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A COMPARISON OF SITE INDEX CURVES FOR NORTHERN HARDWOOD SPECIES

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Northern hardwoods are among the more important and widespread forest types found in the eastern hardwood forests of the United States and Canada. In the United States, forest types composed primarily of northern hardwood species cover about 37 million acres in the Northeast, the Lake States, and the Appalachian Plateau (U.S. Department of Agriculture, Forest Service 1973). Characteristic species are sugar maple (*Acer saccharum* Marsh.), red maple (*A. rubrum* L.), yellow birch (*Betula alleghaniensis* Britton), and American beech (*Fagus grandifolia* Ehrh.). In certain areas, American basswood (*Tilia americana* L.), American elm (*Ulmus americana* L.), and white ash (*Fraxinus americana* L.) are important stand components. Other associated species of less frequent occurrence include black ash (*F. nigra* Marsh.), black cherry (*Prunus serotina* Ehrh.), northern red oak (*Quercus rubra* L.), paper birch (*B. papyrifera* Marsh.), and both quaking (*Populus tremuloides* Michx.), and bigtooth aspens (*P. grandidentata* Michx.).[1]

Northern hardwood stands not only have a large number of tree species, but throughout their wide range also occur in a great variety of climates, and grow on a great variety of topographic positions and soils. Site quality and growth rate may vary greatly for each species of tree when growing on these different sites. Faced with such a profusion of tree species and site conditions, a forest manager is often uncertain about how best to estimate site quality in northern hardwood stands.

Site index based on tree height growth is the most widely accepted method for estimating site quality in the United States and Canada (Carmean 1975, 1977). The method is simple and easy to use when suitable forest trees are available for the required height and age measurements. Such trees are most commonly found in even-aged, fully stocked stands not disturbed by past cuttings, severe fires, or heavy grazing. Even-aged, fully stocked stands are common throughout the range of northern hardwood species. They developed following the removal of the original old growth hardwood stands by clearcutting or heavy harvest cutting. Dominant and codominant trees in these young, even-aged northern hardwood stands are well suited for site index estimation, just as the dominant and codominant trees found in even-aged conifer stands are.

Many site index curves are available for use in the various portions of the large area covered by northern hardwood species. However, many of these are older harmonized site curves based only on tree height-age measurements rather than on more precise stem analysis methods. Also many site index curves are only local curves based on a limited range of soil and site conditions. Within the large area covered by northern hardwood species, a forester may find several sets of site index curves, but he may be uncertain about how applicable they may be to the specific site conditions of his local area.

Intensive timber management requires more precise site index estimates than are usually possible using the older, general, harmonized site index curves. We need to critically examine existing site index curves for northern hardwoods to determine if they are accurate and adequate for use in the precise estimation of site index. We need to know what set of site curves are most suitable for local use. If local site index curves are lacking, inaccurate, or too general, we should try to obtain site index curves that are suitable for the forest and site conditions of that area.

[1]*Tree names follow Little (1953).*

I have three goals for this paper: (1) to inventory the many site index curves presently available for northern hardwood species (table 1); (2) to compare the predicted height growth patterns of these many site index curves (figs. 1-3); and, (3) to recommend additional more accurate site inde curves suitable for intensive timber managemen of the future.

Table 1. Inventory of site index curves for northern hardwood forest species.

Species	Area	Study Methods	Reference
Sugar maple, yellow birch, American beech, white ash	Vermont	Single height-age curves	Hawes and Chandler (1914)
Sugar maple, yellow birch, American beech, American basswood	N. Wisconsin and N. Lower Michigan	Single height-age curves	Frothingham (1915)
Sugar maple, white ash	Vermont	Harmonized	Farrington and Howard (1958)
Red maple, American beech, black cherry	NE States	Site Index curve summary	Hampf (1965)
Sugar maple	S. New York	Stem analyses	Farnsworth and Leaf (1963)
Sugar maple, yellow birch, white ash, paper birch	Green Mts. of Vermont	Stem analyses	Curtis and Post (1962)
Sugar maple	N. Lower Michigan	Stem analyses	Shetron (1972)
Sugar maple, red maple, yellow birch, American beech, American elm, American basswood, white ash, black ash, black cherry, northern red oak, paper birch, aspens	N. Wisconsin, Upper Michigan	Stem analyses	Carmean (1978)
Black cherry	NW Pennsylvania	Stem analyses	Ward *et al.* (1965)
American elm	SE and W Iowa	Harmonized	Brendemuehl *et al.* (1961)
Red oak	Lake States	Harmonized	Gevorkiantz (1957)
Paper birch	N. Wisconsin	Harmonized	Cooley (1958)
Quaking aspen, paper birch	Ontario	Stem analyses	Plonski (1956)
Quaking aspen, paper birch	Alaska	Stem analyses	Gregory and Haack (1965)
Quaking aspen	Lake States	Harmonized	Gevorkiantz (1956)
Quaking aspen, bigtooth aspen	N. Lower Michigan	Harmonized	Graham *et al.* (1963)
Quaking aspen	N. Cent. Minnesota	Growth plot remeasurements	Schlaegel (1971)
Quaking aspen	Saskatchewan	Harmonized	Kirby *et al.* (1957)
Quaking aspen	Cent. and S. Rocky Mts.	Stem analyses	Jones (1966, 1967)
Quaking aspen	Newfoundland	Harmonized	Page (1972)

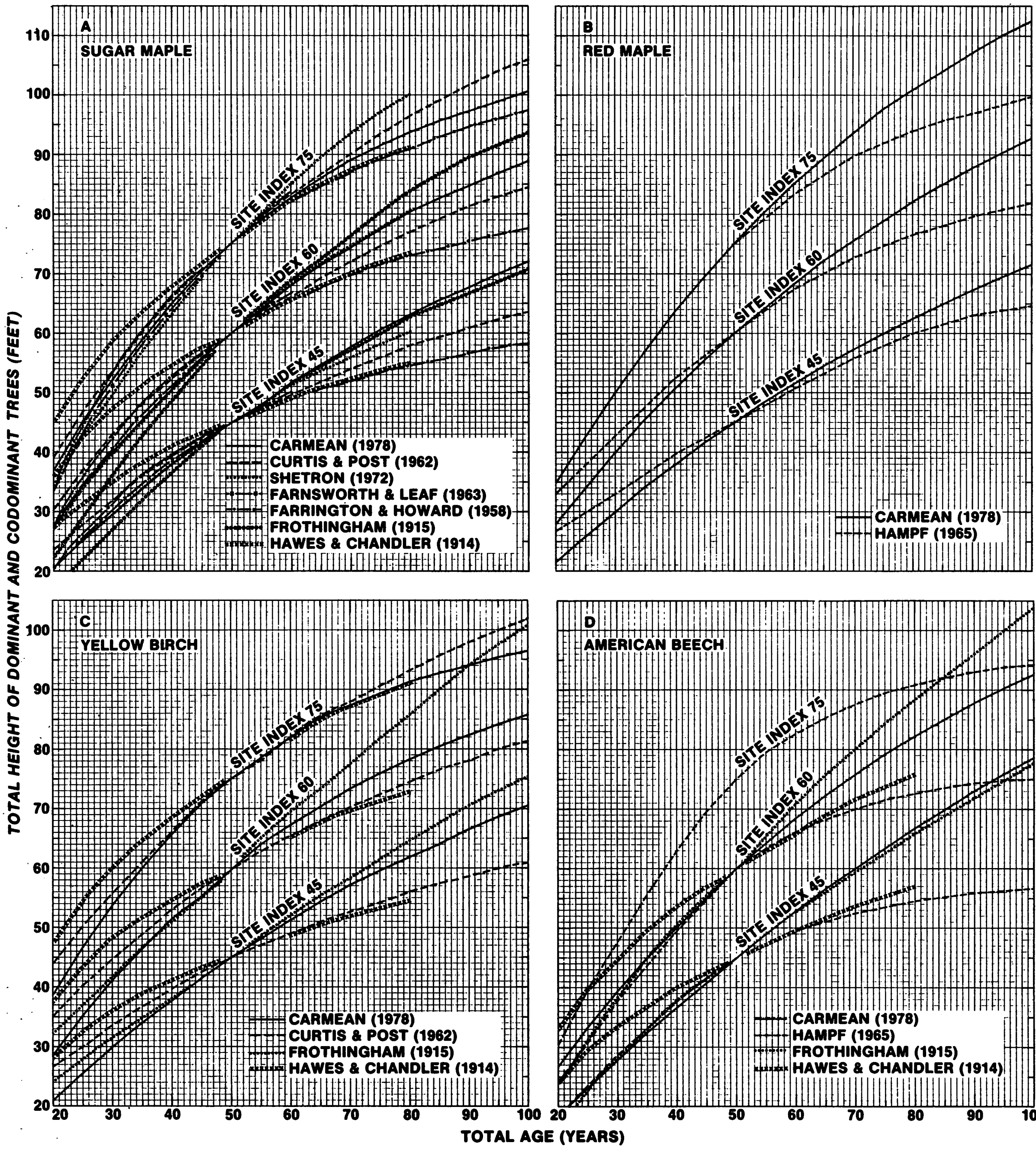

Figure 1.—*Site index curve comparisons at the poor (SI 45), medium (SI 60), and good (SI 75) site index levels for sugar maple, red maple, yellow birch, and American beech.*

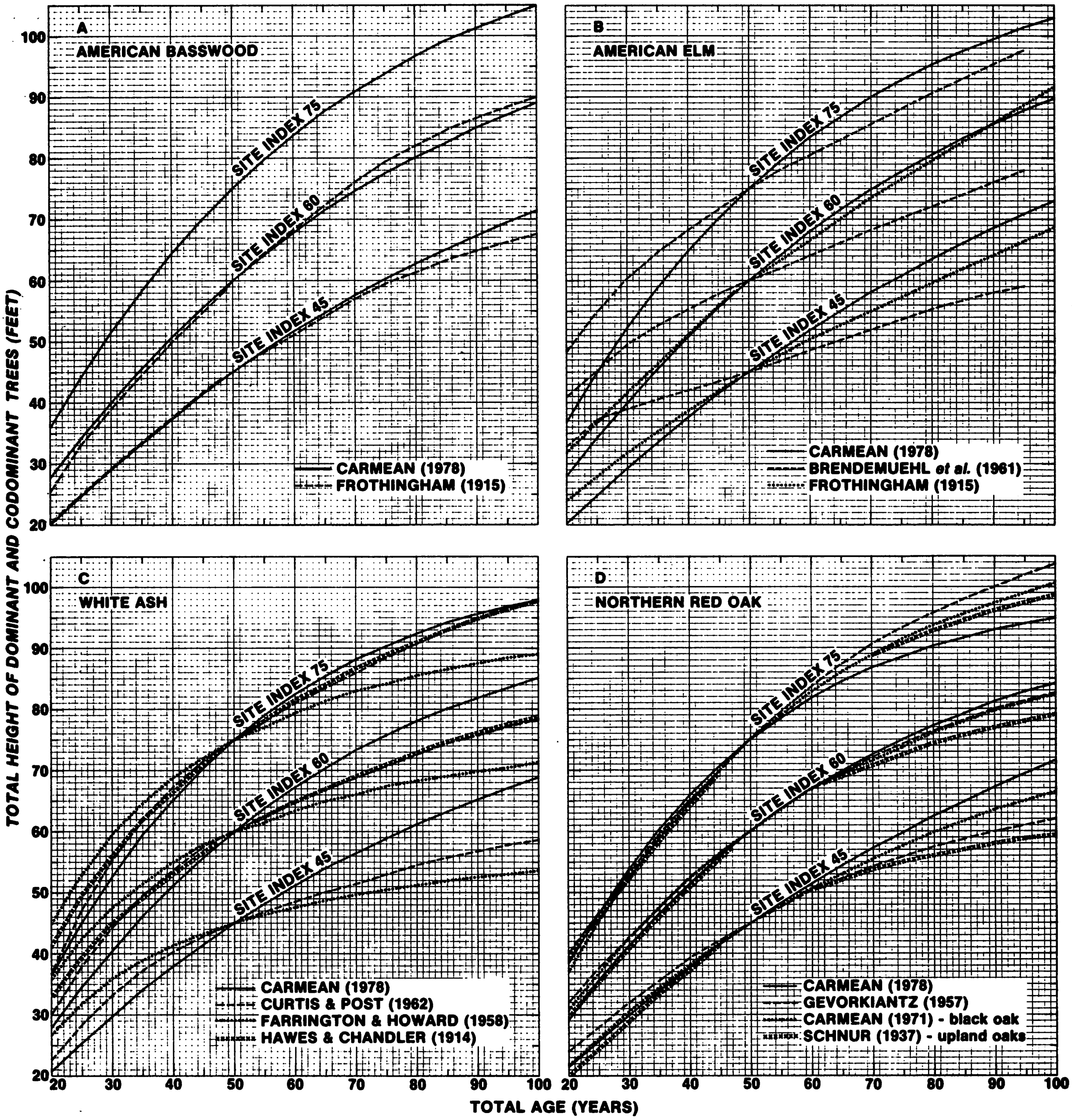

Figure 2.—*Site index curve comparisons at the poor (SI 45), medium (SI 60), and good (SI 75) site index levels for American basswood, American elm, white ash, and northern red oak.*

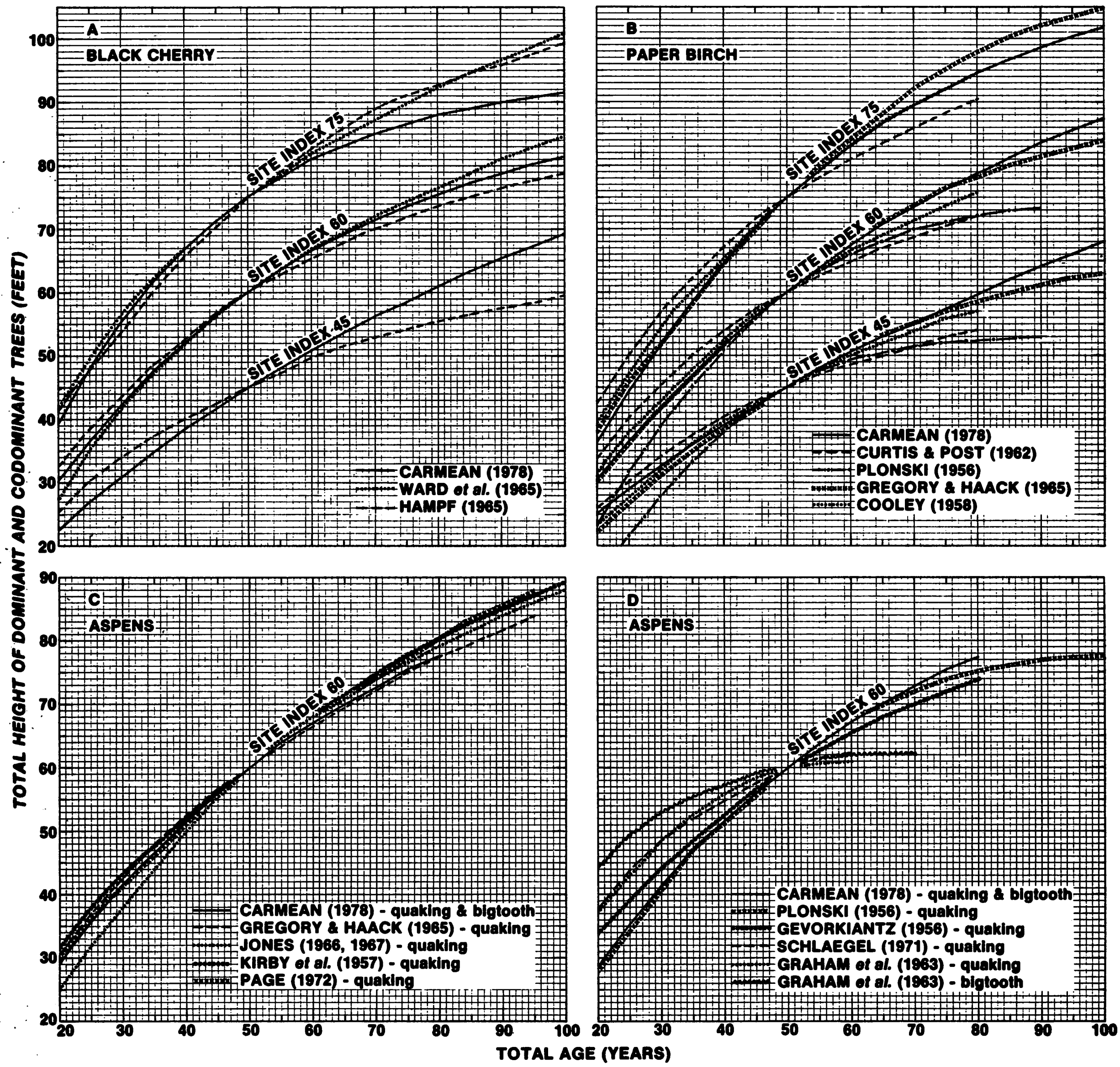

Figure 3.—*Site index curve comparisons at the poor (SI 45), medium (SI 60), and good (SI 75) site index levels for black cherry and paper birch. Site index curves also are compared at the medium (SI 60) site index level for bigtooth and quaking aspens.*

INVENTORY AND COMPARISON OF SITE INDEX CURVES FOR NORTHERN HARDWOOD SPECIES

The inventory revealed that many site index curves have been published for different portions of the large area covered by northern hardwood species (table 1). Also, many of these site index curves have been formulated so that rapid computer computations of site index can replace the slow and tedious interpolations required using site index graphs (Lundgren and Dolid 1970; Payandeh 1974a, 1974b, 1977; Monserud and Ek 1976).

New site index curves are now available for use in northern hardwood stands of northern Wisconsin and Upper Michigan (Carmean 1978). These new curves are based on stem analyses of 3,402 trees growing in even-aged stands on soils having a wide range of site index. Separate site index curves are given for 13 species, including curves combining data for quaking and bigtooth aspens, and the first site curves published for black ash.

Most of the new site curves have pronounced polymorphic height growth patterns. These results agree with previous studies that show many tree species have different height growth patterns for different levels of site quality, or in different parts of their range (Carmean 1970, 1975). The new site curves usually have similar height growth patterns before age 50, even though species such as American basswood, American elm, and the ashes grow more rapidly before that age. However, after age 50, pronounced differences in patterns of height growth usually are evident for species growing on medium and good sites.[2] These later differences in height growth are so great that accurate site index estimation requires separate sets of curves for each species.

The new site index curves for northern Wisconsin and Upper Michigan and the previous site curves were compared at the poor (SI 45), medium (SI 60), and good (SI 75) levels of site index (figs. 1-3). Comparisons also were made at the medium (SI 60) level of site index for quaking and bigtooth aspens (fig. 3C and 3D). Most of the previous site index curves used 50 years as the index age, and most are based on total tree age. However, a few curves used younger (Graham *et al.* 1963), or older (Curtis and Post 1962, Jones 1966, 1967) index ages. Some curves used breast height age instead of total age (Curtis and Post 1962, Jones 1966, 1967, Page 1972, Shetron 1972). Also, some studies do not give site index curves, but only single average height-age curves (Hawes and Chandler 1914, Frothingham 1915, Plonski 1956, Kirby *et al.* 1957, Farnsworth and Leaf 1963, Ward *et al.* 1965). These exceptions were considered and appropriate adjustments were made so that all site index curves could be compared using total tree age, and 50 years as the site index reference age.

[2]*Carmean, Willard H. Site index curves for northern hardwoods in the Lake States. (Unpublished manuscript on file at the North Central Forest Experiment Station, St. Paul, Minnesota.)*

Sugar Maple

Height growth for sugar maple (fig. 1A) has been studied more than for other northern hardwood species. However, three of the seven sugar maple curves (Hawes and Chandler, Frothingham, and Farrington and Howard) are harmonized curves based only on total height and age measurements, and are less accurate than the four curves based on stem analyses. Observe how the Hawes and Chandler, and the Farrington and Howard, curves show a much slower pattern of later height growth than the other curves. In contrast, for medium sites (SI 60) Frothingham's curve shows much more rapid height growth in later years than the other curves; for poor sites (SI 45) and older ages his curve agrees closely with mine.

The Farnsworth and Leaf stem analysis curves for southern New York only extend to about 60 years. Height growth during this period closely parallels the growth pattern of my curves and the Shetron curves for the Lake States. No information is available about height growth patterns after age 60 for sugar maple in New York.

The two curves for the Lake States (Carmean, Shetron) agree closely for medium sites (SI 60), but not for good (SI 75) and poor (SI 45) levels of site index. For good sites my curves show slower later height growth, and for poor sites my curves show faster, later height growth than predicted by Shetron's curves. Before 50 years our curves predict similar height growth, except for good sites where Shetron's curves predict somewhat slower growth than mine.

The differences between Shetron's curves and mine probably are due to his limited amount of data, and to differences in methods of computation. Shetron's curves are based on 15 plots with 25 trees ranging from about site index 43 to 64, while my curves are based on 177 plots with 721 trees ranging from site index 42 to 75. This larger data base over a wider range of site index enables me to better define the polymorphism associated with different levels of site. Furthermore, the nonlinear regression models I used allowed for full expression of polymorphism, whereas the simple quadratic regression model used by Shetron is not suited for expressing polymorhpic height growth.

The close fit between the two Lake States curves at the medium (SI 60) site index level indicates that height growth patterns in my study area are similar to growth patterns in northern lower Michigan. This is to be expected because the two areas have similar climate, soil, and topography. However, the more these conditions differ from my study area, the more caution should be exercised in applying my site curves to other areas.

The Curtis and Post site index curves for the Green Mountains of Vermont differ markedly from the height growth patterns for sugar maple in the Lake States. For both medium (SI 60) and poor (SI 45) sites, their curves predict much slower growth after 50 years than mine; for good sites (SI 75), their curves predict more rapid later growth than mine. For all levels of site index, the Curtis and Post curves predict more rapid growth before 50 years than predicted by the two Lake States curves. Apparently sugar maple in the White Mountains of New Hampshire also has a height growth pattern similar to sugar maple in the Green Mountains of Vermont because Solomon (1968) found that the Curtis and Post site index curves for sugar maple, yellow birch, white ash, and paper birch were applicable in New Hampshire.

These comparisons indicate that sugar maple in Vermont and New Hampshire may have more rapid early height growth, and slower later height growth than sugar maple in northern Wisconsin and Upper Michigan. But additional studies are needed to determine if this same height growth pattern occurs in other New England and Middle Atlantic States where climate, soil, and topography are different from the mountains of Vermont and New Hampshire. Studies also are needed in eastern Canada and in the Appalachian Mountain region to determine height growth patterns and the possible need for separate site index curves.

The polymorphic nature of my site curves is the major reason why they do not agree in later years with the Curtis and Post curves, or with the Shetron curves. Both of the latter curves have an anamorphic pattern of height growth, i.e., the curves have the same shape at all levels of site index. In contrast, my polymorphic curves have different shapes for different levels of site index. As a result, even though my curves agree with Shetron's curves for medium sites, the agreement for other sites is poor due to this polymorphism. Such results emphasize the need to compare site index curves for all sites, not just medium sites. These results also show the need for height growth data at all levels of site index and the need for equation models that will adequately express polymorphic height growth.

Red Maple

Height growth data for red maple (fig. 1B) is limited, and the only previous site curves are those of Hampf. Hampf's curves are based on stem analysis data reported by Foster (1959) for 71 trees located in old fields of northern Connecticut, western Massachusetts, and eastern New York; Hampf extrapolated these curves to 100 years even though Foster's average height-age curve extended only to 60 years. Solomon (1968), using stem analyses for 18 red maples in New Hampshire, concluded that Hampf's site curves could be used with acceptable accuracy for trees older than 40 years. But adjustments were suggested for younger ages because the Hampf curves apparently predicted more rapid early height growth than Solomon observed for red maple in New Hampshire.

Comparisons between my curves and the Hampf curves indicate that both red maple and sugar maple in the northeast may grow more rapidly in early years and more slowly in later years than do maples in the Lake States. My red maple curves predict exceptionally rapid later height growth on good sites, but the accuracy of Hampf's projected pattern of later height growth is questionable because Foster's original data extended only to 60 years.

My red maple curves probably are applicable to northern lower Michigan where climate, soil, and topography are similar to conditions in my study area. However, red maple has a very wide range so more studies in other areas are needed before my curves can be applied with confidence elsewhere. Special efforts should be made to accurately determine the pattern of later height growth on good sites.

Yellow Birch

Four curves were found for yellow birch (fig. 1C), but two of these (Hawes and Chandler, Frothingham) are single average curves that are based only on measurements of total height and age. The Hawes and Chandler curve predicts exceptionally rapid early height growth, and exceptionally slow later height growth. In contrast, the Frothingham curves predict exceptionally rapid later height growth.

The Curtis and Post curves for Vermont, which also are applicable in New Hampshire (Solomon 1968), differ markedly from the height growth patterns for yellow birch and other species in the Lake States. As for sugar and red maple, the Curtis and Post curves predict faster early height growth than do mine. After 50 years, their curves predict slower growth than mine on medium (SI 60) and poor (SI 45) sites; for good sites (SI 75) their curves predict faster later height growth than mine.

As discussed earlier, many of the curve differences on good and poor sites are due to the polymorphic nature of my curves in contrast to the anamorphic nature of the Curtis and Post curves. My yellow birch curves have a particularly strong polymorphic growth pattern resulting in a pronounced slowing in later height growth for trees on good sites, in contrast to the more linear and sustained later height growth for trees on poor sites.

American Beech

Only four site curves were found for American Beech (fig. 1D); of these, only my curves are based on stem analyses. My curve for poor sites (SI 45) is similar to Frothingham's height-age curve, but his curve for medium sites (SI 60) predicts more rapid later height growth than mine. The Hawes and Chandler curves predict unusually rapid early height growth; after 50 years their curves and the Hampf curves predict very slow height growth.

I found that even though beech has a slow early height growth, this growth is sustained in later years resulting in a more linear height growth pattern than for other hardwood species. This slow early height growth for beech produces site indices averaging about 5 to 15 feet shorter than for other species (Carmean 1979). As a result rarely do we find beech having high site indices. The highest beech site index observed in my study was 61 feet. Frothingham, and Hawes and Chandler only give curves for medium and poor sites; they also apparently found few high site indices for beech. Only Hampf gives a curve for good (SI 75) beech sites, but his curve may be an extrapolation beyond observed site conditions.

American Basswood

The only previous site curves for basswood (fig. 2A) are based on average height-age data from northern Wisconsin and northern Michigan. These curves predict early height growth similar to mine, but after 50 years the Frothingham curves predict somewhat faster height growth on medium sites (SI 60), and somewhat slower growth on poor sites (SI 45). Frothingham apparently had few observations for good sites judging from the rather slow growth shown by his average height-age curve.

American Elm

Frothingham's curves (fig. 2B) are based on a single average height-age curve. The Brendemuehl *et al.* harmonized site curves for Iowa are based on total height and age values; they also included some measurements of slippery elm (*U. rubra* Muhl.). My curves appear similar to Frothingham's Lake States curve at the medium (SI 60) site index level, but at the poor (SI 45) site index level his curve predicts slower later growth than mine. The Brendemuehl *et al.* curves shows exceptionally rapid early height growth, and exceptionally slow later growth for all sites. Possibly part of the reason for these differences is that my study area has climate and soil very different from the bottomland soils studied in Iowa. These climate and soil differences may result in a different rate of early height growth, and also in different patterns of tree height growth.

White Ash

The Hawes and Chandler curve (fig. 2C), and the Farrington and Howard harmonized site index curves, are based only on total height and age measurements; the Curtis and Post curves and my curves are based on stem analyses. The Farrington and Howard curves predict unusually rapid early height growth, and unusually slow later height growth for all sites. In contrast, the two Vermont curves (Hawes and Chandler, Curtis and Post) are similar for medium (SI 60) and good (SI 75) sites. My curves predict slower height growth before 50 years, and more rapid later height growth than do any of the other three white ash curves. After 50 years on good sites, my curve is fairly similar to the growth predicted by the Curtis and Post curves. However, for medium sites the Curtis and Post curves predict considerably slower later growth than my curves; for poor sites these differences are even more pronounced.

Northern Red Oak

The only previous curves for northern red oak (fig. 2D) are the harmonized site index curves of Gevorkiantz. At the medium (SI 60) site level his red oak curves agree fairly well with my red oak curves, and, with my stem analysis curves for black oak (*Q. velutina* Lam.) in the Central States. But the older generalized site index curves for all species of oak (Schnur 1937) predict slower later growth for both medium (SI 60) and poor (SI 45) sites than do the other three curves.

The close agreement for medium sites observed between Gevorkiantz's curve and my red oak and black oak curves does not occur for good (SI 75) or poor (SI 45) sites. For good sites my red oak curve predicts slower height growth after 50 years; and for poor sites more rapid later height growth. The reason for these differences at good and poor site levels is that my red oak curves have pronounced polymorphism, my black oak curves have less polymorphism, and the Gevorkiantz curves have only a single anamorphic pattern of height growth.

Black Cherry

My curves agree fairly well with the Ward *et al.* stem analysis curves (fig. 3A), and with the Hampf harmonized curves at the medium (SI 60) level of site index. But for poor sites (SI 45) Hampf's curves predict much slower later height growth than mine, and for good sites (SI 75) both the Hampf and the Ward *et al.* curves predict much more rapid later height growth than predicted by my curves. Data from the Northeast and the Appalachians are limited, thus additional height growth studies are needed for this prized tree.

Paper Birch

Cooley's curves are based on total height-age data and on harmonizing methods, and the other four curves are based on stem analyses (fig. 3B). Comparisons at the medium (SI 60) and poor (SI 45) site index levels show that the previous curves predict slower later height growth than mine; the Plonski curves, and the Curtis and Post curves predict particularly slow later height growth at all levels of site index. In contrast, comparisons at the good (SI 75) site index level show very close agreement between my curve and the Cooley curve; the Gregory and Haack curve for Alaska predicts later height growth that is somewhat more rapid than predicted by mine.

Paper birch has a very wide geographical range covering diverse climatic, topographic, soil, and site conditions. Throughout this wide range site, quality differs greatly as do patterns of height growth (fig. 3B). I recommend many additional stem analyses leading to the construction of polymorphic site index curves for paper birch.

Aspens

My data are limited so all quaking and bigtooth aspen stem analysis data were combined and a single set of aspen site index curves were computed. Because data were limited, polymorphic height growth for aspen was not expressed as well as for other hardwood species, so comparisons (figs. 3C and 3D) are made only for the medium (SI 60) sites.

A greater number of site index curves are available for quaking aspen than for the other northern hardwood species. Of the 9 curves, 4 are harmonized curves (Gevorkiantz, Graham *et al.*, Kirby *et al.*, Page); Schlaegel's curves are based on repeated height measurements from permanent growth plots; the remaining 4 curves are based on stem analyses (Plonski, Gregory and Haack, Jones, Carmean).

My curves combining quaking and bigtooth aspen data agree well with the Gregory and Haack quaking aspen curve for Alaska. Jones' curve for the Rocky Mountains, the Kirby *et al.* curve for Saskatchewan, and the Page curve for Newfoundland, all predict more rapid later growth than mine (fig. 3C). Aspen in the Rocky Mountains is known to be longer-lived than in the Lake States, thus perhaps explaining this more sustained later height growth. In contrast, Plonski's curve for Ontario, and Gevorkiantz's curve for the Lake States, predict slower later height growth than mine (fig. 3D).

Growth prior to 50 years is similar for most quaking aspen site curves. An exception is Jones' curve for the Rocky Mountains that predicts slower earlier height growth than all the other curves; more rapid early height growth also is predicted by the Gevorkiantz, the Schlaegel, and the Graham *et al.* curves.

The Graham *et al.* curves for both quaking and bigtooth aspen, and the Schlaegel quaking aspen curves, have a height growth pattern unlike the other site curves (fig. 3D). A possible explanation for the abrupt slowing shown by the Graham *et al.* curves is that only 11 of their quaking aspen trees were older than 50 years, and 10 of these trees were on poor sites; for bigtooth aspen only 6 trees were older than 60 years, and 5 of these were on poor sites. This abnormal concentration of older trees on poor sites is a common reason for the unrealistic downwarping in later years often shown by harmonized site index curves. The abrupt slowing shown by the Schlaegel quaking aspen curve might be due to few observations for older trees. His curves are based on 34 permanent sample plots from a small geographic area of north central Minnesota that has a limited range of soil conditions and site quality.

Quaking aspen has an extremely wide range that includes a vast variety of climates, topography, soil, and site conditions. These variable conditions probably account for much of the differences between shapes of site index curves illustrated in figures 3C and 3D. Clonal variation in both quaking aspen (Jones and Trujillo 1975) and bigtooth aspen (Zahner and Crawford 1965) also cause large differences in height growth. Other reasons for different patterns of height growth might be related to growth of aspen in pure stands in contrast to growth in mixed stands of other species such as were involved in my studies.

DISCUSSION AND RECOMMENDATIONS

1. Many site index curves are available for northern hardwood species. However, most of the early site curves are harmonized curves not based on stem analysis methods, and these curves are not usually precise enough for modern, intensive forest management. Harmonized site index curves should be considered questionable until we determine how well their predicted height growth agrees with actual growth observed for local climatic, soil and site conditions. If site index curves are lacking, or if existing curves are inaccurate or are not representative, new site index curves should be constructed that will accurately describe tree height growth for local areas where northern hardwoods occur.

2. Comparisons of the many northern hardwoods site index curves reveal pronounced differences in predicted patterns of height growth. These differences can occur at all ages and at all levels of site quality, thus illustrating that site index curve comparisons should be made for all sites rather than only for medium sites.

Some of the differences are due to limited data from limited conditions of soil and site quality. Field measurements and computation methods often are inadequate for expressing polymorphic patterns of height growth. Also, many of the differences between curves may be due to actual differences in height growth for areas contrasting in climate, topography, soil, and site quality. Such major differences in patterns of height growth need to be better defined because they are important in accurately estimating site quality, future yields, rotation lengths, and intensity of timber management.

3. Future site index curves for northern hardwoods, as well as for other tree species, should be based on stem analysis methods, internode measurements, or on observations from permanent growth plots. Data for these studies should fully represent the conditions of climate, soil, topography and site quality of the study area. Standardized methods of data collection are needed, and computation methods should be used that permit an adequate expression of polymorphic patterns of height growth.

SUMMARY

The present paper inventories the site index curves for 13 northern hardwood species including sugar maple, red maple, yellow birch, American beech, American basswood, American elm, white ash, black ash, northern red oak, black cherry, paper birch, quaking aspen, and bigtooth aspen. Graphical comparisons of these site index curves at the good, medium, and poor levels of site index illustrate the variability of height growth in various portions of the range of most of these species. These comparisons also are used for discussions and recommendations about the suitability of existing curves, and the need for more precise site index curves that are applicable to local soil and site conditions.

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Shhhh...noise pollutes too!