SITE INDEX OF PAPER BIRCH IN ALASKA

A

THESIS

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ABSTRACT

Height growth patterns and site index were developed using stem analysis of four dominant or codominant trees from 64 plots located in 50 year-old plus, natural, fully stocked, even-aged stands of paper birch (*Betula papyrifera* Marsh.) in Interior and Southcentral Alaska. Observed height-over-age data were modeled using the Chapman-Richards nonlinear growth model. Plots were grouped into five site quality classes based on tree height at breast-height age of 50 years. Polymorphic site index curves were developed from the data. The families of curves indicate different height growth patterns (polymorphism). Comparison of existing Alaskan anamorphic site index curves with the polymorphic site index curves developed in this study demonstrates differences in predicted heights at different levels of site quality. The polymorphic site index curves developed in this study should replace existing anamorphic curves since they represent a more accurate pattern of height growth for the range of paper birch in Alaska.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

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INTRODUCTION

Paper birch, *Betula papyrifera* Marsh., including several varieties, is an important component of the boreal forest of North America. Its ecological role in the boreal forest is that of a pioneer and it most commonly occupies physiographic sites prone to fire. Paper birch occurs as pure stands and in mixtures with other species. More than 40 percent (4,542 million cubic feet) of the paper birch sawtimber and growing stock volume of the United States is found in Alaska (Waddel et al. 1989).

Paper birch, a major hardwood component of the Boreal Forest Region, is found from the Atlantic Coast of Newfoundland, Labrador, the Canadian Maritime provinces (Hosie 1979), and the New England states (Harlow et al. 1991) to Norton Sound on the Bering Sea coast of western Alaska (Viereck and Little 1972), the Pacific coast of British Columbia (Hosie 1979; Harlow et al. 1991) and northwestern Washington (Hitchcock et al. 1964). Its northern limit in the West is north of the Arctic Circle on the southern slopes of the Brooks Range in Alaska (Viereck and Little 1972), the Richardson Range in the Yukon Territory, and Great Slave Lake in the Northwest Territories (Rowe 1972; Hosie 1979). In eastern Canada, it does not extend north of 60 degrees North latitude (Rowe 1972; Hosie 1979). Its southern limit extends well into the Appalachians in the east (38 degrees North latitude), the southern edge of the Great Lakes-St. Lawrence region (41 degrees North latitude); in the West it is found southward in the Rocky Mountains to Colorado and along the westside of the Cascade Range to King County, Washington with particularly impressive stands growing in the Nooksack River drainage of northwestern Washington (Hitchcock et al. 1964). Along the West coast, it is found scattered northward from Puget Sound to Western coastal Alaska (Harlow et al. 1991).

Within Alaska, it is found northward from Kodiak Island and the Kenai Peninsula to the southern slopes of the Brooks Range, a range of 12 degrees of latitude; its east-west range, from the Canadian border to the Bering Sea, covers 20 degrees of longitude (Figure 1) (Viereck and Little 1972). Three varieties occur in Alaska: *B. papyrifera* var. *commutata* ((Reg.) Fern.) occurs in Southeast Alaska northward from the Taku River, especially along the coast of the Lynn Canal; *B. papyrifera* var. *kenaica* ((W.H.Evans) Henry) is found in the southern part of the interior forest, the Kenai Peninsula, and south to Kodiak Island; *B. papyrifera* var. *humilis* ((Reg.) Fern and Raup) is common throughout the Interior and Southcentral forests but not Southeast Alaska.

Paper birch occupies a wide range of soils which is reflected by the considerable variation in rates of height growth. This is partly demonstrated in Alaska by the rationale for the anamorphic site index curves of Gregory and Haack (1965) and by site index curves developed elsewhere (Carmean 1977). The site index curves of Gregory and Haack range from 35 feet to 65 feet. Hosie (1979) states that paper birch in Canada grows best on well-drained sand or silt loams. In New England, superior growth rates occur at lower elevations on well-drained, northeast aspects having a deep organic mat (Marquis et al. 1969).

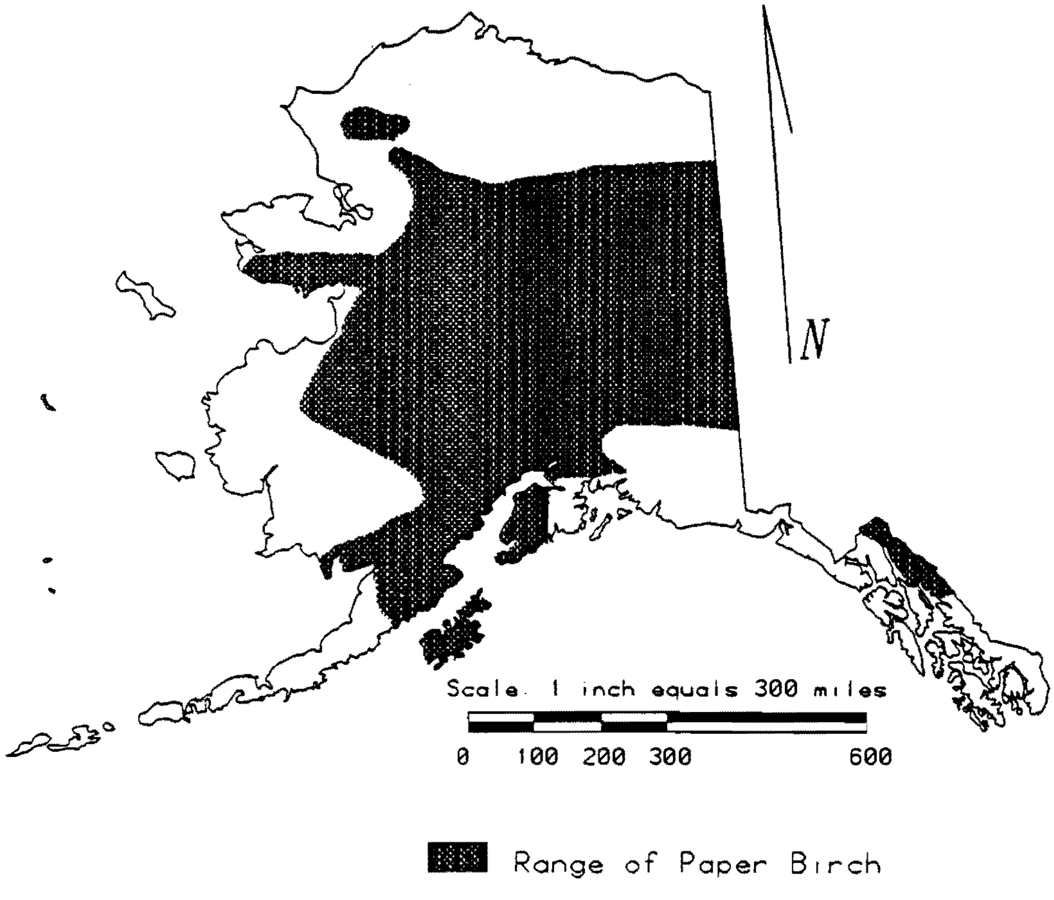

Figure 1. Range of Paper Birch in Alaska (from Viereck & Little 1972).

In Alaska, paper birch is reported to occur predominantly on northeast and northwest-facing slopes (Gregory and Haack 1965) with best growth on well-drained, silty loam, upland sites (Viereck and Little 1972). Although height growth is far superior on well-drained upland sites, paper birch is also found on poorly-drained lowland sites underlain with permafrost. Paper birch's ability to survive and grow across a wide range of ecological conditions demonstrates a wide ecological amplitude. Therefore, one should expect a considerable range of height growth patterns which reflect the diversity of sites occupied by paper birch.

Paper birch is a fast growing, short-lived pioneer species. It is shade intolerant, less tolerant than the majority of associates. In Alaska, its conifer associates with the exception of tamarack (*Larix laricina* du Roi) are decidedly more shade tolerant; hardwood associates (*Populus balsamifera* L. and *Populus tremuloides* Michx.) are about equal in shade tolerance. Light, air temperature, soil temperature, soil moisture, and available nutrients are critical site factors, particularly for newly germinated seedlings. Marquis (1965) states that "... germination of birch seeds is best under conditions of high soil moisture and moderate soil temperature." He suggests that early height growth is often superior on organic seed beds in full sunlight. Organic soil horizons are composed primarily of plant and animal remains in various stages of decomposition (Barbour et al. 1980). The best soil media for both growth and reduced early mortality are mixtures of organic and mineral soil (Marquis et al. 1969). Thus scarification, which mixes mineral and organic horizons, should promote the natural establishment of paper birch (Leak et al. 1969).

Good seed crops occur about every other year (Bjorkbom et al. 1965) and are related to the abundance of male catkins the preceding winter. In New England, paper birch begins bearing seed when at 15 years of age (Marquis et al. 1969; Safford et al. 1990). It is estimated that four seed trees per acre are sufficient to fully restock a site in New England (Leak et al. 1969). Seed dispersal occurs any time between August and April. The bulk of seed dispersal in New England occurs prior to snowfall, regardless of the seed crop size for the year (Bjorkbom et al. 1965). In Alaska, copious amounts of seed are common on fresh snow in December and January. Establishment on the site can be severely impeded by competition with associate species (LaBonte and Nash 1978).

In addition to regeneration from seed, stump sprouting also occurs. Paper birch often stump sprouts when the tree is injured or "killed" by fire or other disturbance. Sprouts have the advantage of a fully developed root system and show greater vigor at an earlier age than seedlings. Sprouts grow quickly, but have shorter lives than stems of seed origin (Marquis et al. 1969).

Unless open grown, paper birch displays a slender bole and narrow crown. The crown is typically composed of ascending branches that end in numerous small branchlets and twigs. It grows fast, dispenses vast quantities of seed, and dies at a relatively young age (Spurr and Barnes 1973). Most stands are mature by 60 to 75 years of age (Post et al. 1969). On favorable sites in Alaska, a mature tree will reach 80-100 years of age and heights of 70-80 feet (Gregory and Haack 1965). The oldest recorded age in Alaska is approximately

230 years (Viereck and Little 1972). After reaching maturity, tree vigor declines rapidly (Safford et al. 1990). As a short-lived pioneer, paper birch is particularly susceptible to disease and decay at advanced ages.

The potential for intensive management of paper birch to produce high yields of quality fiber exists in Alaska. Per acre volume estimates compare favorably with New England and Ontario stands (Table 1). With proper forest management practices, optimal yields can be obtained at younger ages. For example, thinning high quality sites in New England reduced the rotation age from 85 to 68 years with yields of 4,200 cubic feet/acre (Marquis et al. 1969). Release of seedlings and saplings through weeding and cleaning can greatly improve growth and survival and ultimately yield (LaBonte and Nash 1978).

Table 1. Yield comparisons of fully stocked paper birch stands in Alaska, Ontario, and New England at site index 65 (from Safford et al. 1990).

	Stand Age (years)				
Region	40	50	60	70	80
			(cubic feet/acre)		
Alaska	771	1,686	2,571	3,300	3,814
Ontario	1,486	2,071	2,571	2,986	3,286
New England	1,829	2,529	3,043	3,457	3,814

Yields in Alaska compare more favorably to yields in other parts of North America when paper birch stands are fully mature (Table 1). By age 80, Alaskan yields surpass yields in Ontario at all levels of site index (Safford et al. 1990). Gregory and Haack (1965) report yields in Alaska for high quality, unmanaged sites to be 4,000 cubic feet per acre at 100 years. These Alaskan stands are 30 years older than the thinned stands reported for New England by Marquis et al.(1969). Pure, unmanaged birch stands in the Fairbanks area can have volumes in excess of 4,200 cubic feet per acre at 50 years of age[1].

Despite an estimated total net volume of 4,542 million cubic feet of paper birch in Alaska, equivalent to 40% of the growing stock volume in the United States (Waddel et al. 1989), paper birch is currently under-utilized, its primary use being firewood. Due to poor utilization, a significant portion of existing Alaskan birch stands are decadent. Recently, forest products companies have expressed interest in the species. Quality wood fiber is suitable for hardwood lumber, paneling, veneer, plywood, pulp, and furniture. Paper birch is second only to eucalyptus species for pulp in world markets (Breck 1987). There is a significant demand for hardwood fiber and other hardwood products in Pacific Rim nations. One company has completed an exploratory program to determine the available volume of all hardwood species in

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[1] Personal communication, Mr. Steve Clautice, Natural Resource Manager, Division of Forestry, Alaska Department of Natural Resources March 30, 1991.

Interior Alaska; its primary interest is suppling hardwood chips to the export market. Another company has expressed interest in birch for furniture components.

Obstacles exist for full utilization of the birch resource in Alaska. A responsible, value-added forest industry is possible and would be welcomed by many people of the state. Producing value-added products for export to offshore markets will create new wealth and new jobs for Alaska. To maximize development opportunities, an accurate approach for assessing the productivity of forest lands for paper birch is essential.

OBJECTIVES

The primary goal of this study is to provide an accurate method for estimating site quality of paper birch in Interior and Southcentral Alaska. Specific objectives are:

1. Develop polymorphic site index curves using appropriate nonlinear regression techniques;
2. Compare site index curves developed in this study with those previously developed for Alaska;
3. Determine early growth rates (years to reach breast height).

LITERATURE REVIEW

Site Classification

A site may be defined as a piece of land uniform in topography, soil quality, macroclimate, and microclimate (Daniel et al. 1979). Forest site quality is an estimate of the capability of the site to produce trees (Carmean, 1977). Forest site quality, therefore, is the sum total of all environmental factors affecting the site (Spurr and Barnes 1973); these include: climatic (temperature, precipitation, latitude, elevation, solar input); edaphic (soil texture, soil moisture, parent material, organic matter content, nutrient availability); and biologic (genetic pool, competition from plants, consumption by animals, alteration by man).

Forest site productivity is the capacity of the site to produce forest products under specific management regimes. Schmidt and Carmean (1988) state that "...we should view forest site quality not as a fixed and unchangeable characteristic of forest land but as a measure of productivity that can either be improved by intensive management practices or be degraded by improper practices."

Numerous site classification systems exist today. Different purposes lead to different classifications. For forest management purposes, two major objectives of site classification are to (1) identify site productivity, and (2) provide a frame of reference for silvicultural prescriptions (Jones 1969). In Alaska, accurate assessment of forest site quality is essential and a primary objective where most forest lands have received no management and their potential productivity is largely unknown. Hagglund (1981) described the ultimate goal of practical site quality estimation as "...applicable on all present and potential forest land, having an accuracy high enough for any relevant purpose, being simple and fast to use and expressing site quality in terms appropriate to any user."

Classification of forest lands based on site quality is often achieved by dividing the forest into similar ecological units, such as the habitat type units of Daubenmire (1952) or the biogeocoenosis approach of Krajina (1969). Such units include the vegetation, animals, and microorganisms present or capable of occupying the site and the environmental conditions impacting the site. The productivity of the individual species must be determined for each ecological unit since conditions favorable to one species may not be favorable to another species.

Hagglund (1981) identifies three approaches for assessing site productivity for a species: site index, mean annual increment, and descriptive stand characteristics. These expressions are a function of stand variables, site variables, or a combination of stand and site variables. Stand variables include height and age, height growth intercept, form height, and annual growth rings. Site variables include climate, soil, nutrient supply, topography, precipitation, and soil aeration.

Accurate estimation of site quality is essential to forest management decision-making. Individual units of land should receive management efforts that correspond to their potential productivity. Sites with the best growth rates yield the greatest returns. Hence, units capable of the highest productivity should receive the most intensive management practices; less productive sites should receive lower priority or intensity of management. This is demonstrated by a simple set of management regimes (Saltarelli 1988) based on a increasing level of productivity, i.e. low to high productivity:

1) Extensive management - Minimal timber management.

2) Basic timber management - Adequate regeneration of desired species.

3) Intensive management - Prompt regeneration of desired species, plus spacing and thinning to achieve optimal growth.

4) Elite management - Genetically improved stock, planted immediately after harvest, then spaced, thinned, and fertilized through rotation age.

Presently, a large percentage of forest land in the Boreal Forest Region of North America is in the extensive management regime. It is reasonable to assume that more intensive management regimes will become more prevalent in the future. An accurate assessment of site quality is essential to all but the most rudimentary forest management activities.

Site Index

Stand height and age data are commonly used to estimate site quality (Clutter et al. 1983). Site index most simply is the "height of the dominant portion of a forest stand at a specified age" (Spurr and Barnes 1973). Height of dominant and co-dominant trees of a particular species and age is thought to be the best measure of a site's capacity to produce wood (Monserud 1984). Site index, which utilizes height as a function of age, is widely accepted for estimating site quality in both conifer and hardwood stands (Spurr 1952; Jones 1969; Post et al. 1969; Carmean 1977) because it provides a fast, accurate assessment of site quality. Accuracy of the site index approach depends on the quality and quantity of data used in site index curve construction and the techniques used to develop the curves (Hagglund 1981; Schmidt and Carmean 1988).

Site index curves may be anamorphic, polymorphic disjoint, or polymorphic non-disjoint in structure (Clutter et al. 1983). Anamorphic curves are proportional to an average curve formulated from all height/age data collected. Polymorphic curves are not proportional and assume different height growth patterns on contrasting sites.

The anamorphic approach to site index curve development, also referred to as the harmonized approach, has been used for American species extensively in the past (Spurr and Barnes 1973). In Alaska, anamorphic curves were developed for paper birch and have been in use for nearly 30 years (Gregory and Haack 1965). The anamorphic approach assumes a "guide curve" or average curve structure in which height growth patterns are uniform at each level of site index (Carmean 1977). Development of anamorphic curves involves lumping all sample height-over-age data to produce the guide curve. The guide curve is then adjusted up or down to portray different levels of site index. The premise for the anamorphic structure is the assumption that height growth patterns are proportional at all levels of site quality within the sampled area. This premise ignores the reality that growth rate patterns may vary among regions and within regions due to climatic, topographic, or edaphic conditions (Bull 1931; Carmean 1956; Carmean 1970).

Bull (1931) discarded the guide curve method when he found height of older age classes was underestimated due to the normal logging of larger trees, which left only the poor sites representing those age classes. Anamorphic curves have a place; they can be useful for depicting height growth on areas of uniform growth and site, such as intensively managed plantations (Clutter et al. 1983). However, regional yield studies indicate wide variance in height growth patterns of most tree species and warrant site index curves that reflect that variability (Carmean 1977).

Polymorphic disjoint curves assume different growth rates on different sites within a region (Clutter et al. 1983). Nonlinear regression techniques are often employed to develop disjoint curves. The family of curves produced from this technique does not have uniform slope. Data are grouped into site classes and then used to construct the family of curves. Both linear and nonlinear regression techniques are used to formulate parameters for the growth model. The resulting family of curves often have widely varying height growth patterns between site classes. This reflects much of the variation in the relationship between height and age within a region. Polymorphic disjoint site index curves within a family do not, by definition, cross each other.

Polymorphic non-disjoint curves also assume different growth rates on different sites within a region (Clutter et al. 1983). However, polymorphic non-disjoint curves can cross each other at any point along the height-age distribution. The primary difference between polymorphic disjoint and polymorphic non-disjoint curves is that non-disjoint curves employ one or more variables in addition to height and age. These additional variables relate to factors affecting site quality. Soil characteristics, topography, and stand density are variables commonly used to produce non-disjoint curves (Zahner 1962; Alexander et al. 1967; Carmean 1977).

Sample data for the development of site index curves may come from permanent sample plots or temporary sample plots. In Europe, permanent sample plots have been in place long enough to provide height data over the life of a tree or stand (Tesch 1981). In North America, stem analysis of trees collected from temporary plots is the preferred method for development of modern site index curves (Carmean 1977). Two assumptions are basic to the development of site index curves from temporary sample plots (Jones 1969):

1. The dominant and codominant trees comprising the sample data base have in fact been dominant and codominant throughout their lives.

2. Height growth is not significantly influenced by stand density.

The first assumption can be met if sample trees are selected carefully to avoid any indicators of past suppression. Selection of several dominant or codominant trees from a stand usually meet the first assumption if the selected trees are close to each other in height and age.

Some tree species, such as lodgepole pine (*Pinus contorta* Dougl.), are strongly influenced by stocking levels (Jones 1969); but, for most tree species "height growth has been considered to be only slightly influenced by stand density" (Husch et al. 1982).

Several models (Clutter et al. 1983) have been used for the development of polymorphic curves using stem analysis data. Nearly all involve linear or nonlinear regression techniques and the method of least squares. The choice for the most appropriate model is still problematic (Beck 1971). "Because forest growth processes are seldom linear many researchers have resorted to polynomial regression and logarithmic transformations to approximate forest growth" (Lenthall 1985). Biological growth functions that closely follow true height growth patterns, such as the nonlinear Chapman-Richards function (Pienaar and Turnbull 1973), a modification of the Chapman-Richards function (Ek 1971; Monserud 1984; Lenthall 1985), base-age invariant curves based on height growth increment data (Bailey and Clutter 1974), segmented polynomial differential models (Devan and Burkhart 1982), and a modification of the nonlinear Weibull growth function (Yang et al. 1978) have been used successfully. Choice of the model should be based on aptness of fit (maximizing R^2 or minimizing mean square error) and ability to adapt to other species and regions.

Site index curves provide entry into yield tables by the relationship of site index to stand age. Wenger (1984) classified yield tables as:

1. Normal yield tables: Plots established over a range of age and site classes at normal stocking levels. This implies fully stocked stands but "fully stocked" is not precisely defined.

2. Empirical yield tables: Similar to normal yield tables except that they are based on stands of average stocking.

3. Variable density yield tables: Utilize a measure of density as an independent variable along with stand age and site index

Yield tables are indispensable to forest managers for making decisions based on projected fiber or product yields. Thus, accurate site index curves are mandatory for entry into yield tables and for making proper management decisions.

Gregory and Haack (1965) attempted to construct polymorphic site index curves for birch in Alaska. Because of the difficulty in accurately counting rings, the use of stem analysis and regression techniques and the methodology of

Johnson and Worthington (1963) was not successful. Gregory[2] states "I didn't do stem analysis for paper birch...it was too difficult to distinguish accurately the annual rings." Gregory and Haack (1965) state:

> Reliable height-over-age curves from individual stem sections could not be prepared for birch as for aspen. Birch site index curves...were therefore constructed using the older methods of Bruce and Schumacher (1950).

Their site index curves for paper birch were developed using the guide curve method. The guide curve was fitted to the sample data and fixed percentage deviations from the guide curve were used to construct the family of curves. Breast height age, instead of total age, was used due to erratic early height growth and obscured growth rings at stump level on older trees. Since the 1965 publication of those early curves, nonlinear regression techniques as well as computer technology have greatly advanced. Because of the demonstrated polymorphism in height growth patterns for many species (King 1966; Carmean 1977; Clutter et al. 1983; Payandeh 1983), the development of new improved site index curves for paper birch in Alaska is most appropriate. Polymorphic site index curves are believed to be more accurate and useful for basic and intensive forest management than anamorphic curves (Carmean 1977).

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[2] Personal communication, Wilbur A. Farr U.S.D.A. Forest Service, Juneau, Alaska. December 12, 1991.

The Curves

Site index curves are a function of height and age. Their shape and smoothness are products of the type of data used and the mathematical methods used to generate the curve. For example, the site index for an individual site may be constructed by plotting several heights and ages of dominant trees in a stand and choosing, at the developer's discretion, an index age or base age. The height at that age is the site index of that stand. However, selection of the index age can greatly impact the resulting curves. Lloyd and Hafley (1977) quantified the effects of stand age, base age, and sample size on the variance of site index. They found that variance of site index increased inversely with stand age. They tested a linear model with base ages of 25 and 50. Thus, Lloyd and Hafley concluded, "It is not impossible for a young base age to have a larger variance of site index when stand age equals that base age than for a stand age older than the selected age." Heger (1973) compared base age 50 and base age 100 for white spruce using a linear regression model of the general form $H_i = a_i + b_i(SI)$. He found that 10 foot index classes could not be identified with 95% confidence below 50 years of age using base age 100 but 10 foot site classes could be identified between breast height age 20 and 100 by using base age 50. Heger also noted that curve shape differed markedly between base age 50 and base age 100. Hence, when comparing site index curves between species or between regions, it is most important to have a common index age and common curve construction methodology.

Index age is thought to be most applicable when it is near the useful rotation age of the desired species (Clutter et al. 1983; Curtis et al. 1974). "For most northern species 50 years is the index age" (Carmean 1977). This is supported by Almendag (1988), Heger (1971, 1973), and Payandeh (1974).

A height-over-age curve plotted from the dominant trees in one stand certainly reflects the growth of that particular stand. However, such a curve reflects only the productivity for the species of interest on that particular site and provides little information about the regional population. Conversely, a site index curve or family of curves constructed from a large data set from stands throughout a region reflects the growth patterns of the species of interest to a much greater extent and provides information about any stand in that region.

With the advent of computer technology and refined statistical techniques, polymorphic site index curves and equations using nonlinear regression techniques have been developed for many species in many regions of North America and elsewhere (Carmean 1977). Even though site index alone does not represent all productivity variation, it is a primary component of more complex productivity models that do attempt to represent all productivity variation (Jones 1969; Tesch 1981; Payandeh 1983; Harding et al. 1985; McLeod and Running 1988). Precise and accurate estimation of model parameters becomes more critical with increasing model complexity or sophistication.

Model Selection

At present, development of site index curves and prediction equations commonly involves stem analysis to develop the data base and use of nonlinear growth functions to model the data (Carmean 1977).

One of the most flexible growth functions commonly used in recent times is the Chapman-Richards growth function (Pienaar and Turnbull 1973). The function can be expressed as:

$$\text{Height} = a[1 - \exp(-bA)]^{c}$$

Where: H = height from stump
A = age from breast height
a, b, c = parameters of the model

Each parameter of the model has a biological connotation important to growth functions. The first parameter, a, governs the upper asymptote of growth. The second parameter, b, establishes the monotonic growth rate after the point of inflection. The third parameter, c, describes the allometric increase in growth before the point of inflection (Lenthall 1985).

A similar model is the modified Weibull growth function (Yang et al. 1978):

$$\text{Height} = a[1 - \exp(-bA^{c})]$$

Where: H = height from stump
A = age from breast height
a, b, c = parameters of the model

The parameters describe the same biological processes as in the Chapman-Richards model. The Weibull function, originally

METHODS

Study Location

The study area includes paper birch stands accessible by road throughout Interior and Southcentral Alaska. To adequately sample the variability found among accessible sites, plots were located along major roads from the Kenai Peninsula northward to the southern slopes of the Brooks Range (Figure 2). This includes a latitudinal range of 12 degrees and a longitudinal range of 11 degrees. This sampling strategy ensured a sample across a range with climatic conditions from maritime to intensely continental and soil parent materials including glacial, aeolian, fluvial, and colluvial origins.

Tables 2 and 3 provide local environmental information for the sample region. Figure 3 provides the location of selected climatic stations.

These data suggest a mean precipitation range of less than 6.5 inches to more than 28.0 inches and a mean annual temperature from less than 20° F to at least 35° F.

Generally, no glaciation occurred in the majority of the region lying between the lower south slopes of the Brooks Range and the lower northern slopes of the Alaska Range. South of the Alaska Range, loess commonly overlies the coarser glacial materials. Aeolian deposits (loess or sand) are a common parent material in the uplands of non-glaciated areas.

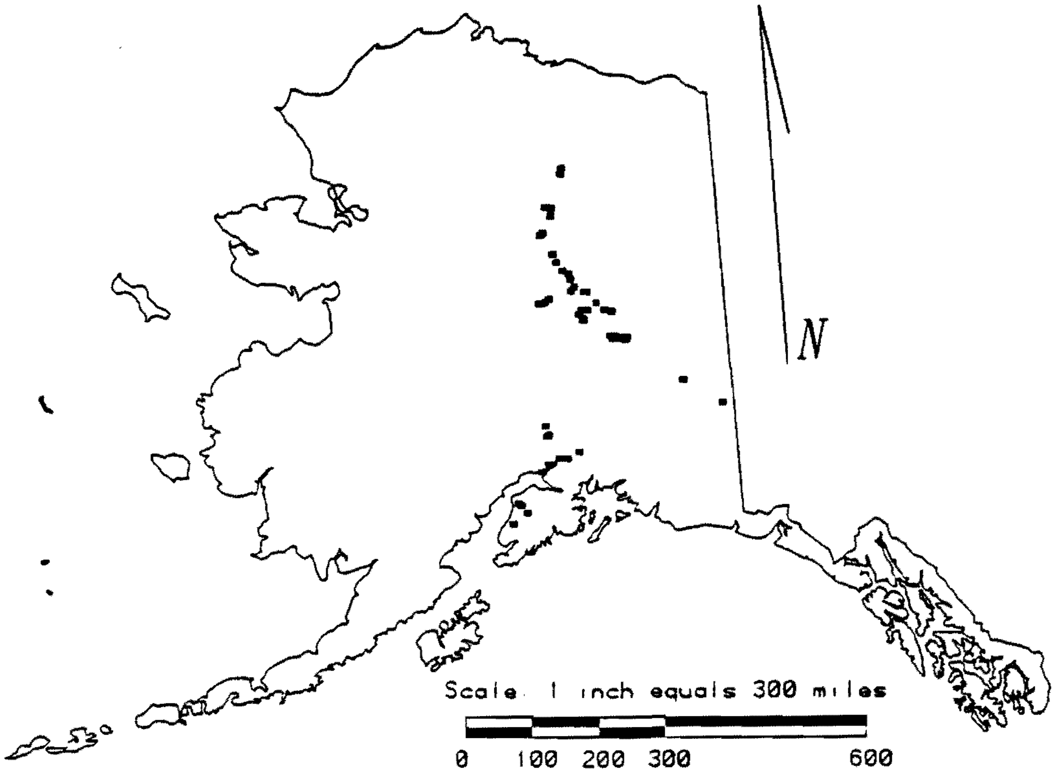

Figure 2. Sample Plot Locations

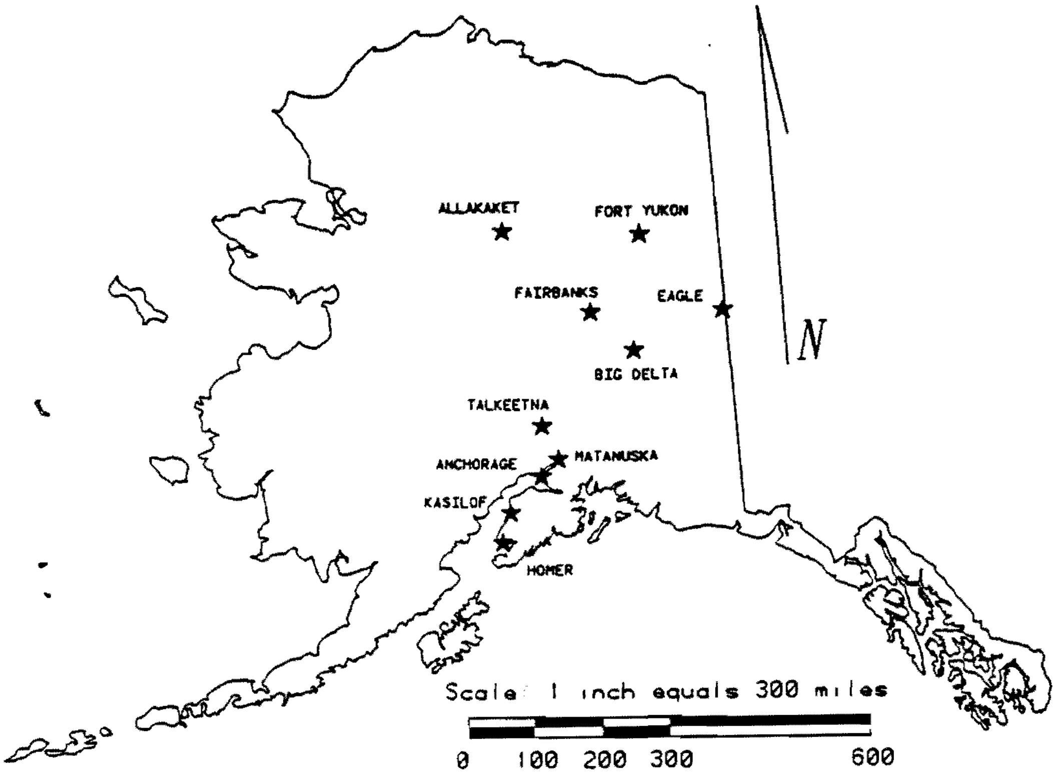

Figure 3. Selected Climatic Stations In Alaska

Table 2: Latitude, longitude, and years of record for selected climatic stations within the sample region. (from Watson et al. 1971).

CLIMATIC STATION	YEARS OF RECORD	LATITUDE & LONGITUDE		GLACIAL	PRECIPITATION (IN.)		
		NORTH	WEST		RAIN	SNOW	TOTAL
Allakaket	30	66°34'	152°44'	No	8.86	76.4	13.87
Anchorage	35	61°10'	149°59'	Yes	10.14	63.3	10.71
Big Delta	24	64°00'	145°44'	No	8.98	36.2	11.53
Eagle	22	64°46'	141°12'	No	7.86	49.8	11.13
Fairbanks	34	64°51'	147°52'	No	8.64	50.6	12.31
Fort Yukon	29	66°35'	145°18'	No	3.58	45.2	6.52
Homer	29	59°38'	151°30'	Yes	20.67	49.2	24.47
Kasilof	26	60°19'	151°15'	Yes	12.77	53.2	17.01
Matanuska	32	61°34'	149°16'	Yes	11.78	47.2	15.54
Talkeetna	34	62°18'	150°05'	Yes	20.28	114.2	28.02

Table 3. Range of temperatures and growing degree days for selected climatic stations within the sample region. (from Watson et al. 1971).

Climatic Station	Degrees F Annual Daily Mean	Max	Min	No. Days Max<32°	Max>70°	Heating Degree Days 65°	35°
Allakaket	19.5	31.7	7.2	184	39	16,387	7,389
Anchorage	35.2	43.0	27.3	120	14	10,864	2,818
Big Delta	27.5	36.3	18.6	158	35	13,823	5,589
Eagle	24.5	35.5	13.4	159	52	15,057	6,626
Fairbanks	27.3	38.4	16.2	139	57	13,723	6,078
Fort Yukon	20.1	30.2	10.0	184	47	16,487	8,872
Homer	37.1	44.4	29.7	71	3	10,332	1,753
Kasilof	34.7	43.8	25.5	60	11	11,188	2,740
Matanuska	35.4	44.7	26.1	97	28	10,719	2,840
Talkeetna	33.4	44.1	22.6	113	36	11,559	3,420

Stand Selection

Public and private lands on which cutting of trees was permissible were delineated. Necessary permission to cut trees was obtained from appropriate resource managers.

Within these areas, suitable stands for sampling were identified using forest inventory data, aerial photography, and knowledge of local managers. A stand had to be pure, even-aged, and at least 50 years old (breast height) to meet initial stand selection criteria. A stand was considered pure if at least 80% of stems were paper birch (Eyre 1980). A stand was considered even-aged when the "difference in age between the oldest and youngest trees did not exceed 20% of the length of rotation" (Smith 1986).

Since site index curves were to be based on height at breast height age of 50 years, a minimum breast height age of 50 years was mandatory. However, older stands were preferred because sample ages would then depict the useful rotation life of the species in question and thus fully represent the height growth of that species (Clutter et al. 1983).

Potential sample stands were visually inspected to determine suitability for sampling. Stand sampling criteria included: minimum breast height age of 50 years, minimum area of 0.20 acre, uniform stocking, uniform landscape position, and the presence of dominant and co-dominant trees exhibiting no damage or evidence of suppression.

Based on the above procedure, 64 sample sites were located.

Plot Selection

To avoid any influences from neighboring sites, a sample plot of 0.10 to 0.25 acre was delineated well within the stand borders. The sample plot had to clearly meet Smith's (1986) definition of a stand, "...a contiguous group of trees sufficiently uniform in species composition, arrangement of age classes, and condition to be a distinguishable unit."

In each potential sample plot, a minimum of four trees was selected from dominant and co-dominant members of the stand. Sample trees were cored to determine age and vigor. Trees younger than 50 years or exhibiting suppressed growth (tight rings) or advanced decay (center rings indistinguishable) were rejected outright. Any potential sample trees with damaged tops or unhealthy crowns were excluded. An age difference of more than ten years from the mean of other sample trees on the plot indicated potentially poor correlation with other sample trees on the plot; such trees were also rejected. If four acceptable trees were found on a site, the plot was accepted.

Field Data Collection

The four acceptable trees were felled. Each tree was assigned a letter (A, B, C, D). Total length was recorded to the nearest inch. Crown length and crown width were recorded to the nearest foot. Cross-sectional disks were removed from each tree at 4-foot intervals from a 6-inch stump to the tip of the tree. Disks from each tree were labeled with the tree letter and numbered sequentially beginning with stump = 0. All trees from the site were also labeled with the site number. While still on site, diameter (nearest 0.1 inch) and bark thickness (nearest millimeter) were recorded for each disk. Disks from each tree were taped together for transport to the laboratory.

Vegetation classification on each plot followed that of Shimwell (1971). Species identification was verified using descriptions of Hulten (1968). The vegetation cover descriptions were collected for future correlations with plant community types such as the habitat type designation of Daubenmire (1968) and Pfister et al. (1977).

Other data collected on each plot included bedrock type, land contour, thickness of organic horizon, soil texture, slope position, landform, and soil moisture regime. Such data will be used in the future for correlation with site quality and further refinement of site index curves and yield equations.

Topographic maps (1:63,360) were used to determine plot location (to the nearest 1/4 section) and elevation to the nearest 50 feet. Slope to the nearest percent was determined with a clinometer. Aspect to the nearest degree was determined with a compass. A physical description of each plot (road name, milepost, nearest distinctive landmark) was also recorded.

Laboratory Procedures

A radial line representing the average growth and diameter of each disk was identified. Along that radial line, all disks were sanded with a belt sander to obtain a smooth surface. Disks from each tree were prepared individually and grouped by site so that they would not lose their identification. All disks from each tree and corresponding site were then brought into the laboratory. Generally, the four trees from each site were aged and measured as a group. In this way, anomalous data were detected early in the process.

A Bannister Incremental Measuring Machine was used to count and measure tree rings. Each measured width was equal to one year of radial growth. For the purpose of this study, site index curves, only the age of each disk was needed. The computer software package used (Evans 1981), automatically recorded the distance between rings to the nearest .01 mm; the annual radial growth data will be utilized in the future for developing new individual tree volume tables. The software package arrayed ring counts by 10 year age increments on a standard floppy disk; this allowed for full editing of the data. All data were again screened for anomalies at this stage. If satisfactory (e.g., consistent age, radial growth, and height relationships), the data were transferred to a VAX mainframe computer.

Statistical Analysis

On the VAX mainframe computer, data were arrayed by stand number, tree number, disk number, diameter, total age, breast height age, and height using SAS (SAS Institute 1985a, 1985b, 1985c) statistical software.

The data were further scrutinized at this point for anomalies in age data for particular disks. Ring counts were sometimes too high or too low in relation to other disks due to poor resolution. Those anomalies were corrected by re-reading the disks or, in some cases, deleting the entire disk from the data set.

All cleaned data are stored on the VAX mainframe computer at the University of Alaska Fairbanks and are available to other researchers through the Agriculture and Forestry Experiment Station (E.C. Packee, Assoc. Prof. of Forest Management).

Height-over-age curves were produced for each stand, again using SAS. Curves were plotted by setting breast height age to zero and plotting each height-over-age data point from all trees in the stand; this yielded a set of height-over-age curves for each stand. Each plot was visually inspected for closeness of fit. At this point, any additional anomalous data were corrected or removed from the data set.

Two nonlinear regression growth functions, the Chapman-Richards model and the Weibull model, were then fitted to the data from each sample plot. The purpose of this step was to produce a fitted curve yielding a specific site index for each sample plot, thereby allowing the grouping of sample plots into site index classes. The least squares solutions for each parameter of the model were reached using the Gauss-Newton, Marquardt and multivariate secant or false position (DUD) methods of iteration available in the nonlinear procedures of the SAS statistical computing package. With the exception of DUD, partial derivatives of the model with respect to each parameter were required input. The Gauss-Newton and Marquardt methods regress the residuals onto the partial derivatives of the model until the iterations converge. Initial starting values were obtained from Clutter et al. (1983). It was recommended that values that converge with one iterative procedure be input into the other iterative procedure to ensure stability of the model[3]. The Weibull function did not fit the data set as well as the Chapman-Richards model and, therefore, was not included in further fitting procedures. When fitted to the individual sample plots, MSE for the Weibull function was generally much higher than MSE for the Chapman-Richards function. In several cases, iterative procedures used to estimate the parameters of the Weibull model did not converge, despite the input of a wide range of starting values.

Sample plots were divided into five productivity classes based on the site index of each plot (Table 4). All trees from sample plots included in each productivity class were then processed as a "single stand" to produce parameters of the model and the resulting fitted curves.

Individual sites were grouped into five separate productivity classes before final curve fitting. This was done to account for the varied growth patterns observed when individual plots were fitted to the Chapman-Richards growth equation. The resulting height growth and site index curves are based on breast height age 0 and site index base age 50. The Chapman-Richards equation was modified to account for breast height age 0 in the following manner:

$$\text{Height} - 4 = a[1 - \exp(-bA)]^c$$

where (Height - 4) accounts for the difference between stump height (6 inches) and breast height (4.5 feet). Data fitted to this equation and directly plotted would result in a curve

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[3] Personal communication P.X. Quang, 1988

passing through the origin (0,0) but properly fitted to the equation. Thus, the same adjustment (Height - 4) must be made to the equation before plotting the fitted curve to reflect age 0 at breast height. The fitted curves were then adjusted to pass through the five levels of site index.

The model was fitted using the method of least squares. Final estimates for the parameters were obtained using Marquardt and modified Gauss stepwise procedures available in SAS statistical software. Least squares criteria require minimizing the error term, represented by MSE.

Age to Breast Height

Age to breast height was determined using two data sets; the stem analysis ring count data and a set of data from 30 paper birch sapling stands. Because of difficulty in measuring stump-level disks from the stem analysis data, the sapling data set should be considered more representative for years to reach breast height. Gregory and Haack (1965) had similar, if not greater, difficulty in measuring paper birch disks. Trees meeting minimum sampling criteria (50 years at breast height) are often stained or discolored, show some level of decay, and often have false growth rings at stump height. Basic descriptive statistics (mean, median, standard deviation, and standard error of the mean) were calculated for the stem analysis data by site class and the independent data set.

Total age and, hence, years to reach breast height was calculated from site index sample trees in this study. Total age was obtained from ring counts at 6 inches (stump height).

Poor correlation between ring counts at stump height and breast height often occurred. The stump-height disk was often heavily stained and/or decayed. In some cases, obtaining an accurate ring count from the stump-level disk was virtually impossible. This contributed to the decision to base site index curves on breast height age zero.

Prior to this study, 30 plots throughout the range of paper birch were sampled for age-to-breast-height data. As part of the same overall growth and yield project, data collection proceeded in much the same way as this project. Sample trees for the age to breast height data were selected if free growing, 10 to 15 ft. tall, and showed no signs of suppression. Three to five trees were collected from each site. The same environmental plot data that was collected for my study was gathered in the age to breast height study. Therefore, age to breast height data collected in the independent study can be related to environmental parameters and ultimately, site index, from my study.

RESULTS

Table 4 provides a summary of the site class categories and the number of stands in each.

Table 4. Site Index Classes Within Study Area.

Site Class	Site Index Range	Number of Stands Included
70	66 - 75	5
60	56 - 65	12
50	46 - 55	15
40	36 - 45	25
30	26 - 35	7

Height-over-age and site index curves by site quality class are shown in Figures 4 through 8. In each figure, height growth for all trees in that quality class and the resulting fitted curve are shown.

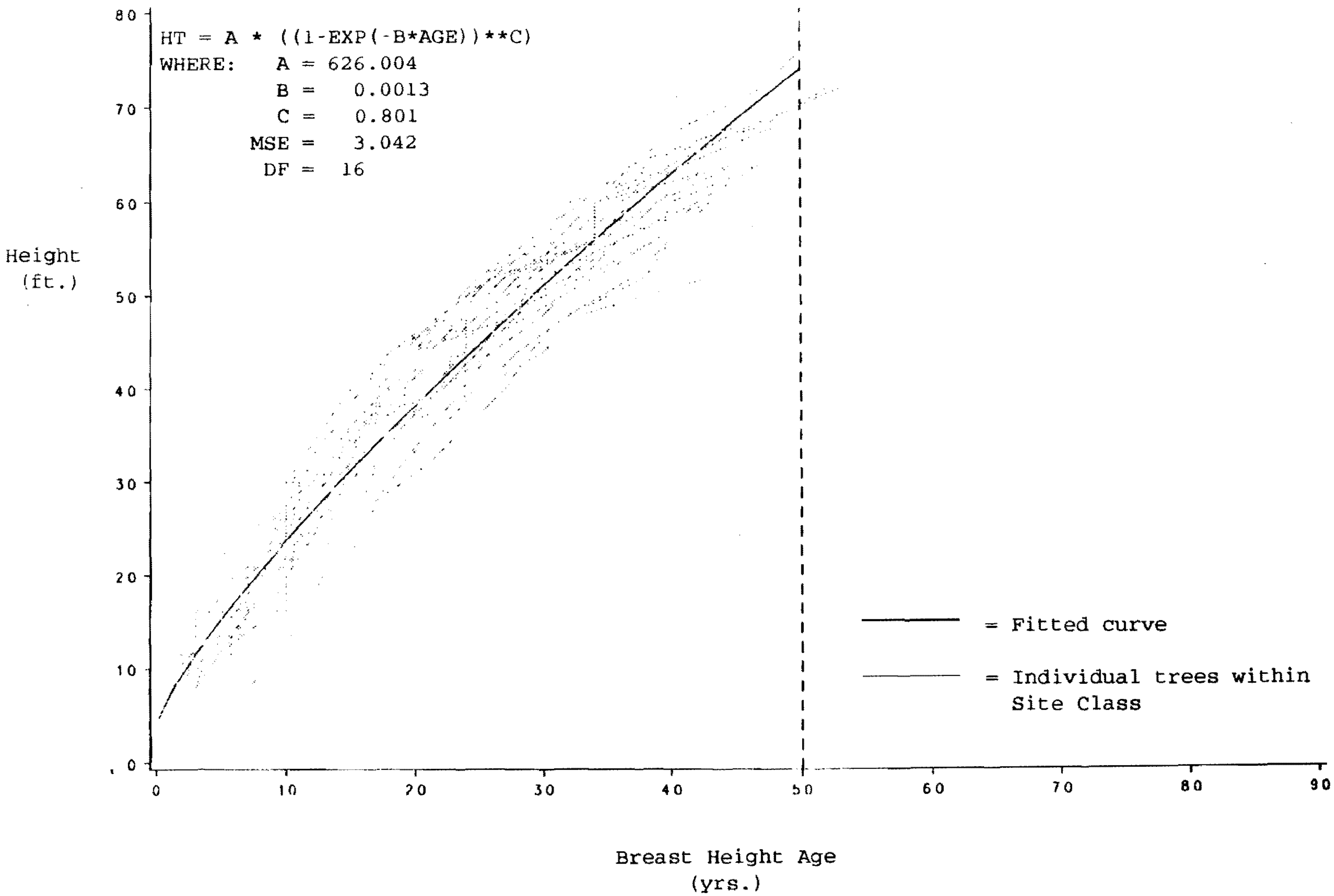

Figure 4. Height Growth and Fitted Curve for Site Index Class 70.

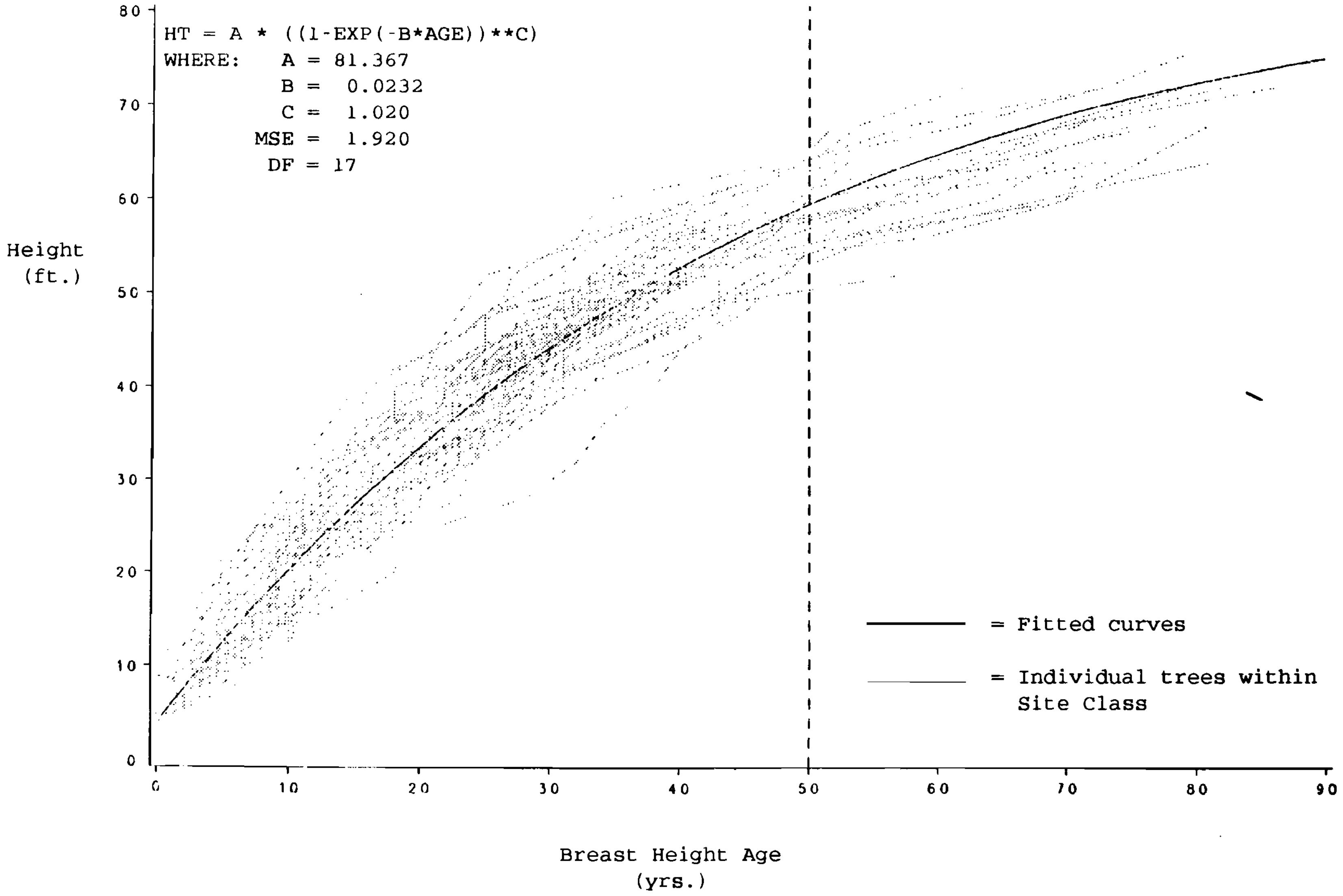

Figure 5. Height Growth and Fitted Curve for Site Index Class 60.

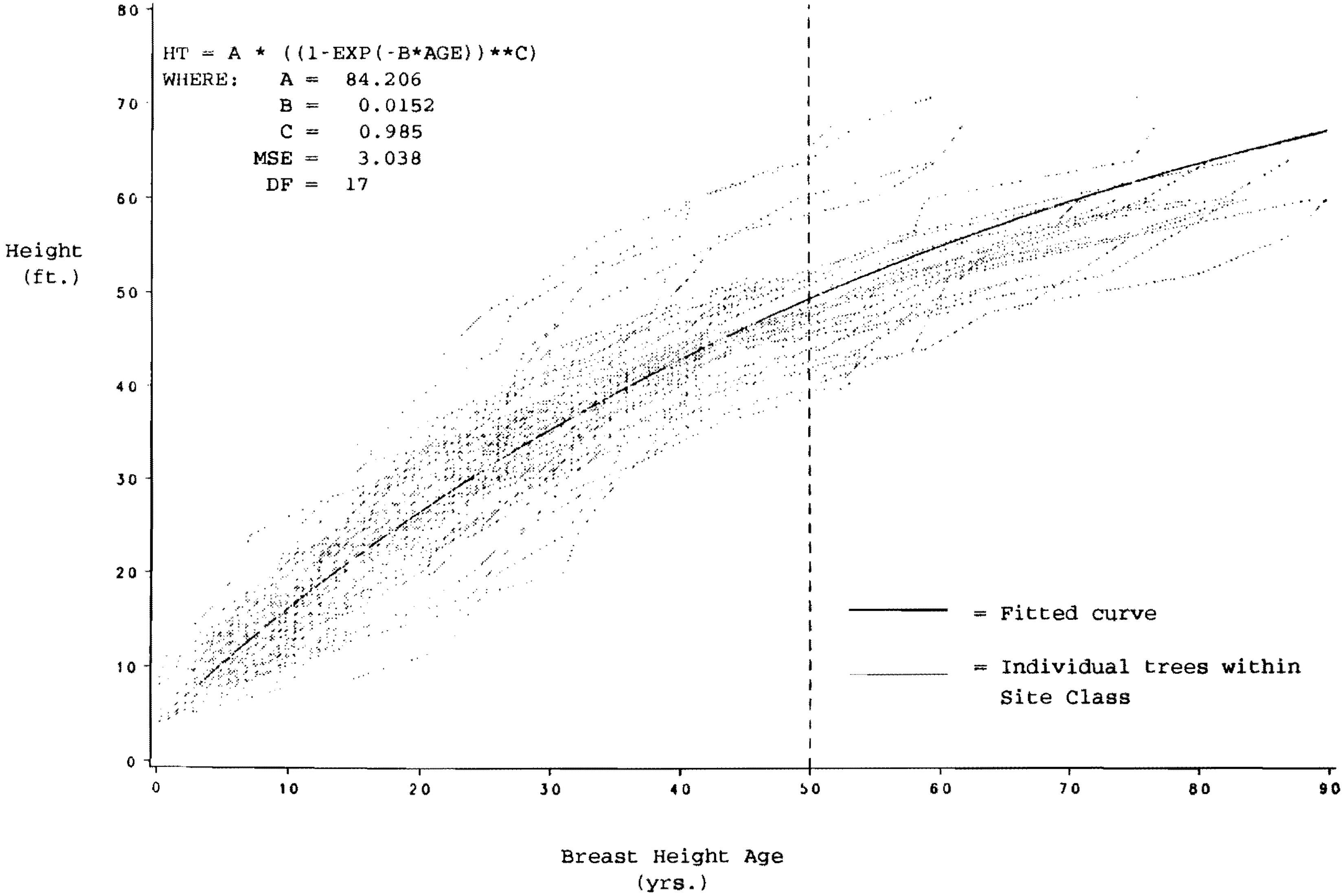

Figure 6. Height Growth and Fitted Curve for Site Index Class 50.

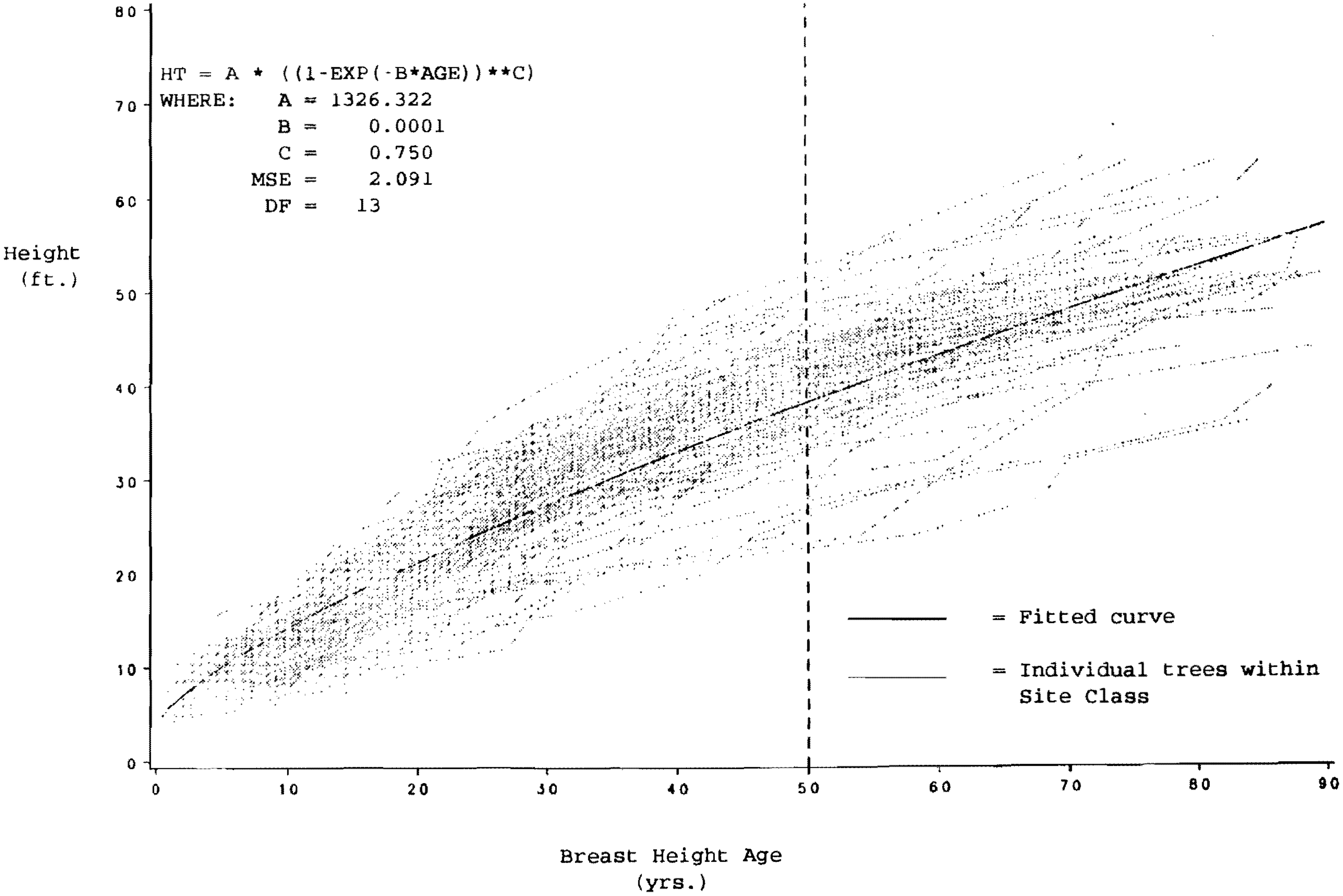

Figure 7. Height Growth and Fitted Curve for Site Index Class 40.

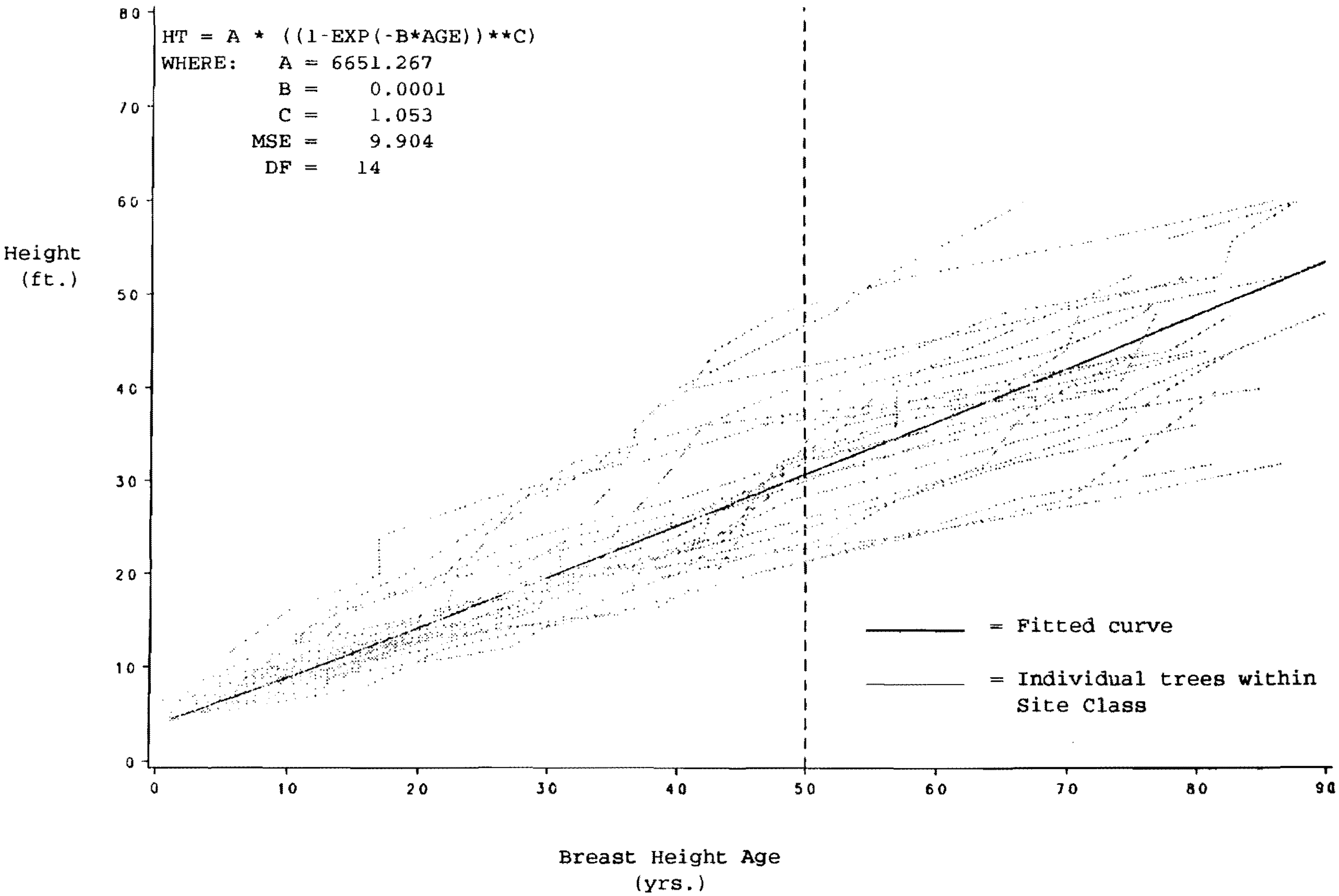

Figure 8. Height Growth and Fitted Curve for Site Index Class 30.

Site index curves, by definition, must pass through a particular height at a base age, 50 years in this study. Site index curves are commonly reported in 10-foot height increments and reflect different levels of site quality for an individual species in a particular region. Therefore, the site index curves reported in this study are by 10 foot height increments from 30 through 70 feet. Inspection shows that the family of curves is polymorphic.

The fitted curve for each site index class falls near the center but is not exactly at the height specified for site index. Therefore, each curve was adjusted incrementally to force it through the specified site index (Carmean 1972). This was done in the following manner:

Height = (Desired Site Index/Predicted Site Index)*Chapman-Richards Equation

Table 5 shows the unadjusted and adjusted site index for each site index class. This adjustment procedure results in the fitted curve passing precisely through each level of site index (i.e., 30, 40, 50, 60, 70). Figure 9 shows the difference between predicted and adjusted site index. Solid lines represent the adjusted site index and dashed lines represent the predicted site index.

Table 5. Adjustment values for each site index class.

Site Index Class	Unadjusted Site Index	Adjusted Site Index
70	70.15	70.00
60	55.49	60.00
50	45.36	50.00
40	34.26	40.00
30	26.72	30.00

Final paper birch site index curve forms are given in Figure 10. Mean squared error (MSE), degrees of freedom (DOF), and parameters of the Chapman-Richards model are listed in Table 6. A low MSE indicates a good fit[4]. An MSE of less than 12 is considered good. All curves from this study have an MSE of less than 12.

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[4] Personal communication, P.X. Quang, 1991.

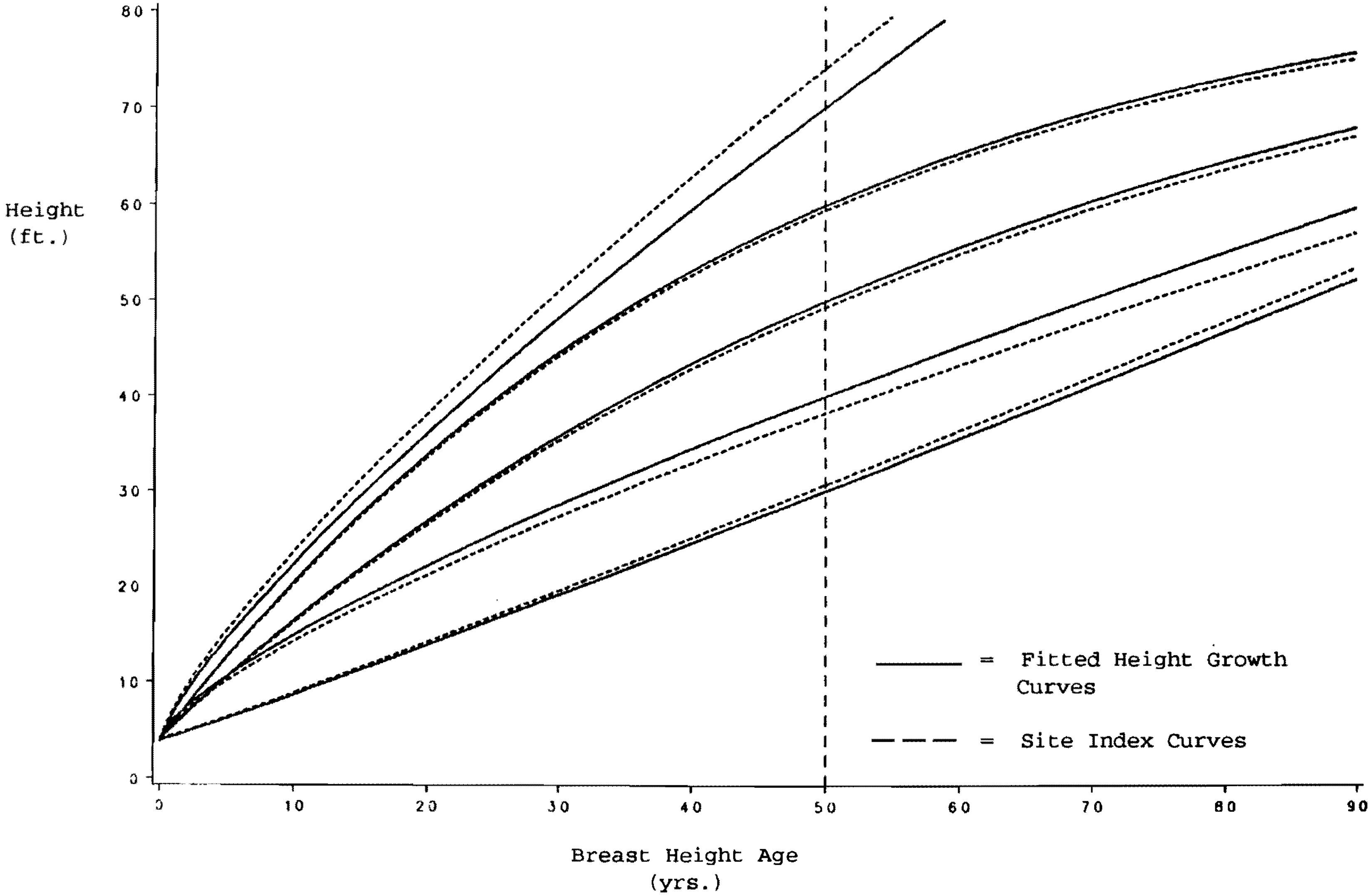

Figure 9. Comparison of Fitted Height Growth and Site Index Curves for Paper Birch in Alaska.

Table 6. Parameters and MSE for site index classes in study.

Site Index Class	A	B	C	MSE	DOF
	Parameters				
70	626.004	0.0013	0.801	3.042	16
60	81.367	0.0232	1.020	1.920	17
50	84.206	0.0152	0.985	3.038	17
40	1,326.322	0.0001	0.750	2.091	13
30	6,651.267	0.0001	1.053	9.904	14

The height-over-age combinations used to fit the site index curves are observed values, rather than estimated values. Therefore, the site index curves shown in Figure 10 are based on the actual height growth patterns of the 256 sample trees used in this study.

Site index class 30, representing the lowest site quality class in this study, has the poorest, but still adequate fit of the five site classes (MSE = 9.90411804). The remaining site classes had excellent fits, which indicate that the Chapman-Richards model is suitable for the data set.

Figure 11 compares the polymorphic site index curves developed here and the anamorphic curves developed by Gregory and Haack (1965). The anamorphic curves were reproduced using the equation and parameters of Gregory and Haack (1965):

$$\text{Birch Site Index} = \text{Height} / [0.16 + (0.021845\text{Age}) - (0.0001006\text{Age}^2)]$$

or

$$\text{Height} = [\text{Birch Site Index}(0.16 + 0.021845\text{Age}) - (0.0001006\text{Age}^2)]$$

The solid lines in Figure 11 represent the polymorphic curves from this study and the dashed lines represent the anamorphic curves of Gregory and Haack. Reproducing the anamorphic curves by entering site index 30 through 70 into the equation should have resulted in the dashed curves passing through index age 50 at the same location that the solid polymorphic curves passed through. I cannot explain why some of the curves are not passing through the same index age. This is particularly evident at site index 70. Perhaps the parameters of the Gregory and Haack (1965) prediction equation were rounded to ease use. The anamorphic curve fits most closely at site index 50, suggesting that the mean of the data used to construct the guide curve strongly represented this level of site index. The anamorphic curves follow the polymorphic curve shapes closely between ages 20 to 60. After age 60, the anamorphic curves depict slower growth than the polymorphic curves except for site index 60.

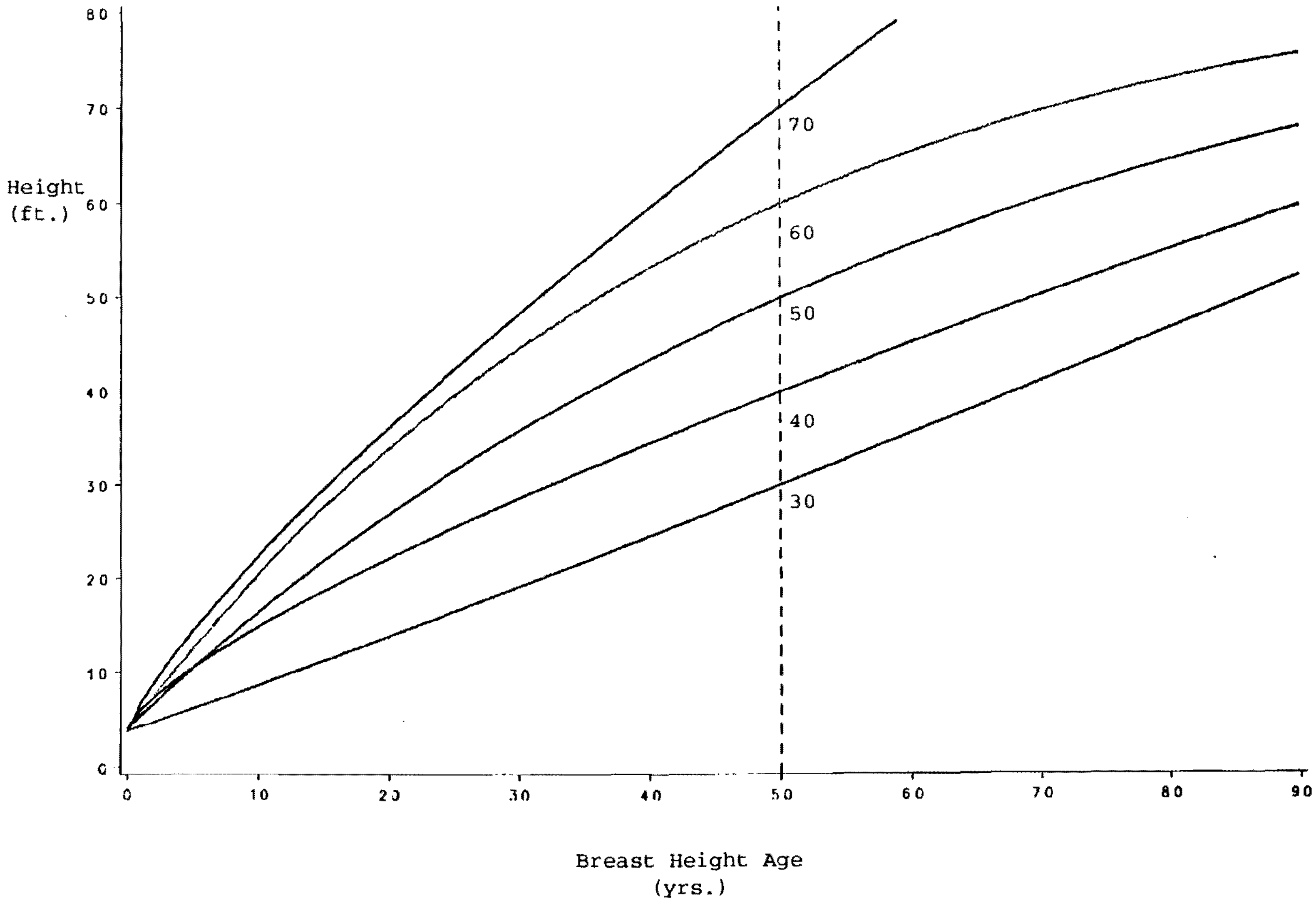

Figure 10. Site Index Curves for Paper Birch in Alaska.

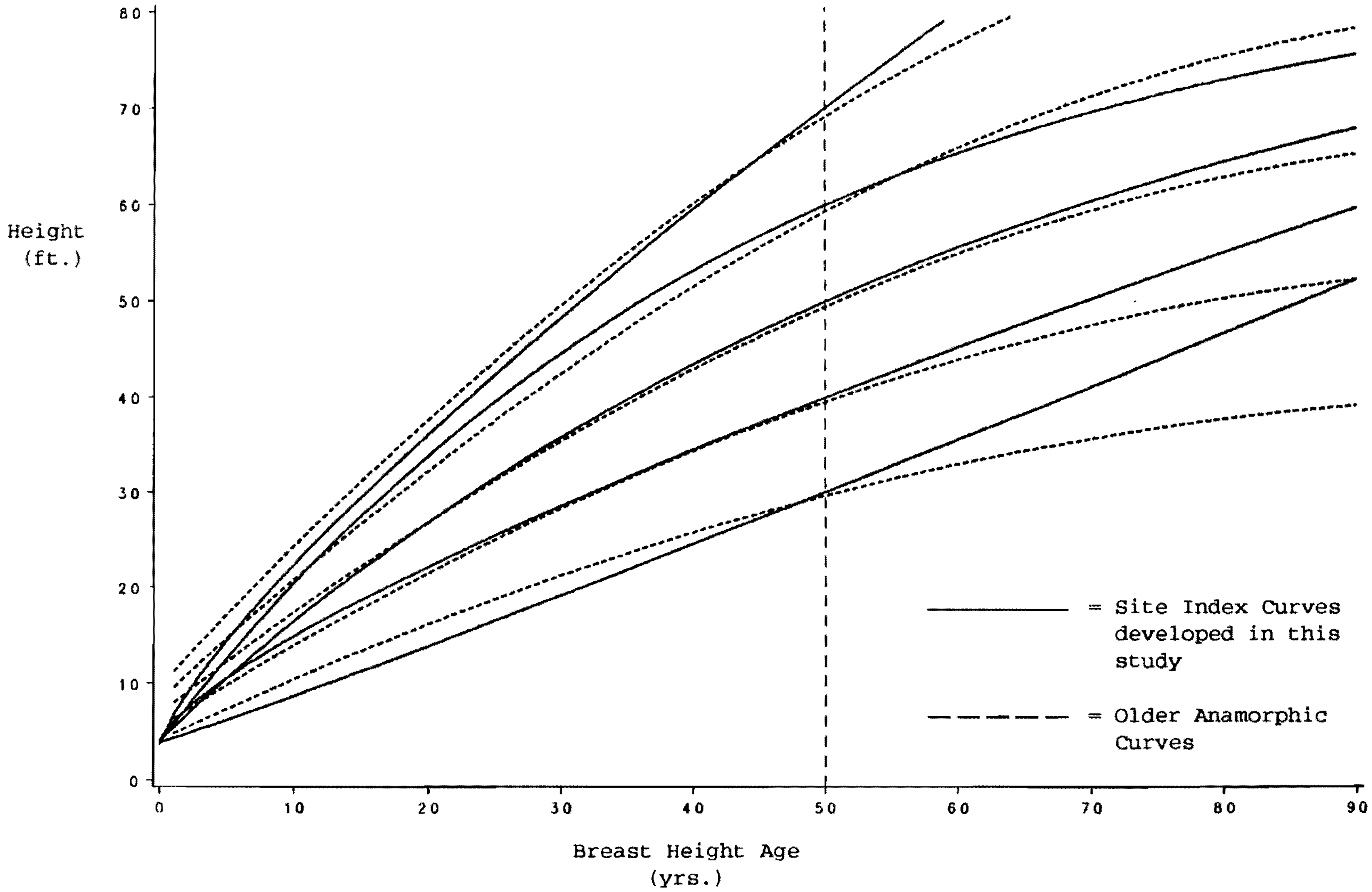

Figure 11. Comparison of Site Index Curves Developed in this Study with Older Anamorphic Curves of Gregory and Haack (1965).

Age to Breast Height

The site index curves from this study are based on breast height age 0. Early height growth rates are often erratic and poorly correlated to levels of site quality (Lenthall 1985). For this reason, many site index curves available today ignore early growth and are based on breast height age zero. Use of the curves for yield forecasts and rotation age determination requires additional information.

Table 7 shows basic statistics for all age to breast height data used in this study. There is a significant difference between the independent age-to-breast-height data and the stem analysis data. The independent data set exhibits a much closer fit around the mean than any of the stem analysis data. This is directly related to difficulties in obtaining accurate ring counts from stump-level disks in the stem analysis data set due to butt rot and staining.

Table 7. Age to breast height, years.

Site Index Class	Mean	Median	Standard Deviation	Standard Error of the Mean
70	10.450	11.000	4.359	0.975
60	11.273	10.000	4.310	0.750
50	12.458	10.000	6.323	0.823
40	16.109	16.000	5.638	0.705
30	16.740	17.000	5.940	1.360
Combined Classes	13.429	12.000	5.988	0.429
Independent Data	4.250	4.100	1.438	0.263

DISCUSSION

Growth and Yield

Currently, forest management in the boreal forest region is mostly at the extensive level. This is particularly true in Alaska. It is difficult to practice forest management at a level greater than rudimentary without a sound understanding of species productivity and the site characteristics impacting the success of an individual species. Because of the generally poor condition of large areas of the boreal forest due to over-maturity, natural and man-caused disturbance, and a long history of removing the best trees from the forest (high-grading), there is an urgent need for an approach to site classification that is not dependent on existing conditions. Determination of site quality can be based on vegetation existing on the site. Vegetative characterization that is sensitive to factors affecting the site is preferable. Site index is one such measure and is commonly used in conjunction with other site characteristics to classify forest land capability.

The site index curves developed in this study may be considered a replacement to the older anamorphic site index curves (Gregory and Haack 1965) for paper birch in Alaska. Consider the following:

1. The site index curves developed in this study show polymorphic height growth patterns. The older anamorphic curves, by definition, assume that height growth patterns at all levels of site index (hence site quality) are proportional to a single height growth

pattern. As early as 1931, Bull recognized polymorphic growth patterns and documented them for North American tree species. Since the anamorphic curves were developed (Gregory and Haack 1965) for paper birch in Alaska, polymorphic site index curves (often using nonlinear regression techniques) have replaced older anamorphic curves for many species in North America.

2. The data used to develop site index curves for this study are based on stem analysis and a minimum breast height age of 50 years. Stem analysis resulted in an observed height growth pattern for each tree based on ring counts at 4-foot increments from stump to tip. The exact procedures used by Gregory and Haack (1965) are unclear. Since all of their data were lumped together to produce the guide curve, site index cannot be related to other environmental factors affecting the site. Site index curves developed in this study are related to site specific factors affecting height growth based on data collected from each sample plot.

3. The Chapman-Richards growth model used in this study is biologically based and has been used successfully to model height growth patterns for many other species (Hagglund 1981). A least-squares solution was obtained for the five site index classes and each solution had low mean squared error term. A low MSE indicates good fit. Therefore, the Chapman-Richards model adequately describes the height growth patterns of paper birch in Alaska.

4. Site index is a basic management tool used to estimate site quality of individual timber stands, and as a component of yield tables, for predicting future per acre volumes. If an estimate of site index is incorrect, any management decisions based on that estimate will be seriously flawed. Therefore, the site index curves developed in this study should replace the older, anamorphic curves for paper birch since the older curves do not indicate true height growth patterns, and, hence, may lead to incorrect management decisions.

The anamorphic curves pass through the same levels of site index as the curves from my data. It is clear that several differences exist. Polymorphic height growth patterns are evident at every level of site index. At ages 0 - 10, the anamorphic curves overestimate height growth for all but site index class 40. At site index 30, the anamorphic curves overestimate height growth from ages 0 - 48 and underestimate height growth from ages 50 - 90. At site index 60, the anamorphic curves overestimate height growth at ages less than 10 years, underestimate height growth from 10 to 50 years, and overestimate height growth in later years. At site index 70, the anamorphic curves again overestimate height growth until near base age (50 years) and underestimate height growth at greater ages.

The Chapman-Richards equation is biologically based. There should be a relationship between the parameters of the model and levels of height growth. Beck (1971) describes in detail the relationship between parameters a and b of the Chapman-Richards model and levels of site index for white pine (*Pinus strobus* L.) in the Appalachians. Lenthall (1985) found no relationship between the a and b parameters and levels of site index for jack pine (*Pinus banksiana* Lamb.) in Ontario. Even though the model is biologically based, parameter values sometimes show no obvious relationship with levels of site index. Like Lenthall's study, I could find no relationship between parameters of the model and levels of site index in this study.

The results of this study are based on 64 plots containing 256 mature, free-growing, paper birch trees. The sample data set was limited by time constraints and access constraints. The sample data set was not limited to one eco-region, but rather was extended as far across the range of paper birch as possible in the two field seasons allocated for data collection. The curves should be validated with an independent data set using stem analysis methods to ensure good fit. Of particular concern is the paucity of data for site index class 70; the true shape of the curve is unknown since no suitable trees over 56 years of age were found and sampled in that site class.

Much work remains to be done to relate site index to other information collected on each sample plot. The height growth pattern of a tree is considered to be a phytometer of site potential, but several environmental factors in combination dictate that site potential. Understory vegetation, slope, aspect, elevation, soil moisture, soil texture, landform type, and depth of organic matter are just some of the variables that control or explain site quality. In combination, these variables can be used to provide a precise estimate of site quality, particularly when used in conjunction with site index. Knowledge of the interrelation of these factors can lead to a more accurate and broader-based site quality classification system. The results of this study would be greatly amplified if the relationship between site index and environmental factors affecting the site were known.

Comparison With Previous Research

The site index curves produced in this study show definite polymorphic height growth patterns. Based on these polymorphic growth patterns, the older curves of Gregory and Haack (1965) do not provide an accurate record of height growth at different levels of site quality for paper birch in Alaska. If, in fact, height growth was proportional at all levels of site quality for paper birch in this region, the curves from this study would have been very similar to the curves published by Gregory and Haack. The site index curves resulting from this study, however, appear to be quite different than the older curves. One must conclude that the anamorphic curve design has no biological basis nor does it provide an accurate estimate of height growth for natural stands of paper birch in Alaska.

Implications To Management

Site index curves developed in this study provide a more accurate picture of paper birch height growth patterns than the older anamorphic curves. There are several implications to management. Use of the older curves can result in overestimates or underestimates of site index, depending on the age of the stand. This is most apparent (Figure 11) at ages greater than 50 on lower quality sites. For instance, a

90 year old tree at site index 30 would result in a site index of 40 ft. when using the anamorphic curves as a guide.

Site index is used for entry into yield tables. Yield tables are based on expected volumes at different levels of site quality. If the site index value entered into a yield table is off by 10, the expected volume will be wrong. This error will be exponentially increased when applied to any tract larger than 1 acre. An error of this nature can result in incorrect rotation length, incorrect annual allowable cut, and incorrect investment decisions. In short, basic site quality information such as site index has a great impact on both present and future management decisions. Forest managers should use the best basic information available for planning purposes. The site index curves presented in this study should be used in place of the older curves.

However, the use of the new curves creates a dilemma for the land manager; "what does he use for yield forecasts since currently there is no corresponding yield table?"

Inspection of the curves in Figure 11 suggest that yield table of Gregory and Haack (1965) can be used temporarily and with caution with the polymorphic curves up to about 50 or 60 years. The need for new, improved yield tables is essential!

Age to Breast Height

Based on the figures presented in Table 7, I recommend that a mean age to breast height of 4.25 years for paper birch be used by forest managers for all sites in Alaska. Forest managers can expect birch seedlings to attain breast height during their fourth year, although birch can reach breast height in less time. After the fourth year, the quality of the site will dictate further growth potential. While age to breast height may be held constant for all sites, further height growth at older ages is much more dependent on the quality of the site.

A seedling needs smaller quantities of nutrients and occupies less space in the forest than a sapling, poletimber or sawtimber-sized tree. Resources available on the forest site become more limited as the tree grows. Hence, at some time in the life of the tree, growth is limited by the resources available on the site. Paper birch on all sites may reach breast height during their fourth growing season, yet at 50 years of age levels of site quality will greatly influence the height of trees on any given site.

RECOMMENDATIONS

Alaska forest management is mostly in the extensive management regime. In fact, there is much forest left to be inventoried and timber-typed. Coupled with the fact that volume tables and equations and, hence, yield tables are highly suspect, there is much forestry work to be done in this region.

In Interior and Southcentral Alaska, nearly all commercial sales have centered around white spruce sawtimber of export quality. Interest in hardwoods has been primarily for firewood, although feasibility studies have been conducted for large scale chip operations. It is a matter of economics, especially in Alaska, that transportation costs are a substantial portion of the operation costs. There is no doubt that the volume needed for a large-scale operation is available and that the key to development of this resource will be cheaper transportation. Large scale chip operations will require at least a 5-year commitment from land owners and large tracts coming under management in each succeeding year. It is in everyone's interest to identify the most productive areas available for such an endeavor.

Specific Sites Suited to Management

"One of the first steps for intensively managing forest land is to determine the site quality of land for various trees so that the most productive and valuable tree can be selected for each parcel of land" (Carmean 1977). Correspondingly, the highest quality sites should receive the most intensive management efforts to realize the greatest returns. The site index curves developed for paper birch in this study can be used to identify the growth potential of a paper birch stand in the following manner:

1. Measure the height and age of dominant and co-dominant birch trees in the stand.

2. Average the height and age measurements and subtract 4 years if the age measurement was taken at stump height. Do not subtract any years if age was taken at breast height.

3. Enter into the site index graph and match height and age to a site index curve. The curve closest to the average height and age for the stand is the site index for that stand.

Recommendations for Future Research

1. Validate the site index curves from this study with independent data from the range of paper birch in this region; particular emphasis should address the shape of the curve for site index 70.

2. Develop new volume tables for paper birch: total height and to 2-inch and 4-inch tops.

3. Develop new yield tables for paper birch that accurately portray volume for all levels of site index; use a permanent sample plot approach to ensure regular refinement.

4. Expand current knowledge on the interrelationship of environmental factors that directly affect or indicate level of site quality.

5. Establish permanent sample plots to study the factors affecting growth and yield of paper birch.

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APPENDIX I

Understory species found on sample sites

Aconitum deplhinifolium
Adoxa moschatellina
Alnus crispa
Alnus tenuifolia
Arctostaphylos rubra
Athyrium filix-femina
Betula glandulosa
Calamagrostis canadensis
Cladonia sp.
Cornus canadensis
Delphinium glaucum
Dicranum sp.
Dryopterus dilatata
Epilobium angustifolium
Equisetum pratense
Equisetum silvaticum
Eritrichium splendens
Fragaria virginiana
Galium boreale
Geocaulon lividum
Geranuim erianthum
Gymnocarpium dryopteris
Hylocomium splendens
Ledum groenlandicum
Lycopodium annotinum
Menziesia ferruginea
Mertensia paniculata
Minaceae
Oplopanax horridus

(Appendix 1 continued)

Peltigera aphthosa
Pleurozium schreberi
Polytrichum sp.
Polygonum alpinum
Potentilla fruticosa
Ptillium ciliare
Pyrola grandiflora
Pyrola secunda
Ranunculus lapponicus
Ribes hudsonianum
Ribes sp.
Rosa acicularis
Rubus chamaemorus
Rubus idaeus
Rubus pedatus
Rubus spectabilis
Rumex fenestratus
Salix bebbiana
Salix planifolia
Salix sp.
Sanguisorba stipulata
Spiraea beauverdiana
Stellaria sp.
Streptopus amplexifolius
Thelypteris phegopteris
Tomenhypnum nitans
Trientalis borealis
Trientalis europaea
Vaccinium ovalifolium
Vaccinuim vitis-idaea

(Appendix 1 continued)

Veratrum viride
Vibernum edule
Viola sp.