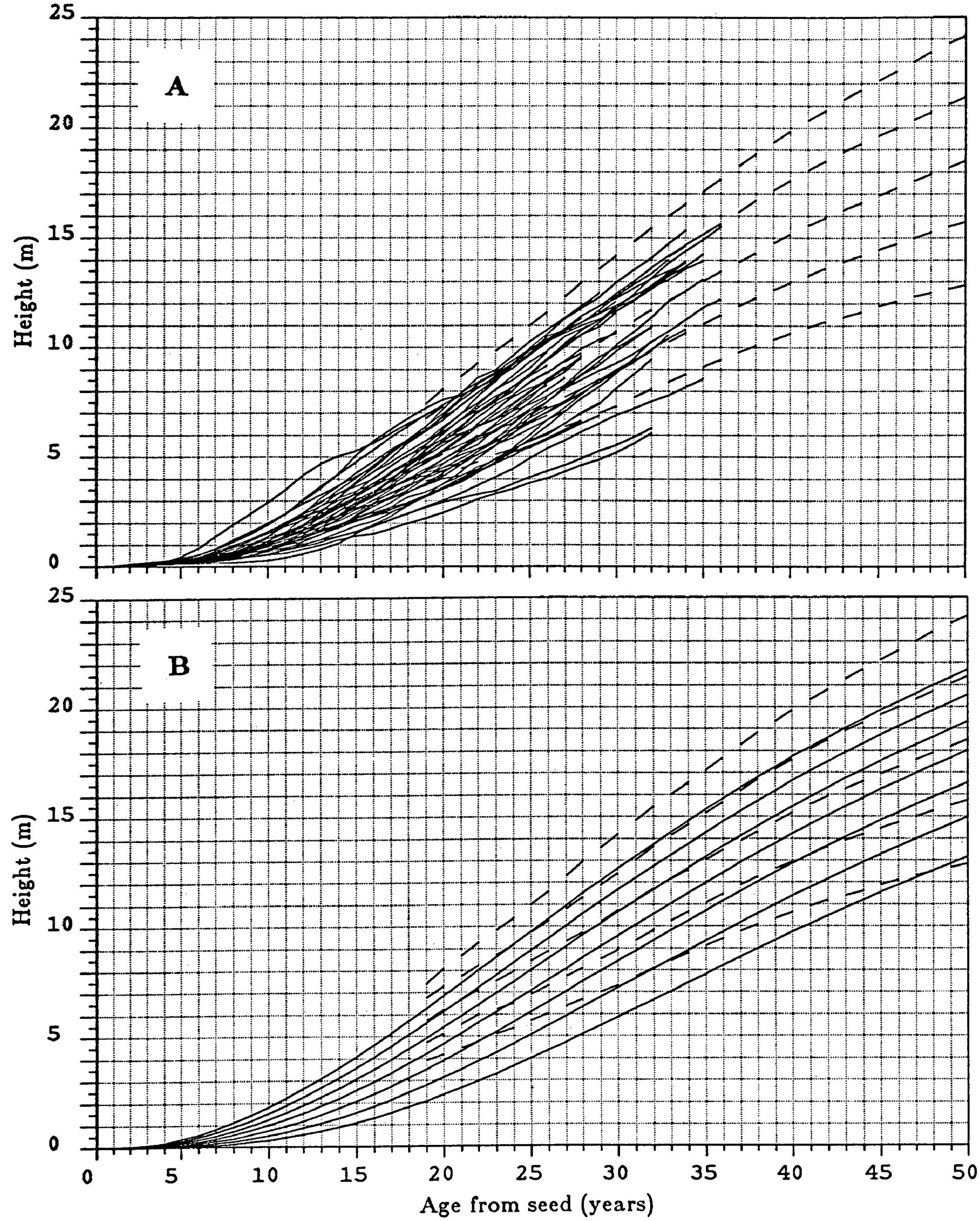

Figure 18. Berry's (1978) white spruce height growth curves (dashed lines) compared with white spruce study plot height growth patterns. Berry's curves are shifted four years to correspond with age from seed. A. Berry's height growth curves superimposed on white spruce plot average total height-age height growth curves. B. Berry's height growth curves superimposed on formulated white spruce total height-age height growth curves.

patterns observed in these study plots. However, Berry's lower height growth curves for poor sites show a much slower rate of height growth than is portrayed in these white spruce study plots.

The red pine plot average total height-age height growth patterns observed in these study plots do not follow closely the height growth patterns portrayed in Berry's (1984) red pine height growth curves (Figure 19). Berry's height growth curves show a slower rate of height growth than is expressed in these red pine study plots. In addition, Berry's curves show a maximum 50 year height exceeding 25 m, in contrast to 22 m for these red pine study plots.

The red pine height growth curves given by Wilde *et al.* (1965) also differ from the height growth patterns observed in these red pine study plots. In contrast to Berry's height growth curves, Wilde's curves show a lower height at 50 years than is shown by these these red pine study plots (Figure 20). These red pine study plots also show more rapid height growth than is portrayed in Wilde's height growth curves. Wilde's height growth curves suggest that the maximum rate of height growth is achieved almost immediately after planting. In contrast, these red pine study plots show much slower early height growth before reaching the maximum rate of height growth.

Unlike Berry's and Wilde's height growth curves, the red pine breast height-age height growth curves given by Richards *et al.* (1962) are very similar to the breast height-age height growth patterns observed in these red pine study plots (Figure 21). The rate and pattern of height growth displayed in the upper range of height growth of Richards' curves is almost identical to the rate and pattern of height growth displayed in the upper range of height growth observed in these red pine study plots. However, Richards' curves show a slower rate of height growth for the intermediate and poor sites than was observed in these red pine study plots.

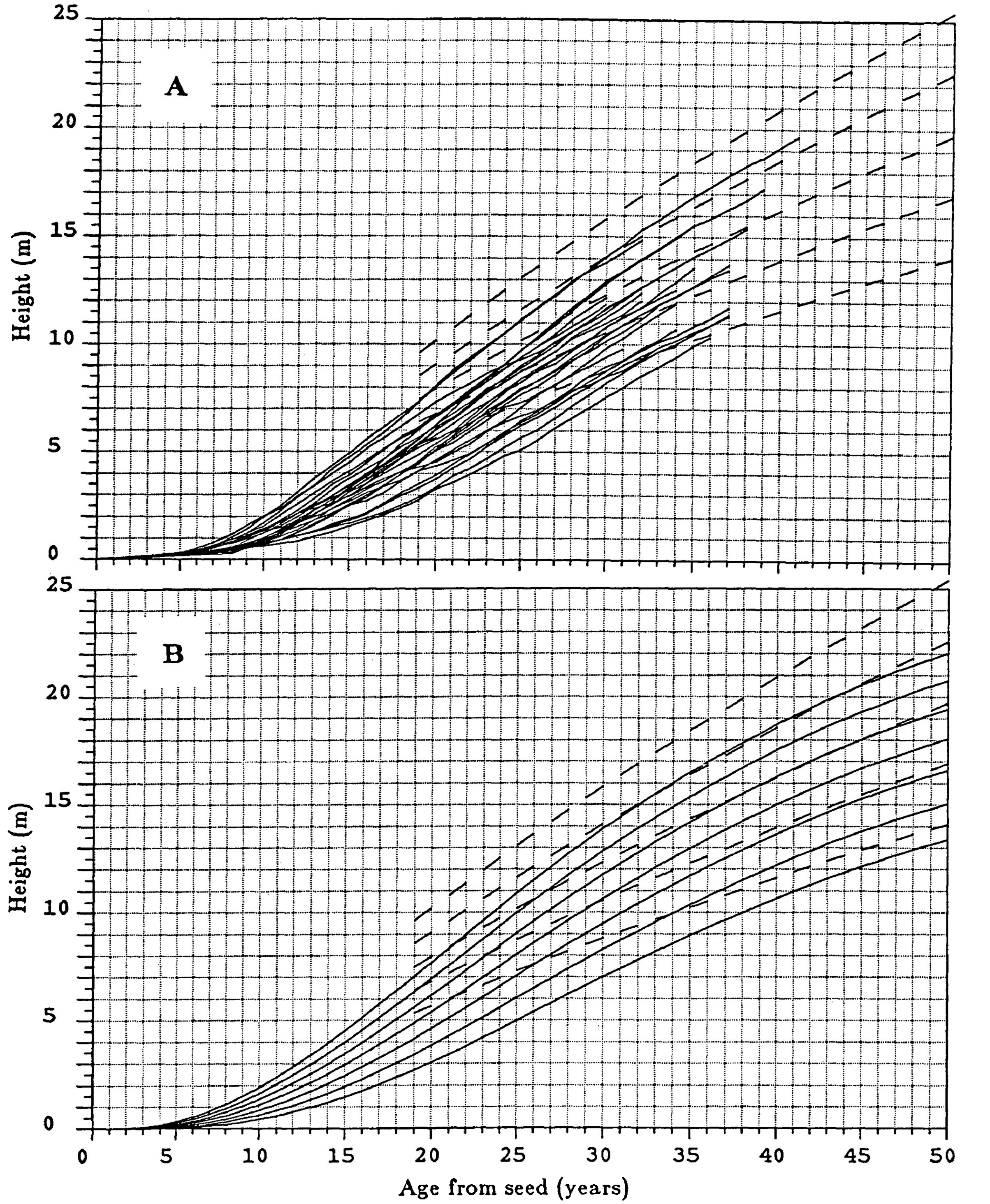

Figure 19. Berry's (1984) red pine height growth curves (dashed lines) compared with red pine study plot height growth patterns. Berry's curves are shifted four years to correspond with age from seed. A. Berry's height growth curves superimposed on red pine plot average total height-age height growth curves. B. Berry's height growth curves superimposed on formulated red pine total height-age height growth curves.

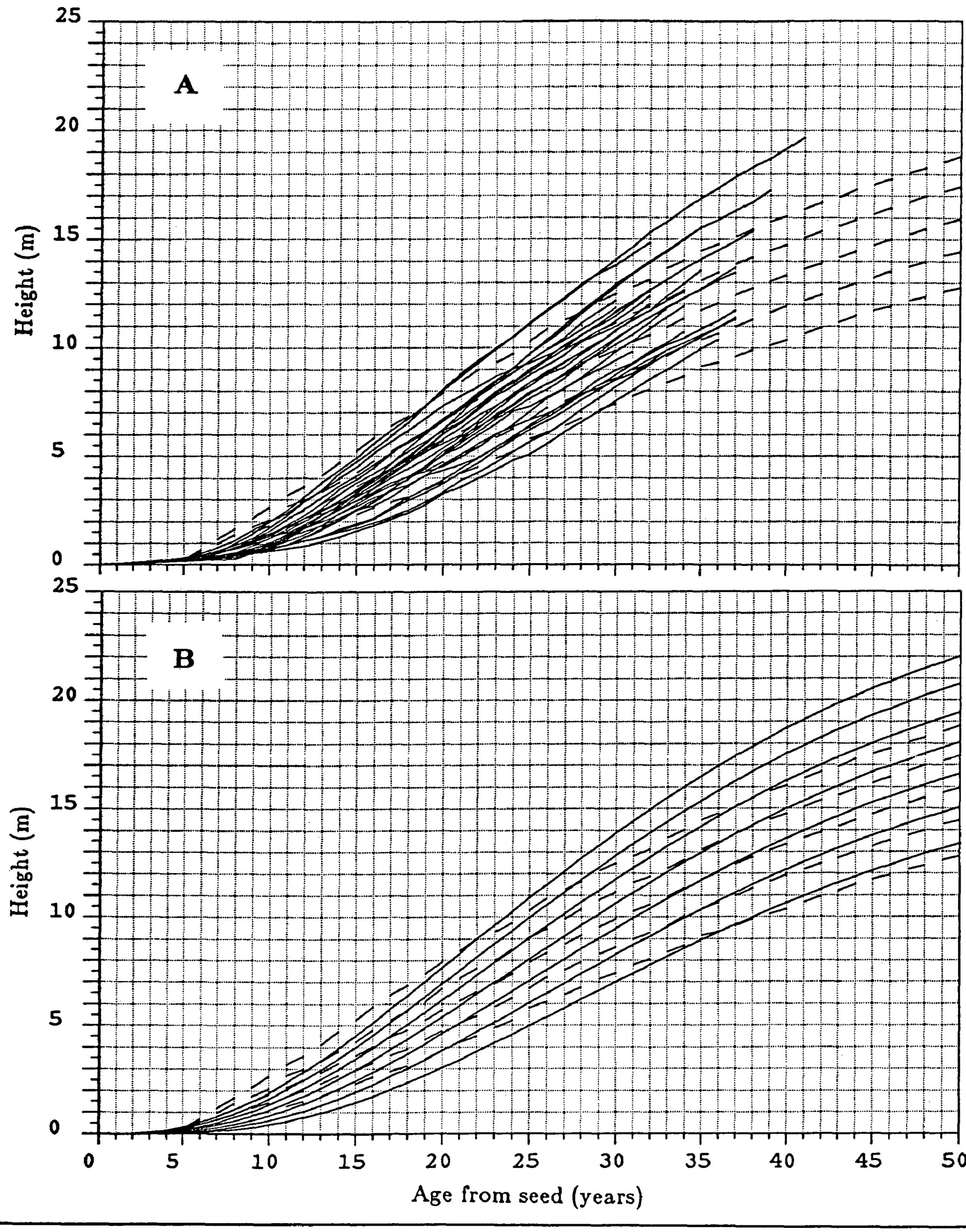

Figure 20. Red pine height growth curves given by Wilde *et al.* (1965) (dashed lines) compared with red pine study plot height growth patterns. Wilde's curves are shifted four years to correspond with age from seed. A. Wilde's height growth curves superimposed on red pine plot average total height-age height growth curves. B. Wilde's height growth curves superimposed on formulated red pine total height-age height growth curves.

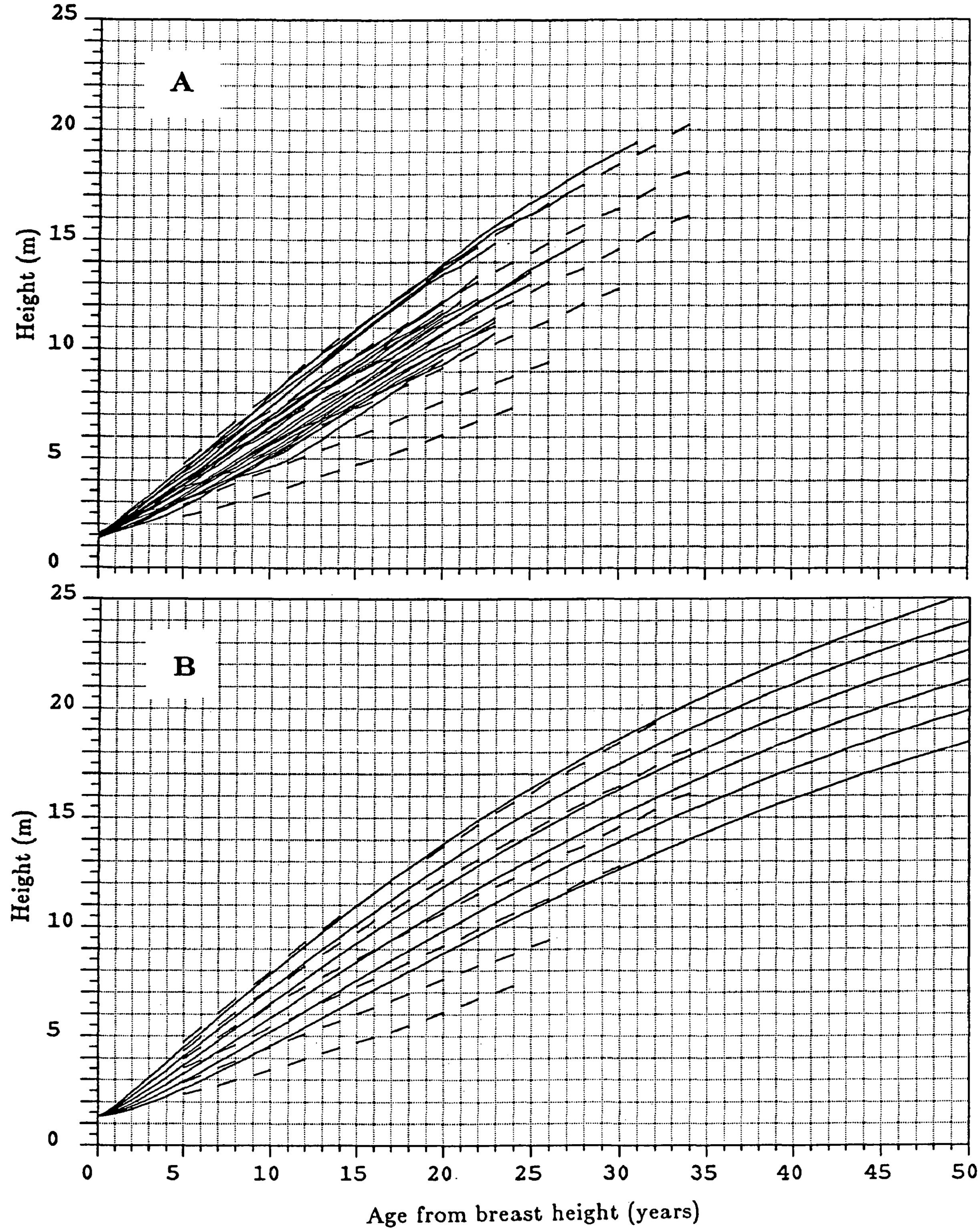

Figure 21. Red pine height growth curves given by Richards *et al.* (1962) (dashed lines) compared with red pine study plot height growth patterns. A. Richards' height growth curves superimposed on red pine plot average breast height-age height growth curves. B. Richards' height growth curves superimposed on formulated red pine breast height-age height growth curves.

Predicting Site Index from Height and Age

Equations 30 and 31 did not accurately predict $BHSI_x$ from total height and age from breast height observations. Payandeh's (1974) model (Eq. 30) equating site index as a function of height and age did not adequately describe the breast height-age height growth data generated with Ek's model (Eq. 23) using the coefficients given in Tables 18 and 19. Thus, Equation 30 could not be expected to accurately describe the more variable plot average breast height-age height growth data. The author's site index Equation (Eq. 31) fit the generated height growth data after 10 years breast height-age with a standard error of the estimate of approximately 0.10 m. This model predicted $BHSI_x$ with a standard error of the estimate of approximately 0.25 m when fit to plot average breast height-age data older than 10 years of age. However, accurate estimates of $BHSI_x$ could not be obtained below a breast height-age of 10 years.

Linear interpolation between the formulated breast height-age height growth curves using Equation 32 provided the only reasonably accurate estimates of $BHSI_x$ from total height and age from breast height observations. Table 20 compares the average absolute error of estimates of $BHSI_x$ computed from growth intercepts and from formulated breast height-age height growth curves using Equation 32 and the same height and age data. Growth intercepts provide more accurate estimates of $BHSI_x$ than breast height-age height growth curves when the same height and age data are used. This is expected because the procedure used to compute the growth intercept equations (linear least squares regression) dictates that the sum of the errors must be zero (i.e. $\sum e_i = 0$). However, when trees exceed the ages used by these growth intercepts, breast height-age height growth curves that use progressively more height growth should provide better estimates of $BHSI_x$ than growth intercepts that use only a fixed portion of early height growth.

Table 20. Average absolute error (m) of estimates of $BHSI_x$ using the same height and age data with growth intercepts and breast height-age height growth curves.

Species	3 Internodes		4 Internodes		5 internodes	
	GI	HGC	GI	HGC	GI	HGC
White Spruce	0.49	0.61	0.46	0.50	0.39	0.50
Red Pine	0.36	0.54	0.28	0.45	0.26	0.45

GI = growth intercept
HGC = breast height-age height growth curves

Appendix VII gives the error for each white spruce and red pine study plot when $BHSI_x$ is computed from both growth intercepts and breast height-age height growth curves using the same height and age data. Appendix VIII gives a simple BASIC program using Equation 32 to predict the $BHSI_{15}$ of white spruce and the $BHSI_{20}$ of red pine from total height and age from breast height observations. These programs can be easily used with a programmable pocket calculator under field conditions.

Years to Reach Breast Height

White spruce and red pine height growth below breast height is very erratic and is not significantly related to height growth above breast height, and therefore is not related to site quality. Only seven per cent of the variation in the $BHSI_{15}$ of white spruce and 20 % of the variation in the $BHSI_{20}$ of red pine is explained by the number of years for sample trees in study plots to reach breast height from planting (Table 21). Figure 22 shows the regressions of $BHSI_x$ and the number of years for sample trees in study plots to reach breast height from planting.

The average number of years for sample trees in white spruce and red pine study plots to reach breast height from planting was virtually identical (Table 22). However, the

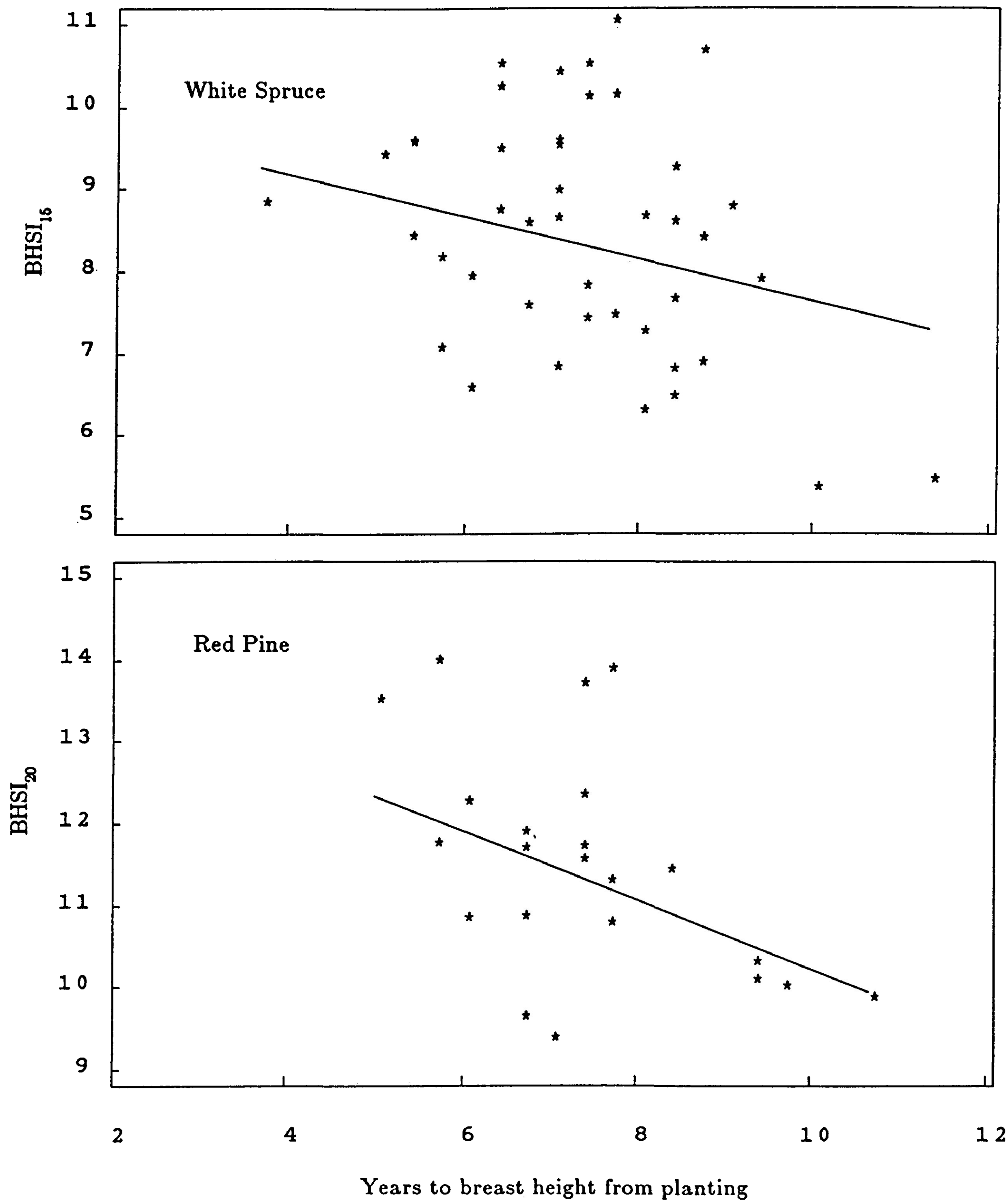

Figure 22. Regressions of the BHSI$_x$ of white spruce and red pine on number of years for sample trees in study plots to reach breast height from planting.

Table 21. Statistics of regressing $BHSI_x$ on number of years for sample trees in study plots to reach breast height from planting using Equation 33.

Species	b_0	b_1	$s_{Y.X}$	R^2
White Spruce	11.2206	-0.2560	1.467	0.070
Red Pine	16.1363	-0.4221	1.236	0.204

Table 22. Mean, standard error, and range of number of years for sample trees in white spruce and red pine study plots to reach breast height from planting.

Species and Plot Type	Number of Plots (n)	Average Number of Years to reach Breast Height ($\bar{x}$)	Standard Error ($s_{\bar{x}}$)	Range of Years to reach Breast Height min.	max.
White Spruce					
All plots	46	7.38	1.55	3.67	11.33
Old fields	9	8.33	1.29	7.00	11.33
Cutovers	37	7.16	1.53	3.67	11.33
Red Pine					
All plots	25	7.34	1.45	5.00	10.66
Old fields	8	6.67	1.33	5.00	8.67
Cutovers	17	7.62	1.46	4.67	10.67

number of years for the sample trees in white spruce study plots to reach breast height from planting was slightly more variable than for red pine. The average number of years for sample trees to reach breast height in both white spruce and red pine study plots located in plantations on abandoned agricultural fields was not significantly different at the 95 % level of confidence from sample trees in study plots located in plantations on former cutovers. Table 22 gives the average, standard error, and range of numbers of years to reach breast height from planting for all red pine and white spruce study plots, study plots located in plantations on abandoned agricultural fields, and study plots located in plantations on former cutovers.

Relating Estimated Site Quality to Height at 50 Years

Sample trees in both white spruce and red pine study plots reached breast height, on the average, in their eighth year from planting (Table 22). Accordingly, the height of trees at 50 years from planting was approximated by the estimated height of trees at a breast height-age of 42 years (i.e. 50 – 8 = 42). Virtually all planting stock was four years of age (2+2) when planted. Consequently, the height of trees at 50 years from seed was approximated by the estimated height of trees at a breast height-age of 38 years (i.e. 50 – (8 + 4) = 38).

The relationship of the estimated height of trees at 50 years from seed and 50 years from planting to $BHSI_x$ was slightly curvilinear. Virtually all variation in height at 50 years was explained by Equation 34. Table 23 gives the regression statistics for computing the estimated height at 50 years from planting and 50 years from seed, using the $BHSI_{15}$ of white spruce and the $BHSI_{20}$ of red pine estimated from either growth intercepts or from breast height-age height growth curves.

Table 23. Regression statistics for estimating height at 50 years using $BHSI_x$ and Equation 34.

Species and Dependent Variable	Independent Variable	b_0	b_1	b_2	R^2	SEE
White Spruce						
$Ht_{50/pltg}$	$BHSI_{15}$	3.9065	2.1182	-0.0382	0.9999	0.0134
$Ht_{50/seed}$	$BHSI_{15}$	3.1163	2.0421	-0.0352	0.9999	0.0121
Red Pine						
$Ht_{50/pltg}$	$BHSI_{20}$	3.2958	1.6004	-0.0131	0.9999	0.0019
$Ht_{50/seed}$	$BHSI_{20}$	2.5931	1.5368	-0.0116	0.9999	0.0016

$Ht_{50/pltg}$ = Height at 50 years from planting estimated by a breast height-age of 42 years
$Ht_{50/seed}$ = Height at 50 years from seed estimated by a breast height-age of 38 years

DISCUSSION

GROWTH INTERCEPTS

White Spruce

The precision of the 56 white spruce growth intercepts to estimate $BHSI_{15}$ increased with the number of internodes and with starting height (Figure 10). As expected, these increases were rapid at first, then increased at a decreasing rate until using additional internodes, or starting growth intercepts higher up the tree resulted in insignificant increases in the precision of the estimate. Significant increases in precision were achieved by starting growth intercepts up to 2.0 m. This suggests that the early erratic height growth of these white spruce study plots also continues up to about 2.0 m.

The precision of the estimates of $BHSI_{15}$ obtained from computing white spruce growth intercepts from internodes starting from 1.3 m (breast height) were lower than estimates obtained from computing growth intercepts from internodes starting above 1.0 m. This anomaly has no obvious biological foundation, thus is probably a peculiarity of the data. The precision of estimating $BHSI_{15}$ was still increasing after breast height (1.30 m), suggesting that early erratic height growth is also persisting after breast height.

The relationship between $BHSI_{15}$ and the length of white spruce growth intercepts computed from three, four, and five internodes starting from 2.0 m is positive with a slightly downward curvilinear trend (Figure 11). This relationship reflects the polymorphic height growth pattern of white spruce. White spruce trees on good sites reach a maximum rate of height growth earlier than trees on poor sites. Thus, the relationships between $BHSI_{15}$ and growth intercept lengths show a progressively smaller increase in $BHSI_{15}$ with larger growth intercept lengths.

The three white spruce growth intercepts chosen to estimate site quality are based on three, four, and five internodes measured from 2.0 m. These three growth intercepts have similar coefficients using Equation 5 (Table 9); accordingly, the $BHSI_{15}$ predicted using these coefficients also are similar. Consequently, only one set of coefficients are needed to predict the $BHSI_{15}$ of white spruce from growth intercept lengths computed from either three, four, or five internodes. The coefficients computed using four internodes predict $BHSI_{15}$ values that are between those of three and five internodes. Thus, these coefficients are recommended for computing $BHSI_{15}$ using Equation 5 and growth intercept lengths computed from either three, four, or five white spruce internodes above 2.0 m.

Red Pine

The response surface showing the precision of predicting $BHSI_{20}$ with the 80 red pine growth intercepts computed from one to 10 internodes from the eight height starting heights was somewhat erratic (Figure 12). A predictable increase in precision was observed for growth intercepts up to 1.3 m. The estimate of the $BHSI_{20}$ of red pine obtained from using three, four, and five internodes from 1.5 m were the most accurate, regardless of number of internodes or starting height. The accuracy of the estimate then decreased and assumed a relatively constant value when more than five internodes were used to compute growth intercept lengths starting from 1.5 m. This suggests that early erratic height growth in these red pine study plots is confined below about 1.50 m. Starting growth intercepts at heights greater than 1.5 m resulted in a general decrease in the accuracy of the estimate. Again, this anomaly has no obvious biological foundation. The peculiar response of some red pine growth intercepts is probably due to the small number of study plots (25) used in the analysis. The effect of a few study plots is probably having a dramatic influence on the overall response.

The relationship between the $BHSI_{20}$ of red pine and the red pine growth intercept lengths shows a positive, slightly upward curvilinear trend (Figure 13). This indicates that a unit increase in growth intercept length is met with a progressively larger increase in $BHSI_{20}$. This suggests that trees on poor sites reach a maximum rate of height growth earlier than trees on good sites. Again, this unexpected relationship between $BHSI_{20}$ and red pine growth intercept lengths is probably the result of only a few study plots affecting the overall response.

Although there are no single outliers or influential points, the four study plots clustered in the upper right corner of the scatterplots of $BHSI_{20}$ versus growth intercept lengths are influential as a group (Figure 13). Collectively, these four observations have the effect of pulling the regression line up at the extreme right end. All four of these study plots are located within about 20 km of each other on deep, medium textured deltaic sands near the Kaministiquia river, near Thunder Bay. There is no reason to suspect that other trees with similar growth intercept lengths would produce different height growth patterns. However, results of other studies suggest that the relationship between $BHSI_{20}$ and the red pine growth intercept lengths would probably assume a linear to somewhat downward curvilinear pattern with further sampling. Nevertheless, this relationship accurately describes the distribution of $BHSI_{20}$ over the range of growth intercept lengths observed in these red pine study plots.

Other workers report linear relationships between site index at 50 years and various growth intercepts for red pine (Alban, 1972; Day *et al.*, 1960), Ponderosa pine (Oliver, 1972), and white pine (Beck, 1971). Alban (1979) reports a positive, slightly downward curvilinear relationship between the 50 year site index of red pine and growth intercepts starting from 2.5 m, similar to the relationship between $BHSI_{15}$ and these white spruce growth intercept lengths.

As with white spruce, the coefficients computed for predicting $BHSI_{20}$ using Equation 11 and growth intercept lengths computed using three, four, and five internodes above 1.5 m are very similar (Table 11). Thus, the coefficients for using four internodes are recommended for computing $BHSI_{20}$ with Equation 11 and growth intercept lengths computed from either three, four, or five internodes above 1.5 m.

Internode Selection Methods

The yearly variation in height growth observed in these study plots does not appear to introduce a major source of error in these growth intercepts. It is only in the period of erratic height growth below 2.0 m in these white spruce study plots and below 1.5 m in these red pine study plots where removal of the smallest internode from a series (the second internode selection method) improved the estimates of $BHSI_{15}$ and $BHSI_{20}$, respectively. After this erratic growth period, height growth increases rapidly, the yearly variation in height growth is reduced, and the modified internode selection methods then fail to improve the estimates of $BHSI_x$. The modified internode selection methods did improve the accuracy of the estimate in the period of early erratic height growth. However, these estimates were not accurate enough to be of practical use for estimating site quality.

HEIGHT GROWTH PATTERNS

White Spruce

These white spruce study plots are expressing polymorphic height growth patterns, i.e. the shape of the height growth curves varies with site quality. This is evident in Figure 14 where the formulated white spruce total height-age height growth curves are evenly spaced at index age (25 years), but are unevenly spaced when projected to 50 years of age. Polymorphic height growth patterns are still evident when the erratic height growth below breast height is removed by starting height growth curves at breast height (Figure 16). The same pattern of unevenly spaced curves after index age is shown in the formulated white spruce breast height-age height growth curves. Figures 14 and 16 also show that white spruce trees growing on good sites reach the maximum rate of height growth much sooner than white spruce trees growing on poor sites.

Ek's expanded Chapman-Richards function (Eq. 23) best described both white spruce total height-age and breast height-age height growth patterns. This is further evidence that these study plots are showing polymorphic height growth patterns. Ek's model is the only growth model used in this study that is capable of expressing polymorphic height growth. Lundgren and Dolid's model (Eq. 22) would have provided an equally good fit if the height growth patterns were similar in shape over varying levels of site index, i.e., if the height growth patterns were anamorphic in shape.

The rate of white spruce height growth portrayed in Berry's (1978) height growth curves for good sites is similar to the rates observed for good sites in these white spruce study plots (Figure 18). This suggests that the quality of these growing sites are similar. However, Berry's height growth curves for poor sites show a rapid decline in the rate of height growth after about 35 years of age. This trend is not evident in the formulated height growth curves describing the plot average total height-age height growth patterns of these white spruce study plots (Figure 18). These formulated height growth curves are based on data less than 35 years of age from seed, thus are only extrapolations beyond this age. Stiell and Berry (1973) observed that height growth clearly starts to decline at approximately 35 years of age from planting. Thus, the formulated height growth curves describing these white spruce plot average height growth patterns may overestimate actual height growth after about 40 years of age from seed, and should be interpreted with caution in this range.

Differences in total height between Berry's white spruce height growth curves and these height growth curves may be caused by a prolonged establishment period in these white spruce study plots. If Berry's white spruce height growth curves were shifted by two years, simulating two additional years in the establishment period, the total height of Berry's height growth curves for good sites would correspond closely with the observed total height growth of these white spruce study plots on good sites (Figure 23). This illustrates the significant effect of the establishment period on total height and the serious error introduced when total age is

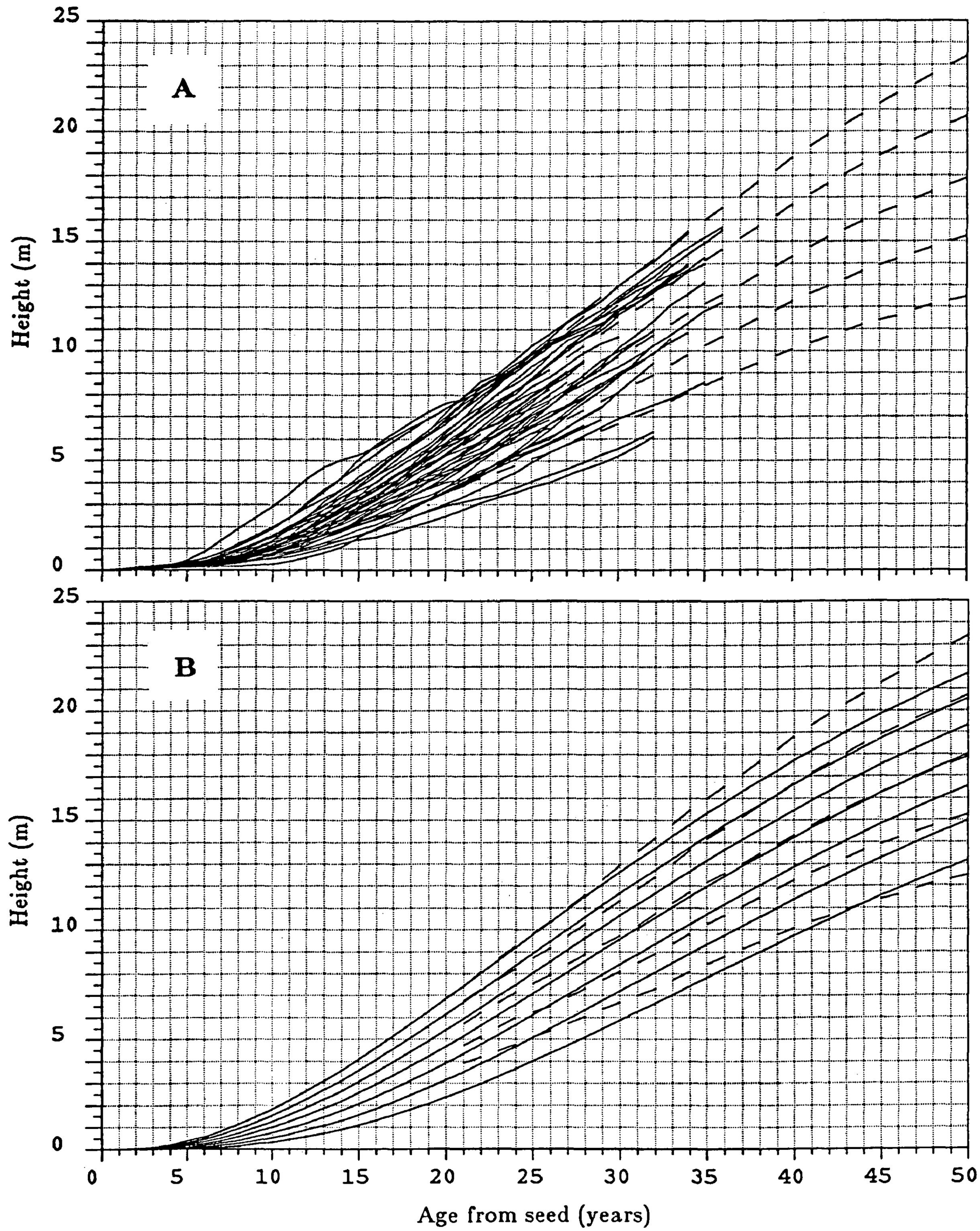

Figure 23. Berry's (1978) white spruce height growth curves (dashed lines) shifted to simulate two additional years in the establishment period. A. Berry's shifted height growth curves superimposed on white spruce plot average total height-age height growth curves. B. Berry's shifted height growth curves superimposed on formulated white spruce total height-age height growth curves.

used to estimate site quality. Consequently, site quality cannot be accurately estimated from height growth when this period of early erratic height growth is included. Figure 22 clearly shows the lack of association between white spruce height growth above and below breast height. Using breast height-age height growth curves eliminates this erratic height growth below breast height; this method provides more accurate estimates of site quality than can be obtained from using curves based on total age. Therefore, the formulated breast height-age height growth curves resulting from this study should provide more accurate estimates of site quality in white spruce plantations in the Thunder Bay area than can be obtained using Berry's (1978) white spruce total age height growth curves.

The significant differences between these formulated white spruce total height-age height growth curves and Berry's white spruce height growth curves are probably due to : 1) the differences in methods used to construct the height growth curves; 2) the significant error introduced by including early erratic height growth in total height-age height growth curves; and 3) the fact that these height growth curves are based only on data less than about 35 years of age.

The range of height observed in these white spruce study plots (Figure 17) at 15 years from breast height is very similar to the range of height observed for white spruce plantations in northern Minnesota (Harding, 1982). Harding reported the range of height as 5.32 - 10.59 m, while the height of samples trees in these white spruce study plots range from 5.28 - 10.97 m. Harding's plot selection methods were similar to the procedures used in this study, thus neither are considered to represent unbiased estimates of the respective populations. However, if the range of sites were adequately sampled in both studies, these similar height growth patterns suggest that the site quality for planted white spruce in the Thunder Bay area also is very similar to the site quality for planted white spruce in northern Minnesota.

Red Pine

These red pine study plots also show polymorphic height growth patterns (Figures 14 and 16). However, the uneven spacing between the formulated red pine height growth curves after index age is less pronounced than was shown for white spruce. This shows that polymorphic height growth is not as pronounced in these red pine study plots as in these white spruce study plots. Figures 14 and 16 show that red pine trees growing on good sites reach the maximum rate of height growth sooner than trees growing on poor sites. Ek's model also best described both red pine total height-age and red pine breast height-age height growth patterns. Again, this is further evidence that these red pine study plots are showing polymorphic height growth patterns.

The rate of height growth observed in these red pine study plots is higher than Berry's (1984) red pine height growth curves, while the total height of these red pine study plots is lower (Figure 19). This suggests that establishment periods in these red pine study plots are longer than those in the Petawawa area as shown by lower total heights. However, the higher growth rates shown in these red pine study plots suggests that these growing sites are better than those in the Petawawa area. There is no obvious reason why growing sites in the Thunder Bay area are better than those at Petawawa. Therefore, the significant differences between these formulated red pine height growth curves and Berry's red pine height growth curves are probably the same as previously discussed for white spruce. That is, the differences in the curves are probably due to: 1) differences in the methods used to construct the height growth curves; and 2) the significant error introduced by including early erratic height growth in these total height-age height growth curves.

These red pine plot average breast height-age height growth curves are very similar to the breast height-age height growth curves given by Richards *et al.* (1962) for New York (Figure 21). This suggests that the site quality and height growth patterns observed in these red pine study plots also are similar to New York. This further reinforces the hypothesis that

Planting more red pine in the Thunder Bay area would provide a more diverse supply of raw materials for the local forest products industry. The relatively high strength of red pine makes it desirable for girders, joists, studs, and trusses (Lothner and Bradley, 1984). The excellent form, low taper, and receptivity of red pine to pressure treating with preservatives also make red pine a desired species for poles, posts, pilings, and cabin logs. Red pine also is used for pulp. Several large paper companies in the upper Lake States region presently have extensive reforestation programs where red pine is the primary species being planted (Ticknor, 1985).

Furthermore, red pine may also result in higher yields per unit area than white spruce, jack pine, or black spruce. Alban (1978) found that red pine produced more volume per unit area than adjacent jack pine plantations on similar sites over a wide range of site conditions occurring throughout the northern Lake States. A more recent report by Alban (1985b) confirms his previous findings, showing that red pine produced more volume per unit area on similar sites than white spruce, jack pine, and aspen (*Populus tremuloides* Michx.). Alban further suggests that red pine yields will be dramatically higher than for black spruce on similar sites. Wilde *et al.* (1965) also showed that red pine planted on good and medium sites in Wisconsin produced more volume per unit area than jack pine on similar sites. MacArthur (1959) reported that even with higher rates of mortality, red pine still produced more volume per unit area than jack pine on similar sites. Lundgren (1982) showed that red pine managed on long rotations in the Lake States may even produce more volume per unit area than loblolly or slash pine in the southern United States. The outstanding biological productivity of red pine means more wood can be produced per unit area. This increased productivity in turn means lower costs per unit area and consequently higher financial returns.

differences between total age height growth curves are due primarily to the inclusion of the early erratic height growth below breast height. Furthermore, Alban (1972) states that the height growth patterns of red pine in the Lake States also are similar to the height growth patterns in New York. Thus, it logically follows that the height growth patterns of these red pine study plots also are similar to height growth patterns of red pine in the Lake States.

This similarity in the height growth patterns of red pine also provides a preliminary basis for the transfer of growth and yield data. If the stem form of red pine is similar between these areas, then growth and yield also may be similar. Thus, growth and yield data already available for these areas may be applicable to the Thunder Bay area. The accuracy of these growth and yield data must be monitored as growth and yield data become available from older local plantations. Growth and yield of red pine has been shown to be similar between Petawawa and the Lake States (Lundgren, 1983). Therefore, the growth and yield for red pine in these areas also may be similar to the Thunder Bay area. The very low genetic variation in red pine coupled with these results showing similar height growth patterns between local plantations and those reported elsewhere, provide a preliminary basis to justify using growth and yield data from Petawawa and the Lake States for red pine plantations in the Thunder Bay area.

These results also show that height growth observed on the best sites in the Thunder Bay area are similar to the height growth observed on the best sites in the Lake States. This suggests that red pine grows equally well in the Thunder Bay area as it does in the Lake States. Therefore, red pine should be seriously considered for planting on better sites in the Thunder Bay area that are now usually planted with black spruce (*Picea mariana* (Mill.) B.S.P.) or white spruce. Red pine should also be considered as an alternative to planting jack pine (*Pinus banksiana* Lamb.) on poor sites.

Predicting Site Index from Height and Age

The non-linear estimation technique used in NONLINWOOD (Daniel and Wood, 1980) requires preliminary estimates of the model coefficients. These estimates must be reasonably accurate otherwise the algorithm will stop at a local minima in the sum of squares response surface and will not converge on the best values. Initial estimates for using Payandeh's (1974) site index equation (Eq. 30) with these relatively young breast height-age height growth data could not be found in the literature. Consequently, I was restricted to using "educated guesses" of the initial values of these coefficients. Most of the initial estimates were rejected by the program as being unrealistic. Although several attempts to obtain realistic initial coefficients were eventually successful, the resulting final estimates did not achieve even reasonable levels of accuracy. This suggests that only a local minima in the error sum of squares was reached. Therefore, the usefulness of Payandeh's site index equation to describe $BHSI_x$ as a function of total height and age from breast height cannot be judged based on this study and should receive further attention.

The site index equation (Eq. 31) that I proposed as an alternative to Payandeh's model seemed much less sensitive to the preliminary estimates of the coefficients. As a result, fewer guesses were required to obtain initial estimates that converged on the best values. This model may have potential for accurately estimating site index, but did not accurately describe $BHSI_x$ at early ages. The distribution of the residuals was highly systematic, suggesting that transformations of height and age, or further modification to the model may result in the accurate prediction of $BHSI_x$ from total height and age from breast height data. Unfortunately, the scope of this study did not allow sufficient time to explore this problem in further detail.

Predicting $BHSI_x$ by mathematically interpolating between formulated breast height-age height growth curves is not a desirable method of estimating $BHSI_x$ because this technique involves an iterative process that cannot be expressed as a single function. However, this method is preferred to visual interpolation. The relationship between these breast height-age height growth curves for varying levels of site is linear only at index age, i.e. the height growth curves are evenly spaced at index age. However, the slight departure from linearity between adjacent curves above and below index age is small and the error introduced through linear interpolation is insignificant.

APPLICATION OF SITE QUALITY ESTIMATES

The estimates of site quality obtained from these growth intercepts and formulated breast height-age height growth curves can be used to rank white spruce and red pine plantation site quality on a relative scale. Estimates of the $BHSI_{15}$ of white spruce and the $BHSI_{20}$ of red pine can be related to other plantations in the Thunder Bay area using Table 8. This ability to rank plantation site quality on a relative scale will provide forest managers with a quantitative base that can be used for making important management decisions. Decisions to release, thin, or prune the most productive white spruce and red pine plantations can now be supported by quantitative, rather than qualitative estimates of site quality. Appendices IX and X give detailed procedures for using growth intercepts and breast height-age height growth curves for estimating site quality in white spruce and red pine plantations in the Thunder Bay area.

The $BHSI_{15}$ of white spruce and the $BHSI_{20}$ of red pine can also be used to estimate height at 50 years from seed and 50 years from planting, thus providing a link between these estimates of site quality and published yield tables. Using $BHSI_x$ to estimate heights at 50 years must be done with caution and should be used only to provide a general estimate of site index. There are two basic assumptions in this procedure: 1) $BHSI_x$ is accurately estimated; and 2) the formulated breast height-age height growth curves (used to project $BHSI_x$ to height at 50 years) accurately portray actual height growth patterns beyond the range of observed data. This procedure can provide valuable information if the user is fully aware of the effect that violations of these assumptions will have on the estimated height at 50 years and the resulting estimates of growth and yield.

The formulated white spruce breast height-age growth curves are extrapolated for about 15 to 20 years beyond the range of observed data to a breast height-age of 42 years, approximating 50 years from planting. The estimated height at 50 years from planting can be estimated from $BHSI_{15}$ using Equation 34 and the coefficients given in Table 23. This estimated height can then be used to obtain a rough estimate of yields in the Thunder Bay area using Berry's (1978) white spruce yield tables for Petawawa. Berry's white spruce height growth curves show a rapid decline in the height growth of trees on poor sites that is not shown in the extrapolation of these formulated white spruce height growth curves. Thus, extrapolated white spruce height growth on these poor sites may overestimate actual height growth at 50 years.

The formulated red pine breast height-age height growth curves are extrapolated for about 10 to 20 years beyond the range of observed data to reach a breast height-age of 42 years, approximating 50 years from planting. The estimated height at 50 years from planting and 50 years from seed can be estimated from $BHSI_{20}$ using Equation 34 and the coefficients given in Table 23. Yields for estimated heights at 50 years of age from planting can be obtained from Berry's (1984) red pine yield tables for Petawawa. Yields for estimated heights at 50 years of age from seed also can be obtained from REDPINE (Lundgren, 1985; Lundgren and Belcher, 1982), a computer stand growth and yield simulation model for the Lake States. Yields obtained from REDPINE are very similar to red pine plantation yields at Petawawa (Lundgren, 1983). The growth models used in REDPINE appear to be generally applicable to a wide geographic area, and therefore, may also provide accurate estimates of growth and yield for the Thunder Bay area. REDPINE allows the user to evaluate alternative management strategies such as various spacings and thinning regimes (Lundgren, 1981), thus provides a more flexible tool than conventional yield tables.

HEIGHT GROWTH AS A MEASURE OF SITE QUALITY

White spruce plantations have not been widely studied, thus, the variation in the height growth patterns of white spruce plantations is not clear. Consequently, the degree to which the variation in height growth of these white spruce plantations is expected to change is also not clear. However, it is reasonable to assume that most individual white spruce trees will maintain their relative position in height growth beyond a breast height-age of 15 years. Therefore, the $BHSI_{15}$ of white spruce used to represent site quality of these white spruce study plots should provide reasonably accurate estimates of site quality.

Red pine maintains a very uniform pattern of height growth in both natural stands and plantations for at least 50 years. Therefore, the error of predicting heights at 20 years of breast height should be indicative of the error of prediction in later years. Hence the $BHSI_{20}$ estimated with these red pine growth intercepts and formulated breast height-age height growth curves also should provide accurate estimates of site quality.

Height growth below breast height in these white spruce and red pine study plots is not related to site quality (Figure 22). Therefore, total height at a specific total age cannot be used to accurately estimate site quality in these white spruce and red pine plantations. Including this erratic height growth below breast height can result in enormous errors when estimating site quality in young plantations. For example, there is virtually no relationship between the number of years for sample trees to reach breast height and the $BHSI_{15}$ of these white spruce study plots. Thus, the number of years for any white spruce sample tree to reach breast height could range from four to 12 years (Table 22). Consequently, a white spruce tree measured as 3.0 m in height at 15 years from planting could have three years growth above breast height (i.e. $15 - 12 = 3$) for a $BHSI_{15}$ of 10.2 m, or could have 11 years growth above breast height (i.e. $15 - 4 = 11$) for a $BHSI_{15}$ of 4.0 m. The number of years for trees in plantations to reach breast height will directly affect the rotation length and is important for evaluating forest management treatments. However, the number of years to reach breast height is not directly related to the site quality of these white spruce and red pine plantations.

Many provenance studies show that height growth of white spruce is significantly affected by the genetic variation in the species. As a result, the effect of the genotype is confounded with site quality when height growth is used to estimate site quality. This variation results in less accurate estimates of site quality for other genotypes, or for the species, than would be obtained if less genetic variation were present in the species. In spite of this fact, the height growth of white spruce plantations in the Thunder Bay area can be used to accurately estimate the site quality for the trees presently growing on the site. The genetic variation in the height growth of white spruce does not decrease the usefulness of this study, but simply means the growth response observed on a particular site may be somewhat different if another genotype were grown on the site. Height growth is still closely related to volume growth, therefore, height growth is still a good measure of site quality. The only difference now is that estimates of white spruce site quality are applied to a specific genotype instead of the entire species.

In contrast, previously cited provenance studies and electrophoretic analyses show the genetic variation in red pine is very low to nil. Thus, the height growth of these red pine plantations will provide accurate estimates of site quality for the species. Consequently, the growth response observed on a particular site should be the same for any red pine genotype managed under similar conditions.

SCOPE OF INFERENCE

Theoretically, these growth intercepts and breast height-age height growth curves can be applied only in the study plots from which they were derived. This is a result of the purposive selection of sample units (Cochran, 1977) from a non-random portion of the target population. The target population was defined as all white spruce and red pine plantations in the Thunder Bay area. However, early height growth could only be related to later height growth by sampling white spruce and red pine plantations 20 years of age and older. As a result, the sample population constitutes only a small part of the target population. From a theoretical point of view, the following assumptions must be made if the results of this study are to be applied to the target population, i.e., if these growth intercepts and breast height-age height growth curves are to be used in other white spruce or red pine plantations in the Thunder Bay area.

In the first place, it must be assumed that unbiased estimates of height growth patterns from each stratum (site condition) in the sample population have been obtained by the purposive selection of samples. Sampling the full range of site conditions is assured with purposive sampling; however, the samples obtained will be biased. The magnitude of this unknown bias depends partially on the variation in height growth patterns within the stratum of the population and the number of samples taken from this stratum. The larger the variation and smaller the sample size, the higher the probability of a large bias. Relatively few study plots were taken in red pine plantations, but height growth patterns were very uniform with little variation. White spruce height growth patterns were more variable, but many more study plots were taken. Thus, I believe the probability of a large bias occurring in height growth patterns from the purposive selection of sample plots is not significant.

In the second place, it must be assumed that height growth patterns in plantations sampled from the sample population are similar to height growth patterns in plantations that were not sampled from the sample population. Height growth patterns of plantations that could not be located or accessed because of poor road conditions should not be different from those that were accessed and subsequently sampled. However, plantations not sampled because of poor stocking or severe competition may be different in some respect from the plantations that were sampled. Differences in soil or drainage conditions may have contributed to conditions that caused the poor stocking or severe competition that led to their subsequent exclusion from the sample. These plantations may have resulted in height growth above or below the average, but it is unlikely that the pattern of height growth would have been significantly different. The non-inclusion of these plantations should not affect these results.

Thirdly, and most importantly, it must be assumed that the height growth patterns of the plantations in the sample population are not different from the height growth patterns of the target population. The conditions contributing to the development of plantations in the sample population are probably different from those of the target population. The location of planting sites has become less selective with time. Most sites are now planted regardless of soil or site conditions. In contrast, older plantations were often located on sites where planting conditions were considered favourable and many plantations were located on abandoned agricultural fields. Older plantations often employed different hand planting methods than are used today and some were planted with machines. Planting stock is now healthier and more vigorous. Site preparation methods also have changed. Those older plantations receiving site preparation were probably treated with barrels and chains. Patch scarifiers and disc trenchers are more commonly used today. These differences may influence total height growth by affecting early height growth, but should not affect the pattern of later height growth. Thus, I believe that the breast height-age height growth patterns of these study plots are representative of the height growth patterns in all white spruce and red pine plantations in the Thunder Bay area.

RECOMMENDATIONS FOR FUTURE STUDIES

The growth intercepts and breast height-age height growth curves resulting from this study should provide accurate estimates of site quality for white spruce and red pine plantations in the Thunder Bay area. However, these results are based on relatively young plantations. The true value of these growth intercepts and breast height-age height growth curves can only be confirmed through their application in plantations that are close to rotation age (approximately 50 years of age). Therefore, I recommend that these growth intercepts and breast height-age height growth curves be recomputed using stem analysis or permanent sample plot data approximately every five years, when older plantations become available for study. The accuracy of these results can then be reassured on a regular basis.

White spruce and red pine account for approximately 30 and three per cent of the total area planted to date in the Thunder Bay District, respectively. Therefore, these white spruce growth intercepts and breast height-age height growth curves should be of significant use to local forest managers. The relatively small area planted with red pine reduces the overall usefulness of these red pine growth intercepts and breast height-age height growth curves. However, if more red pine is planted in the future, these tools will be of great use to local forest managers.

Black spruce is now the most widely planted species in the Thunder Bay District. Accordingly, methods for evaluating site quality in black spruce plantations are greatly needed. The annual branch nodes of black spruce are easily recognized. Thus, both growth intercepts and breast height-age height growth curves can be developed for black spruce following the same procedures used in this study. Accordingly, I recommend that growth intercepts and breast height-age height growth curves be developed for black spruce in the next five to 10 years when enough older black spruce plantations are available for study.

Jack pine is also commonly planted in the Thunder Bay District. Identifying annual nodes of jack pine is difficult because of its multinodal branching. Growth intercepts have been used successfully in some multinodal southern pines, but have not yet been used with jack pine. The utility and accuracy of the growth intercept method justifies studying the applicability of this technique to jack pine. Breast height-age height growth curves also can be used to estimate site quality in jack pine plantations. Thus, I recommend that breast height-age height growth curves be developed in the next five to 10 years, when enough older jack pine plantations are available for study.

The data used in this study could only be collected through the destructive sampling of trees. This procedure not only destroys potential crop trees, but also is time consuming and expensive. The establishment of adequately selected permanent sample plots would provide the needed data for further growth and yield studies, thereby avoiding the need for further destructive sampling. Permanent sample plots should be immediately established in plantations of all species in the Thunder Bay area and remeasured at least every five year. The initial expenditure of establishing these plots is high, however, the real benefits are realized from the wealth of information derived over a long time period. Intensive forest management in the Thunder Bay area must be based on accurate, quantitative growth and yield data from local plantations. The only cost effective method of collecting this data is through permanent sample plots.

This study was concerned only with the height growth of trees in white spruce and red pine plantations. Accordingly, sampled trees were selected solely for the purpose of reconstructing the height growth patterns of these species. As a result, these data can be used only for studying the height growth of these species. If destructive sampling must be used in future studies, I strongly recommend that a multi-purpose approach be used in the selection of sample trees in site quality research. Specifically, I recommend that when dominant trees are selected to represent the height growth potential of a plot, they also should represent the volume growth of the plot. Site quality research demands certain criteria be met in the selection of study plots and sample trees. However, these two objectives can be simultaneously achieved with minimal additional effort and expense, and will provide valuable data to accompany the site data or for use in other studies.

White spruce and red pine plantations are the oldest in the Thunder Bay area, however, these plantations are still relatively young. As a result, it was logistically possible to consider all plantations 20 years of age and older for sampling. The increasing number of plantations entering these older age classes each year will soon eliminate the need for sampling all existing plantations. In the future, statistically valid sampling techniques can be used in the selection of sample plots. This is rarely done in mensurational and site studies in the natural forest because it is virtually impossible to enumerate and access the target population. However, computer technology has made the enumeration of the target population a relatively simple task.

The OMNR in Thunder Bay has recently established a computer data base containing information on all plantations in the District. Plantations are now easily selected by species, planting date, stock type, seed source, site preparation method, and so on. With the recent advances in the development and application of Geographic Information Systems (GIS), these data can be combined with virtually any layer of information allowing researchers and practitioners to sort, select, and stratify plantations (and other populations) on many different criteria. For example, randomly selecting plantations stratified by species, age class, and origin of seed used for planting stock is now easily achieved. This recently applied technology will facilitate the application of statistically valid sampling designs in future growth and yield studies.

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APPENDICES

APPENDIX I

AGE, STOCK TYPE, SEED ZONE, AND LOCATION BY SITE REGION OF WHITE SPRUCE AND RED PINE STUDY PLOTS

A. Red pine study plots.

Plot Number	Plantation Age	Stock Type	Age from Seed	Seed Zone[2]	Site Region[3]	Soil Type
7[1]	37	2+2	41	?	4w	Medium sand
8[1]	28	2+2	32	?	4w	Medium sand
9[1]	34	2+2	38	?	4w	Medium sand
17	28	2+2	32	4	4w	Loamy sand
18	28	2+2	32	4	4w	Loamy sand
19[1]	28	2+2	32	4	4w	Loamy sand
22[1]	28	2+2	32	4	4w	Sandy loam
23	28	2+2	32	4	4w	Silty sand
28	20	2+2	24	4[3]	4w	Loamy sand
31	22	2+2	26	6[3]	4w	Medium sand
40	23	2+2	27	3,4	4w	Loamy sand
42	23	2+2	27	3,4	4w	Loamy sand
45	30	2+2	34	6	4w	Loamy sand
46	30	2+2	34	6	4w	Loamy sand
50	30	2+2	34	6	4w	Loamy sand
58	33	2+2	37	3,6	3w	Fine sand
59	33	2+2	37	3,6	3w	Fine sand
60	33	2+2	37	3,6	3w	Fine sand
61	33	2+2	37	3,6	3w	Fine sand
62	33	2+2	37	3,6	3w	Medium sand
63	32	2+2	36	?	3w	Fine sand
64	26	2+2	30	5	3w	Sandy till
71[1]	31	2+2	35	4	4w	Fine sand
72[1]	31	2+2	35	4	4w	Medium sand
73[1]	35	2+2	39	4	4w	Medium sand

[1] planted on abandoned agricultural field

[2] based on Hills (1952) Site Regions (Figure 2)

[3] based on Hills (1960) Site Regions (Figure 3)

B. White spruce study plots (see A. for explanation of superscripts).

Plot Number	Plantation Age	Stock Type	Age from Seed	Seed Zone[3]	Site Region[3]	Soil Type
1	29	2+2	33	?	4w	Clay loam
2	29	2+2	33	?	4w	Clay loam
3	30	2+2	34	?	4w	Clay loam
4	31	2+2	35	?	4w	Sandy loam
5	31	2+2	35	?	4w	Sandy till
6	31	2+2	35	?	4w	Sandy till
11	25	2+2	29	4	4w	Silty clay
12	23	2+1	26	4	4w	Clay loam
13	23	2+1	26	4	4w	Sandy loam
14	22	2+1	25	5	4w	Sandy loam
15	28	2+2	32	4[2]	4w	Sandy loam
16	28	2+2	32	4[2]	4w	Sandy loam
20[1]	28	2+2	32	4[2]	4w	Medium sand
21[1]	28	2+2	32	4[2]	4w	Loamy sand
24	28	2+2	32	4[2]	4w	Sandy loam
25	28	2+2	32	4[2]	4w	Silty sand
26	20	2+2	24	4	4w	Loamy sand
27	20	2+2	24	4	4w	Sandy till
29[1]	24	2+2	28	3	4w	Silty sand
30	26	2+2	30	?	4w	Medium sand
32	21	2+2	25	?	4w	Fine sand
33	20	2+2	24	5	4w	Medium sand
34	20	2+2	24	5	4w	Silty sand
35	20	2+2	24	5	4w	Coarse sand
36	32	2+2	36	?	3w	Fine sand
37	32	2+2	36	?	3w	Fine sand
38	32	2+2	36	?	4w	Fine sand
39	26	2+2	30	4	4w	Medium sand
41	23	2+2	27	3	4w	Medium sand
43[1]	21	2+2	25	4	4w	Sandy clay
44[1]	30	2+2	34	4[2]	4w	Clay loam
47	24	2+2	28	3	4w	Coarse sand
48	19	2+2	23	4	4w	Sandy silt
49	19	2+2	23	4	4w	Sandy loam
51[1]	30	2+2	34	4[2]	4w	Loamy sand
52[1]	30	2+2	34	4[2]	4w	Sandy Loam
53	30	2+2	24	5[2]	3w	Medium sand
54	19	2+2	23	7	4w	Organic
55	20	2+2	24	5	3w	Coarse sand
65	26	2+2	30	5	3w	Loamy sand
66	25	2+2	29	4,6	3w	Fine sand
67	25	2+2	29	4,6	3w	Loamy till
68	22	2+2	26	3	3w	Loamy till
69[1]	30	2+2	34	4[2]	4w	Clay loam
70[1]	31	2+2	35	4[2]	4w	Fine sand
74	21	2+2	25	?	4w	Medium sand

APPENDIX II

SUMMARY OF HEIGHT STATISTICS FOR WHITE SPRUCE AND RED PINE STUDY PLOTS

A. Red Pine study plots.

Plot No.	$BHSI_{20}$	Age from Seed	Total Tree Height				Years to Breast Height (from seed)		
			Tree 1	Tree 2	Tree 3	Avg	Tree 1	Tree 2	Tree 3
7	13.90	41	20.00	19.45	19.55	19.67	9	10	10
8	13.42	32	14.60	14.85	15.10	14.85	9	9	9
9	11.13	38	14.90	16.20	15.17	15.42	8	9	10
17	9.52	33	9.39	10.31	9.92	9.87	12	13	12
18	11.63	32	12.05	12.00	12.05	12.03	11	12	11
19	12.25	32	12.00	13.50	12.45	12.65	12	10	12
22	11.60	32	12.70	12.35	12.15	12.40	11	11	10
23	11.35	33	12.01	11.79	11.64	11.81	12	12	13
28	9.55	31	10.16	10.32	9.00	9.83	10	10	11
31	10.76	30	9.92	11.09	11.26	10.76	10	10	10
40	12.18	30	12.23	12.05	12.27	12.18	10	10	10
42	11.80	31	12.20	12.37	11.82	12.13	10	10	11
45	11.47	34	12.80	12.45	12.45	12.57	11	12	11
46	10.70	34	11.85	12.00	11.90	11.92	12	11	12
50	9.30	34	10.40	11.05	10.73	10.73	11	11	11
58	10.77	37	14.25	13.20	13.00	13.48	10	10	12
59	10.00	37	11.20	11.60	11.20	11.33	14	13	13
60	10.22	37	12.10	11.55	11.50	11.72	14	14	12
61	11.21	37	12.75	13.80	14.60	13.72	12	12	11
62	9.93	37	11.80	11.00	11.40	11.40	14	14	13
63	9.78	36	10.85	10.20	10.10	10.38	14	15	15
64	11.67	30	12.05	11.80	11.70	11.85	9	10	10
71	12.17	35	13.30	14.10	13.30	13.57	12	13	13
72	13.62	35	15.60	15.30	15.80	15.57	11	14	9
73	13.80	39	17.30	17.20	17.30	17.27	12	12	11

B. White spruce study plots.

Plot No.	$BHSI_{15}$	Age from Seed	Total Tree Height				Years to Breast Height (from seed)		
			Tree 1	Tree 2	Tree 3	Avg	Tree 1	Tree 2	Tree 3
1	7.17	33	10.25	10.20	11.30	10.58	13	12	11
2	8.75	33	13.50	14.70	13.90	14.03	8	7	8
3	7.33	34	10.75	12.00	9.80	10.85	11	11	12
4	9.50	35	13.70	13.25	14.90	13.95	9	10	9
5	9.33	35	14.70	15.40	12.70	14.27	8	9	10
6	6.48	35	7.60	9.75	8.35	8.57	14	13	15
11	7.37	29	9.20	8.25	8.20	8.55	11	12	12
12	10.05	28	10.30	10.40	11.50	10.73	11	11	13
13	9.48	26	10.45	9.85	10.95	10.42	11	9	8
14	7.57	28	7.17	7.71	8.75	7.88	13	13	11
15	8.52	32	11.55	11.00	10.25	10.93	12	12	13
16	5.28	32	6.70	6.85	5.40	6.32	14	14	14
20	6.80	32	9.60	9.40	9.35	9.45	12	13	13
21	7.80	32	10.40	10.35	10.15	10.30	14	13	13
24	8.70	32	10.10	11.00	11.75	10.95	13	13	13
25	5.37	32	6.40	5.70	6.20	6.10	14	17	15
26	5.60	27	6.08	5.83	6.50	6.14	10	12	9
27	6.20	29	7.33	7.12	6.21	6.89	10	14	12
29	9.17	28	9.30	9.15	10.15	9.53	13	13	11
30	8.65	30	10.25	10.60	11.10	10.65	10	11	10
32	8.07	26	8.46	8.42	8.60	8.49	9	11	9
33	6.48	26	5.95	6.32	8.37	6.88	11	9	10
34	7.85	26	8.12	8.47	8.17	8.25	11	9	10
35	6.98	25	7.22	7.56	6.67	7.15	9	10	10
36	8.32	36	12.90	12.40	11.35	12.22	12	12	14
37	9.45	36	15.70	15.30	15.50	15.50	11	12	10
38	10.42	36	15.50	16.70	14.80	15.67	11	11	12
39	9.50	30	11.80	10.80	12.20	11.60	11	11	11
41	7.73	27	8.80	7.90	7.90	8.20	12	11	11
43	8.89	27	8.89	9.63	9.59	9.37	12	11	10
44	10.03	34	13.45	14.00	14.20	13.88	11	12	11
47	8.50	28	9.30	9.00	10.40	9.57	13	9	10
48	6.73	27	6.11	8.27	6.92	7.10	10	11	12
49	8.55	27	9.27	9.32	8.72	9.10	10	11	12
51	10.97	34	16.00	15.05	15.05	15.37	10	12	13
52	10.58	34	14.70	12.70	14.50	13.97	13	14	11
53	8.58	27	8.63	8.54	8.57	8.58	12	12	12
54	7.49	26	6.79	7.77	8.41	7.66	11	11	10
55	6.38	28	6.41	6.58	6.93	6.64	13	12	12
65	10.15	30	12.55	12.35	11.45	12.12	11	9	11
66	6.71	29	7.00	7.20	8.20	7.47	13	11	13
67	10.42	29	12.75	12.47	12.15	12.46	10	11	10
68	8.33	26	9.25	8.97	9.25	9.16	9	10	9
69	10.33	34	12.70	13.75	15.10	13.85	12	11	10
70	10.15	35	12.85	13.50	13.05	13.13	15	15	15
74	9.40	26	9.21	9.34	10.80	9.78	11	11	9

APPENDIX III

STANDARD ERROR AND NUMBER OF YEARS REQUIRED TO EXTRAPOLATE SAMPLE TREES IN WHITE SPRUCE AND RED PINE STUDY PLOTS TO A BREAST HEIGHT-AGE OF 15 AND 20 YEARS, RESPECTIVELY

A. White spruce study plots.

Plot Number	Standard Error (m)			Years Extrapolated
	Tree 1	Tree 2	Tree 3	
12	0.150	0.146	0.174	2
14	0.156	0.141	0.105	3
26	0.110	0.100	0.050	3
27	0.132	0.099	0.115	5
32	0.266	0.101	0.176	1
33	0.074	0.189	0.190	2
34	0.181	0.190	0.156	2
35	0.162	0.207	0.121	1
43	0.120	0.104	0.178	2
48	0.172	0.084	0.144	4
49	0.066	0.110	0.076	4
53	0.104	0.102	0.135	3
54	0.094	0.058	0.114	3
55	0.069	0.084	0.069	4
74	0.174	0.190	0.140	1

B. Red pine study plots.

Plot Number	Standard Error (m)			Years Extrapolated
	Tree 1	Tree 2	Tree 3	
17	0.174	0.126	0.185	1
23	0.262	0.122	0.130	1
28	0.089	0.154	0.107	7
31	0.073	0.066	0.075	4
40	0.107	0.097	0.148	3
42	0.197	0.106	0.105	4

APPENDIX IV

WHITE SPRUCE AND RED PINE COEFFICIENTS OF DETERMINATION USING EQUATION 5 AND GROWTH INTERCEPTS FROM THE FOUR INTERNODE SELECTION METHODS

A. White spruce - Internode selection method 1 (all internodes included in a series).

Number of Internodes	Starting Height (m)							
	0.0	0.5	1.0	1.3	1.5	2.0	2.5	3.0
1	0.000	0.078	0.506	0.599	0.553	0.676	0.638	0.719
2	0.000	0.162	0.599	0.683	0.637	0.764	0.757	0.743
3	0.000	0.286	0.705	0.746	0.710	0.829	0.802	0.777
4	0.000	0.416	0.733	0.790	0.794	0.853	0.837	0.787
5	0.000	0.521	0.792	0.836	0.848	0.890	0.876	0.807
6	0.000	0.590	0.829	0.859	0.869	0.917	0.885	0.846
7	0.000	0.657	0.853	0.899	0.910	0.928	0.906	0.899

B. White spruce - Internode selection method 2 (smallest internode removed from a series).

Number of Internodes	Starting Height (m)							
	0.0	0.5	1.0	1.3	1.5	2.0	2.5	3.0
1	NA	NA	NA	NA	NA	NA	NA	NA
2	0.000	0.243	0.606	0.655	0.644	0.741	0.757	0.704
3	0.000	0.364	0.719	0.731	0.721	0.831	0.793	0.731
4	0.000	0.469	0.745	0.801	0.801	0.850	0.826	0.778
5	0.000	0.555	0.806	0.835	0.851	0.893	0.864	0.797
6	0.000	0.628	0.838	0.858	0.873	0.912	0.884	0.842
7	0.000	0.698	0.855	0.891	0.910	0.923	0.901	0.901

NA = not applicable

C. White spruce - Internode selection method 3 (largest internode removed from a series).

Number of Internodes	Starting Height (m)							
	0.0	0.5	1.0	1.3	1.5	2.0	2.5	3.0
1	NA	NA	NA	NA	NA	NA	NA	NA
2	0.000	0.076	0.556	0.670	0.594	0.685	0.649	0.721
3	0.000	0.170	0.682	0.717	0.696	0.766	0.768	0.767
4	0.000	0.312	0.721	0.778	0.759	0.842	0.826	0.766
5	0.000	0.454	0.771	0.835	0.819	0.878	0.859	0.783
6	0.000	0.557	0.815	0.851	0.866	0.904	0.877	0.816
7	0.000	0.624	0.845	0.893	0.909	0.920	0.894	0.878

D. White spruce - Internode selection method 4 (both the smallest and largest internodes removed from a series).

Number of Internodes	Starting Height (m)							
	0.0	0.5	1.0	1.3	1.5	2.0	2.5	3.0
1	NA	NA	NA	NA	NA	NA	NA	NA
2	NA	NA	NA	NA	NA	NA	NA	NA
3	0.000	0.244	0.721	0.717	0.719	0.748	0.783	0.718
4	0.000	0.388	0.760	0.781	0.777	0.847	0.820	0.755
5	0.000	0.510	0.790	0.829	0.824	0.888	0.852	0.777
6	0.000	0.590	0.826	0.846	0.869	0.906	0.873	0.821
7	0.000	0.659	0.845	0.890	0.904	0.921	0.899	0.877

E. Red pine - Internode selection method 1 (all internodes included in a series).

Number of Internodes	Starting Height (m)							
	0.0	0.5	1.0	1.3	1.5	2.0	2.5	3.0
1	0.000	0.199	0.334	0.565	0.745	0.744	0.654	0.637
2	0.000	0.267	0.554	0.785	0.865	0.756	0.834	0.646
3	0.000	0.347	0.731	0.851	0.905	0.858	0.776	0.608
4	0.000	0.459	0.786	0.866	0.920	0.876	0.725	0.682
5	0.000	0.535	0.841	0.891	0.944	0.830	0.756	0.732
6	0.000	0.657	0.841	0.887	0.908	0.844	0.764	0.761
7	0.000	0.723	0.841	0.885	0.898	0.845	0.802	0.800
8	0.000	0.755	0.844	0.872	0.905	0.854	0.815	0.836
9	0.000	0.758	0.860	0.886	0.909	0.869	0.870	0.873
10	0.000	0.759	0.866	0.888	0.907	0.913	0.905	0.906

F. Red pine - Internode selection method 2 (smallest internode removed from a series).

Number of Internodes	Starting Height (m)							
	0.0	0.5	1.0	1.3	1.5	2.0	2.5	3.0
1	NA	NA	NA	NA	NA	NA	NA	NA
2	0.000	0.324	0.558	0.824	0.833	0.690	0.666	0.590
3	0.000	0.407	0.749	0.852	0.871	0.820	0.702	0.659
4	0.000	0.509	0.801	0.874	0.913	0.826	0.725	0.721
5	0.000	0.579	0.848	0.892	0.925	0.805	0.732	0.745
6	0.000	0.713	0.856	0.880	0.903	0.813	0.740	0.773
7	0.000	0.758	0.842	0.871	0.878	0.833	0.787	0.798
8	0.000	0.777	0.834	0.870	0.889	0.844	0.821	0.842
9	0.000	0.796	0.860	0.882	0.884	0.873	0.881	0.880
10	0.000	0.779	0.876	0.882	0.904	0.913	0.913	0.910

G. Red pine - Internode selection method 3 (largest internode removed from a series).

Number of Internodes	Starting Height (m)							
	0.0	0.5	1.0	1.3	1.5	2.0	2.5	3.0
1	NA	NA	NA	NA	NA	NA	NA	NA
2	0.000	0.199	0.493	0.682	0.790	0.724	0.844	0.597
3	0.000	0.300	0.685	0.803	0.859	0.842	0.745	0.571
4	0.000	0.375	0.732	0.833	0.899	0.860	0.705	0.623
5	0.000	0.509	0.783	0.875	0.927	0.825	0.715	0.707
6	0.000	0.574	0.812	0.873	0.901	0.821	0.754	0.755
7	0.000	0.663	0.812	0.867	0.883	0.841	0.794	0.787
8	0.000	0.693	0.828	0.866	0.897	0.859	0.802	0.812
9	0.000	0.731	0.842	0.887	0.894	0.860	0.859	0.865
10	0.000	0.724	0.871	0.883	0.906	0.900	0.893	0.896

H. Red pine - Internode selection method 4 (both the smallest and largest internodes removed from a series).

Number of Internodes	Starting Height (m)							
	0.0	0.5	1.0	1.3	1.5	2.0	2.5	3.0
1	NA	NA	NA	NA	NA	NA	NA	NA
2	NA	NA	NA	NA	NA	NA	NA	NA
3	0.000	0.374	0.736	0.791	0.837	0.800	0.622	0.624
4	0.000	0.456	0.740	0.839	0.903	0.812	0.677	0.656
5	0.000	0.548	0.792	0.861	0.908	0.806	0.695	0.736
6	0.000	0.637	0.815	0.855	0.891	0.804	0.718	0.754
7	0.000	0.717	0.826	0.864	0.873	0.817	0.791	0.781
8	0.000	0.739	0.828	0.856	0.886	0.845	0.810	0.831
9	0.000	0.771	0.846	0.873	0.881	0.872	0.855	0.870
10	0.000	0.756	0.867	0.877	0.903	0.904	0.901	0.888

APPENDIX V

COMPUTATION OF 95 % CONFIDENCE INTERVALS FOR THE CHOSEN WHITE SPRUCE AND RED PINE GROWTH INTERCEPTS

$$CI(Y) = Y \pm t_{(0.025,(n-p-1))}\ s\ \left[\mathbf{X'}_0\,(\mathbf{X'X})^{-1}\,\mathbf{X}_0\right]^{1/2}$$

where: Y = predicted value of BHSI_x

s = standard error of the estimate

$\mathbf{X'}_0 = 1 \times (\mathrm{p}+1)$ vector $[1, X_1, X_2, \ldots, X_p]$

$\mathbf{X} = \mathrm{n} \times (\mathrm{p}+1)$ matrix of X values

n = number of observations (study plots)

p = number of independent variables in the regression equation

Species and Number of Internodes	n	p	$t_{(0.025,(n-p-1))}$	s	min CI(±)	max CI(±)
White Spruce						
3	46	2	2.017	0.63588	0.2719	0.6308
4	46	2	2.017	0.58927	0.2635	0.5903
5	46	2	2.017	0.51026	0.1472	0.3614
Red Pine						
3	25	1	2.069	0.43460	0.1808	0.3933
4	25	1	2.069	0.39286	0.1634	0.3893
5	25	1	2.069	0.32665	0.1357	0.3135

APPENDIX VI

RED PINE COEFFICIENTS OF DETERMINATION USING EQUATION 11 AND GROWTH INTERCEPTS BASED ON THE FIRST INTERNODE SELECTION METHOD

Number of Internodes	Starting Height (m)							
	0.0	0.5	1.0	1.3	1.5	2.0	2.5	3.0
1	0.000	0.199	0.333	0.557	0.731	0.744	0.652	0.624
2	0.000	0.267	0.530	0.765	0.857	0.756	0.824	0.643
3	0.000	0.346	0.702	0.840	0.902	0.857	0.776	0.605
4	0.000	0.453	0.771	0.866	0.920	0.864	0.725	0.665
5	0.000	0.531	0.833	0.890	0.944	0.828	0.752	0.698
6	0.000	0.655	0.833	0.887	0.908	0.844	0.756	0.721
7	0.000	0.720	0.840	0.885	0.898	0.845	0.787	0.783
8	0.000	0.752	0.843	0.872	0.905	0.854	0.815	0.836
9	0.000	0.757	0.860	0.886	0.909	0.869	0.870	0.873
10	0.000	0.758	0.866	0.888	0.907	0.913	0.905	0.906

APPENDIX VII

ERROR OF PREDICTING $BHSI_X$ FOR WHITE SPRUCE AND RED PINE STUDY PLOTS FROM GROWTH INTERCEPTS AND BREAST HEIGHT-AGE HEIGHT GROWTH CURVES

A. Red Pine Study Plots

Plot	$BHSI_{20}$	GI3	HGC	GI4	HGC	GI5	HGC
7	13.90	-0.40	0.06	0.21	0.28	-0.11	-0.14
8	13.42	0.39	0.09	0.15	-0.04	0.05	-0.24
9	11.13	0.46	1.60	0.40	1.33	0.58	1.24
17	9.52	0.41	1.60	0.13	0.91	0.37	1.09
18	11.63	0.20	0.27	0.02	0.12	0.30	0.20
19	12.25	0.20	0.51	0.04	0.33	0.18	0.26
22	11.60	-0.55	0.46	-0.41	0.37	-0.35	0.23
23	11.35	-0.07	0.18	-0.10	0.09	0.16	0.19
28	9.55	-0.04	0.71	-0.09	0.41	-0.09	0.32
31	10.76	-0.46	-0.11	-0.64	-0.41	-0.42	-0.26
40	12.18	0.44	0.46	0.17	0.28	0.14	0.10
42	11.80	0.21	0.74	0.11	0.56	-0.03	0.30
45	11.47	-0.19	0.95	-0.16	0.74	-0.16	0.52
46	10.70	0.58	1.72	0.55	1.46	0.06	0.82
50	9.30	0.72	0.77	0.74	0.72	0.43	0.36
58	10.77	-0.07	-0.12	-0.01	-0.10	0.15	0.00
59	10.00	0.17	0.06	0.26	0.11	0.05	-0.11
60	10.22	-0.17	0.13	-0.01	0.19	0.07	0.21
61	11.21	0.14	0.15	-0.08	-0.04	-0.29	-0.29
62	9.93	-0.57	-0.77	-0.40	-0.67	-0.38	-0.61
63	9.78	-0.02	0.11	0.23	0.26	0.08	0.09
64	11.67	0.69	0.98	0.49	0.79	0.26	0.46
71	12.17	-0.73	-0.09	-0.69	-0.19	-0.66	-0.33
72	13.62	-0.61	-0.25	-0.78	-0.45	-0.71	-0.62
73	13.80	-0.50	-0.49	-0.16	-0.33	0.32	-0.22

GI = growth intercept
HGC = breast height-age height growth curve (Figure 16)

B. White spruce Study Plots.

Plot	$BHSI_{15}$	GI3	HGC	GI4	HGC	GI5	HGC
1	7.17	-0.11	-0.64	0.16	-0.57	0.30	-0.53
2	8.75	1.09	2.27	1.08	2.10	0.95	1.74
3	7.33	0.53	0.99	0.43	0.79	0.07	0.44
4	9.50	0.38	1.29	0.26	1.06	0.26	0.88
5	9.33	0.15	0.76	0.57	1.08	0.74	1.17
6	6.48	-0.23	-0.06	-0.00	-0.09	0.10	-0.10
11	7.37	-0.17	0.77	-0.26	0.48	-0.25	0.31
12	10.05	-1.25	-0.73	-1.14	-0.78	-0.72	-0.61
13	9.48	-0.56	0.20	-0.67	-0.03	-0.56	-0.13
14	7.57	-0.28	1.00	-0.39	0.67	-0.37	0.48
15	8.52	0.31	1.00	0.48	0.98	0.94	1.22
16	5.28	0.71	1.14	0.30	0.81	-0.30	0.48
20	6.80	-0.74	0.13	-0.91	-0.17	-0.23	0.05
21	7.80	-0.07	-0.52	-0.23	-0.65	-0.30	-0.75
24	8.70	-1.05	-0.41	-0.92	-0.51	-0.64	-0.49
25	5.37	0.59	0.77	0.37	0.55	0.30	0.48
26	5.60	1.35	0.88	0.92	0.63	0.83	0.57
27	6.20	0.53	0.30	0.68	0.29	0.31	0.08
29	9.17	-0.60	-0.88	0.14	-0.43	0.16	-0.47
30	8.65	0.40	-0.04	0.26	-0.12	0.27	-0.18
32	8.07	-0.48	-0.61	-0.25	-0.56	-0.34	-0.69
33	6.48	0.12	1.16	0.27	0.98	0.13	0.75
34	7.85	-0.20	0.96	-0.73	0.41	-0.56	0.28
35	6.98	0.27	0.98	0.08	0.69	0.34	0.69
36	8.32	-0.55	-0.07	-0.43	-0.15	0.04	0.01
37	9.45	0.17	-0.94	0.24	-0.76	0.28	-0.72
38	10.42	-0.08	0.95	-0.06	0.87	-0.09	0.73
39	9.50	-0.30	-0.39	-0.04	-0.19	-0.12	-0.36
41	7.73	1.03	0.29	0.76	0.15	0.27	-0.18
43	8.89	-0.06	0.14	-0.17	-0.01	-0.42	-0.32
44	10.03	-0.42	-0.38	-0.38	-0.35	-0.31	-0.41
47	8.50	1.16	0.94	1.29	1.09	1.19	0.93
48	6.73	-0.92	0.23	-0.57	0.13	-0.51	0.03
49	8.55	0.21	-0.64	0.49	-0.41	0.60	-0.36
51	10.97	-1.17	-1.10	-1.11	-1.04	-0.95	-0.94
52	10.58	-0.74	0.12	-0.76	0.00	-0.79	-0.22
53	8.58	0.44	0.26	-0.06	-0.10	-0.07	-0.22
54	7.49	0.71	0.11	0.71	0.09	0.66	0.01
55	6.38	-0.06	0.23	0.11	0.16	0.05	0.07
65	10.15	-0.11	0.23	-0.08	0.25	-0.13	0.09
66	6.71	0.23	0.30	0.63	0.38	0.26	0.13
67	10.42	-0.19	0.55	-0.32	0.33	-0.41	0.08
68	8.33	0.37	0.20	-0.08	-0.13	-0.09	-0.24
69	10.33	0.00	0.31	-0.12	0.13	-0.10	0.09
70	10.15	-1.07	-0.86	-0.93	-0.81	-0.72	-0.77
74	9.40	0.48	0.43	0.18	0.17	-0.01	-0.09

APPENDIX VIII

BASIC PROGRAMS TO COMPUTE $BHSI_X$ FOR WHITE SPRUCE AND RED PINE PLANTATIONS FROM HEIGHT AND AGE OBSERVATIONS WITH HAND HELD CALCULATORS

A. White Spruce

```
10    REM CALCULATES WHITE SPRUCE BHSI15
20    DIM PREDHT(10)
30    B1 = 11.9403
40    B2 = 0.412608
50    B3 = -0.0276888
60    B4 = 4.0323
70    B5 = -0.526281
80    FOR J = 1 TO 25
90    PRINT "WH. SPRUCE BHSI"
100   PRINT "*=OUT OF RANGE"
110   INPUT "ENTER HEIGHT"; HT
120   INPUT "ENTER AGE"; AGE
130   FOR I = 1 TO 8
140   A = B1*(I+7)^B2
150   C = (1-EXP(B38AGE))
160   D = B4*(I+7)^B5
170   PREDHT(I) = 1.46+(A*C^D)
180   UI = I
190   IF HT <= PREDHT(I) THEN 210
200   NEXT I
210   DEFF = PREDHT(I)-PREDHT(UI-1)
220   OVER = HT-PREDHT(UI-I)
230   SI = ((UI-1)+(OVER/DEFF))
240   IF SI < 8.0 OR SI > 15.0 PRINT "BHSI = "; SI;"*"
250   IF SI >= 8.0 AND SI <= 15.0 PRINT "BHSI = "; SI
260   INPUT "DO AGAIN Y/N? "; A$
270   IF A$ = "N" THEN 290
280   NEXT J
290   END
```

B. Red Pine

```
10   REM CALCULATES RED PINE BHSI20
20   DIM PREDHT(10)
30   B1 = 7.62328
40   B2 = 0.552179
50   B3 = -0.0287362
60   B4 = 5.06122
70   B5 = -0.558397
80   FOR J = 1 TO 25
90   PRINT "RED PINE BHSI"
100  PRINT "*=OUT OF RANGE"
110  INPUT "ENTER HEIGHT"; HT
120  INPUT "ENTER AGE"; AGE
130  FOR I = 1 TO 8
140  A = B1*(I+7)^B2
150  C = (1-EXP(B38AGE))
160  D = B4*(I+7)^B5
170  PREDHT(I) = 1.46+(A*C^D)
180  UI = I
190  IF HT <= PREDHT(I) THEN 210
200  NEXT I
210  DEFF = PREDHT(I)-PREDHT(UI-1)
220  OVER = HT-PREDHT(UI-I)
230  SI = ((UI-1)+(OVER/DEFF))
240  IF SI < 8.0 OR SI > 15.0 PRINT "BHSI = "; SI;"*"
250  IF SI >= 8.0 AND SI <= 15.0 PRINT "BHSI = "; SI
260  INPUT "DO AGAIN Y/N? "; A$
270  IF A$ = "N" THEN 290
280  NEXT J
290  END
```

APPENDIX IX

FIELD ESTIMATION OF SITE QUALITY FOR WHITE SPRUCE PLANTATIONS IN THE THUNDER BAY AREA

Introduction

Site quality for white spruce in the Thunder Bay area can be estimated using the growth intercepts and breast height-age height growth curves given in this Appendix. To achieve accurate estimates of site quality, plantations should be at least three years older than the year in which a height of 2.0 m was reached, or approximately six to seven m in total height. Estimates of site quality from several suitable sample trees are averaged to represent a given area. This average is then compared to the range of site quality observed in the Thunder Bay area to obtain a relative ranking of good, medium, or poor site quality. Estimates of average site quality also can be used obtain rough estimates of the yield of the plantation by estimating height at 50 years of age, and using this height with yield tables for planted white spruce at Petawawa (Berry, 1978).

Selection of Sample Trees

1) Select five to 10 dominant, uninjured, free-to-grow white spruce trees from the area for which site quality is to be estimated. Five sample trees should provide accurate estimates of average height growth in very homogeneous conditions, but up to 10 trees may be required where height growth is variable. Some plantations cover large areas having different soil and site conditions. Estimates of site quality for such plantations should be obtained from five to 10 sample trees selected from each of several areas throughout the plantation.

2) Identify the first annual node occurring above a height of 2.0 m. If between three and five internodes occur above the 2.0 m height, estimate the height of the sample tree at a breast height-age of 15 years ($BHSI_{15}$) using the procedure detailed below for growth intercepts. If more than five internodes occur above the 2.0 m height, estimate $BHSI_{15}$ using the procedure detailed below for breast height-age height growth curves.

White Spruce Growth Intercepts

1) Determine the total length of the first three, four, or five internodes occurring above 2.0 m (use the most internodes available). This total length can be determined using a graduated telescopic range pole to measure the heights of the designated internodes. Alternatively, the

total length of the designated internodes can be measured by marking the distance between internodes with a willow or alder stick.

2) Divide the total length of the designated internodes by the number of nodes used in the growth intercept (either three, four, or five) to obtain the average internode length in metres (m).

3) Estimate $BHSI_{15}$ using the average internode length (m) with the following equation. If a pocket calculator is not available, $BHSI_{15}$ can be approximated using the following table. This equation and table should not be used for average internode lengths less than 0.25 m or greater than 0.65 m.

$$\boxed{BHSI_{15} = 0.07 + 26.7(GI_x) - 16.6(GI_x)^2}$$

Average Internode Length (m)	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65
$BHSI_{15}$	5.71	6.59	7.38	8.09	8.72	9.26	9.72	10.10	10.40

White Spruce Breast Height-Age Height Growth Curves

1) Accurately estimate the total height of the sample tree at the end of the last full growing season. If height estimates are taken during the period of shoot elongation (from approximately mid May to the end of July) the total height must be taken at the previous years terminal branch whorl. The total height of small trees is most accurately determined using a graduated telescopic range pole. Total height for larger trees can be estimated using an hypsometer.

2) Determine the total age of the sample tree at breast height (1.30 m) by counting the annual growth rings from an increment core. If these estimates are being obtained during the period of shoot elongation (as discussed above), count the annual rings to the end of the previous years growth. Subtract one year from the total age determined at breast height to use for estimating $BHSI_{15}$ with the white spruce breast height-age height growth curves.

3) The total height and age from breast height values determined in Steps 1 and 2 above are then used with a hand held programmable calculator and the BASIC program given in Appendix VIII to compute $BHSI_{15}$. A less desirable method of visually interpolating between the height growth curves can also be used by plotting the total height and age from breast height values on the white spruce breast height-age height growth curves included in this Appendix.

Relative White Spruce Site Quality for the Thunder Bay area

1) Compute the average $BHSI_{15}$ for all sample trees estimated from growth intercepts and from breast height-age height growth curves.

2) The relative site quality for the area being studied can then be estimated by locating the average $BHSI_{15}$ value in the ranges given in the following table for the Thunder Bay area.

Site Quality for Planted White Spruce in the Thunder Bay area					
Site Class	Very Good	Good	Medium	Poor	Very Poor
$BHSI_{15}$	> 11.00 m	11.00 - 9.11 m	9.10 - 7.21 m	7.20 - 5.30 m	< 5.30 m

Estimating Growth and Yield

1) Estimate the height of dominant white spruce trees at 50 years from planting ($Ht_{50/pltg}$) using the average $BHSI_{15}$ value for all sample trees and the following equation:

$$\boxed{Ht_{50/pltg} = 3.9 + 2.12\ (BHSI_{15}) - 0.038\ (BHSI_{15})^2}$$

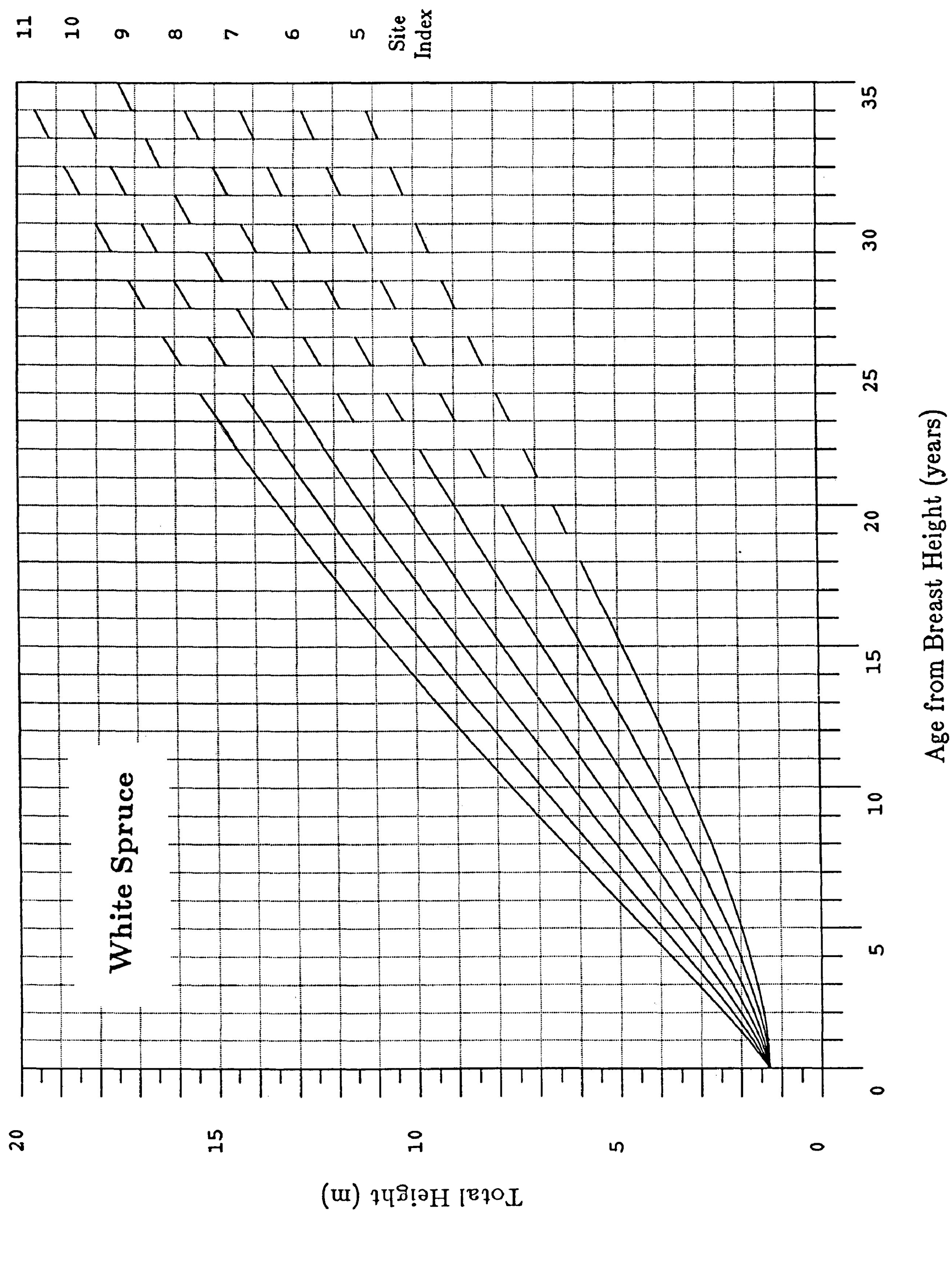
2) The estimated height at 50 years from planting ($Ht_{50/pltg}$) can then be used with the following table of total and merchantable volumes (m^3/ha) for white spruce planted at 1.75 m spacing. This table is extracted from Berry's (1978) yield tables for planted white spruce at Petawawa. The accuracy of the above procedure is not known. Thus, growth and yield estimates obtained using this procedure should be used only as rough approximations.

Total and Merchantable Volume (m^3/ha)				
Age from Planting	Site Index Class (m)[1]			
	15	18	21	24
25	58[2] (32)[3]	90 (62)	124 (94)	162 (131)
30	94 (66)	138 (108)	188 (156)	238 (205)
35	136 (106)	190 (160)	249 (214)	313 (275)
40	173 (142)	238 (205)	304 (268)	377 (332)
45	201 (169)	273 (238)	349 (307)	426 (375)
50	225 (191)	307 (270)	391 (344)	473 (416)

[1] total height of dominant trees at 50 years from planting
[2] total volume
[3] merchantable volume

3) Some computer growth and yield simulation models may use height at 50 years from seed ($Ht_{50/seed}$) as site index. Accordingly, the height at 50 years from seed can be estimated with the following equation.

$$\boxed{Ht_{50/seed} = 3.12 + 2.04\ (BHSI_{15}) - 0.035\ (BHSI_{15})^2}$$


White Spruce
Site Index
11
10
9
8
7
6
5
Age from Breast Height (years)
0
5
10
15
20
25
30
35
Total Height (m)
0
5
10
15
20

APPENDIX IX

FIELD ESTIMATION OF SITE QUALITY FOR RED PINE PLANTATIONS IN THE THUNDER BAY AREA

Introduction

Site quality for red pine in the Thunder Bay area can be estimated using the growth intercepts and breast height-age height growth curves given in this Appendix. To achieve accurate estimates of site quality, plantations should be at least three years older than the year in which a height of 1.5 m was reached, or approximately three to four m in total height. Estimates of site quality from several suitable sample trees are averaged to represent a given area. This average is then compared to the range of site quality observed in the Thunder Bay area to obtain a relative ranking of good, medium, or poor site quality. Estimates of average site quality also can be used obtain rough estimates of the yield of the plantation by estimating height at 50 years of age, and using this height with yield tables for planted red pine at Petawawa (Berry, 1984).

Selection of Sample Trees

1) Select five to 10 dominant, uninjured, free-to-grow red pine trees from the area for which site quality is to be estimated. Five sample trees should provide accurate estimates of average height growth in very homogeneous conditions, but up to 10 trees may be required where height growth is variable. Some plantations cover large areas having different soil and site conditions. Estimates of site quality for such plantations should be obtained from five to 10 sample trees selected from each of several areas throughout the plantation.

2) Identify the first annual node occurring above a height of 1.5 m. If between three and five internodes occur above the 1.5 m height, estimate the height of the sample tree at a breast height-age of 20 years ($BHSI_{20}$) using the procedure detailed below for growth intercepts. If more than five internodes occur above the 1.5 m height, estimate $BHSI_{20}$ using the procedure detailed below for breast height-age height growth curves.

Red pine Growth Intercepts

1) Determine the total length of the first three, four, or five internodes occurring above 1.5 m (use the most internodes available). This total length can be determined using a graduated telescopic range pole to measure the heights of the designated internodes. Alternatively, the

total length of the designated internodes can be measured by marking the distance between internodes with a willow or alder stick.

2) Divide the total length of the designated internodes by the number of nodes used in the growth intercept (either three, four, or five) to obtain the average internode length in metres (m).

3) Estimate $BHSI_{20}$ using the average internode length (m) with the following equation. If a pocket calculator is not available, $BHSI_{20}$ can be approximated using the following table. This equation and table should not be used for average internode lengths less than 0.25 m or greater than 0.65 m.

$$\boxed{BHSI_{20} = 8.1 + 15.1(GI_x)^2}$$

Average Internode Length (m)	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65
$BHSI_{20}$	9.04	9.50	9.95	10.52	11.16	11.88	12.67	13.54	14.48

Red pine Breast Height-Age Height Growth Curves

1) Accurately estimate the total height of the sample tree at the end of the last full growing season. If height estimates are taken during the period of shoot elongation (from approximately mid May to the end of July) the total height must be taken at the previous years terminal branch whorl. The total height of small trees is most accurately determined using a graduated telescopic range pole. Total height for larger trees can be estimated using an hypsometer.

2) Determine the total age of the sample tree at breast height (1.30 m) by counting the annual growth rings from an increment core. If these estimates are being obtained during the period of shoot elongation (as discussed above), count the annual rings to the end of the previous years growth. Subtract one year from the total age determined at breast height to use for estimating $BHSI_{20}$ with the red pine breast height-age height growth curves.

3) The total height and age from breast height values determined in Steps 1 and 2 above are then used with a hand held programmable calculator and the BASIC program given in Appendix VIII to compute $BHSI_{20}$. A less desirable method of visually interpolating between the height growth curves can also be used by plotting the total height and age from breast height values on the red pine breast height-age height growth curves included in this Appendix.

Relative Red Pine Site Quality for the Thunder Bay area

1) Compute the average $BHSI_{20}$ for all sample trees estimated from growth intercepts and from breast height-age height growth curves.

2) The relative site quality for the area being studied can then be estimated by locating the average $BHSI_{20}$ value in the ranges given in the following table for the Thunder Bay area.

Site Quality for Planted Red Pine in the Thunder Bay area					
Site Class	Very Good	Good	Medium	Poor	Very Poor
$BHSI_{20}$	> 13.90 m	13.90 - 12.41 m	12.40 - 10.81 m	10.80 - 9.30 m	< 9.30 m

Estimating Growth and Yield

1) Estimate the height of dominant red pine trees at 50 years from planting ($Ht_{50/pltg}$) using the average $BHSI_{20}$ value for all sample trees and the following equation:

$$\boxed{Ht_{50/pltg} = 3.3 + 1.6\ (BHSI_{20}) - 0.013\ (BHSI_{20})^2}$$

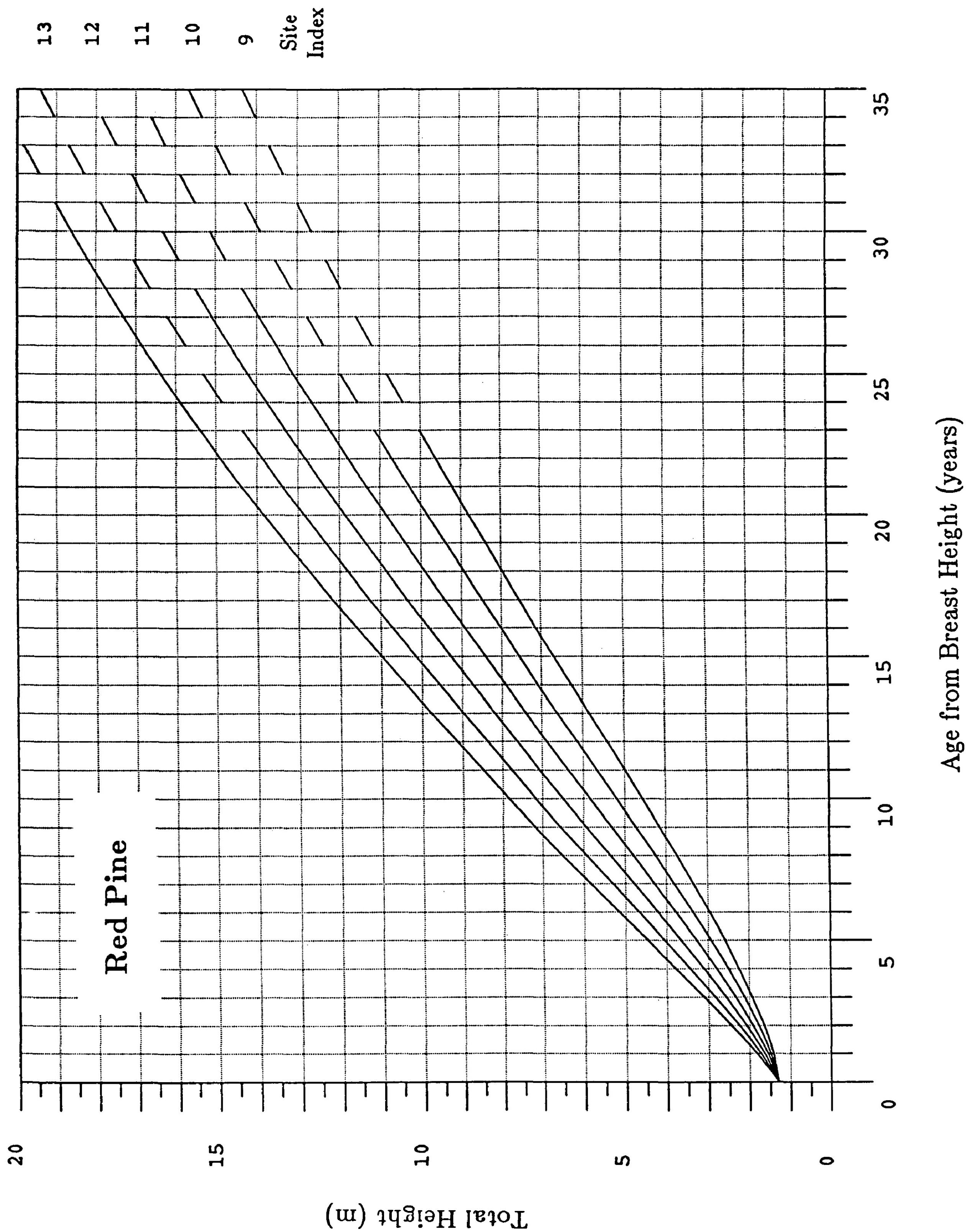
2) The estimated height at 50 years from planting ($Ht_{50/pltg}$) can then be used with the following table of total and merchantable volumes (m^3/ha) for red pine planted at 1.75 m spacing. This table is extracted from Berry's (1984) yield tables for planted red pine at Petawawa. The accuracy of the above procedure is not known. Thus, growth and yield estimates obtained using this procedure should be used only as rough approximations.

Total and Merchantable Volume (m^3/ha)					
Age from Planting	Site Index Class (m)[1]				
	15	18	21	24	27
25	100[2] (43)[3]	145 (77)	196 (118)	248 (161)	304 (210)
30	140 (73)	199 (121)	262 (176)	324 (230)	393 (295)
35	177 (103)	248 (161)	324 (230)	401 (301)	483 (382)
40	217 (135)	301 (208)	387 (286)	476 (371)	569 (461)
45	258 (170)	349 (251)	447 (344)	548 (444)	645 (535)
50	295 (204)	397 (298)	504 (398)	613 (503)	720 (612)

[1] total height of dominant trees at 50 years from planting
[2] total volume
[3] merchantable volume

3) Some computer growth and yield simulation models may use height at 50 years from seed ($Ht_{50/seed}$) as site index. Accordingly, the height at 50 years from seed can be estimated with the following equation.

$$\boxed{Ht_{50/seed} = 2.6 + 1.54\ (BHSI_{20}) - 0.012\ (BHSI_{20})^2}$$


Red Pine
Site Index
13
12
11
10
9
Age from Breast Height (years)
0
5
10
15
20
25
30
35
Total Height (m)
0
5
10
15
20