Preliminary Site-Quality Evaluation Tools for the Hardwood Forests of Central Ontario

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M.Sc.F. Thesis

Faculty of Forestry and the Forest Environment

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PRELIMINARY SITE-QUALITY EVALUATION TOOLS FOR THE HARDWOOD FORESTS OF CENTRAL ONTARIO

By

Nick Buda

A graduate thesis submitted in partial fulfillment of the
Requirements for the degree of Master of Science in Forestry

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ABSTRACT

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Key Words: American beech (*Fagus grandifolia* Ehrh.), hardwoods, height-growth models, red oak (*Quercus rubra* L.), site form, site index, site quality, site-quality evaluation, sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula alleghaniensis* Britton)

There are currently no locally-derived, quantitative site-quality evaluation tools available for major tree species in the tolerant hardwood forests of central Ontario. To estimate potential site productivity, site-index curves from the Lake States and a preliminary set of site-form curves for sugar maple are currently being used. Whether these tools are applicable to central Ontario is of concern. The use of site index as a site-quality evaluation tool in uneven-aged mixed-species stands is also questionable. It is also possible site form may not be a valid measure of forest site quality in these types of stands either.

A random sample of 62 pure and mixed-species stands with a variety of age-class structures in central Ontario yielded stem analyses data and stand structure information for sugar maple (*Acer saccharum* Marsh.), American beech (*Fagus grandifolia* Ehrh.), yellow birch (*Betula alleghaniensis* Britton) and red oak (*Quercus rubra* L.). An exploration of height-growth patterns for each species as a function of age and diameter revealed pronounced differences in shape (polymorphism) of height-age curves for all species with changes in site quality. Polymorphism was also evident for suppressed vs. free-growing sugar maple trees, and for sugar maple growing in even- vs. uneven-aged stands and pure vs. mixed-species stands. Differences were less pronounced in height-diameter curves for all species.

Preliminary height-growth and site-index equations and curves were developed for sugar maple, American beech, yellow birch and red oak. The central Ontario data, and curves from this study, were then used to examine the applicability of site-index curves for these species from the Lake States to central Ontario. The Lake States curves were shown to differ substantially from those developed in this study, and were inaccurate in application to data from central Ontario. A preliminary assessment of age and stand structure and species mixture impacts on sugar maple height-growth and site index, and forest floor chemistry, revealed no significant differences in sugar maple site index between stands of different composition or age-class structure, and minor differences in forest floor chemistry between stands of different species composition.

Preliminary height-growth and site-form equations and curves were also developed for these species. The curves for sugar maple were used to validate existing preliminary curves for sugar maple in Ontario. The curves in this study differed substantially from the preliminary curves and the existing curves were shown to be inaccurate in application to data from this study. An examination of site form as a site productivity measure in uneven-aged, mixed-species stands using data from this study revealed it was unrelated to site index, basal area or ecological variables known to affect forest site quality for these species.

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NJB, February 2004

CHAPTER 1: INTRODUCTION TO THE THESIS

1.1 INTRODUCTION

Mixed hardwood forests occupy some 3.6 million hectares across the Great Lakes-St. Lawrence and Deciduous forest regions in Ontario (Anderson *et al.* 1998), and their importance to the two regions cannot be understated. They provide a number of benefits to the public, including wildlife habitat, recreational opportunities and jobs through the local forest industry. Due to the significance of many forest products in these regions (Anderson *et al.* 1998), it is important that the forests are managed in an economically and ecologically sustainable manner that is socially acceptable.

To achieve sustainable forest management and meet the requirements of the *Crown Forest Sustainability Act*, Ontario has developed a number of tools to assist government, industry and other interest groups in the development and implementation of optimal forest management plans. These management plans are most successful when they are able to balance the needs of industry and the public, as well as environmental and wildlife concerns in a manner that minimizes conflicts while sustaining all forest values. Tools such as the Sustainable Forest Management Model (SFMM) are instrumental to the planning process.

An integral part of applying tools such as SFMM is the identification of forest sites most suitable for the various forms of forest use and development. Additionally, foresters require methods of evaluating which of the forest lands available to them are most productive in order to determine which species to manage on different sites, along with the appropriate level of management intensity.

Forestry in Ontario is rapidly evolving toward this "site-specific management", with the most intensive silvicultural and timber management practices concentrated on the most productive and accessible sites (Carmean 1996). Much of the forest land in central Ontario is close to major population centres, and foresters need to select and prioritize management of forest lands for a variety of purposes, while market demands for high-value forest products are increasing (Natural Resources Canada 2003). As more land is set aside for parks, reserves and urban development, less is available for commercial forestry. Foresters must therefore produce greater yields from less land.

Forest site quality evaluation - analogous to land-capability estimation in agriculture (Carmean 1996) - is therefore extremely important. Site-quality evaluation refers to the estimation of the capability of forest land for growing trees (Carmean 1996).

Unfortunately, many of the site quality evaluation tools available to foresters in other areas have not been satisfactorily developed for the mixed hardwood forests in central Ontario (Woods *et al.* 1998). Foresters instead have to rely on techniques and information derived from other regions such as the Midwestern United States. While many of these techniques are sound, their validity in application to central Ontario needs to be tested. What is unequivocally needed is a set of original, locally-derived site-quality estimation tools to provide foresters with a solid basis for management decisions, and to determine the applicability of site-quality evaluation techniques derived in other areas to central Ontario.

Hardwood tree species such as sugar maple (*Acer saccharum* Marsh.), red oak (*Quercus rubra* L.), American beech (*Fagus grandifolia* Ehrh.) and yellow birch (*Betula alleghaniensis* Britton) comprise a major component of the forest tree species in this region, contributing 43%, 4%, 11% and 3% respectively of the total harvest of tolerant hardwoods in the region (Anderson *et al.* 1998). As such, adequate growth and yield data for these species are important if foresters are to manage them responsibly. A shortfall currently exists in local growth and yield forecasting tools for these species in central Ontario. There is an overwhelming need for this to be addressed.

In 2001, Ontario's Living Legacy funded a project under the auspices of Lakehead University to investigate and develop preliminary forest site-quality evaluation tools for mixed hardwood stands in central Ontario. This thesis constitutes a major portion of that study; its general structure, objectives and hypotheses are summarized below.

1.2 THESIS OVERVIEW

This thesis is organized into five chapters. The objectives and hypothesized outcomes for each chapter are as follows:

1. General introduction to the project, including background information on site-quality evaluation in the region, thesis overview and brief summary of the critical silvics and autecology of major tree species included in the thesis study.
2. Development and examination of height-growth models, based on age and diameter, for sugar maple and other major species in central Ontario's hardwood forests. General growth models for each species are presented along with results of a qualitative examination of height-growth patterns for a variety of tree and stand conditions. Height-age patterns were expected to be more affected by variables such as age-class structure and suppression, while height-diameter relationships were expected to be less affected. Height-diameter relationships were also expected to be less affected by variations in forest site quality. Such an investigation is important since it provides a preliminary indication of the suitability of utilizing various methods of site-quality evaluation for species in the region.

3. Development and validation of local site-index (height-age) curves and equations for sugar maple and other major tolerant hardwood species in central Ontario. Since site-index is the most widely-accepted method of forest site quality evaluation in North America, preliminary height-growth models based on age and site index were developed and validated for four major hardwood species in the region. These models were used to investigate the applicability of site-index models developed in the Lake States region to central Ontario. In addition, a preliminary investigation into the effects of species composition on sugar maple site index was carried out. Due to differences in site types and stand history, the Lake States site-index models were expected to differ substantially from the local models, and thus be inapplicable in the region. In addition, substantial effects on sugar maple site index were expected as a result of species composition.
4. Development and validation of local site form (height-diameter) curves and equations for sugar maple and other major hardwood species in central Ontario. Site form is a relatively new method of site-quality evaluation that has been touted as suitable for uneven-aged, mixed species stands such as those prevailing in central Ontario. Accordingly, preliminary height-growth models as a function of dbh and site-form were developed and validated for four tolerant hardwood species. The site form curves for sugar maple were compared to those developed in another study in the same region. In addition, the viability of using site form as a measure of forest site quality in the region was examined. Site form was expected to be proven a less adequate measure of forest site quality than site index.
5. Conclusions. The results of this study are summarized and recommendations are made for future research.

1.3 SILVICS OF MAJOR TOLERANT HARDWOODS

1.3.1 Sugar Maple

Sugar maple is a characteristic tree in the hardwood forests of central Ontario (Farrar 1995). Reproducing aggressively, sugar maple can occur in pure or mixed, even- or uneven-aged stands on a variety of upland sites in the region. In uneven-aged stands, sugar maple is commonly associated with American beech on fresh sites and yellow birch on moist sites. In relatively even-aged stands, sugar maple can occur with less shade-tolerant species such as black cherry (*Prunus serotina* Ehrh.), white ash (*Fraxinus Americana* L.), basswood (*Tilia Americana* L.) or yellow birch (Anderson *et al.* 1998).

Sugar maple can grow in relatively acidic soils over a range of moisture and texture classes, but tends to perform best on well-drained loams with a comparatively neutral pH. The best quality timber and highest yields come from sites with a moisture regime of 2 (fresh) to 3 (very fresh) (Godman *et al.* 1990, Anderson *et al.* 1998).

Being shade tolerant, sugar maple exhibits good response to release in both height and diameter growth, even after long periods of suppression (Farrar 1995, Anderson *et al.* 1998). Immature trees display the most elastic growth responses (Anderson *et al.* 1998). Sugar maple's ease of reproduction, shade tolerance and response to disturbance make it quite suitable for the single-tree selection silvicultural system (Anderson *et al.* 1998), which is commonly employed in hardwood forest management in central Ontario (Corlett *et al.* 1998).

Sugar maple is of enormous commercial importance in central Ontario, accounting for 43% of the total 0.65 million m^3 tolerant hardwood harvest in 1988-89 (Anderson *et al.* 1998) Its wood is used for furniture, flooring, toys, cabinetwork, veneer, plywood, turned woodenware and cutting blocks (Farrar 1995).

1.3.2 Red Oak

Though moderately shade-tolerant when young, mature red oak is somewhat shade intolerant when compared to other central Ontario hardwoods (Farrar 1995). Red oak grows best on fresh to moist, well-drained soils in coves and middle or lower slope positions. The very best sites for red oak in central Ontario are characterized by fresh, loamy soils, though it is found more frequently on drier, coarser-textured sites in the region (Anderson *et al.* 1998). In addition, red oak tends to occur in stunted forms on dry, rocky ridges along the northern limit of its range (Farrar 1995), as with much of the oak in Algonquin Park (Fletcher 2003).

Red oak does not survive for more than a few years under a dense canopy, especially during establishment, but will respond well to release from moderate suppression (Sander 1990). In central Ontario, group selection and shelterwood silvicultural systems are typically favoured (Anderson *et al.* 1998).

Red oak is in demand for furniture, flooring, veneer and a number of other high-value forest products (Sander 1990). It accounted for 4% of the tolerant hardwood harvest by volume in 1988-89 (Anderson *et al.* 1998).

1.3.3 Yellow Birch

Yellow birch occurs on a comparatively wide range of ecosites in central Ontario, and typically forms a dominant part of the forest canopy on fresh to wet, moderately fertile to rich sites when it occurs. As an early successional species it depends on disturbance for regeneration, and so is typically replaced by shade-tolerant species such as sugar maple over time in undisturbed stands (Anderson *et al.* 1998).

Yellow birch thrives most commonly in pure, even-aged stands following a fire or other disturbance. On upland sites it can occur mixed with other hardwoods or conifers

(Anderson *et al. 1998*). In hardwood stands in central Ontario, yellow birch is most commonly associated with beech and sugar maple (Farrar 1995); beech usually replaces it in association with sugar maple on dry to fresh sites (Anderson *et al.* 1998).

Though opinions differ, possibilities for managing yellow birch include shelterwood systems for even-aged management or group selection systems when it is being managed with uneven-aged sugar maple (Anderson *et al.* 1998, Wang 2003).

Yellow birch wood has high-value as a source of hardwood lumber in eastern Canada, and is in demand for value-added forest products such as furniture, cabinetwork, flooring, doors, veneer and plywood (Farrar 1995).

1.3.4 American Beech

Though it occasionally forms pure stands, American beech is most often found in uneven-aged mixtures with sugar maple, yellow birch and hemlock (Anderson *et al.* 1998). It is a commonly observed secondary component of uneven-aged sugar maple stands.

Beech survives for a very long time and is very shade tolerant and slow-growing (Farrar 1995). Pure stands of beech are rare in central Ontario; rather, it is a common associate of sugar maple. In this region, it occurs on a variety of soils but grows best on fertile, well-drained, fresh, loamy soils, especially those with high humus incorporation (Anderson *et al.* 1998).

Beech wood is used for flooring, furniture, containers, handles and woodenware; beech nuts are a favoured food of many birds and animals (Farrar 1995). The generally low timber quality of beech often makes it a target for removal in stand improvement cuts, especially in single tree selection systems. Only a few trees may be retained to ensure the presence of beech regeneration in the understory and a food source for wildlife (Corlett *et al.* 1998).

CHAPTER 2: GENERAL QUALITATIVE HEIGHT-GROWTH MODELS

2.1 INTRODUCTION

This portion of the thesis details a qualitative investigation of general height-growth models for sugar maple, American beech, yellow birch and red oak in central Ontario. This part of the study was intended as an exploration of the general height-growth patterns for each species across the study area, for a variety of stand conditions and site types. Height-age and height-dbh relationships are examined in an effort to determine the relative merits and weaknesses of each as possible methods of forest site-quality evaluation. In addition, some basic forest management implications of the observed relationships are discussed.

2.2 LITERATURE REVIEW

2.2.1 Importance of Height-Growth Models

The vast majority of forest growth and yield studies incorporate measurements or estimates of tree height growth, largely due to its importance as a parameter in estimating tree volume (Philip 1994). Individual tree heights are an important forest inventory measure for calculating and estimating timber volumes as well as site indices (Martin and Flewelling 1998). Tree height data are also becoming important for characterizing and assessing forest and stand structure and diversity for a variety of non-timber forest values, including biodiversity and wildlife habitat suitability (Martin and Flewelling 1998; Woods *et al.* 1998).

Tree height growth is commonly related to age and diameter. The relationships between these two variables and height are particularly useful in forest inventory and growth and yield studies (Philip 1994). They allow foresters to directly measure or estimate a number of present and future characteristics (e.g. volume and yield) about the forest crop.

Tree height-age relationships have a number of uses in forest growth and yield, including estimation of forest site quality (Carmean 1996; Nigh and Sit 1996; Nigh 1998; Chen *et al.* 1998), time to green-up estimates (an important parameter in timber supply analyses) (Nigh and Courtin 1998), prediction of tree top height on sites with known site index (Chen *et al.* 1998) and anticipation of future values of a number of forest parameters including volume, yield and growth increments (Philip 1994). In addition, height-age relationships are used to quantify and estimate the development of forests over time and determine annual allowable cut and rotation length.

Tree height-diameter relationships, and height-diameter at breast height (ht-dbh) in particular, also have a number of important uses in forest growth and yield. Diameter observations or estimates are necessary for accurate estimation of volume at the individual tree, stand and broader scales (Philip 1994). Because height is often a time consuming variable to measure compared to other inventory data (i.e. diameter), has a great chance of observer error, and may be inhibited by visual obstructions, subsampling of heights is now common practice (Martin and Flewelling 1998; Colbert *et al.* 2002). As a result, average tree height-diameter relationships are often used to complete forest inventory datasets by predicting unknown tree heights (Colbert *et al.* 2002). In addition, these relationships can be used to calibrate local volume tables to different stand conditions (Philip 1994, Martin and Flewelling 1998, Colbert *et al.* 2002). Height-dbh relationships have been used to quantitatively assess forest site quality (Stout and Shumway 1982; Vanclay and Henry 1988; Huang and Titus 1993). Finally, height-dbh relationships are commonly used to develop and measure the effects of forest management activities and silivicultural prescriptions such as thinning (Tubbs 1977).

2.2.2 Height-Growth Models for Hardwoods in Ontario

Height growth models have been developed for a number of species and purposes for hardwood forests in Ontario. A number of height growth models used for assessing forest site quality, assisting in silvicultural prescriptions and making stand-level forest management decisions have been summarized (OMNR 1998). A general height-age curve for assessing forest site quality of tolerant hardwoods has been presented (Plonski 1960), along with an associated height-growth model (Payandeh 1974). More recently, a number of height-diameter models in their application to boreal forest species, including yellow birch were assessed (Peng *et al.* 2001). Jayaraman and Zakrzewski (2001) developed an approach to calibrating height-diameter models for natural sugar maple stands in Ontario.

None of the above studies included a direct comparison between height-age and height-dbh characteristics of central Ontario hardwood species. While height-age relationships have been used in forest site-quality evaluation (see above), only one study (OMNR 1998) has utilized height-dbh relationships in this manner. In addition, the suitability of height-age and height-dbh relationships for site-quality evaluation in central Ontario's uneven-aged, mixed-species stands has not yet been investigated beyond theoretical discussion.

2.3 OBJECTIVES AND HYPOTHESES

2.3.1 General Height-Growth Models

Though species-independent height-age models have been developed for some regions (Nigh 2001), including tolerant hardwoods in Ontario (Plonski 1960; Payandeh 1974), it is generally recognized that height-growth patterns are often species-specific, particularly when trees are adapted to different ecological niches and react differently to abiotic factors such as suppression or shading (Lanner 1985; Carmean *et al.* 1989). A preliminary qualitative investigation was therefore undertaken to develop general height-growth models based on age and diameter at breast height for sugar maple, American beech, yellow birch and red oak.

Forest tree height-age and height-dbh relationships are known to be influenced by a number of factors, including site quality (Carmean 1975, 1978, 1996; Nigh 1998; Stout and Shumway 1982; Huang and Titus 1993; Philip 1994; Jayaraman and Zakrzewski 2001), management and silvicultural practices (Smith *et al.* 1997; Philip 1994; Carmean 1996), stand dynamics factors such as density or canopy position (Smith *et al.* 1997; Raulier *et al.* 2003), age structure (Woods *et al.* 1998), species composition (Longpre *et al.* 1994; Carmean 1996; Wang 1998) and a number of other biotic (Lanner 1985) and abiotic factors.

Accordingly, the qualitative effects of some of these factors (summarized below) on tree height-age and height-dbh growth patterns were investigated by developing and comparing different height-growth models for sugar maple, American beech, yellow birch and red oak. Models were developed and examined by species.

2.3.2 Different Levels of Forest Site Quality

Tree height growth patterns are known to be polymorphic (different in shape) for most species across differing levels of forest site quality (Carmean and Lenthall 1989; Carmean 1996; Chen *et al.* 1998). Trees on rich sites generally exhibit rapid early initial height growth followed by a rapid slow down as the curve approaches an asymptote; trees on poor sites typically show a more linear pattern in height-growth curves (Carmean 1996). This relationship may not necessarily hold true for all tree species, and anamorphic (similarly-shaped) height-growth curves may be adequate to describe height-growth of some forest tree species (Nigh and Courtin 1998). Height-diameter curves in particular may be more anamorphic for species growing on different sites (Huang and Titus 1993).

Sites were classified into good, medium or poor sites on the basis of soil/site characteristics, overall stand vigour and observed site index. Separate height-growth models were developed by species for each level of site quality and examined for these expected differences in height-growth patterns.

2.3.3 Height-Growth Differences Between Species

Sugar maple is commonly the dominant component of mixed hardwood stands in central Ontario (Chambers *et al.* 1997; Anderson *et al.* 1998), while American beech is commonly present in the understory before being released and forming part of the upper canopy (Anderson *et al.* 1998). In addition, the species have different autecological characteristics, and may use available nutrients and soil horizons on the same site differently (Godman *et al.* 1990). Accordingly, one would expect the height growth curves for each species growing on similar sites to be different.

Height-growth patterns for sugar maple and American beech growing on the same site were examined for evidence of the above pattern; height-growth models for free-growing and suppressed sugar maple trees were also developed and examined. The findings were used to qualitatively assess the viability of using height-age and height-dbh models as methods of site-quality evaluation in these types of stands.

2.3.4 Even-Aged vs Uneven-Aged Height Growth Models

Because sugar maple is shade tolerant and can respond well to release even after long periods of suppression (Anderson *et al.* 1998), it is likely that height-age models for even-aged stands (where main canopy trees have developed together with equal access to light over time) would differ considerably from those of uneven-aged stands where many dominant trees may have been suppressed for long periods of time before release (Raulier *et al.* 2003). It is likely that tree form (the height-dbh relationship) would be less affected (Shout and Shumway 1982, Vanclay and Henry 1988). Accordingly, height-growth curves were also developed separately for trees occurring in even-aged and uneven-aged stands.

2.4 METHODS

2.4.1 Study Area and Field Data Collection

Stands used in developing height growth models were sampled across central Ontario near the southwestern limit of the Great Lakes-St. Lawrence forest region, and included portions of the Algonquin-Pontiac (L4b), Georgian Bay (L4d) and Sudbury-North Bay (L4e) Forest Sections (Rowe 1972). The study area was subdivided on the basis of administrative convenience into three sections: Haliburton Forest and Wildlife Preserve; the southern half of Algonquin Provincial Park; and the portion of crown forest extending north from Huntsville to North Bay, and west from Algonquin Park to Parry Sound. This area occupies parts of Hills (1959) Site Regions 4E and 5E (Figure 2.1).

Forest Resources Inventory (FRI) maps from crown, commercial and private forests, Permanent Sample Plot (PSP) databases (OMNR) and landowner knowledge were used to identify candidate stands across the study area. An effort was made to ensure representation of a variety of stand conditions across the whole range of site types and site quality over which sugar maple occurs in the region. A random selection was made from the candidate stands in each administrative region. Listed stands were deliberately visited and sampled,

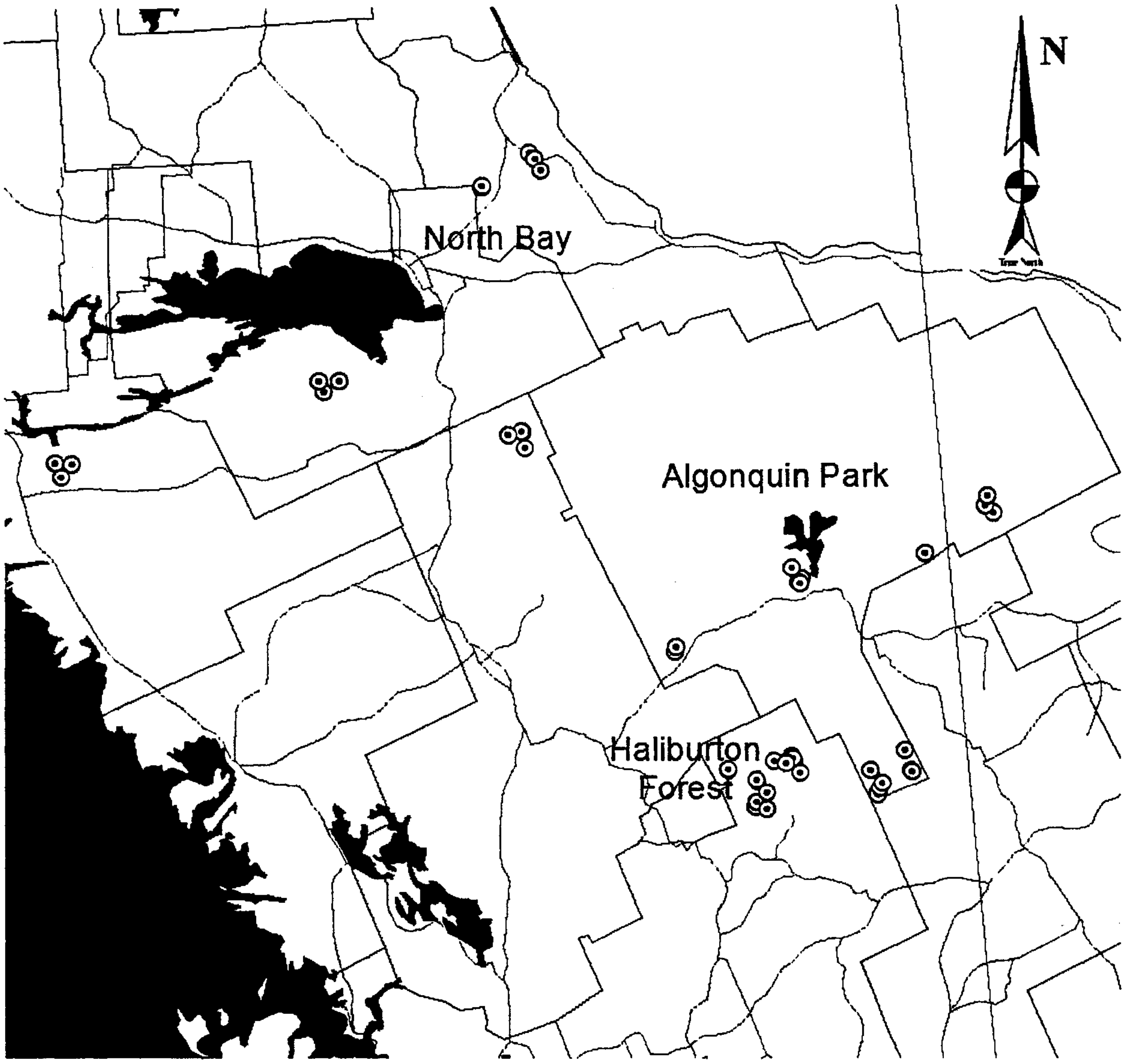

Figure 2.1: Study area map showing approximate plot locations. 1:100000 (approximate).

until at least three each of good, medium and poor sites[1] for sugar maple were sampled in both managed and unmanaged stands, in each administrative region. Other major hardwood species were sampled wherever opportunities arose, yielding smaller samples for American beech, yellow birch and red oak (Table 2.1).

Table 2.1. Total number of sample plots and stem analysis trees by species. Number of plots is the first number; the parenthesized value is the number of trees.

	Species				
Region	Sugar Maple	American Beech	Yellow Birch	Red Oak	Total
Algonquin	14 (37)	8 (18)	1 (3)	4 (12)	29 (70)
Haliburton	12 (29)	9 (25)	8 (13)	4 (12)	33 (79)
North Bay	7 (21)	0 (0)	2 (6)	3 (9)	12 (36)
Total	33 (87)	17 (43)	11 (22)	11 (33)	62* (185)

**Note: Some plots had more than one species occuring in them, hence this number is less than the sum of individual plots by species.*

One or two 100 m^2 study plots per stand were located within an area that was relatively uniform in overall stand characteristics, soils and understory vegetation. In each plot, five 1 m X 1 m square forest vegetation subplots were located, one in the plot centre and the other four on the polar axes near the plot edge. All herb and shrub layer vegetation occurring in the plot were recorded, along with percent cover and average height (shrubs and regeneration only). All trees greater than 4 cm dbh were measured for total height using a Suunto clinometer, dbh using a diameter tape, and age of representative trees using an increment corer.

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[1] As no reliable quantitative method of forest site-quality existed in the region at the time of sampling, stands were qualitatively classified as good, medium or poor during field data collection on the basis of overall stand vigour characteristics, soil/site conditions, forest ecosystem classifications and personal experience.

Three soil pits were deliberately located within the plot in areas that were deemed representative of the overall soil conditions on the site. Soil pit descriptions and samples were taken according to the Ontario Centre for Soil Resource Evaluation (1993) guidelines. Plots were then classified on the basis of ecosite, vegetation and soil type according to Chambers *et al.* (1997). Information about site and stand characteristics and history was also recorded, and plot locations were recorded with a Garmin eTrex Legend GPS.

In each stand, two or three (wherever possible) healthy, undamaged and otherwise vigorous trees of each available target tree species were felled for stem analysis. In most cases, trees chosen for stem analysis appeared to be free growing dominants with no evidence of suppression (based on inspection of growth rings on increment core samples). A small number of sample trees showing signs of mild suppression were deliberately sampled for sugar maple and American beech, to facilitate examination of height-growth patterns for these types of trees relative to free-growing cohorts. All trees sampled for stem analysis were greater than 50 years age at breast height. The total height of trees was measured in the field both before and after felling to ensure accuracy. Trees were sectioned at ground level (0.0 m), 0.3 m, 1.0 m, breast height (1.3 m), and every metre after beginning at 2.0 m. Any tip remaining under one metre was brought back to the lab and sectioned every 25 cm with a handsaw.

In the laboratory, each disc was prepared with a belt sander and cut into strips along the minimum and maximum radii from the pith centre to outside edge. Sample strips were then scanned at 800 or 1600 dpi using an Epson scanner. Samples with hard-to-identify rings were inspected with a hand lens and refinished with a sharp knife, or stained with water or various dyes to improve ring countability. WinDendro tree-ring increment measurement software (Regent 2001) was used to count tree rings.

2.4.2 Data Processing

As trees exhibit a conical growth pattern, the true total height of the tree at the age corresponding to the ring count at a crosscut will almost always be located some distance above the crosscut (Dyer and Bailey 1987). Carmean's (1972) method of adjusting raw tree height data was used to calculate the true tree height corresponding to the age of the sample disc, as this has been demonstrated to be the best of a number of available techniques (Dyer and Bailey 1987).

The XLStem 1.3 Microsoft Excel macro (Regent 2001) was used to compile the WinDendro data and generate paired height-age and height-dbh estimates for each year of growth for all sampled trees using linear interpolation. All height-growth models in this study were fitted to these height-age and height-dbh datum pairs.

Plots of height versus breast height age and height versus dbh were graphically examined for errors and any obvious signs of suppression or damage in sample trees. Trees showing signs of suppression or damage in their height-growth plots were retained for general height-growth modeling but not used in estimating the site quality (see below) of a plot. These trees included those showing signs of suppression that were deliberately sampled, as well as some trees that appeared free-growing but were later found to be suppressed upon examination of their height-age curves.

2.4.3 Data Analyses

A number of models have been fitted to height-age (Carmean 1975; Longpre *et al.* 1994; Chen *et al.* 1998; Nigh 2001) and height-diameter data (Martin and Flewelling 1998; Murphy and Graney 1998; Jayaraman and Zakrzewski 2001; Colbert *et al.* 2002) for various forest tree species. The Chapman-Richards three-parameter growth function (Richards 1959) in particular has been shown to be a consistently reliable nonlinear model for describing height-age (Danjon and Herve 1994; Longpre *et al.* 1994; Magnussen and Penner 1996), and height-diameter relationships (Martin and Flewelling 1998; Peng *et al.* 2001).

The Chapman-Richards model is a three-parameter sigmoid growth function with logical and easily understood growth parameters, desirable characteristics in a height-growth model:

$$H = b_1(1 - e^{-b_2 A})^{b_3} \qquad [2.1]$$

where H is the total height of the tree, A is the reference age or diameter, b_1 is a parameter describing the asymptote, b_2 is a parameter related to relative growth rate and b_3 is a shape parameter (Danjon and Herve 1994).

Most forest tree species exhibit early erratic height growth patterns (Carmean 1996) and can vary considerably in the time taken to reach breast height (Vasiliauskas and Chen 2002), while height-growth patterns after trees reach breast height tend to be less erratic (Carmean and Lenthall 1989). Accordingly, breast height-age is commonly used in developing height-age models. As a result, equation [2.1] needs to be modified to account for the "shift" in height measurements when fitted to height vs. breast-height age or height-dbh data:

$$H = 1.3 + b_1(1 - e^{-b_2 A})^{b_3} \qquad [2.2]$$

Equation [2.2] was used in all subsequent analyses.

Standard nonlinear least squares regression techniques (Neter *et al.* 1996) were used to fit equation [2.2] to the various data subsets described below. SYSTAT 10 statistical software (SPSS Inc. 2000) was used in fitting all regression models and for subsequent analyses. A cursory visual inspection of residuals plots and estimated versus observed heights from the fitted model was carried out to evaluate the fit of the model to the data. As these preliminary analyses were exploratory in nature, minimal evaluation of model bias and accuracy was conducted.

2.4.4 Overall Height-Growth Models

The intent of these analyses was to examine height-growth patterns of the four study species under a variety of stand conditions and across differing levels of site quality. Equation [2.2] was fitted to all individual tree data for each species to obtain general height growth models for all four species, to use for predicting tree height based on average age and diameter measurements in a stand.

2.4.5 Height Growth at Different Levels of Site Quality

Sampled stands were then classified into good, medium and poor sites for each species on consideration of observed site index (defined as total height of uninjured, free-growing dominant or codominant trees at 50 years breast height age (Carmean 1975)), overall stand vigour and observed site and soil characteristics. Site index criteria were as follows:

- Good: greater than $SI_{BHA50} = 16$ m
- Medium: greater than $SI_{BHA50} = 11$ m, less than $SI_{BHA50} = 16$ m
- Poor: less than $SI_{BHA50} = 11$ m

Equation [2.2] was then fitted to the individual tree height-age and height-dbh data for each site quality class, generating three separate models for each species: sugar maple (Mh), American beech (Be), yellow birch (By) and red oak (Or) (Tables 2.2 and A2.1 – Table A2.1 is presented in Appendix 1).

Table 2.2. Site-index descriptive statistics for total number of sample plots by species and site quality class.

	Site Quality Class				Site Index			
Species	Good	Medium	Poor	Total	Min	Max	Mean	SD
Sugar Maple	11	16	6	33	8.28	21.75	15.00	3.25
American Beech	2	9	6	17	8.17	17.17	12.65	3.01
Yellow Birch	5	3	2	11	6.70	21.54	15.43	6.12
Red Oak	4	5	2	11	10.58	18.08	14.08	2.58

Note: Site quality classes are as follows: *Good:* $16 < SI_{BHA50}$,
Medium: $11 < SI_{BHA50} < 16$,
Poor: $SI_{BHA50} < 11$

2.4.6 Comparing Height-Growth Models Between Species and Stand Compositions

As a result, equation [2.2] was fitted to data from sugar maple and American beech trees growing on the same site together. In addition, sugar maple height-growth curves were fitted to data from pure (sugar maple at least 85% of stand basal area) as well as mixed (sugar maple less than 85% of stand basal area) stands and the results examined (Table A2.2, Appendix 1).

2.4.7 Even-Aged versus Uneven-Aged Height Growth Models

Height-growth curves were also developed separately for trees occurring in even-aged and uneven-aged stands. Even-aged stands were defined as stands having a range of no more than 15 years in breast height age of dominant and codominant trees in the stand; uneven-aged stands were those that exceeded this critical value on average. Stand age structure was assessed using a combination of individual tree height-age plots from stem analysis and increment core samples on at least five other trees in the stand (Table A2.3, Appendix 1).

In addition, individual tree height-age plots were examined for signs of suppression, and equation [2.2] was fitted to a smaller subset of suppressed trees and compared to a model for free-growing trees for all four species (Table A2.3, Appendix 1).

2.5 RESULTS

2.5.1 Overall Height-Growth Models

The height-age models based on equation [2.2] all fit the data reasonably well based on their respective coefficients of determination (R^2) and mean squares error (MSE) (Table 2.3). Red oak had the highest precision (highest R^2 and lowest MSE), while yellow birch had the lowest. All curves appeared to fit their respective datasets well when plotted against observed data (Figure 2.2). When fitted to height-dbh data, equation [2.2] showed good precision with consistently high R^2 and low MSE values for all four species. The fit of these models was revealed to be accurate in Figure 2.3.

Table 2.3. Results of fitting equation [2.2] to height-growth data by species. R^2 is the corrected coefficient of determination, MSE is the residual mean square and DFE is the residual degrees of freedom.

	Parameters					
Species	b_1	b_2	b_3	R^2	MSE	DFE
Height (m) vs. Age $_{BH}$ (years):						
Mh	22.078	0.019	1.275	0.793	8.325	8600
Be	22.852	0.014	1.389	0.738	10.905	5022
By	16.172	0.037	1.134	0.639	11.749	1817
Or	16.742	0.027	1.043	0.804	4.758	2917
Height (m) vs. DBH (cm):						
Mh	24.905	0.051	0.778	0.939	2.451	8600
Be	22.944	0.072	1.015	0.947	2.188	5022
By	25.883	0.042	0.770	0.913	2.187	1817
Or	23.876	0.029	0.665	0.902	2.375	2917

Differences in height-growth curves between species (Figure 2.4a)[2] are readily apparent. Sugar maple reaches the greatest total height after 150 years, while American beech is considerably slower growing and has a more linear height-age pattern. Yellow birch and red oak both exhibit rapid height growth after breast height but quickly taper off and are surpassed in height growth by sugar maple at about 60 years and American beech after 100 years breast height age. The height-age curves for yellow birch and red oak are similar in shape, with yellow birch displaying slightly faster early height growth and red oak

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[2] Curves shown in Figure 2.4 are general growth models based on all data for each species across the entire region, in a variety of stand types, and do not necessarily represent comparisons between species occurring on the same sites or growing together. The intent is to compare the general growth patterns among species.

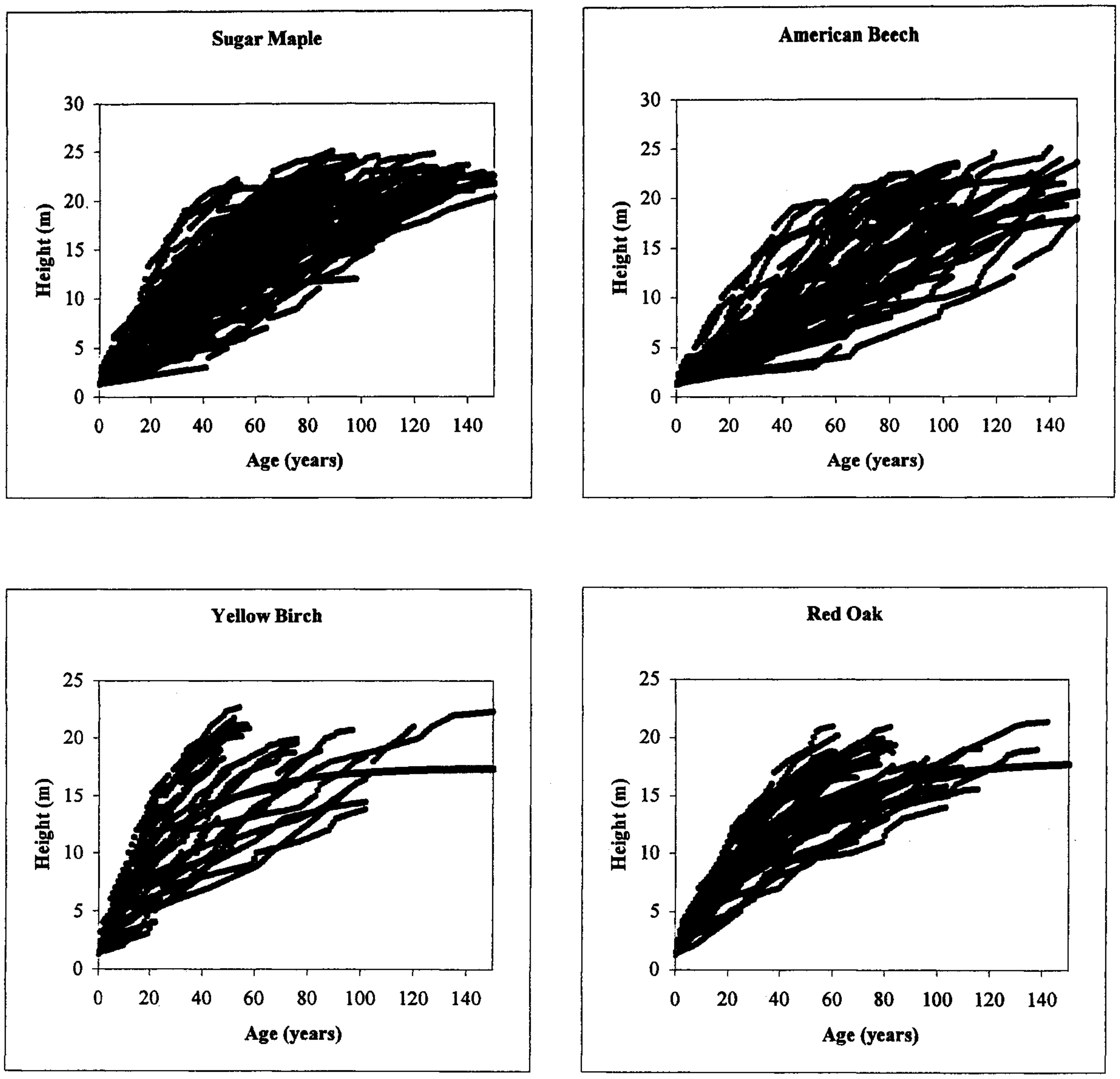

Figure 2.2: Fitted general height-age curves (solid black line) against observed data (red points) by species.

being slightly higher after 100 years breast height age. Total heights of red oak and yellow birch are considerably lower than those of American beech and sugar maple after 150 years.

The height-dbh curves (Figure 2.4b) for all species are quite similar in shape, and nearly identical for sugar maple, American beech and yellow birch; red oak has a consistently lower height for a given dbh than the other three species, meaning it has greater

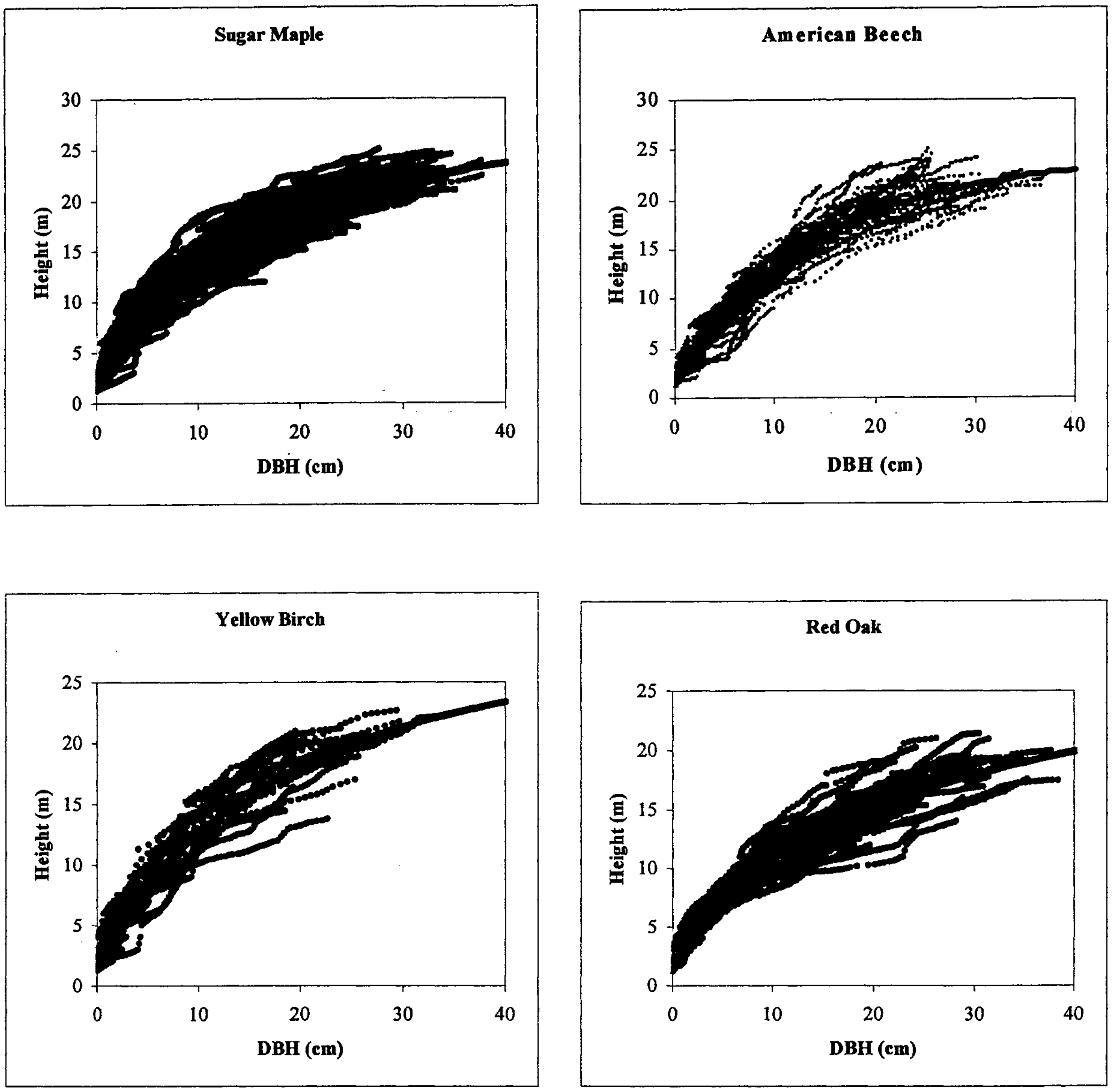

Figure 2.3: Fitted general height-dbh curves (solid black line) against observed data (red points) by species.

taper for a given height. Sugar maple has the consistently lowest taper (greatest height for a given diameter) of all three species, though not by much.

2.5.2 Height Growth at Different Levels of Site Quality

Distinct polymorphism is clearly visible in the height-age curves for sugar maple (Figure

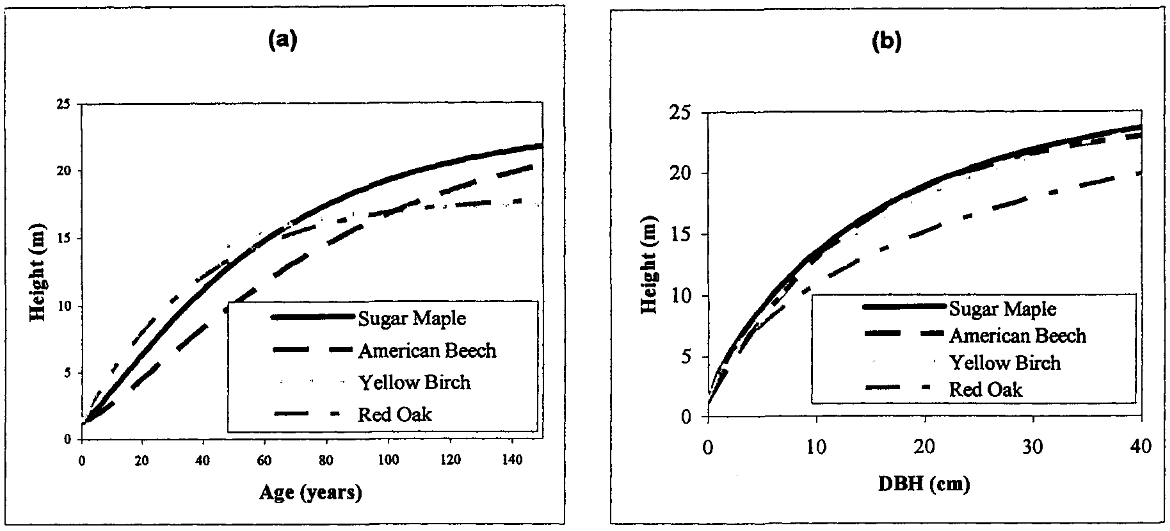

Figure 2.4: Overall height-age (a) and height-dbh (b) curves among species compared. Curves shown are general growth models based on all data for each species across the entire region, in a variety of stand types, and do not necessarily represent comparisons between species occurring on the same sites or growing together. The intent is to compare the general growth patterns between species in the region.

2.5a)[3]. Good sites show rapid early initial height growth followed by a period of less rapid height growth after 50 years, and are distinctly curvilinear. Total height of trees after 150 years is significantly greater than on medium and poor sites. Medium sites follow a similar pattern though do not achieve the same total height after 150 years. Poor sites, however, display a more linear pattern. The relative growth rate remains consistent over time.

The differences are much less pronounced in the height-dbh curves (Figure 2.5b); all three curves are similarly-shaped, though the total height is slightly higher on good sites for a given dbh. The curves for medium and poor sites are nearly identical.

American beech also exhibits markedly different height-age curves (Figure 2.6a) across different levels of site quality. Good sites show a similar pattern to sugar maple, beginning with an early period of more rapid height growth before growth rate slows steadily

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[3] The results of fitting the height-growth models are presented by species in Table A2.4 (Appendix 1).

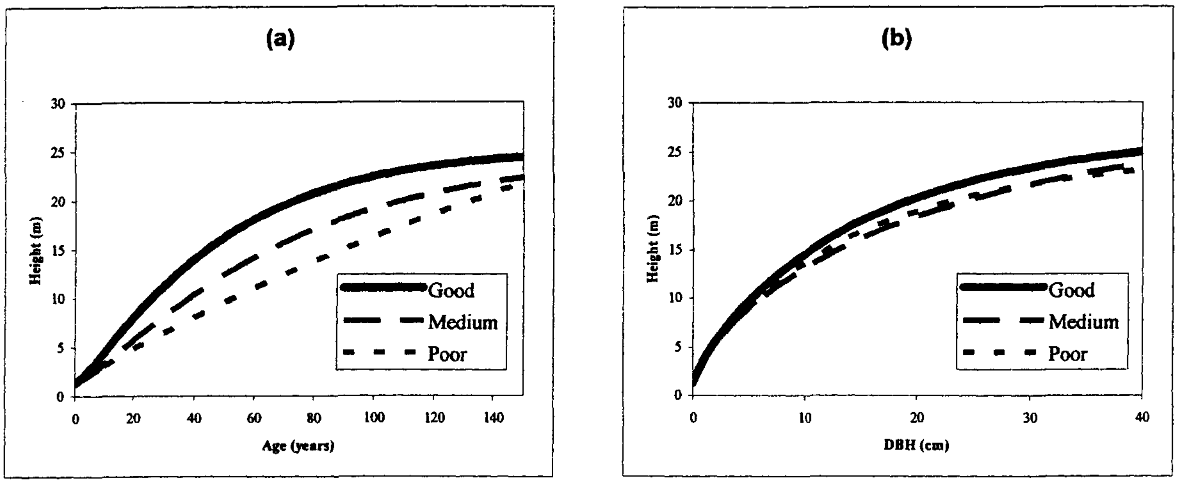

Figure 2.5: Fitted height-age (a) and height-dbh (b) growth curves for sugar maple across different levels of site quality.

over time. Medium sites are similar in shape, but achieve a substantially lower total height for a given age. The shape of poor sites differs considerably; trees are initially slower growing but increase in height growth rate at about 40 years and ultimately surpass the total height of trees on medium sites after 120 years.

Height growth relative to dbh for beech (Figure 2.6b) has an opposite pattern to sugar maple as site quality improves. Trees on rich sites actually show greater taper (lower height relative to a given dbh), while trees on medium and poor sites are more cylindrical.

Pronounced polymorphism is evident in the height-age curves for yellow birch (Figure 2.7a) also; the trends are similar to those of sugar maple where rich sites are more curvilinear and poor sites exhibit a more linear pattern. Interestingly, poor sites exceed the total height of good sites after 150 years, though this is likely a spurious pattern due to extrapolation. Height-dbh relationships (Figure 2.7b) follow a similar pattern to height-age (Figure 2.7a), though the trend is more curvilinear as site quality decreases.

Red oak shows a similar pattern in height-age curves (Figure 2.8a) as for the other three species, though the linear trend on poor sites could not be verified as the model would

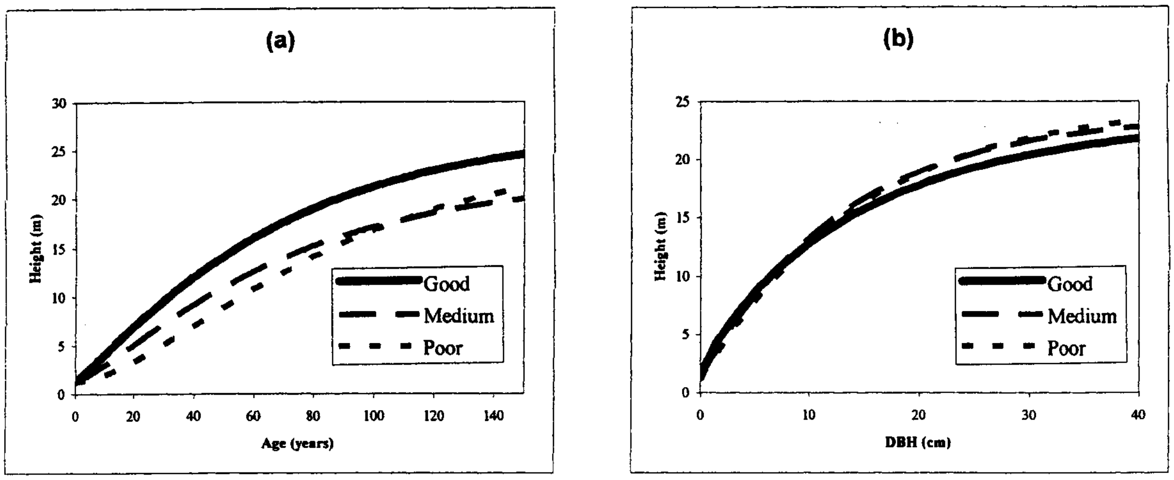

Figure 2.6: Fitted height-age (a) and height-dbh (b) growth curves for American beech across different levels of site quality.

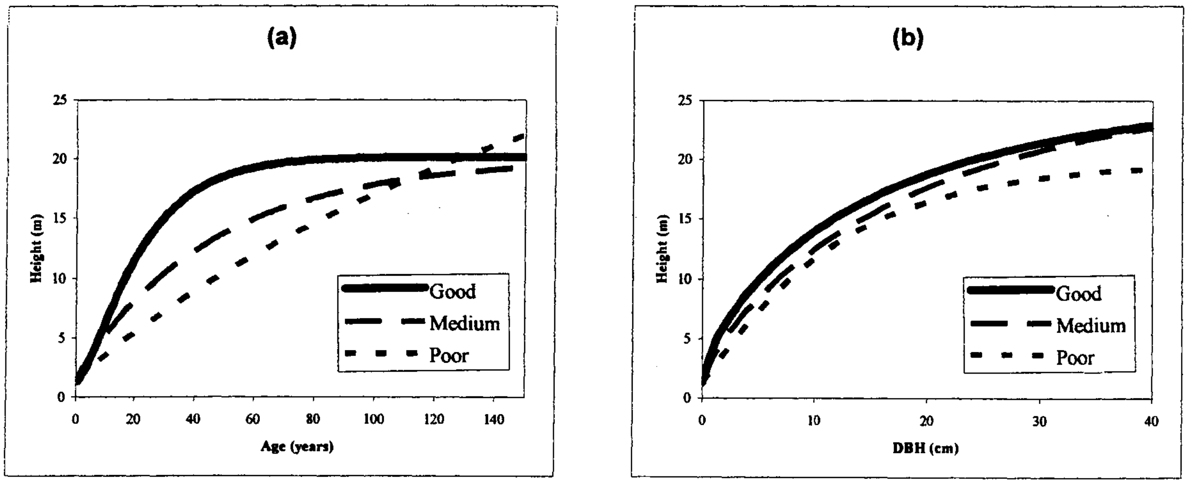

Figure 2.7: Fitted height-age (a) and height-dbh (b) growth curves for yellow birch across different levels of site quality.

not converge (probably due to insufficient samples and an irregular non-sigmoidal growth pattern). Height-dbh relationships (Figure 2.8b) were also similar, though the curve on medium sites became more linear and total height on medium sites exceeded that on good sites relative to dbh at the largest diameters.

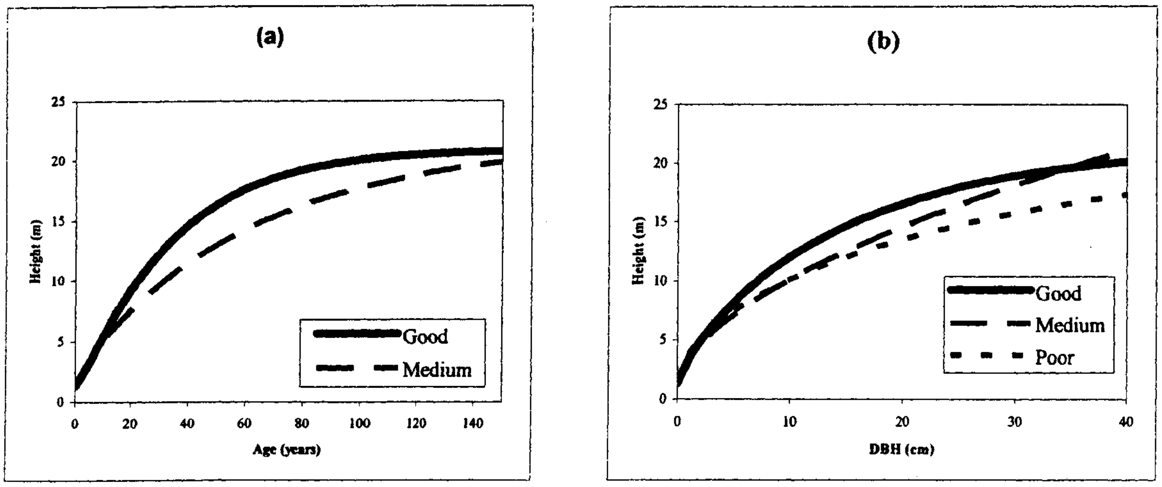

Figure 2.8: Fitted height-age (a) and height-dbh (b) growth curves for red oak across different levels of site quality.

2.5.3 Comparing Height-Growth Models Between Species and Stand Compositions

Though the curves have similar shapes and trends for both species (Figure 2.9), sugar maple is consistently taller for a given age than American beech (Figure 2.9a). The differences between the height-dbh curves (Figure 2.9b) for the two species are much less pronounced, being almost non-existent at larger diameters. Beech consistently has slightly greater taper for a given diameter than maple.

Height-growth models for sugar maple growing in pure versus mixed stands were also developed (Figure 2.10, Table A2.5 in Appendix 1). Height growth over time (Figure 2.10a) is slightly lower for sugar maple in mixed stands. Taper is initially greater in pure stands, while mixed stands have slightly more taper at larger diameters; the curves are quite similar overall (Figure 2.10b).

2.5.4 Even- versus Uneven-Aged and Suppressed-Tree Height-Growth Models

Height-growth curves for sugar maple growing in even- vs. uneven-aged stands

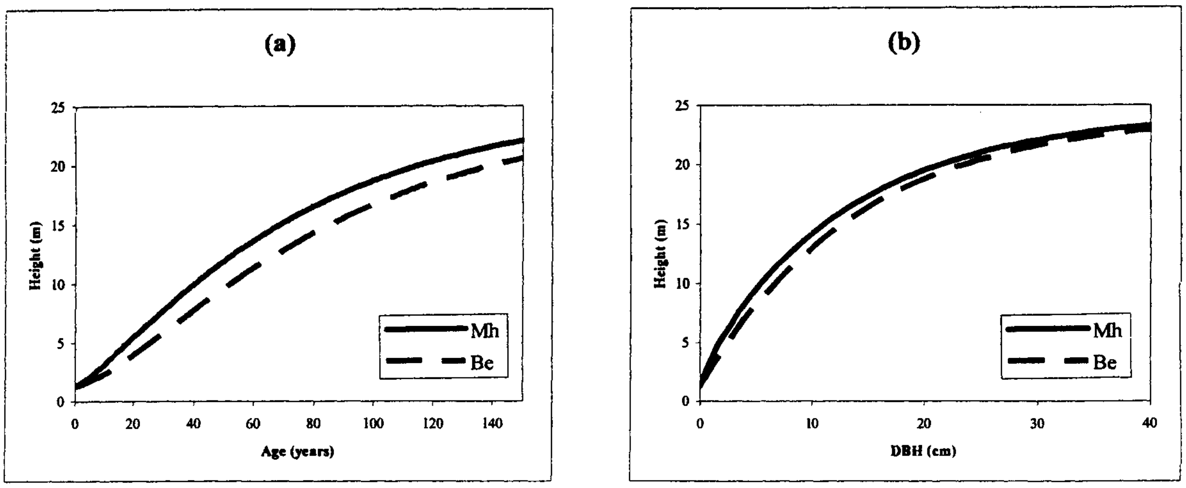

Figure 2.9: Height-age (a) and height-dbh (b) curves for sugar maple and American beech growing together on the same sites. The results of fitting equation [2.2] and the parameter estimates for these curves are presented in Table A2.5 (Appendix 1).

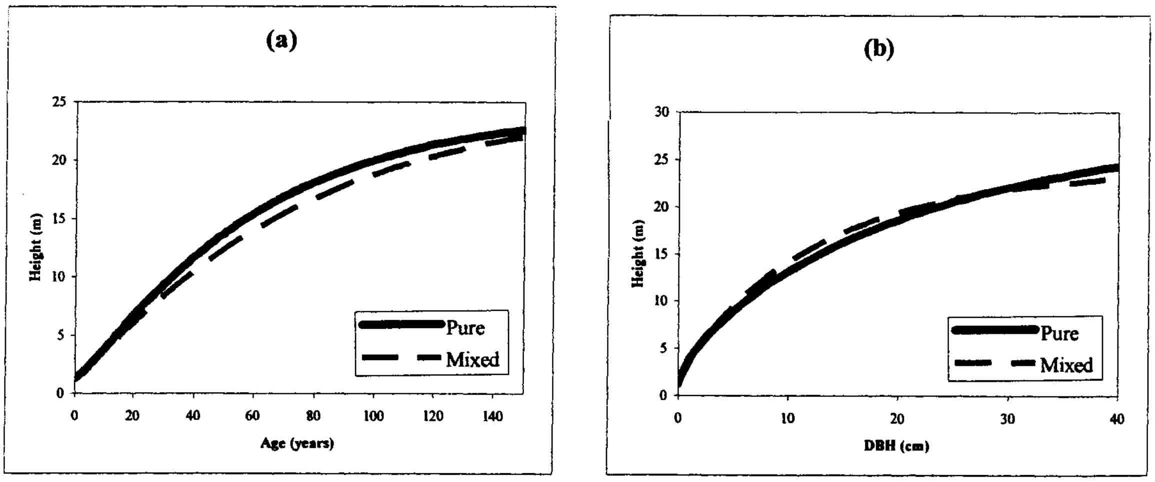

Figure 2.10: Height-age (a) and height-dbh (b) curves for sugar maple in pure vs. mixed stands.

(Figure 2.11) are quite similar; trees in uneven-aged stands seem to grow faster at younger ages but are surpassed by those in even-aged stands after about 60 years, though growth appears to be similar at 150 years (Figure 2.11a). Height-dbh curves (Figure 2.11b) are also quite similar, with trees in even-aged stands having slightly less taper (taller for a given

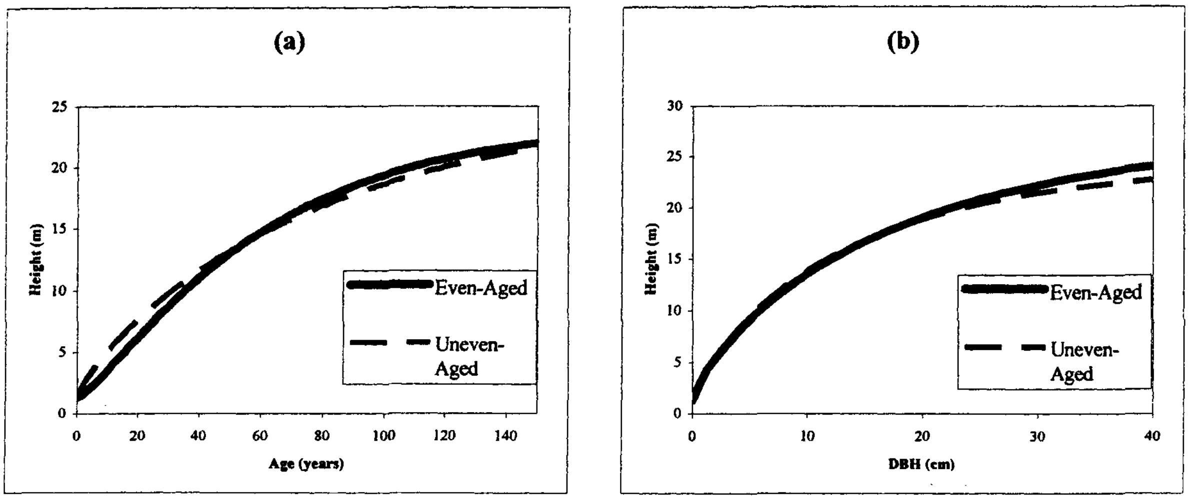

Figure 2.11: Height-age (a) and height-dbh (b) models for sugar maple growing in even- vs. uneven-aged stands. The results of fitting these models are in Table A2.5 (Appendix 1).

diameter) at larger diameters.

Suppressed versus free-growing sugar maple height-age curves (Figure 2.12a) differ markedly. Suppressed trees have a linear growth curve versus a curvilinear trend for free-growing trees, somewhat similar to results for good versus poor sites. The height-dbh curves (Figure 2.12b) are nearly identical suggesting taper is less affected by tree conditions such as canopy position and prolonged suppression.

The results are similar for American beech (Figure 2.13). Insufficient samples of suppressed trees were obtained for yellow birch and red oak; thus suppressed height-growth models were not developed for these species.

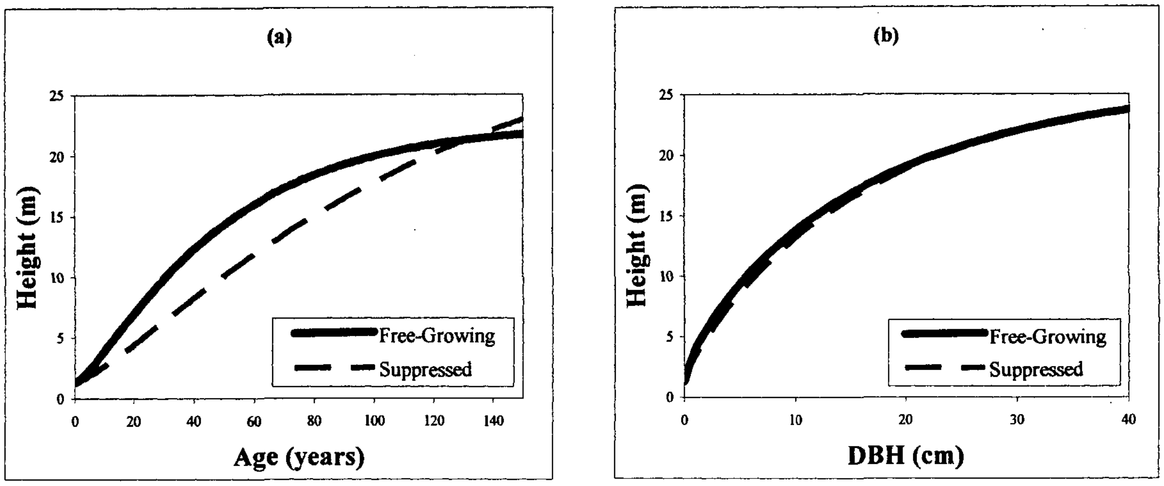

Figure 2.12: Height-age (a) and height-dbh (b) curves for suppressed and free-growing sugar maple trees.

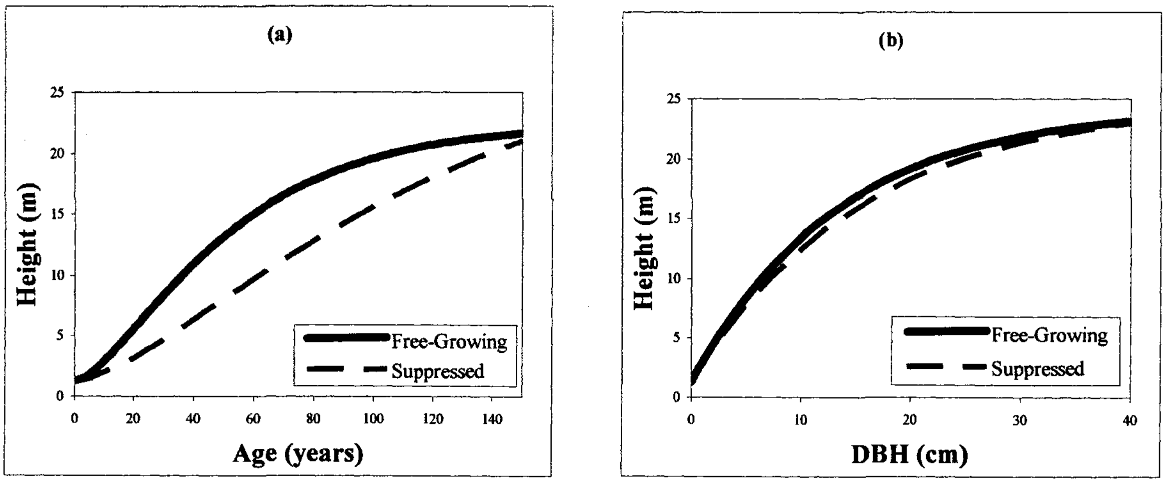

Figure 2.13: Height-age (a) and height-dbh (b) curves for suppressed and free-growing American beech trees.

2.6 DISCUSSION

The general height-growth models developed in this preliminary investigation are an accurate representation of height growth relationships for sugar maple and American beech in the region, due to sufficient numbers of samples and sampling across the full range of site quality and stand conditions over which those species occur in the study area. Height growth models, and general conclusions based on them, for yellow birch and red oak are probably less accurate due to a smaller number of samples (due to lack of good sample stands for these species) and less adequate representation of the variety of stand types for these two species. Conclusions for these are really limited to the dataset and are harder to interpret as general trends for the region.

As highlighted in Figures 2.2 and 2.3, height-growth models for height-dbh in general were a better fit than for height-age. This was likely because the height-dbh data were less variable and deviated less from the mean value for a given dbh, while height-age data appeared considerably more dispersed. Variation in height-age data and patterns was particularly evident between different levels of site quality and stand conditions.

These differences in variation between height-age and height-dbh data may be explained when the sampling methodology is considered. Most of the plots were in fully-stocked stands, and thus this limited stocking range could result in a more limited range of diameters. The plots were located across a wide range of site quality, however, and this could have more of an impact on the height-age relationships, since they are known to be affected by variations in forest site quality.

The differences in the general height-age curves among the four species are explained when the silvics of those species in relation to one another, as well as their autecology, are considered. American beech seedlings develop best under a moderate canopy closure, which usually consists of other species (e.g. sugar maple) due to beech occurring only rarely in pure stands (Farrar 1995; Anderson *et al.* 1998). Due to its shade tolerance, beech will typically remain in the understory for a long period of time as a sapling before release, while species such as sugar maple predominate in the upper canopy (Anderson *et al.* 1998). If other variables are constant, beech will therefore experience slower height growth relative to maple over time. This relationship is further verified by examining the height-age relationships for maple and beech growing on the same sites (Figure 2.9).

It seems that height-growth over time, but not necessarily relative to dbh, is reduced for sugar maple in mixed-species stands (Figure 2.10); this does not imply that overall stand productivity may be reduced, however – especially when the species mixture consists of species adapted to different ecological niches and conditions. Overall stand productivity, and possibly height growth, may be increased when species have different patterns of resource use via competitive reduction and facilitative reproduction (Chen *et al.* 2003). Height-dbh growth patterns for sugar maple (Figure 2.9) seem less affected by species mixture, since they were quite similar in both pure and mixed stands.

All four species demonstrated pronounced polymorphism with varying levels of site quality for both height-age and height-dbh curves (Figures 2.5, 2.6, 2.7, 2.8). Height-age curves were most linear on poor sites and most curvilinear on good sites. This is consistent with other studies relating height-age curves to site quality for tolerant hardwoods (Carmean 1975, 1979, Hahn and Carmean 1982).

Polymorphism and general differences were also evident in height-dbh curves for all species, and general trends were similar to those for height-age curves, though less pronounced. American beech differed from the other three species in that good sites had the most taper (the overall curve for good sites was lower in Figure 2.6b). One possible explanation for this trend (assuming it accurately represents the true relationship in the region) is beech trees occurring on richer sites may be less successful in establishing themselves in the main canopy due to competition from more vigorous hardwood species such as sugar maple. This may result in their being suppressed for longer periods of time and becoming less capable of reaching full height-growth potential for a given diameter.

Height-growth curves for suppressed trees were lower for a given age than for free-growing maple and beech trees (Figure 2.12). This is logical since suppressed trees generally exhibit a slower height growth pattern due to competition for light and other resources from free-growing cohorts. The magnitude of this slowing in height growth probably depends on both stocking and crown class, and so would vary from tree to tree.

Minimal differences in the height-dbh curves were observed for maple and beech for free-growing vs. suppressed trees, indicating these relationships are less affected by tree canopy position for these shade tolerant species. This is consistent with claims by other authors citing this as an advantage when relating height-dbh relationships to forest site quality (Stout and Shumway 1982, Vanclay and Henry 1988, Huang and Titus 1993).

Minimal differences were observed for both height-age and height-dbh curves for sugar maple in even- vs. uneven-aged stands (Figure 2.11). Curves were similar at 50 years breast-height age and 20 cm dbh respectively. Minor differences were observed before and after 50 years breast height-age, and at diameters greater than 20 cm at breast height. This indicates site index (at breast height age 50 years) and site form (at reference dbh of 20 cm) are not strongly affected by stand age class structure in mixed hardwood stands in central Ontario.

2.7 CONCLUSIONS

Height-age curves varied considerably for all species in a predictable manner with forest site quality. Variable stand conditions also had pronounced effects on height-age curves for most species, particularly sugar maple and American beech. Effects were minimal for sugar maple growing in even- vs. uneven-aged stands, and noticeable for sugar maple in pure vs. mixed stands. Dramatic effects were observed for free-growing vs. suppressed trees.

Effects of prevailing stand conditions and structure on height-dbh curves were less pronounced for most species, yet effects of varying site quality were evident and varied in a predictable manner with forest site quality.

Because both height-age and height-dbh curves were affected by forest site quality, both types of curves have potential use as a stand-level forest site quality evaluation tool for hardwood forests in the study area. It is possible that height-dbh curves may be a more robust site quality evaluation tool for many hardwood stands as they seem to be less affected by variable stand conditions such as species mixture, suppression of site trees and age structure.

More detailed quantitative analyses are required to develop these tools further and assess their relationships to forest site quality and quantitative variables known to affect it for these species. Since height growth was revealed to differ between species and between sites, species-specific and site-specific height-growth curves are a necessity for hardwood species in central Ontario, and should be considered in the development of appropriate site-quality evaluation tools.

CHAPTER 3: HEIGHT-GROWTH AND SITE-INDEX MODELS

3.1 INTRODUCTION

Chapter 2 examined general height-growth patterns of sugar maple, American beech, yellow birch and red oak. Preliminary height-growth and site-index prediction models, and associated site-index curves, are developed in this chapter. Two separate models, the logistic and modified Chapman-Richards functions, were fitted to the data, validated and examined for superiority as height-growth and site-index models. Preliminary site-index curves were developed for all four study species in central Ontario. These curves were then used to assess those currently in use from the Lake States region. Finally, an examination of the effects of species composition on sugar maple site index is detailed.

Height-growth and site-index models and curves developed in this study were expected to differ significantly from the Lake States models, and the Lake States models were expected to have significant bias in application to central Ontario. In addition, variation in species composition and age-class structure was expected to substantially affect sugar maple site index due to theoretical limitations of site index.

3.2 LITERATURE REVIEW

3.2.1 Need for Site Quality Evaluation

Forestry in Ontario is evolving toward site-specific management with the most intensive timber management concentrated on the most productive and most accessible forest lands that are located near mills and urban centres (Carmean 1996). Forest site quality evaluation, analogous to land capability estimation in agriculture (Carmean 1975), is therefore an essential tool in identifying which forest sites are most productive and worthy of intensive forest management (Carmean 1996). Site quality, or the productivity potential of forest lands, is a result of the integration of soil, climate, topographic and other variables that influence species composition and growth patterns of forest trees (Woods *et al.* 1998).

Carmean (1996) summarized some advantages of concentrating intensive management on the most productive forest lands: productive sites produce a greater quantity of yield; productive sites produce a better quality of yield; productive sites produce large trees sooner, thus shorter rotations are possible; productive sites are best for species valued for sawlog and veneer log production; and productive sites are more responsive to management practices such as site preparation, release and thinning.

In addition, many regions are facing reduced access to forest fiber (Shaw and Packee 1998), including central Ontario, while demands for forest products are increasing. In addition, more forest lands are being designated for non-commercial uses such as parks and protected areas. Adequate growth and yield information and applicable site quality evaluation tools therefore become important decision support tools in identifying and prioritizing areas for commercial forest management (Carmean 1996; Shaw and Packee 1998). Good stand-level growth and yield estimates are essential to managing forests in a sustainable manner (Woods *et al.* 1998).

3.2.2 Site Index

Estimation of tree volume and site quality, description of stands and their development over time or relative to other variables, and estimation of growth by stand projection methods all rely heavily on good height prediction models (Curtis 1967; Carmean 1975). A useful measure of forest site quality would therefore provide a quantitative estimate of tree height to facilitate growth forecasting and forest management planning.

Carmean (1978) states site index is the most widely accepted method for estimating forest site quality in North America. Site index is a quantitative value that states tree height at an arbitrarily chosen index age (Carmean 1996), and varies according to species (Woods *et al.* 1998). For most eastern tree species, this refers to the height of dominant and codominant, free-growing, healthy trees at an index age of 50 years breast height (Carmean 1996).

Site index is widely accepted as a standard measure of forest site quality for a number of reasons. Tree height is closely related to tree volume (Philip 1994) – it is a required measure in order to calculate tree volume, which is perhaps the best indicator of potential production of a site (Vanclay and Henry 1988). Height growth is also relatively unrelated to stand density (Woods *et al.* 1998), except at exceptionally high or very low densities (Lanner 1981, Carmean 1996). Finally, tree height growth has been shown to be closely related to a number of variables known to affect forest site quality (Klinka and Carter 1990; Carmean 1996; Chen *et al.* 1998; Kayahara *et al.* 1990; Nigh 1998; Beaumont *et al.* 1999).

For estimates and decisions based on site index to work, some traditional assumptions must be satisfied. First, trees used in estimating site index must be dominant or codominant, uninjured, well-formed, healthy and free from suppression or damage (Carmean 1978, 1996). In addition, they should occur in pure stands (Wang 2003) to eliminate poor estimates arising from the interaction and competition of site trees with other species, though exceptions to this rule exist for comparisons between species in some cases (e.g. Nigh 1995; Carmean 1996; Hostin and Titus 1996). Finally, "site" trees (trees used for estimating site index) should occur in fully-stocked stands, away from stand edges or disturbances (Carmean 1996).

Modern site-index estimates utilize age at breast height rather than total age as early height growth of forest trees has been shown to be slow and erratic in many cases (Carmean and Lenthall 1989; Carmean 1996; Nigh 1998). Height growth of forest trees is generally more consistent in most species after breast height (Carmean 1996). Using breast height-age rather than total age makes for more accurate models and estimates based on those models, and age at breast height is easier to obtain in the field than total age in many cases. Breast height age should not be used as the stand age, however, since species vary considerably in time taken to reach breast height, and this can result in misinterpretation of growth and yield and forest succession (Vasiliauskas and Chen 2002).

The most accurate site-index estimates (and models – see below) are derived from precise stem analysis data (Carmean 1996), though this is not practical in many cases when making stand-level management decisions in the field.

3.2.3 Site-Index Curves

Foresters and researchers utilize site-index curves – curves based on height-growth patterns of "site" trees growing at different levels of site quality (Carmean 1975) – in estimating forest site quality and predicting future stand yields. Site-index curves are derived from multiple observations of site index and height-age relationships for a given species across the whole range of soils and site quality over which that species occurs (Carmean 1996). Multiple paired height and age observations from sample plots or stem analysis methods (Elfving and Kiviste 1997), are used to create a dataset for model fitting. Nonlinear regression methods (Neter *et al.* 1996) are used to fit growth curves to these datasets for height as a function of age and site index (Carmean 1996; Nigh 1996). Foresters can then make simple height and age measurements in the field and compare them to a set of site index curves to determine site index for a stand. Alternatively, nonlinear regression methods may be used to generate equations that predict site index as a function of height and age where more precise estimates of site index are required (Carmean 1996).

Separate curves are typically plotted for a range of site index values, usually in arbitrary site-index classes. Early site-index curves used a few, broad site-index classes – good (1), medium (2) and poor (3) in Ontario (Plonski 1974). Modern curves utilize more precise site-class intervals; two-metre site classes are common in eastern North America (Carmean 1978; OMNR 1998).

Most early site-index curves (Plonski 1960), and some modern site-index curves for shade-intolerant species (Nigh and Courtin 1998; Chen *et al.* 1998), were anamorphic, meaning they were of a similar shape for all site-index classes. While such curves can provide an efficient tool for estimation of site index using total height and breast height age observations (Chen *et al.* 1998), it is now generally accepted that tree height-growth patterns differ across site quality classes (Carmean and Lenthall 1989; Carmean 1996). This polymorphism (variation in curve shape) is evident for many species, and has been shown to exist in the height growth patterns for hardwood species in other regions (Carmean 1978). Specifically, height-age curves are nearly linear on poorer sites, while trees on the best sites exhibit rapid early height growth which tapers as the trees mature on the best sites (Carmean 1996). Polymorphic models according to site-index class, ecological site quality, or individual site may therefore significantly reduce estimating error for various site-index classes, site quality classes, or individual sites (Klinka *et al.* 1996; Chen *et al.* 1998). Such curves can lead to substantial improvements in related growth and yield estimates; consequently, modern site index curves are now most commonly polymorphic with different shapes across site index classes (Carmean and Lenthall 1989; Carmean 1996).

Finally, site indices, parameters for height-prediction equations and their associated curve shapes often differ from region to region for a given species (Carmean 1996; Nigh 1998). Consequently, it is important that foresters use the appropriate estimates and curves for their region; to ensure their reliability, curves should be based on locally-derived data collected on stands for which site-index estimates are needed (Carmean 1996; Nigh 1998). Unfortunately, locally-derived curves applicable to central Ontario do not yet exist (Woods *et al.* 1998), and so foresters instead rely on curves from other regions. It is important to assess and calibrate these curves from other regions before using them locally (Woods *et al.* 1998; Carmean 1989).

3.2.4 Estimating Site Index

Comparing accurate height-age measurements to locally-valid site-index curves is one direct method of estimating site index, as is deriving estimates from height vs. age and site-index prediction equations. Direct methods are based on direct measurements of "site" trees which meet the assumptions of site index outlined above (Carmean 1996). On sites where even-aged stands of suitable site trees do not exist, such as recently disturbed areas, areas that do not currently support trees, or where stand height does not accurately reflect potential productivity of the site (due to suppression or top damage), indirect methods must be used (Carmean 1996; Nigh 1998).

Direct and indirect methods for estimating site index were summarized by Carmean (1996). Direct methods of estimating site index from forest trees include site-index curves (both harmonized and polymorphic), growth intercepts and site-index comparisons between species. Indirect methods of site-index estimation from soil, vegetation and topography include soil-site evaluation, soil types, and habitat, ecosystem and physiographic typing.

Growth intercepts are based on measurements between nodes on tree species that exhibit determinate height growth. Such measurements are then related to site index using regression methods (Carmean 1996). Certain coniferous species are well suited to growth intercepts, allowing accurate estimates of site-index using this technique. Practical application of growth intercepts requires that site trees retain their lower branch whorls ensuring nodes are readily visible, thus this method is most suitable for young plantations where branches persist and site trees are too young for traditional height-age estimates of site index (Carmean 1996); however, growth intercept methods have also been developed for species without distinct annual branch whorls (Nigh 1996).

Where two or more species may grow together on the same site, and where suitable site trees of both species occur, paired site-index observations can be made for those trees. Regression techniques can then be used to develop linear models that predict the site index of one species not present on a site based on the observed site index of another species that is present on the site (Nigh 1995, Carmean 1996). Known as site-index comparison (or conversion) graphs and equations, these relationships can be used by foresters to determine if one species might be better suited to grow on a given site.

It is important to realize that site index relationships developed from sites supporting stands with two or more species may be compromised by the interaction of those species growing together (i.e. one of the basic requirements of site index stipulates that models be derived from pure stands to eliminate this possibility as noted earlier) (Wang 2003). Despite this seeming violation of assumption, site index comparison graphs and equations developed from these stands remain an important site quality estimation tool and foresters regularly use them to make management decisions. Wang (2003) has developed an ecologically based model that provides one way of addressing this issue.

Soil variables known to be closely related to site index are those variables influencing the quality and quantity of growing space for tree roots (Coile 1952). Detailed measurements of such soil variables can be related to observed site indices on various sites using multiple regression methods. Resulting regression equations can then be used to develop soil-site relations that predict site index of forest trees from observed soil variables where no suitable site trees exist (LeBlanc 1994; Carmean 1996).

There is a possible limitation of these soil-site relationships. The soil on a given site may have different chemistry and nutrient relationships when a given species is present than when it does not occur on that site. Utilizing precise soil nutrient and chemical relationships to predict site index on sites not currently supporting a given tree species could lead to inaccurate estimates if these variables were included in soil-site relationship models being used. Most studies in Ontario (e.g. LeBlanc 1994) focus on physical soil properties such as rooting depth, coarse gravel content and texture class that are quick and easy to measure in the field, thus overcoming this limitation. Using these more easily observable properties also makes the studies more useful as decision tools for foresters in the field.

On the same note, if soil, ecosystem and physiographic classification systems are stratified based on these variables known to be closely related to forest site quality and site index, they may be used to classify and estimate forest site quality and site index (Carmean 1996).

3.2.5 Site-Index Models for Hardwoods in Central Ontario

At the present time there is a lack of useful site-index models and curves for hardwood species in Ontario. Plonski (1960) presented one set of anamorphic curves and tables arranged in three broad site classes for all tolerant hardwood species in Ontario.

Plonski (1960) developed his curves empirically by hand fitting a curve through stem analysis measurements for multiple plots of tolerant hardwoods. This guide curve was then used to draw secondary curves one standard deviation below and above, thus creating the site class boundaries (Woods *et al.* 1998). As no estimates of reliability or precision were published, nor were there any equations associated with the curves, Payandeh (1974) provided a nonlinear model with parameter estimates for Plonski's (1960) site-index curves.

These curves are obviously of limited use. Since we know little about Plonski's (1960) methods (i.e. no tables summarizing his data were published, and he did not indicate the range of site indices sampled), uncertainty prevails regarding the accuracy and range of applicability of these models. In addition, the models are based on total age, and begin at 20 years. Because height-growth data were unavailable before 20 years age, Payandeh's (1974) parameter estimates are likely inaccurate since this early height growth would affect the shape of the curve and associated parameter estimates (Carmean and Lenthall 1989). Payandeh (1974) did not provide an equation for direct estimation of site index from height and age either.

Later on, a complete set of polymorphic site index curves based on total age for northern hardwoods in northern Wisconsin and upper Michigan was published (Carmean 1978), along with a complete set of equations for predicting height from age and site index, and site index from age and height (Hahn and Carmean 1982). Currently, these curves and equations are the only alternatives to Plonski (1960) and Payandeh's (1974) models. Unfortunately, no attempt has ever been made to assess the use of these models in central Ontario and verify their accuracy and applicability to the region. It is likely they significantly overestimate the height-growth of hardwoods in the region as soils in central Ontario are generally less productive than those in the Lake States (Hills 1959), and as a result of climatic differences between the two regions. In addition, height growth and site-index models have been shown to vary between different regions for other species (Carmean and Lenthall 1989; Nigh and Courtin 1998; Chen *et al.* 1998) as well as hardwoods (Carmean 1979).

3.2.6 Site-Quality Evaluation and Hardwoods in Central Ontario

There are some clear challenges to using traditional site index as a measure of forest site quality in central Ontario's hardwood forests. These arise from stand structure and species composition.

Many hardwood stands in central Ontario are of mixed species composition, partly as a result of site characteristics (Chambers *et al.* 1998) and past forest history. Site index estimates are traditionally only derived from and applied to pure stands of a given species (Carmean 1996), though some methods of estimating site index are derived from mixed stands (Nigh 1995; Carmean 1996; Wang 2003). Interactions between species on the same site may have an impact on site index (Chen *et al.* 2003); it has not yet been investigated whether these impacts increase or decrease site index for central Ontario hardwoods. Possible mechanisms for increasing site index include competitive reduction (where trees utilize resources differently via root or canopy stratification) and facilitative reproduction (where soil nutrients are used differently) (Chen *et al.* 2003). If species are competing directly with one another for resources on a site then site index and potential productivity could be reduced. Chen *et al.* (2003) investigated whether mixed-species stands were more productive than pure stands for even-aged forests in British Columbia, and found the effect of one species on the productivity of another to be species- and site-specific. Sterba and

Monserud (1995) also noted potential productivity (assessed by volume yield levels) varied with respect to habitat type and stand structure.

Longpre *et al.* (1994) examined the effect of companion species on the growth of jack pine (*Pinus banksiana* L.) in even-aged stands by comparing site index, average dbh and height, and forest floor nutrient availability between three different jack pine-dominated stand types on similar sites. Height growth of jack pine was found to be unaffected with different species compositions while dbh growth increases were observed in mixed stands. While these results were applicable to even-aged, shade-intolerant species, a similar approach might be taken in assessing the effects of species mixture on site index of tolerant hardwoods.

Since many stands in central Ontario have an uneven age-class structure and are composed of shade-tolerant species, it is difficult to obtain traditional site-index estimates for them. Dominant tree dynamics can have a significant impact on site-index curves, and estimates derived from them, when they are based on stem analysis data from stands composed of shade-tolerant species (Raulier *et al.* 2003). Raulier *et al.* (2003) found that stem analyses-based curves can strongly over predict true dominant height growth due to changes in social status of dominant trees over time. Dominant jack pine and black spruce (*Picea mariana* (Mill.) B.S.P.) trees were observed to be replaced over time by other individuals and thus dominant trees may not have always occupied the same canopy position over the life of the stand. Stand dominant-height curves (such as site-index curves) were found to be more rapidly asymptotic than those of individual trees as a result of this (Raulier *et al.* 2003).

This problem is likely a more significant issue for shade tolerant hardwood species occurring in uneven-aged stands, since tree species such as sugar maple and American beech are capable of remaining in the understory for long periods of time, then responding well to release and assuming a dominant position in the upper canopy (Farrar 1995). They could then appear to be valid "site" trees and lead to poor estimates of forest site quality. As sustainable forest management practices in the region currently involve managing some hardwood species using uneven-aged practices (Anderson *et al.* 1998), the effects and impacts of this on site index need to be assessed before using it as a method of forest site-quality evaluation in such stands.

There is a clear need for immediate development of a complete set of modern, locally-derived site-index curves for central Ontario. Such curves could then be used to verify or dispute the curves from other regions currently being used in their absence. An investigation into the effects of uneven-aged stand structure and species mixture on site index and site quality is also warranted for these forests. Assessment of these effects and relevant conclusions could then be used to refine future site-index models to more accurately reflect the potential productivity of forests in the region. Thus would be formed the basis for better stand-level sustainable forest management decisions in the future.

3.3 OBJECTIVES AND HYPOTHESES

3.3.1 Height-Growth and Site-Index Models

In light of the above literature review, the objectives of this chapter were to develop and validate height-growth and site-index models for the hardwood data from central Ontario (Chapter 2). Preliminary height-growth and site-index models, and site-index curves, were produced for sugar maple, American beech, yellow birch and red oak. These models and curves were then used to assess the application of Carmean's (1978) site-index curves for hardwoods in the Lake States to central Ontario.

Height-growth and site-index models and curves developed in this study were expected to differ significantly from the Lake States models as a result of differences in soils, climate and stand structure and history between the two regions. The Lake States models were expected to be inaccurate in application to data from central Ontario. In particular, total predicted heights for trees after index age in the Lake States models were expected to greatly exceed the observed heights and predictions based on the central Ontario models.

3.3.2 Stand Effects on Sugar Maple Site Indices

A preliminary assessment of the impacts of age structure, stand structure and species mixture on sugar maple site index and basic forest floor chemistry was also undertaken, to investigate the viability of using site index in mixed and uneven-aged stand types. Substantial effects on sugar maple site index were expected as a result of variation in stand species composition. These effects could arise from competitive and complimentary relationships between sugar maple and companion species.

3.4 METHODS

3.4.1 Study Area and Sample Plots

A detailed description of the study area and general sampling method was given in Chapter 2; briefly, it covered the following areas: Haliburton Forest and Wildlife Preserve; the southern half of Algonquin Provincial Park; and the portion of crown forest extending north from Huntsville to the North Bay area, and west from Algonquin Park to Parry Sound.

An effort was made to sample sugar maple over the full variety of stand conditions, stand types, site quality and management regimes over which it occurs in the region using a random sampling method (described in detail in Chapter 2). Other major hardwood species were sampled wherever opportunities arose, yielding smaller samples for American beech, yellow birch and red oak. The total number of sample plots and sample trees by species were summarized in Table 2.1. Total number of sample plots by broad site quality classes for each species were presented in Table 2.2.

Detailed stand structure, vegetation and soils information were recorded according to the methods outlined in Chapter 2 for each sample plot. Details of sample tree selection and stem analyses can also be found in Chapter 2. Laboratory preparation methods are also detailed, along with how preliminary data were corrected and processed.

3.4.2 Data Preparation

Plots of height versus breast-height age and height versus dbh were graphically examined for errors and any obvious signs of suppression or damage in sample trees. Trees showing signs of suppression or damage in height-growth plots before breast-height age 50 years were not used in estimating the site index of a plot, nor for developing site-index models. Trees showing signs of suppression after breast-height age 50 years were retained for site-index modeling but had the information after breast height age 50 discarded (after Nigh 1996). According to Nigh (1998), deleting a tree does not necessarily bias the results since any one of the three trees could have been deleted from the plot. Within-plot variation is increased, though stem analysis data is too costly to reject whole plots on the basis of one tree and the site index estimates themselves would be biased if these trees were retained in the plot for model fitting (Nigh 1998).

Several such trees showing signs of gradual release after suppression were found, since this condition is harder to see in field increment core samples (Splechtna 2001). Table 3.1 summarizes the number of trees rejected for site index determination and model

Table 3.1. Total number of sample plots and sample trees by species utilized in height-growth and site index model development. Sample plots with less than two acceptable “site” trees were rejected for height and site-index model development.

	Plots		Trees	
Species	n_{SI}	$n_{rejected}$	n_{SI}	$n_{rejected}$
Sugar Maple	30	3	65	22
American Beech	17	0	21	23
Yellow Birch	11	0	20	2
Red Oak	11	0	32	1

development; Table 3.2 summarizes sample plots by species and good/medium/poor site-quality classes. Sample plots having fewer than two trees were rejected for height versus age and site index, and site index versus age and height, model development.

Table 3.2. Total number of sample plots by species and site quality class used in development of height-growth and site-index models.

	Site Quality Class			
Species	Good	Medium	Poor	Total
Sugar Maple	11	16	6	33
American Beech	2	9	6	17
Yellow Birch	5	3	3	11
Red Oak	4	5	2	11

Because sample sizes were small, American beech and yellow birch site-index models included some trees showing signs of suppression – this had an impact on the models fitted for these species since site index estimates should only be based on free-growing trees with no history of suppression (Carmean 1996; Nigh 1996; Chen *et al.* 1998). As models for these species were intended as a preliminary approximation, the trees were included in the final dataset for these species. While curves for all other species were developed based on even-aged stands, curves fitted for American beech also included some uneven-aged sample plots due to small samples. General statistics for sample plots used in model development are presented by species in Table 3.3.

Because the sites, rather than the individual trees, are of interest in developing site-index models and curves (Chen and Klinka 2000), an average height versus age curve was fitted to trees growing in each plot. This enabled estimates of average height growth and site index for the plot rather than the individual sample trees. Three main techniques exist for doing this (Chen and Klinka 2000), including fitting an average nonlinear line by hand through a scatterplot of height vs. age observations (Curtis 1964), fitting a nonlinear model and curve to the individual plot data (e.g. Richards (1959) model), and using linear interpolation (after Nigh 1996, 1998). Shaw and Packee (1998) visually fitted and then extrapolated a flexible spline function to get estimates of site index from plots below index age.

Despite the fact that linear interpolation can sometimes lead to errors in height estimates between observations (Chen and Klinka 2000), this method was chosen and average height growth curves were derived for the plot by averaging the yearly estimates of height for each tree in the plot up to the age of the youngest sample tree in the plot (Nigh 1996, 1998; Nigh and Courtin 1998). This procedure eliminated the risk of inaccurate plot height-growth curves due to later height growth being determined by only one or two trees.

3.4.3 Height-Growth and Site-Index Models

A number of different functions have been used to fit models for predicting height

Table 3.3. General statistics for plots and sample trees used in height-growth and site index model development by species. Min is the minimum observed value, Max is the maximum observed value, Mean is the mean or average value, and SD is the sample standard deviation. *Due to a low number of sample for American beech and yellow birch, data used in fitting models for these species included some trees showing signs of suppression and some plots located in uneven-aged stands.

		Breast Height Age (years)			
Species	n	Min	Max	Mean	SD
Sugar Maple	65	50	134	88	15.5
American Beech	43*	50	181	112	31.2
Yellow Birch	22*	52	156	78	27.6
Red Oak	32	60	142	86	19.6

		Total Height (m)			
Species	n	Min	Max	Mean	SD
Sugar Maple	65	15.1	25.1	19.9	2.7
American Beech	43*	16.7	25.0	21.1	1.8
Yellow Birch	22*	13.8	22.6	19.3	2.5
Red Oak	32	15.3	21.3	18.0	1.7

		Site Index (m)			
Species	n	Min	Max	Mean	SD
Sugar Maple	65	8.28	21.75	15.00	3.25
American Beech	43*	8.17	17.17	12.65	3.01
Yellow Birch	22*	6.70	21.54	15.43	6.12
Red Oak	32	10.58	18.08	14.08	2.58

from breast-height age and site index and for producing polymorphic site index curves. The conditioned logistic function [3.1] (Nigh and Sit 1996; Nigh 1998; Nigh and Courtin 1998; Chen *et al.* 1998) is reliable 3-parameter model conditioned to go through the site index (Nigh 1998):

$$H = 1.3 + (S - 1.3)\frac{1 + e^{[b_1 + b_2 \ln A_1 + b_3 \ln(S - 1.3)]}}{1 + e^{[b_1 + b_2 \ln A + b_3 \ln(S - 1.3)]}} \qquad [3.1]$$

The 5-parameter Ek (1971) modification of the Chapman-Richards (Richards 1959) function [3.2] has been used in a number of studies (Carmean and Lenthall 1989; Payandeh and Wang 1994), including some for tolerant hardwoods (Payandeh 1974; Hahn and Carmean 1982):

$$H = 1.3 + b_1 (S - 1.3)^{b_2} (1 - e^{b_3 A})^{b_4 (S - 1.3)^{b_5}} \qquad [3.2]$$

where H is the adjusted (Carmean 1972) height in metres, A is the breast-height age in years, S is the observed site index from the average plot curve, e is the base of the natural logarithm and b_1, b_2, b_3, b_4 and b_5 are parameters to be estimated that describe the slope, inflection point and shape of the curve and its location on the height-age plot. Systat 10 (SPSS Inc. 2001) statistical software was used for all modeling. Least squares nonlinear regression techniques (Neter *et al.* 1996) were used to fit height-growth and site-index (below) models for all four species.

To obtain more precise estimates of site index than those given by graphical methods from the height-age curves, a conditioned logistic function [3.3] (Nigh and Sit 1996; Nigh 1998; Chen *et al.* 1998):

$$S = 1.3 + (H - 1.3)\frac{1 + e^{[b_1 + b_2 \ln A_1 + b_3 \ln(H - 1.3)]}}{1 + e^{[b_1 + b_2 \ln A + b_3 \ln(H - 1.3)]}} \qquad [3.3]$$

and modified Chapman-Richards function [3.4] (Carmean and Lenthall 1989, Payandeh and Wang 1994):

$$S = 1.3 + b_1 (H - 1.3)^{b_2} (1 - e^{b_3 A})^{b_4 (H-1.3)^{b_5}} \qquad [3.4]$$

was fit to predict site index as a function of height and age. Coefficients and parameters are the same as for equations [3.1] and [3.2].

3.4.4 Model Accuracy Assessment

Height and site-index model accuracy assessment techniques used in this study closely follow the methods outlined by Chen *et al.* (1998). Residual plots of estimated heights and site indices versus age, height and site index were examined for signs of bias and lack of precision (Chen *et al.* 1998; Nigh 1998). In addition, plots of estimated versus observed site indices were tested against regression y = x; after Chen *et al.* (1998) and Chen and Klinka (2000). Regression and ANOVA assumptions were examined prior to regression fitting and testing as outlined by Neter *et al.* (1996) and Zar (1996); after Chen *et al.* (1998).

3.4.5 Assessment of Site-Index Models from the Lake States Region

The site-index curves developed above were used to assess the application of Carmean's (1978) site-index curves for the same species in northern Wisconsin and Upper Michigan to central Ontario. Carmean's (1978) curves were based on the 5-parameter Chapman-Richards model (equation [3.2]); however, these models were based on total rather than breast-height age, and were developed in imperial rather than metric units. Accordingly, these issues had to be addressed before direct comparisons between models and validation of the curves using data from central Ontario could be carried out.

The metric conversion issue was simple to overcome and was addressed by introducing appropriate conversion factors as constants into the equations[1] given by Hahn and Carmean (1982). Carmean (1979) shows curves based on total age, but notes early and erratic height growth was observed in the data. In an effort to improve his curves, Carmean (1979) discarded the information below breast-height age and added a constant of 4 years to convert the data back to total age. To facilitate direct comparisons to the breast-age models developed in this study, the curves were shifted back four years on plots by subtracting a constant of four years to Hahn and Carmean's (1982) models. The fully modified model is presented below:

$$H = 1.3 = b_1(S * 3.2808 - 1.3 * 3.2808)^{b_2}(1 - e^{b_3(A-4)})^{b_4(S*3.2808-1.3*3.2808)^{b5}} * 0.3048 \qquad [3.5]$$

Predicted values and residuals from this model were then calculated for each species based on the data from this study. The model was assessed for accuracy in the same manner as models [3.1], [3.2], [3.3] and [3.4] developed in this study.

In addition, direct graphical comparisons were made between Carmean's (1978) curves and those developed in this study to further assess the extent and nature of differences between them. Height-growth models such as those developed in this study produce computed curves that do not pass exactly through the specified height at index age (Newnham 1988; Carmean and Lenthall 1989). Accordingly, an iterative mathematical process (Carmean and Lenthall 1989) was adapted for graphing the curves in this study, and

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[1] *Note: A similar correction from metric to imperial units is given in Carmean's (1978) site index curves as they are presented in the Silvicultural Guide for the Tolerant Hardwood Forest in Ontario (OMNR 1998). The equation and conversion factors included in it as presented there are incorrect. The first two conversion factors should be 3.2808, not .3048 as published. The correct conversions and equation form is presented above.*

those of Carmean (1979) to facilitate accurate graphical comparisons. The site-index values input into the height-growth models were iteratively adjusted until the height-growth models produced estimates of height at index age that matched the specified site indices. The curves were then plotted together and direct comparisons were made between them that could be used to confirm and further illustrate the results of the above accuracy assessment.

3.4.6 Effects of Species Composition on Height Growth and Site Index of Sugar Maple and Forest Floor Chemistry

As mentioned above, there are numerous factors which make the application of site index particularly challenging for many hardwood stands in central Ontario. Using methodology adapted in part from a study on jack pine height growth (Longpre *et al.* 1994), the effects of companion species and species mixture on the forest floor and height growth/site index of sugar maple were investigated. In addition, the effects of age-class structure and tree canopy position of height growth and site index were also investigated.

Using methods adapted from Longpre *et al.* (1994), the effect of companion-species growth and species mixture on the height growth and site index of sugar maple was investigated first. To minimize influences of site and abiotic factors on sugar maple height growth, a subset of stands was identified on the basis of similarity in influential site characteristics between them. Rahi (2003) identified a number of soil variables for both the A and B horizons which were shown to affect sugar maple height growth and site index the most: horizon thickness (cm), percent coarse fragments, bulk density (g/cm^3) and percent sand, silt and clay.

Descriptive statistics for these soil variables are presented by stand type in Table A3.1 (Appendix 2). These variables, along with overall soil depth on the site (cm) and elevation

(m) were subjected to a one-way analysis of variance (ANOVA) to test for differences among plots and stands selected for this portion of the study. Stands found to be significantly different on the basis of the above variables were deemed different in terms of overall site characteristics and rejected from the study.

These methods were used in conjunction with plot stand information to classify and select stands of three different species compositions to examine their effects on sugar maple height growth and site index. Stands selected for further analyses (Table 3.4) were classified as: pure stands of sugar maple (Mh > 90% of stand by basal area); sugar maple-dominated stands with a major component of American beech (Be > 25% of stand by basal area); and sugar maple-dominated stands with a major component of American beech and yellow birch (Be and By each > 15% of stand by basal area). A one-way ANOVA was used to test for differences in the site index of sugar maple between the three stand types.

Table 3.4. Sugar maple site index and sample sizes for the three stand types sampled.

		Site Index (m)			
Species	N	Min	Max	Mean	SD
Sugar Maple	7	12.9	20.5	15.9	2.9
Sugar Maple-American Beech	6	8.3	15.8	12.6	2.9
Sugar Maple-American Beech-Yellow Birch	4	13.3	21.5	16.0	3.7

Since forest floor chemistry is known to be affected by species composition in many cases (Longpre *et al.* 1994), six forest floor variables were also examined between stand types: pH (in distilled water), total calcium (Ca), total magnesium (Mg), total potassium (K), total phosphorous (P), the carbon-nitrogen ratio (C:N).

Descriptive statistics by stand type are presented for these variables in Table A3.2 (Appendix 2). A one-way ANOVA was used to examine differences in these variables between stand types and assess whether the different species compositions affected forest floor chemistry.

The Chapman-Richards 3-parameter model (Richards 1959) (equation [2.2]) was fitted to the average height data for sugar maple for each stand type, resulting in a sugar maple height-growth curve for each stand type. In addition, a separate height-growth model was fitted for all three species across all stand types, resulting in a general height-growth curve for each species. This allowed comparisons in sugar maple height growth between different species compositions and comparisons in height growth patterns between the species on the same site type.

3.5 RESULTS

3.5.1 Height-Growth and Site-Index Models

Equation [3.2] provided a slightly better fit on the basis of R^2 and mean square error (Table 3.5). Both [3.1] and [3.2] were, however, evaluated further because R^2 is a less reliable indicator of goodness of fit for nonlinear models, since the fitted model may not always pass through the mean value of the dependent and independent variables (Neter *et al.* 1996).

Some lack of precision is evident in the residuals plots for this model (Figure A3.1, Appendix 2). All four species show varying degrees of positive error with respect to age for equation [3.1]. Residuals are zero at the index age (50 years breast height), a result of the model being conditioned to pass through site index (total height at breast height age 50)

Table 3.5. Results of fitting height growth models using equations [3.1] and [3.2]. R^2 is the corrected R^2, MSE is the mean square error and DFE are the degrees of freedom error.

		Parameters							
Species	Model	b_1	b_2	b_3	b_4	b_5	R^2	MSE	DFE
Sugar Maple	Eq. [3.1]	14.961	-2.338	-2.368			0.818	6.623	1766
	Eq. [3.2]	9.085	0.399	-0.019	8.356	-0.712	0.966	1.239	1764
American Beech	Eq. [3.1]	15.817	-2.594	-2.523			0.813	7.554	1185
	Eq. [3.2]	8.938	0.439	-0.022	8.669	-0.641	0.965	1.405	1183
Yellow Birch	Eq. [3.1]	11.384	-2.171	-1.653			0.764	6.662	574
	Eq. [3.2]	3.849	0.796	-0.011	1.614	-0.209	0.979	0.597	572
Red Oak	Eq. [3.1]	9.949	-1.872	-1.545			0.801	4.484	923
	Eq. [3.2]	2.065	0.948	-0.015	0.87	0.015	0.99	0.22	921

(Chen and Klinka 2000). This mild lack of precision coincided with evidence of bias in the models when the regression y = x was compared to the regression line (forced through the origin) for the plots of estimated (from equation [3.1]) versus observed heights (Figure A3.2, Appendix 2).

Since accuracy assessment and model validation alone should only guide the researcher in assessing the effectiveness of a model (Nigh and Sit 1996), site-index curves based on the logistic model were plotted and compared to observed height-age data for each species (Figure A3.3, Appendix 2); despite the above evidence they might not be suitable models. These curves were obviously a poor fit to the observed data; curves for all four species showed strong bias and lack of fit in estimating juvenile height growth (underestimated) and height growth after index age (overestimated) in particular. As such, they were rejected as suitable models for site-index curves in this study.

Compared to equation [3.1], equation [3.2] was a slightly better fit to the dataset for all four species on the basis of its corrected R^2 and MSE. Residuals plots for equation [3.2] indicated considerably higher precision than for equation [3.1] (Figure 3.1). The residuals in Figure 3.1 average between ±3 m for equation [3.2]. No patterns of bias were evident in the plots and they were much less dispersed than residuals for equation [3.1].

To further test for bias, the fitted models were evaluated on the basis of estimated versus observed heights (Figure 3.2). Regression models fitted to estimated versus observed values for all four species were not significantly different from the regression line $y = x$ ($p > 0.05$), and were concluded to be unbiased in estimation of height for all four species.

On the basis of these accuracy assessments, equation [3.2] was chosen as the height versus age and site index model for tolerant hardwood species in central Ontario. Site-index curves for all four species based on equation [3.2] are plotted against observed values for these species and are presented in Figure 3.3.

The results of fitting equation [3.3] to predict site index from observed breast height age and total height are presented in Table 3.6. Residuals plots and regression plots for estimated versus observed site indices are present in Figures A3.4 and A3.5 (Appendix 2). Corrected R^2 values for equation [3.3] were considerably poorer than for height-age models [3.1] and [3.2] in this study, indicating the model did not fit the data well; mean square error values were better than for equation [3.1], but poorer than for equation [3.2]. On the basis of the earlier height-growth model findings, it is possible equation [3.4] (the corollary of equation [3.2]) provides a more accurate site-index prediction model. Equation [3.4] is considerably more difficult to fit than equation [3.3] in this context, and after exhaustive attempts at fitting was unfortunately dropped from the analyses.

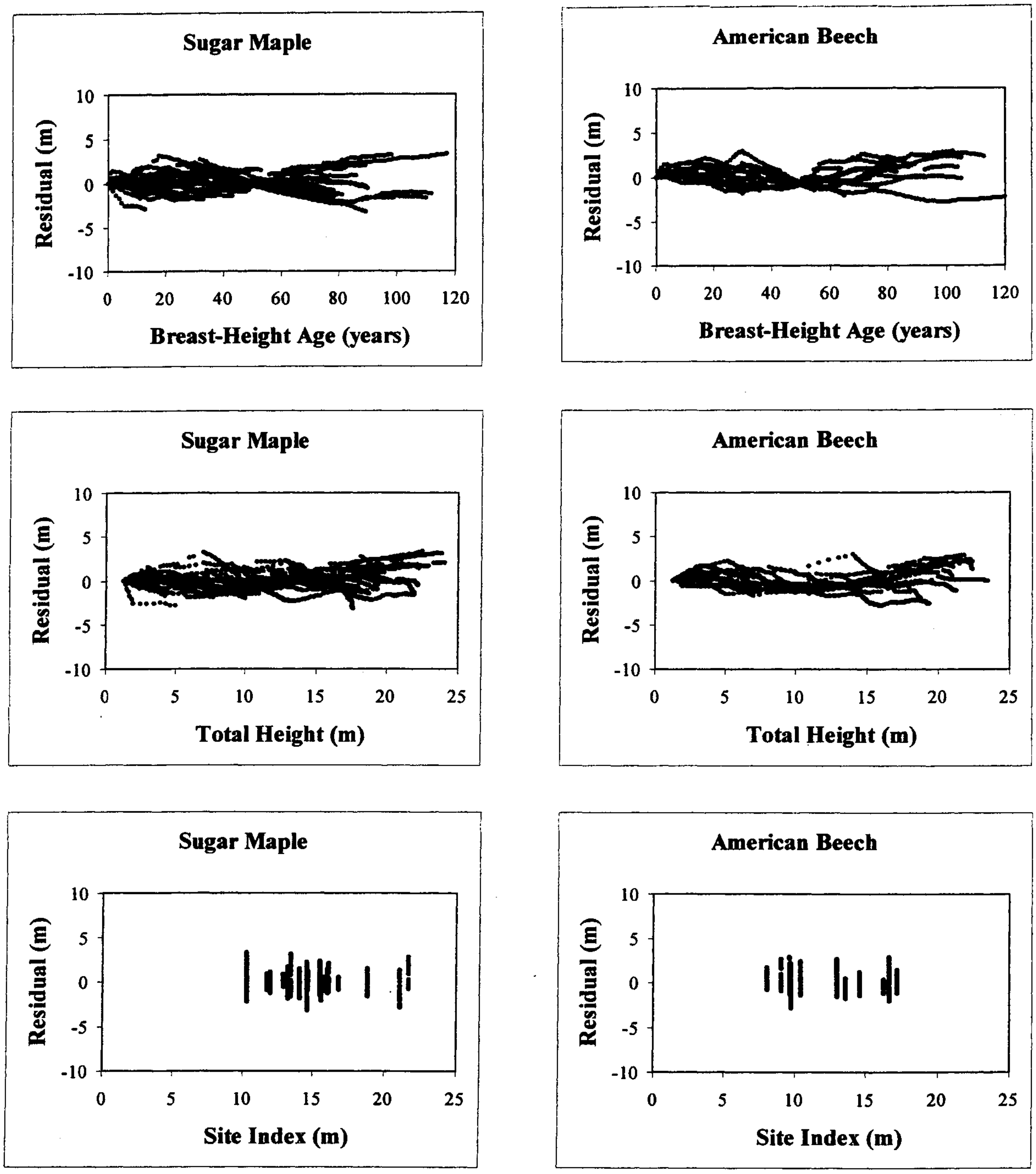

Figure 3.1. Residuals of Chapman-Richards height-growth model [3.2] versus breast-height age (years), total height (m) and site index (m) for sugar maple and American beech.

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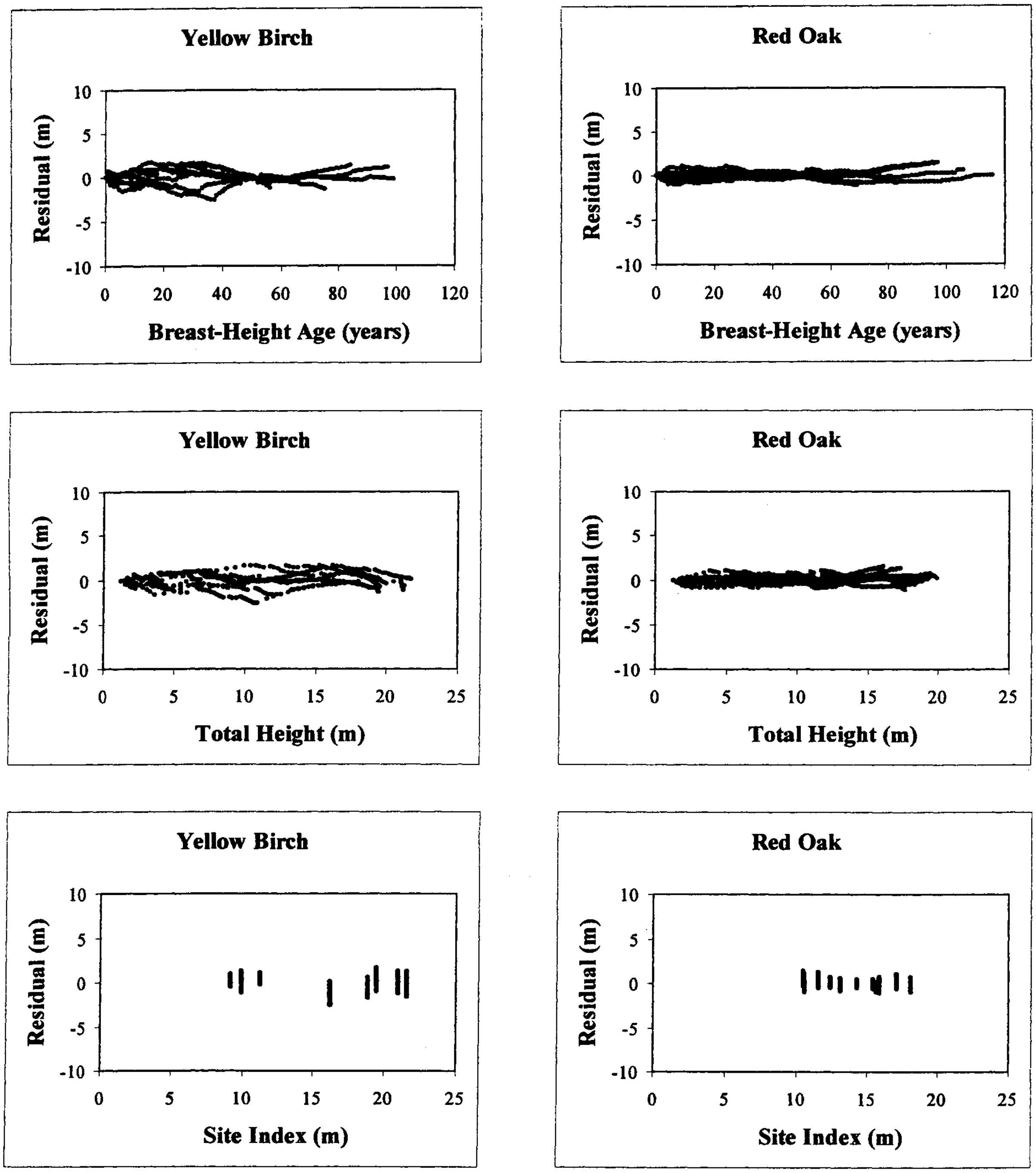

Figure 3.1 (continued). Residuals of Chapman-Richards height-growth model [3.2] versus breast-height age (years), total height (m) and site index (m) for yellow birch and red oak.

Regression lines forced through the origin of estimated versus predicted site indices for equation [3.3] were not significantly different ($p > 0.05$) from the line $y = x$ on the basis of a two tailed t-test comparing their slope coefficients (Zar 1996) (Figure 3.8, Appendix 2),

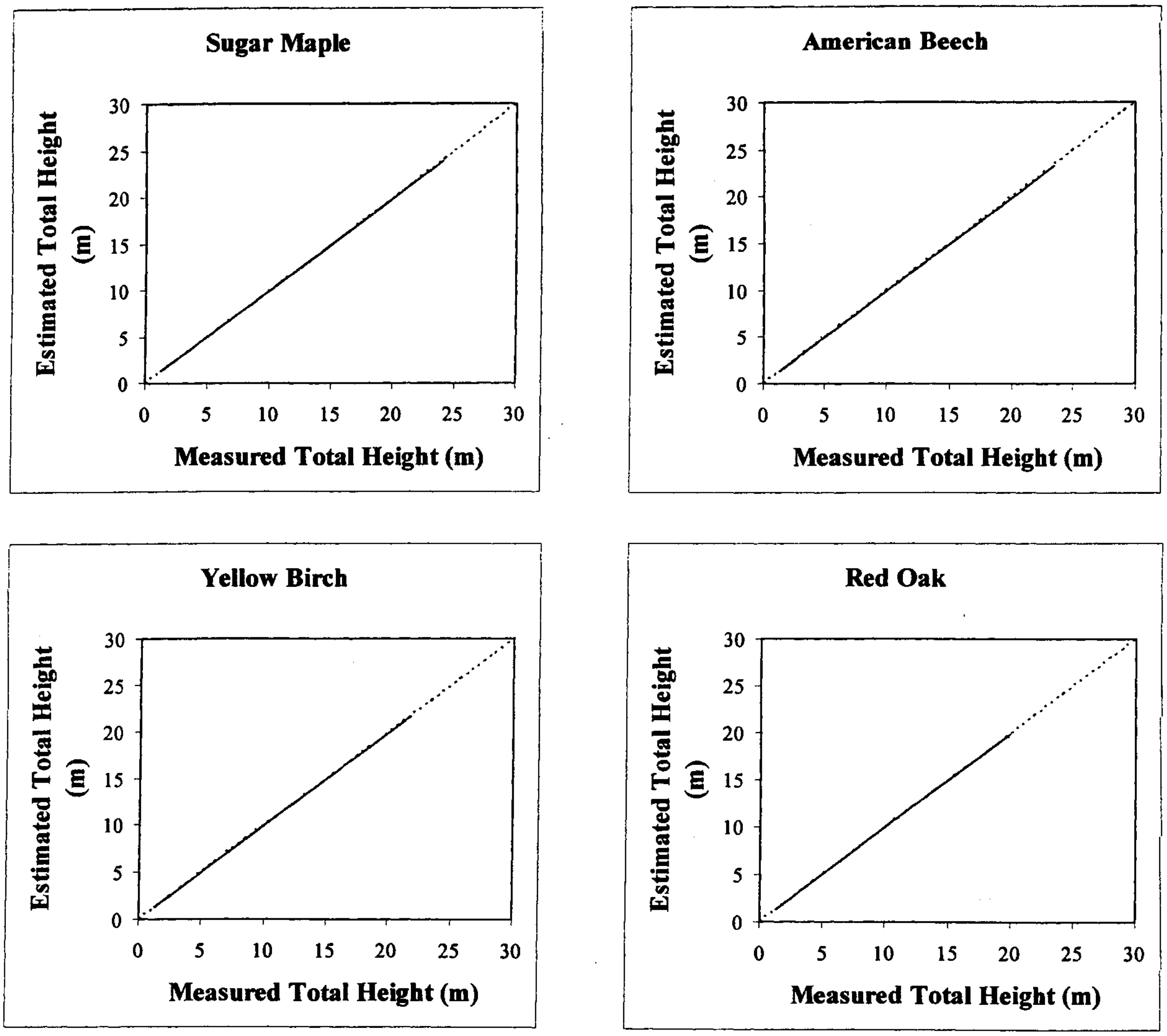

Figure 3.2. Graphical results of regression of measured total height (m) versus total height predicted by equation [3.2] by species. Solid lines are regression lines and dashed lines represent $y = x$. Regression models for all four species were shown to be similar ($p > 0.05$) from the line $y = x$ in a two-tailed t-test comparing slopes (Zar 1996).

indicating equation [3.3], while imprecise, was not a biased estimator of site index for all four species.

In summary, equation [3.2] was chosen as the best height-growth prediction model, while [3.3] was chosen as the site-index prediction model for this study.

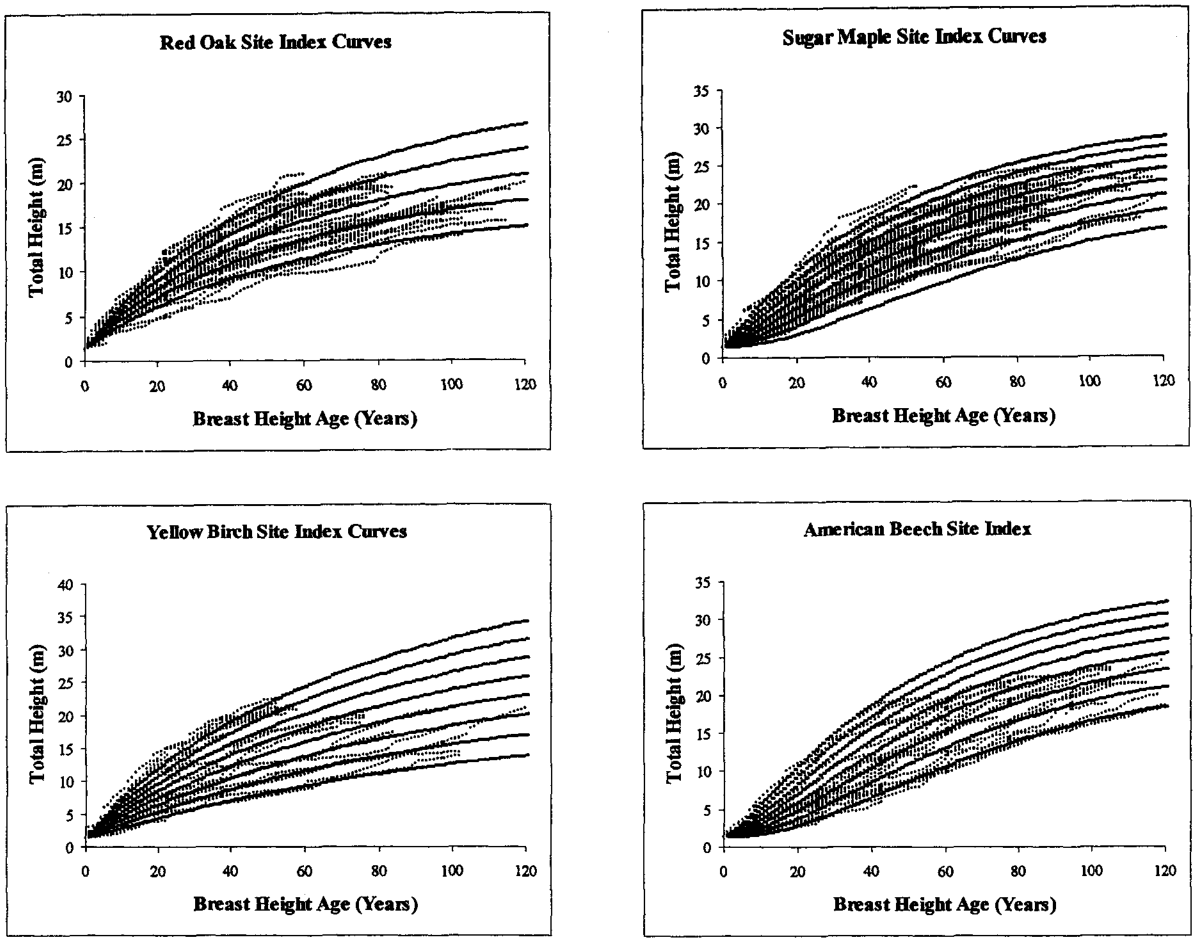

Figure 3.3. Preliminary site-index curves for sugar maple, American beech, yellow birch and red oak in central Ontario, based on equation [3.2].

Table 3.6. Results of fitting equation [3.3] to predict site index from breast-height age and total height. R^2 is the corrected R^2, MSE is the mean square error and DFE are the degrees of freedom from error.

	Parameters					
Species	b_1	b_2	b_3	R^2	MSE	DFE
Sugar Maple	-3.853	1.689	-1.053	0.312	5.236	1766
American Beech	-4.932	1.910	-0.962	0.535	3.612	1185
Yellow Birch	-1.048	1.107	-0.973	0.740	5.997	574
Red Oak	-1.367	1.125	-1.079	0.416	3.356	923

3.5.2 Assessment of Site-Index Models from the Lake States Region

The results of the accuracy assessment on Hahn and Carmean's (1982) site-index models from the Lake States as applied to the data from central Ontario are shown in Figures A3.6 and A3.7 (Appendix 2). Residuals plots for sugar maple and yellow birch appear relatively precise against breast-height age but appear less precise when compared to site index and total height. Residuals plots for yellow birch and red oak appear imprecise and seem to show a curvilinear rather than random trend, indicating some bias (Neter *et al.* 1996). The bias is further confirmed in Figure A3.7 (Appendix 2), where regression lines fitted to observed heights versus those predicted from Hahn and Carmean's (1982) equations were significantly different ($p > 0.05$) from the line $y = x$ (Zar 1996), indicating they were biased (Chen *et al.* 1998).

Figure 3.4 contains plots by species of the site-index curves developed in this study against those of the Lake States (Carmean 1978). There are clear differences in these two sets of curves. Juvenile height growth of red oak in central Ontario is considerably underestimated using Carmean's (1978) curves, while height growth after index age on poor and medium sites is in Ontario considerably overestimated. Height growth after index age on richer sites is comparable to the locally-derived curves though.

Carmean's (1978) curves for sugar maple are closer to those developed in this study. Differences in juvenile height growth before index age are less pronounced, though differences after index age become apparent. Trees on poorer sites have considerably slower height growth while the height growth of trees on richer sites exceeds that predicted by the curves from this study.

Carmean's (1978) curves for yellow birch underestimate juvenile height growth and considerably overestimate height growth after index age in central Ontario. Both studies

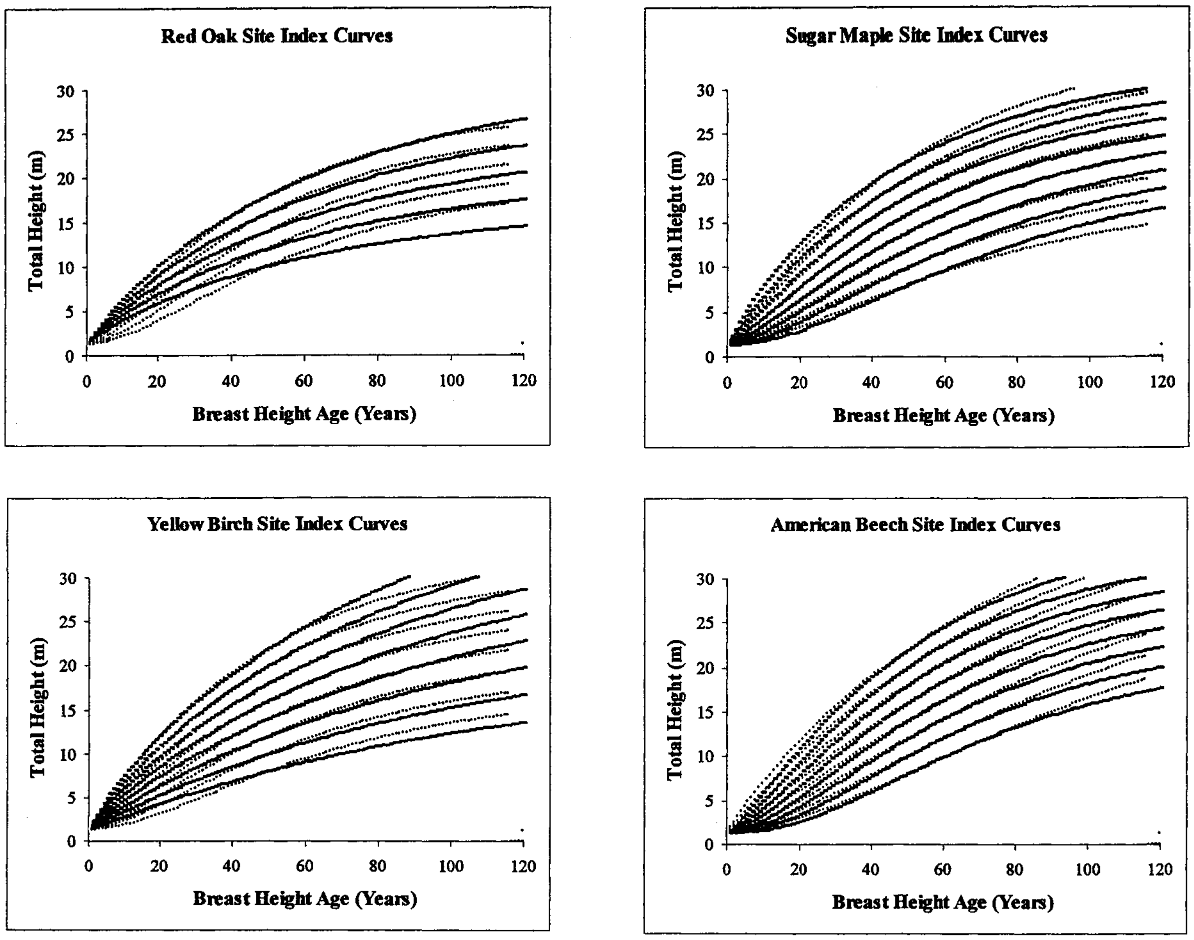

Figure 3.4. Graphical comparisons by species of Hahn and Carmean's (1982) site-index curves (red) with those developed in this study (black).

show similar yellow birch height-growth patterns on medium and good sites until approximately 80 years breast-height age where Carmean's (1978) curves underestimate height growth in central Ontario predicted by the curves from this study.

Curves for American beech developed in this study predicted slower juvenile height growth than those of Carmean (1978), and also slower height growth after index age. Height growth close to index age was similar for curves from both studies.

3.5.3 Effects of Species Composition on Height Growth and Site Index of Sugar Maple

Table 3.7 contains the results of the one-way ANOVAs used to assess the similarity of site variables known to be related to sugar maple height growth between the three stand types (pure sugar maple, sugar maple-American beech and sugar maple-American beech-yellow birch). Significant differences ($p > 0.05$) were detected between the three stand types for bulk density and percent sand in the B horizon. All other variables were similar ($p > 0.05$) on sites between the three stand types. As the majority of variables were shown to be similar between sites, the overall sites supporting the three stand types were deemed to be similar and further comparisons between the sites proceeded.

Table 3.7. Results of one-way ANOVAs on sugar maple height growth-site variables.

Site Variable	F-Ratio	P
Total Depth (cm)	0.436	0.655
Elevation (m)	1.114	0.356
A Thickness (cm)	0.221	0.804
A Coarse Frag %	1.895	0.187
A Bulk Density (g/cm^3)	0.408	0.673
A % Sand	2.856	0.091
A % Silt	3.701	0.051
A % Clay	1.221	0.325
B Thickness (cm)	0.692	0.517
B Coarse Frag %	1.583	0.24
B Bulk Density (g/cm^3)	4.869	0.025*
B % Sand	4.495	0.031*
B % Silt	3.715	0.051
B % Clay	1.252	0.316

**Indicates variables that were significantly different between stand types at the 0.05 level.*

The one way ANOVA revealed no significant differences ($p > 0.05$) in site index of sugar maple between the three stand types ($F = 2.272$, $P = 0.140$). The lowest observed mean site index was for the sugar maple-American beech composition, while pure sugar maple and sugar maple-American beech-yellow birch stand types were very close to each other (Table 3.4).

No significant differences ($p > 0.05$) were detected between stand types for forest floor chemical variables (Table 3.8).

Table 3.8. Results of one-way ANOVAs on forest floor chemistry between stand types.

F Layer Variable	F	P
pH	0.574	0.576
Total Ca (kg/ha)	0.200	0.821
Total Mg (kg/ha)	0.082	0.922
Total K (kg/ha)	0.454	0.644
Total P (kg/ha)	0.874	0.439
C:N Ratio	0.621	0.552

Table 3.9 presents the results of fitting the three parameter Chapman-Richards function [2.2] to the height-age data for sugar maple growing in each species association; these height-growth curves are plotted in Figure 3.5. General height-growth models for sugar maple, American beech and yellow birch growing on the same sites are presented in Table 3.10 and Figure 3.6.

Height-growth models for all species provided reasonably good fit based on MSE and R^2 values; the R^2 for yellow birch was low (0.570), probably a result of the small number of sample plots for the stand type and inherent lower number of sample trees for height-growth

Table 3.9. Results of fitting equation [2.2] to height-age data for sugar maple in different stand types. R^2 is the corrected R^2, MSE is the mean square error and DFE are the degrees of freedom from error.

Stand Type	Parameters b_1	b_2	b_3	R^2	MSE	DFE
Mh	22.907	0.023	1.402	0.840	7.071	1677
MhBe	22.435	0.022	1.722	0.854	6.762	1985
MhBeBy	25.995	0.015	1.363	0.722	10.364	847

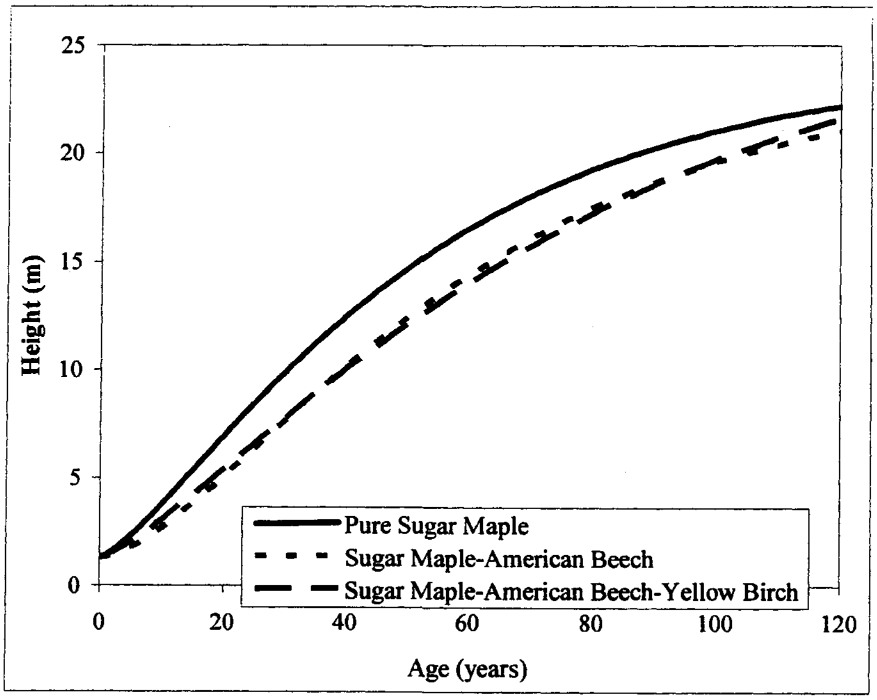

Figure 3.5. Fitted sugar maple height-growth curves based on equation [2.2] reflecting sugar maple height growth in pure stands and in two different species mixtures (associated with American beech, and associated with both American beech and yellow birch).

model fitting. Figure 3.5 shows a distinctly better (more rapid), but similar-shaped height-growth pattern for sugar maple occurring in pure stands. Height-growth patterns for sugar

Table 3.10. Results of fitting equation [2.2] to height-age data for sugar maple, American beech and yellow birch on the similar sites. R^2 is the corrected R^2, MSE is the mean square error and DFE are the degrees of freedom from error.

	Parameters					
Stand Type	b_1	b_2	b_3	R^2	MSE	DFE
Sugar Maple	22.397	0.022	1.522	0.815	8.461	4515
American Beech	22.305	0.015	1.586	0.753	10.314	2942
Yellow Birch	14.358	0.079	1.966	0.570	15.034	441

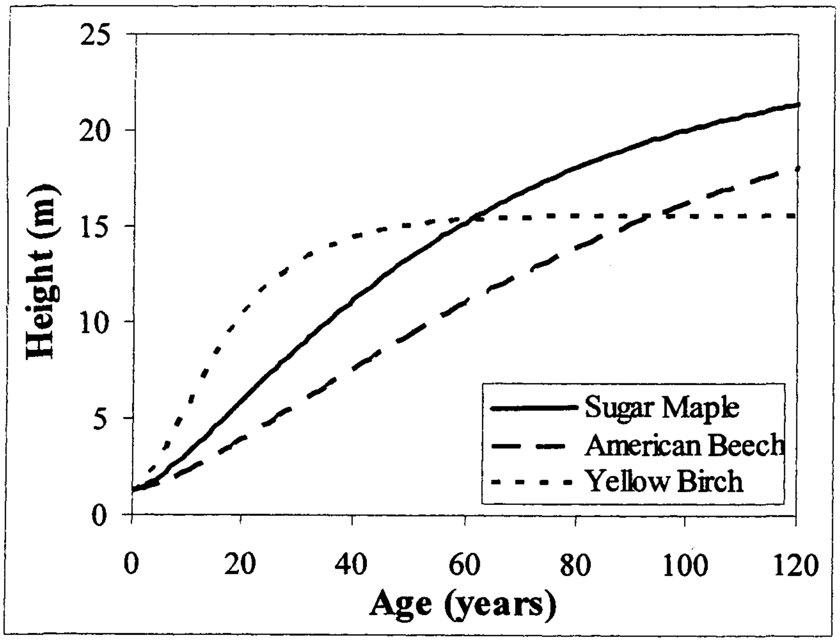

Figure 3.6: Fitted height growth curves based on equation [2.2] for sugar maple, American beech and yellow birch growing on the same sites.

maple growing in association with American beech, and American beech and yellow birch, are nearly identical but substantially lower than for pure maple stands.

Height-growth patterns for sugar maple are similar to, but higher than, American beech occurring on the same sites based on Figure 3.6. Yellow birch exhibits considerably more rapid early height growth but quickly tapers off and is surpassed by sugar maple at 60 years and American beech after 90 years.

3.6 DISCUSSION

3.6.1 Model Accuracy Assessment

Model accuracy refers to the closeness of a predicted value based on the model to its true (observed) value, which is affected by bias and precision (Nigh and Sit 1996, Chen *et al.* 1998). Height-growth and site-index model assessment in this study closely followed the methods outlined by Chen *et al.* (1998). The intent of site-index models is to provide good (unbiased) estimates of top height or site index for any given breast height age (Chen *et al.* 1998) within the range of observed site indices for the model. Deviation of values predicted by the model from observed actual values is a good measure of unbiasedness, and residual variance is a good measure of precision (Nigh and Sit 1996; Chen *et al.* 1998).

Residual plots of estimated heights and site indices versus age, height and site index were examined for signs of bias (Chen *et al.* 1998; Nigh 1998). The errors were not independent since multiple observations were taken from within a plot (Nigh 1998), and conditioning of equations [3.1] and [3.2] to go through the site index resulted in heteroscedasticity among residuals; both usually become apparent in residuals plots such as these (Nigh 1998).

In addition, a site-index model can only be considered an unbiased estimator when predicted site indices are not different from measured site indices across their full range (Chen *et al.* 1998). Fitted regression lines (with intercept = 0) of estimated versus measured site indices should not be significantly different from the regression y = x (with intercept = 0 and slope = 1) (Chen *et al.* 1998). Accordingly, plots of estimated versus observed site indices were tested against regression y = x; after Chen *et al.* (1998) and Chen and Klinka (2000). Regression and ANOVA assumptions were examined prior to regression fitting and testing as outlined by Neter *et al.* (1996) and Zar (1996); after Chen et al. (1998).

There has been considerable debate among researchers regarding nonlinear model validation procedures (Neter *et al.* 1996). The procedures used in this study are similar to those from numerous similar studies, and were adequate for these preliminary height-growth and site-index models. Ways of improving height-growth model validation procedures do exist (e.g. Nigh and Sit 1996).

The validation procedures used for the height-growth and site-index models in this study should also be interpreted carefully, since they are a reflection of the dataset from which they were derived (Nigh and Sit 1996). The inherent errors in precision and bias observed for some of the models in this study may have shown the data used in building them were in fact biased (Nigh and Sit 1996), a distinct possibility given the small sample sizes and complex stand conditions in central Ontario (see below). While the validation procedures outlined by Nigh and Sit (1996) overcome some of the problems of lack of independence in the dataset and non-constant variance in the residuals, the best validation procedure would be to test the models against an independent dataset or subset of samples from this study (Neter *et al.* 1996). The small number of samples and lack of any previous studies in the region precluded this possibility. Access to additional stem analysis data or permanent sample plot data for the region might provide a source of validation data for this study in the future.

3.6.2 Curve Adjustment

Direct graphical comparisons were required between Carmean's (1978) curves and those developed in this study. Site-index curves suitable for graphically estimating site index can be computed using models such as those developed in this study and by Hahn and Carmean (1982), but curves computed using these models will not pass exactly through the specified height and the index age (50 years) (Newnham 1988; Carmean and Lenthall 1989). Curves computed for the site index class closest to the approximate mean site index for the data will agree closely with the specified height at index age, but curves with site indices above or below this mean will have larger errors proportional to their distance from the mean (Newnham 1988; Carmean and Lenthall 1989). The number of samples and site indices well above and below the mean might also influence model fit.

Newnham (1988) addressed this issue with a modification of Ek's (1971) model, which forces computed curves to pass through both the correct height at index age as well as the origin. In addition, graphical as well as mathematical methods could be used to correct this deficiency, which probably arises as a result of averaging or rounding errors (Carmean and Lenthall 1989).

Carmean and Lenthall (1989) introduced an iterative mathematical process which was adapted for graphing the curves in this study, and those of Carmean (1979) to facilitate accurate graphical comparisons. The curves were then plotted together and direct comparisons were made between them which could be used to confirm and further illustrate the results of the above accuracy assessment. A secondary height-growth model could have been computed from these corrected curves to produce more precise estimates of total tree height and index age which might have been more precise (Carmean and Lenthall 1989). It is likely, however, that such a model would still produce some error in height estimates due to the wide range of site indices in a study such as this for reasons similar to those given for errors in total height predicted by the original model above. As a result, iterative corrections were limited to producing site-index curve plots, and no secondary equation was fitted to these "corrected observations".

3.6.3 Height-Growth Models

While various functional forms have been proposed for site-index curves and general tree height-age models, the logistic equation [3.1] seems most widely used for forest tree species in western Canada where it has been shown to fit height-growth patterns of various tree species best (e.g. Nigh 1996; Nigh 1998; Nigh and Courtin 1998; Chen *et al.* 1998). The logistic function was also chosen as the most suitable model for a species-independent height age model in British Columbia (Nigh 2000). Site-index curves for eastern Canadian tree species seem to most commonly favour the 5-parameter Ek-Payandeh (1974) modification of the Chapman-Richards (1959) function (e.g. Payandeh 1974; Carmean and Lenthall 1989; Newnham 1988), and this was the functional form chosen for a species-independent tolerant hardwood model (Payandeh 1974) and for hardwoods in the Lake States (Hahn and Carmean 1982).

The logistic function is advantageous in that it has fewer (three) parameters to be estimated, thus making it slightly easier to work with. In addition, these parameters are easily interpreted, while the (five) parameters in the Ek-Payandeh (1974) model are less easily interpreted on their own. Both models are characterized by their nonlinear and asymptotic features (Chen *et al.* 1998) which make them well-adapted to height-growth modeling. The logistic model was less suited to this study, possibly because it has fewer parameters affecting the slope at various points in the model (fewer rate parameters).

In addition, the Ek-Payandeh model [3.2] was the same as that used for site-index curves produced for the same species in the Lake States, and has the added advantage of facilitating more direct comparisons in the models with respect to specific parameter estimates.

Weaknesses of the models developed in this study centre around sample size issues, validation procedures (discussed earlier) and the nature of hardwood stands in central Ontario. Limitations in funding and time constraints prevented larger samples for all four species, and the curves, with the exception of those for sugar maple, can at best be considered preliminary approximations of the true height-growth patterns of these species in the region. Larger samples are clearly necessary, especially for American beech, yellow birch and red oak. Ideally, a minimum of 30 sample plots are required for the development of good site-index and height-growth curves for most forest tree species (Chen 2003).

Hardwood forests in central Ontario are composed of predominantly uneven-aged, mixed-species stands with a history of disturbance from selection logging and other sources (OMNR 1998). There are no satisfactory long-term records of past disturbance histories for the sampled stands. Many of the stands with a relatively even-aged structure or a pure species composition at the time of sampling may not have always been in this condition, despite efforts to sample these types of stands. In addition, the smaller samples sizes for American beech and yellow birch led to the development of site-index curves based on stands less acceptable for traditional site-index curve development on the basis of species composition and age structure.

The differences in height-growth patterns expressed in the site-index curves for each species are probably a reflection of the different silvical and autecological characteristics of these species. American beech in particular is a commonly occurring understory component of sugar maple-dominated stands (Anderson *et al.* 1998), and so nearly all sample trees of this species in the study were probably affected by suppression at some point during their lives – despite sampling efforts to the contrary. It is likely that site-quality estimation techniques such as site index are simply not suitable for American beech in central Ontario because it occurs only rarely in pure stands (Anderson *et al.* 1998).

Yellow birch is less shade tolerant (Anderson et al. 1998) and thus exhibits the rapid early height growth as demonstrated in the curves produced in this study. It is also comparatively short-lived, being replaced by later successional species such as sugar maple due to its inability to reproduce effectively without disturbance to the forest floor (Anderson *et al.* 1998). This led to the relatively flat, near-asymptotic height-growth observed as the curves for this species were extrapolated beyond the range of observed data (Figure 3.3) to 120 years breast height age.

The primary target species in this study, sugar maple, had a larger number of samples (adequate) for curve development, and on the basis of sample size alone probably has the most accurate and valid site-index curves of the species in this study. Unfortunately, it was very difficult to find even-aged stands of pure sugar maple in this study, and it is very likely many of the plots were not always even aged as defined in this study (e.g. due to removal of suppressed trees in prior logging). These curves are, however, probably a good approximation of sugar maple height-growth patterns in the region.

Red oak, which is comparatively shade-intolerant, and commonly occurring in even-aged stands as a result (Anderson *et al.* 1998), is the tree species most suited to application of site index in this study. Despite a small number of sample plots, a good range of site types and site indices were covered in the study and so the curves are a good first approximation of how curves based on a larger sample might appear.

Polymorphic patterns of height growth are evident for the shade tolerant sugar maple and American beech species in this study, which vary according to site quality. This coincides with Carmean's (1978) site-index curves for these species. Curves for comparatively shade-intolerant yellow birch and red oak are more anamorphic, coinciding with height-growth curves developed for other shade-intolerant early-successional species (e.g. Chen *et al.* 1998; Nigh and Courtin 1998).

3.6.4 Site-Index Models

The function form of the site-index prediction equation [3.3] chosen for this study was the corollary of the logistic model [3.1]. Most studies use the corollary of the height-growth model chosen in the same study. This includes studies for tolerant hardwoods (Hahn and Carmean 1982). In this study, the direct corollary would have been that of equation [3.2]. The 3-parameter equation [3.1] was chosen as a site-index prediction model because of its relative simplicity to fit, and because of the smaller relative sample sizes in this study. The 5-parameter model was disregarded because of difficulties in fitting it to the smaller dataset in this study. In addition, equation [3.3] was shown not to have significant bias in estimates of site index for species in this study (Figure A3.5). Future studies based on larger datasets might be better suited to comparing the suitability of either of these models for this purpose.

3.6.5 Applicability of Carmean's (1978) Site-Index Curves to the Region

Significant bias and lack of precision was noted in the residuals and estimates from Hahn and Carmean's (1982) height-growth models as applied to the central Ontario data. Differences in height-growth patterns for all species were apparent when Carmean's (1978) site-index curves were plotted against those developed in this study. Small differences in how the models were developed, as well as differences in soils and stand history and composition between the two regions are two possible reasons for these discrepancies.

Early erratic height-growth was observed for tree species in this study and by Carmean (1978) before trees reached breast height; both studies developed models based on data after breast height for all species. Carmean (1978) added a constant of four years to the data before fitting his models to base them on total age, while models in this study were based on breast-height age. This small addition would have influenced the shape of Carmean's (1978) curves, particularly with regard to early-juvenile height-growth patterns, and this could explain some of the differences in early juvenile height growth observed between the two regions within species. It may also have led to small errors in plotting the curves against those generated in this study when the four year shift was removed.

Differences in forest vegetation arising from different site types and potentially richer sites in the Lake States might also explain some of the differences in height-growth patterns within species between the two regions. Species such as red oak occur on a wider variety of site types that are, on average, richer than those in central Ontario, and thus the potential for more intense competition from other vegetation exists during the stand establishment stage than for similar stands in central Ontario (J. Wang, personal communication, Lakehead University, October 2003). This might explain the slower juvenile height growth predicted by Carmean's (1978) curves relative to those in this study for species such as red oak.

In addition, Carmean's (1978) curves present a much greater range of site indices, particularly for richer sites, than was observed for the species in this study. Specifically, much higher site indices are presented for all four species than were observed anywhere in the region for this study. As some of Carmean's (1978) curves were shown to underestimate juvenile height growth for all site indices, using these curves in central Ontario could have led to serious overestimates in the site index and potential future height growth of trees in the region. Carmean (1996) notes that care must be taken not to extrapolate estimates of height growth based on site-index curves too far above or below index age.

Finally, Carmean (1978) had the luxury of ready access to even-aged, fire origin stands and a large dataset for the development of his curves. In this regard, his curves might be a more accurate reflection of potential height growth and site index of species in this study, particularly for American beech, since the concept of site index is more applicable in these types of stands. Because beech was not observed to occur in pure stands within the study area, it is possible that site index is not a good method of site-quality evaluation for this species at all – in which case neither study would be applicable.

In addition, many of the more shade-intolerant species such as yellow birch and red oak occur on a wider variety of soil and site types. These species regenerate more easily in clearcut areas such as those found in the Lake States. Accordingly, more even-aged stands with a greater number of unsuppressed trees were available for Carmean's (1978) study.

3.6.6 Effects of Species Composition on the Height Growth of Sugar Maple

The results of this study indicate there were no statistically significant differences in the site index of sugar maple between stand types occurring on similar site types, though the variables used to identify the site types were broad physical soil variables. No significant differences were observed in forest floor chemical variables between the three stand types either. Differences in height growth curves of sugar maple on the three site types were apparent (Figure 3.6), though not statistically significant. Differences in height growth patterns of the three species dominating the subset of stands used in the study were apparent in height-growth curves for each species.

The results of this study have some limitations and as such can only be considered preliminary. First and foremost, the sample sizes for each stand type, especially sugar maple-American beech-yellow birch stands, were quite small. In addition, the samples were restricted to a comparatively narrow range of site indices over which sugar maple occurs in the region due to the necessity of finding sites with similar soil physical properties, and so cannot be interpreted as the general pattern for sugar maple in all mixtures with American beech and yellow birch. The results do, however, provide a good preliminary approximation of potential companion species effects on sugar maple site index.

Differences in sugar maple height-growth curves are potentially explained by silvical characteristics of, and relationships between the species; prevailing stand dynamics in the sample stands might also play a role. American beech is typically a long-lived tree that is often established in the understory of sugar maple-dominated stand (Anderson *et al.* 1998), and thus may not be in direct competition with sugar maple for light during the early stages of stand development. Sugar maple site indices on average were lower (though not significantly different at the $p > 0.05$ level), however, in mixtures with beech than in pure stands of sugar maple. A possible explanation is that stands with dominant or codominant beech tree components have sugar maple trees that were not always in the dominant canopy component of the stand (maple trees may have been replaced by beech and maple that both once formed part of the understory). As a result, the sugar maple trees in this stand type may have been suppressed in a similar manner as American beech and thus given inaccurate estimates of the true site index for sugar maple on the site.

Of course, the relatively small sample sizes in the mixed stands in this study compared to other similar studies (e.g. Longpre *et al.* 1994) might also have produced results that do not accurately reflect sugar maple stand dynamics in the region.

In a broad study of the productivity of mixed- versus single-species stands in western Canada, Chen *et al.* (2003) noted the effect of species mixture on the productivity of a given species is both tree species- and site-specific. A vastly superior methodology for investigating these relationships and their effects on overall forest productivity is also provided that is beyond the range of this dataset.

Finally, it is hard to quantitatively assess the effects of species mixture on the overall growth patterns of sugar maple, particularly with regard to diameter growth and stand structure due to many of the sample stands in this study being located in stands with evidence of past disturbance. In accordance with this, and the lack of significant differences in sugar maple site index, mixed-species stands cannot be stated to be more or less productive than pure sugar maple stands on the basis of these results. This is also due in part to the lack of estimates of site indices for American beech and yellow birch in these stands.

3.7 CONCLUSIONS

The height-growth and site-index prediction models produced in this study for the four tolerant hardwood species were shown to have good precision and were unbiased estimators of tree height and site index. Models for all four species should be considered preliminary approximations of the height-growth patterns and site-index relationships for these species in central Ontario due to small sample sizes and not all plots meeting the traditional assumptions of site index.

Preliminary investigation of Carmean's (1978) site-index curves from the Lake States has shown they are unsuitable in application to central Ontario, and height growth patterns for hardwoods in this study differ in shape from those of the same species in the Lake States. In addition, they predict greater potential site indices than were observed for these species in the Great Lakes-St. Lawrence study region. Carmean's (1978) curves should therefore not be used in central Ontario as stand-level site-quality estimation tools without calibration to local stand conditions. Carmean's (1978) curves may, however, more accurately describe the potential height-growth patterns of American beech than do the curves in this study due to a lack of pure, even-aged sample stands in the study region. Further validation work is required to determine the applicability of these curves to the region.

An initial investigation indicates the presence of companion species such as American beech and yellow birch does not affect sugar maple site index on sites of medium quality. Further work is required to evaluate the potential productivity of mixed versus pure tolerant hardwood stands and assess the validity of using the concept of site index as a tool for assessing forest site quality in these conditions.

CHAPTER 4: SITE-FORM MODELS AND CURVES AND VALIDATION

4.1 INTRODUCTION

This chapter focuses on the development of local site-form curves and associated models and equations – an alternative method of site-quality evaluation to the site-index models developed in Chapter 3. Preliminary height-growth models as a function of dbh and site form, and site-form curves, are produced for sugar maple, American beech, yellow birch and red oak in central Ontario. Two different equation forms are examined and validated for use in developing site-form curves for these species. Site-form curves for sugar maple are compared to some preliminary site-form curves previously developed for this species in the region. Finally, a preliminary investigation into the validity of using site form as a measure of forest site quality for tolerant hardwood forests in the region is also described.

4.2 LITERATURE REVIEW

4.2.1 Limitations of Site Index

Site-index estimates and height-age curves used to determine site index are developed from information based on suitable site trees (Wang 1998). Such trees are traditionally only found in older, even-aged, well-stocked, free-growing, undisturbed, pure or single-species dominated stands (Carmean 1975; Wang 1998). While site index is somewhat unaffected by disturbances such as thinning (Monserud 1984), it is difficult to apply in uneven-aged, mixed-species stands such as those commonly found in the hardwood forests of central Ontario (Monserud 1988, Wang 1998).

There are some general weaknesses of site index despite its widespread acceptance in North America as a site quality evaluation tool (Carmean 1975). These weaknesses were summarized by Stout and Shumway (1982):

1. polymorphism in height-growth curves introduces errors in extrapolation;
2. measurement of both height and age present mensurational difficulties which may introduce large errors in site index values; and
3. since height alone is only one component of volume, an estimate of site quality based on height alone is not synonymous with volume productivity.

Site index is less accurate in older or overmature stands (Monserud 1985) – a stand type that it is recommended site index not be used in (Carmean 1996). In particular, observed site index can potentially decrease with increasing stand age as prior good site trees become overmature and are replaced by trees that previously showed signs of suppression (Monserud 1985). Even trees in younger stands that would be suitable site trees on the basis of age and canopy position are subject to replacement at regular intervals by less vigorous cohorts or trees with a past history of suppression (Raulier *et al.* 2003). Raulier *et al.* (2003) focused on jack pine and black spruce, two tree species of low and moderate shade tolerance respectively; this probably even more of an issue with shade-tolerant species such as sugar maple and American beech.

Curtis (1964) established a standard for developing site-index curves from stem analysis data, which prevails to this day in most recent studies (e.g. Carmean 1978; Carmean 1996; Nigh 1998; Chen *et al.* 1998); however, there are problems with developing site-index models from stem analyses data. Changes in relative canopy position and tree mortality can result in severe overestimation of dominant tree height growth over time since researchers have no way of accounting for these changes with stem analyses data (Raulier *et al.* 2003).

Curves based on permanent and temporary sample plots with dominant tree dynamics records were shown to be more indicative of true dominant tree height growth on a given site than those developed from stem analyses (Raulier *et al.* 2003).

The use of site index is obviously confined to even-aged stands of known age, and is less suitable as a measure of site productivity for tree species occurring in other stand conditions or with hard-to-define growth rings which make age measurements difficult or impossible (Vanclay and Henry 1988).

4.2.2 Site Form or Site-Productivity Index

Volume production is usually the stand growth parameter of greatest interest to forest managers (Vanclay and Henry 1988); therefore site-quality evaluation and productivity potential expressed in terms of volume is most desirable (Vanclay and Henry 1988; Philip 1994). The inherent challenges in measuring potential volume production on a site have led to the use of site index as the standard for site-quality estimation in many parts of the world (Vanclay and Henry 1988), despite the superiority of volume as a measure of forest site quality.

Diameter is the second required component, along with height, in estimating the volume of tree and ultimately stands (Philip 1994). Diameter growth has long been considered by foresters and biologists (e.g. Lanner 1981) as being considerably more sensitive to biotic and abiotic factors other than forest site quality, such as stand density and structure, than height growth (Stout and Shumway 1982). Accordingly, foresters traditionally have refrained from using diameter for site-quality evaluation (Stout and Shumway 1982; Huang and Titus 1993).

Stout and Shumway (1982) interpreted previous forest yield studies and suggested yield per unit area, irrespective of initial density, tends to converge in time. An assumption was made on the basis of this law of constant yield that the influence of stand density on potential stand productivity estimation was potentially overrated and therefore diameter at breast height could be used in place of age with total height to assess forest site quality (Shout and Shumway 1982). This indicates diameter could be used as part of a site-quality evaluation tool in stands subject to disturbance such as selection harvesting.

In accordance with the above assumption, a number of studies have utilized the total height of dominant or codominant trees at specific reference diameter at breast height, as an alternative to site index, for forest site-quality evaluation (e.g. Stout and Shumway 1982; Vanclay and Henry 1988; Huang and Titus 1993). This measure of forest productivity is termed site form (SF) or site-productivity index (SPI), and is analogous to site index in that height versus dbh curves (site-form curves) are developed using nonlinear regression methods to allow estimation of site quality at diameters other than the specified index diameter. Index dbh has typically been 20 (e.g. Huang and Titus 1993; Wang 1998) or 25 cm (e.g. Vanclay and Henry 1998; Woods *et al.* 1998).

Site form, unlike site index, is claimed to be unaffected by species composition and age-class structure (Huang and Titus 1993), which would seem to make it a more suitable measure of forest site quality in uneven-aged, mixed-species stands such as those found in central Ontario. Like site index, however, it does have some inherent assumptions: decreasing taper (diameter : height ratio) is associated with increasing site productivity (i.e. trees on richer sites are taller at the chosen reference diameter and more cylindrical in form); and stand density does not affect height-diameter relationships of dominant and codominant trees in uneven-aged or mixed species stands (Huang and Titus 1993; Wang 1998). These assumptions have not yet been explicitly tested and thus the validity of site form as a measure of forest site quality is an unverified claim (Wang 1998).

4.2.3 Site-Form Curves for Tolerant Hardwoods in Central Ontario

Very little work has been done in exploring the potential application and development of site form curves for use in the central hardwood forest region, despite its potential in these types of forest conditions.

Basic site-form curves for eastern hardwoods in the central United States exist (Stout and Shumway 1982); these curves are relatively basic as they use simple equations based on height and dbh and separate parameter estimates for each site form class curve. In addition, soils and sites in the region differ significantly from those found in central Ontario, and the models are considered to be inapplicable in central Ontario for this reason.

A provisional set of site form curves for sugar maple occurring in uneven-aged, maple-dominated stands based on "Ontario conditions" has been developed (Woods *et al.* 1998). The authors note that further testing of site form is needed to assess the validity of its use as a site-quality evaluation tool in Ontario's tolerant hardwood stands.

4.2.4 Validity of Site Form as a Measure of Forest Site Quality

Further testing is needed to examine and verify the relationship of site form to ecological site quality, particularly in uneven-aged or mixed-species stands (Wang 1998). Additional testing of site form as measure of forest site quality for tolerant hardwood stands has been recommended for Ontario in particular, especially those managed with partial harvesting systems (Woods *et al.* 1998).

To date, only one study examining whether site form is a valid measure of forest site quality has been completed (Wang 1998). In a study of even-aged white spruce-dominated stands in British Columbia, it was concluded (Wang 1998): height of dominant trees at 20 cm dbh was related neither to site index nor to any ecological measure of forest site quality; taper (diameter : height ratio) did not decrease with increasing site quality; stand density may influence the height-diameter relationships of dominant trees; and height of dominant trees at a specific diameter was not an adequate measure of forest site quality for single-species dominated and even-aged stands.

On the basis of these findings, the usefulness of site form as a measure of site quality for uneven-aged or mixed-species stands should be questioned and perhaps rejected (Wang 1998). Nevertheless, further testing has been recommended to examine the relationship between the site form and ecological site quality on uneven-aged or mixed species stands (Wang 1998).

4.3 OBJECTIVES AND HYPOTHESES

4.3.1 Development of Preliminary Site-Form Curves

Preliminary site-form curves were developed, using two different equation forms, for sugar maple, American beech, yellow birch and red oak based on data from a variety of stand conditions. These curves were then validated using accuracy assessment procedures analogous to those for the site-index models developed in Chapter 3.

4.3.2 Assessment of Ontario's Site-Form Curves for Sugar Maple

The site-form curves for sugar maple developed in this study were used to validate preliminary site-form curves from a prior study (Woods *et al.* 1998) currently in use in the region. Any differences in the curves between the two studies were expected to be minor, since both were based on Ontario datasets.

4.3.3 Adequacy of Site Form as a Measure of Tolerant Hardwood Forest Site Quality

Finally, a preliminary investigation into applying site form as a method of forest site-quality evaluation in central Ontario was undertaken. One prior investigation into whether height of dominant trees at a reference diameter is an adequate measure of forest site quality currently exists (Wang 1998). The study, which examined even-aged, white spruce-dominated mixed stands in Alberta, showed site form was an invalid measure of forest site quality in Alberta for this type of stand (Wang 1998). The validity of applying this concept in uneven-aged mixed stands was therefore questioned, and further research in mixed stands was recommended in light of the support it received in other studies (e.g. Stout and Shumway 1982; Vanclay and Henry 1988). Accordingly, a preliminary investigation was implemented using methods adapted from (Wang 1998).

4.4 METHODS

4.4.1 Study Area and Sample Plots

A detailed description of the study area and general sampling and stem analyses methods was given in Chapters 2 and 3.

4.4.2 Data Preparation

The XLStem 1.3 Microsoft Excel macro (Regent 2001) was used to compile the WinDendro data and generate paired height-dbh estimates for each year of growth for all sampled trees using linear interpolation. All height-growth models in this study were fitted to these height-dbh pairs.

Plots of height versus dbh were graphically examined for errors and any obvious signs of suppression or damage in sample trees. Any sample trees showing signs of suppression or erratic height-growth patterns in their height-dbh curves before 20 cm dbh were rejected for development of site-form models. Trees showing signs of suppression in height-dbh curves after 20 cm dbh merely had that information discarded and were kept for further analyses (Table 4.1).

Table 4.1: Total number of plots and trees kept/rejected for site-form model development after inspection of height-dbh growth plots.

Species	n_{plots}	n_{trees}	
		n_{kept}	$n_{rejected}$
Sugar Maple	33	83	4
American Beech	17	40	3
Yellow Birch	11	21	1
Red Oak	11	32	1

With reference to height-age modeling, deleting a tree does not necessarily bias the results since any one of the trees could have been deleted from the plot (Nigh 1998). Within-plot variation is increased, though stem analysis data is too costly to reject whole plots on the basis of one tree and the site-index estimates themselves would be biased if these trees were retained in the plot (Nigh 1998). The same applies to height-dbh modeling.

Because the site, rather than the individual trees, is of interest in developing site quality evaluation models and curves (Chen and Klinka 2000), an average height versus dbh curve was fitted to the trees growing in each plot. Chen and Klinka (2000) outline three main ways to do this for height-age observations (the methods are applicable to height-dbh observations as well), including fitting an average nonlinear line by hand through a scatterplot of height vs. age observations (Curtis 1964), fitting a nonlinear model and curve to the individual plot data (e.g. Richards (1959) model), and using linear interpolation (after Nigh 1996, 1998). Shaw and Packee (1998) visually fitted a flexible spline function to get estimates of site index from plots below index age through extrapolation.

Linear interpolation can sometimes lead to errors in height estimates between observations (Chen and Klinka 2000). In addition, the data output from Windendro are in a yearly rather that diameter-interval increment format, and so do not necessarily have precise observations of site form (total height for a given reference diameter). Accordingly, a 3-parameter Chapman-Richards function (Richards 1959) was fitted to the height-growth data for each species occurring in each plot using nonlinear least-squares regression techniques (Neter *et al.* 1996). This model was shown to be the best of a number of different models tested for modeling height-diameter relationships for forest tree species in Ontario (Peng *et al.* 2001). The fitted model was then used to generate reliable estimates of height-growth at regular intervals of 1 cm up to 40 cm for each species in the plot, which eliminated the risk of inaccurate plot height-growth curves due to height growth at larger dbh classes being determined by only one or two trees where there were differences in dbh of plot sample trees.

In this study, an index diameter of 20 cm dbh was chosen for the models developed, as it has been the standard in western Canada for similar studies (Huang and Titus 1993, Wang 1998), and the 25 cm reference diameter chosen by Woods *et al.* (1998) was too close to the upper limit in the range of observations for the dataset (Table 4.2).

Table 4.2: General statistics for height and dbh estimates by species for samples used in producing the height-dbh equations and curves. Min is the minimum observed value, Max is the maximum observed value, Mean is the mean or average value of observations and SD is the standard deviation.

	Plots	Trees	Total Height (m)				Total dbh (m)			
Species	n	n	Min	Max	Mean	SD	Min	Max	Mean	SD
Sugar Maple	33	83	15.1	25.1	20.9	2.3	12.8	37.7	26.6	5.2
American Beech	17	40	16.7	25.0	20.8	1.8	14.6	36.7	26.3	6.1
Yellow Birch	11	21	13.8	22.6	18.8	2.2	11.2	34.8	22.5	5.3
Red Oak	11	32	15.3	21.3	17.7	1.2	19.3	38.4	28.1	5.3

4.4.3 Height-Growth and Site-Form Models

A number of different functional forms have been chosen by various authors to fit models for site-form curves. Unlike site-index and height-age models, where a large number of studies exist and authors have used a few reliable equations, site-form studies seem to use a different equation for height-dbh models every time. These equations were largely chosen on the basis of local standards or the authors' own preferences and are not necessarily accepted standards in the literature (e.g. Stout and Shumway 1982, Vanclay and Henry 1988, Huang and Titus 1993).

Most of the function forms are relatively simple height-dbh functions that do not incorporate site form as one of the parameters in the model (e.g. Stout and Shumway 1982; Vanclay and Henry 1988). As a result, they are less desirable as they do not model total height on the basis of dbh and site form, as with site-index models where total height is a function of age and site index. The model used by Huang and Titus (1993) for boreal forest species in mixed stands in Alberta is one exception, and was one model examined in this study:

$$H = 1.3 + b_1 \left[1 - \left(1 - \frac{SF - 1.3}{b_1} \right)^{\left(\frac{dbh}{20} \right)^{b_2}} \right] \qquad [4.1]$$

where H = the observed total height, SF = the observed site form of the plot, dbh = the diameter at breast height, and b_1 and b_2 are parameters to be estimated. A second function form was also employed to assess whether an alternative form might fit the data better. Since no other model existed in the literature with site form as one of the coefficients, the corollary of the 5-parameter Chapman-Richards model (Hahn and Carmean 1982) used for site-index modeling was also fitted to the dataset:

$$H = 1.3 + b_1 (SF - 1.3)^{b_2} (1 - e^{b_3 dbh})^{b_4 (SF - 1.3)^{b_5}} \qquad [4.2]$$

Coefficients and parameters are as defined for equation [4.1].

4.4.4 Model Accuracy Assessment

Height-growth and site-form model accuracy-assessment techniques used in this study were similar to those used for height-growth and site-index models in Chapter 3, and are adapted from the methods outlined by Chen *et al.* (1998) for height-age and site-index models. Residual plots of estimated heights and site-forms versus dbh, height and site form were examined for signs of bias and lack of precision (Chen *et al.* 1998; Nigh 1998). In addition, plots of estimated versus observed site forms were tested against regression y = x; after Chen *et al.* (1998) and Chen and Klinka (2000). Regression and ANOVA assumptions were examined prior to regression fitting and testing as outlined by Neter *et al.* (1996) and Zar (1996); after Chen *et al.* (1998). One model was chosen on the basis of these results for further analyses.

4.4.5 Validation of the Provisional Site-Form Model for Sugar Maple in Ontario

The height-growth model developed by Woods *et al.* (1998) for sugar maple occurring in uneven-aged stands in Ontario was assessed against the model developed for sugar maple in this study. Unfortunately, no information on equation form, let alone parameter estimates or data used in fitting the model(s) are provided in the document (Woods *et al.* 1998). Only a graph showing the curves, and table of total heights for each diameter class at different site form classes are provided.

Accordingly, models based on equation [4.2] were fitted to the Woods *et al.* (1998) table data after they were manually entered into SYSTAT 10 (SPSS Inc. 2001) and checked for errors. Site-form classes used in the Woods *et al.* (1998) model were based on a reference dbh of 25 cm; to facilitate direct comparison with the model developed in this study, the models had to be re-fitted to a reference dbh of 20 cm.

This was accomplished by directly reading heights for the 20 cm dbh class from the data and then using these as the reference diameter to “refit” equation [4.2] to the Woods *et al.* (1998) data (Table 4.3). Predicted values and residuals from this model were then calculated for the data in this study. The model was assessed for accuracy in the same manner as for models developed based on equations [4.1] and [4.2].

To facilitate direct graphical comparisons between the Woods *et al.* (1998) model and the site-form model developed in this study, it was necessary to adjust the curves using an iterative process similar to that used for the site-index curves in Chapter 3. This was

Table 4.3: Results of two-step fitting of equation [4.2] to Woods *et al.* (1998) provisional site form model for sugar maple in Ontario. R^2 is the corrected coefficient of determination, MSE is the mean square of error and DFE are the degrees of freedom from error.

	Parameters							
dbh_{SF}	b_1	b_2	b_3	b_4	b_5	R^2	MSE	DFE
25 cm	1.001	1.090	-0.060	0.385	0.335	1.000	0.009	265
20 cm	1.138	-0.060	0.383	0.349	1.000	1.000	0.011	265

necessary because the curves computed using these models did not pass exactly through the specified height and index diameter (20 cm), as is commonly the case with site index curves (Newnham 1988; Carmean and Lenthall 1989). The magnitude of these errors is proportional to the distance of the plotted curves from the mean site form for the dataset. Accordingly, an iterative numerical process was utilized as for the height-age models in Chapter 3 to facilitate plotting the curves together so direct comparisons between them could be made.

4.4.6 Validity of Site Form as a Measure Tolerant Hardwood Forest Site Quality

On the basis of prior recommendations (Wang 1998), a preliminary investigation into the validity of applying site form to uneven-aged, mixed-species stands in central Ontario was undertaken based on the data in this study. Methods were adapted from Wang (1998).

Site form for sugar maple and American beech was examined in a number of ways to assess its validity in application as a site-quality evaluation tool. In general, univariate correlation analyses (Zar 1996; SPSS Inc. 2001) were used to relate site form and taper to site index, basal area and ecological variables known to affect height growth and site index.

Site form for sugar maple was determined using the methods described above in the development of site-form curves and models for these species for the region. Site indices were determined as for Chapter 3 in this study for sugar maple and American beech, and examined for correlations with site form and taper. Taper was calculated as the diameter at breast height at 50 years breast-height age divided by height at 50 years breast-height age; dbh at 50 years breast height age was determined using fitted equation [2.2] as outlined in the development of site-form models above (Table 4.4).

Table 4.4: Descriptive statistics for site form, site index, taper and basal area observations used in correlation analyses for site form. Min is the minimum observed value, Max is the maximum observed value, Mean is the mean or average for observations and SD is the standard deviation.

		Site Form (m)				Site Index (m)			
Species	n	Min	Max	Mean	SD	Min	Max	Mean	SD
Sugar Maple	31	15.6	21.7	18.9	1.6	8.3	21.5	14.8	3.1
American Beech	16	16.5	21.6	18.7	1.4	8.2	17.2	12.7	3.0

		Taper				Basal Area (m^2/ha)			
Species	n	Min	Max	Mean	SD	Min	Max	Mean	SD
Sugar Maple	31	0.47	0.98	0.75	0.14	11.7	51.9	30.2	11.3
American Beech	16	0.53	1.05	0.73	0.13	16.9	52.0	33.2	11.4

Five soil variables determined to be strongly related to height growth and site index of sugar maple and American beech were identified in soil-site relations study for central Ontario hardwoods (Rahi 2003). The variables (Table A4.1, Appendix 3) were examined for correlations with site form and taper for these two species: total F-layer nitrogen (kg/ha) F-layer potassium concentration (ppm), total A-horizon magnesium (kg/ha), A-horizon nitrogen concentration (ppm), and percent coarse fragments in the B-horizon.

An investigation of site form and taper correlations with stand density (basal area) was also conducted. Since stand basal area is directly affected by removal of forest trees, and many of the stands in the study had been logged under the single-tree selection system, only a very small subsample of undisturbed stands was available for correlation analyses. These analyses were still carried out to examine preliminary results.

4.5 RESULTS

4.5.1 Height-Growth and Site-Form Models

On the basis of their corrected R^2 and mean square error (MSE), equations [4.1] and [4.2] both provided satisfactory fits to the data (Table 4.5). Overall, corrected R^2 and mean square error values for equation [4.2] were slightly better (higher R^2 and lower MSE). Since R^2 is not always a reliable indicator of goodness of fit for nonlinear models due to nonlinear models not necessarily passing through the mean of dependent and independent variables (Neter *et al.* 1996), and since both models produced high corrected R^2 values, both were evaluated further for accuracy.

Residuals plots for equation [4.1] for all four species show curvilinear trends against dbh and total height (Figure A4.1, Appendix 3). A degree of heteroscedasticity is expected in residuals plots for these types of models due to intercorrelation among data (Nigh and Sit 1996), but these plots showed definite curvilinear trends indicating model [4.1] was not a good fit to the dataset.

No significant differences were detected between models in two-tailed t-tests (Zar 1996) of regression lines forced through the origin and fitted to plots (Figure A4.2, Appendix

Table 4.5: Results of fitting height-growth models using equations [4.1] and [4.2] by species. R^2 is the corrected R^2, MSE is the mean square error and DFE are the degrees of freedom from error.

		Parameters							
Species	Model	b_1	b_2	b_3	b_4	b_5	R^2	MSE	DFE
Sugar Maple	Eq.^{n} [4.1]	0.968	0.191				0.952	1.337	928
	Eq.^{n} [4.2]	1.251	1.003	-0.072	0.577	0.14	0.989	0.312	925
American Beech	Eq.^{n} [4.1]	0.963	0.223				0.961	1.240	478
	Eq.^{n} [4.2]	0.998	1.114	-0.062	0.276	0.431	0.993	0.234	475
Yellow Birch	Eq.^{n} [4.1]	0.971	0.191				0.954	1.167	178
	Eq.^{n} [4.2]	2.205	0.82	-0.06	2.752	-0.446	0.985	0.38	175
Red Oak	Eq.^{n} [4.1]	0.974	0.218				0.976	0.49	238
	Eq.^{n} [4.2]	0.910	1.191	-0.041	0.152	0.580	0.997	0.070	235

3) of estimated versus observed heights in comparisons to the line y = x. Still, a strong curvilinear trend is evident in these plots for equation [4.1]; we would expect a linear trend with points tightly dispersed around the line y = x if the model was a good fit to the data.

The inappropriateness of equation [4.1] in describing height-dbh relationships for this dataset is most strongly exemplified in Figure A4.3 (Appendix 3) which shows site form curves based on [4.1] against the observed data for each species. The curves are clearly not a good fit to the data. In all cases they considerably overestimate early juvenile height growth and then develop in a more linear pattern through index diameter which is not representative of the curvilinear patterns evident in the dataset. This may be a result of the limited parameters (only two) which describe the shape of this model and limit its flexibility in describing a more sigmoid growth pattern.

Residuals plots for equation [4.2] indicated it was a much better fit to the data, as no curvilinear trends were observed in the residuals plots and overall precision (dispersion of residuals about the mean) was tighter (Figure 4.1). The residuals are zero at the index dbh (20 cm) as a result of the conditioning of the model to go through this point. No significant differences ($p > 0.05$) were detected between fitted regression lines and the line $y = x$, indicating equation [4.2] was not a biased estimator of total height for the data in the study (Figure 4.2).

The final site-form curves for all four species based on equation [4.2] show it is clearly a better fit and more representative of height-dbh growth patterns evident in the dataset (Figure 4.3). Accordingly, models and curves based on equation [4.2] were accepted as the best choice for site-form equations and were used for all further analyses.

4.5.2 Validation of the Provisional Site-Form Model for Sugar Maple in Ontario

Residuals plots for the provisional sugar maple (Woods *et al.* 1998) model as they were calculated for the data developed in this study are presented in Figure 4.4 (Appendix 3). The residuals plot indicated lower precision than equation [4.2] developed in this study (higher residual dispersion about the mean – Neter *et al.* (1996)) as well as potential bias in height estimation. In particular, the Woods *et al.* (1998) model appeared to underestimate juvenile height growth and considerably overestimate height growth after index diameter (20 cm dbh). Figure A4.5 (Appendix 3) confirms the presence of bias. A regression line forced through the origin for heights estimated by the Woods et al. (1998) model was shown to be significantly different ($p > 0.05$) from the line $y = x$.

The results are obvious in Figure 4.4, which compares the site-form curves developed by Woods *et al.* (1998) to those developed in this study. The Woods *et al.* (1998) curves show substantially lower initial height growth before the index diameter, and overestimate height growth after index diameter compared to the curves developed in this study.

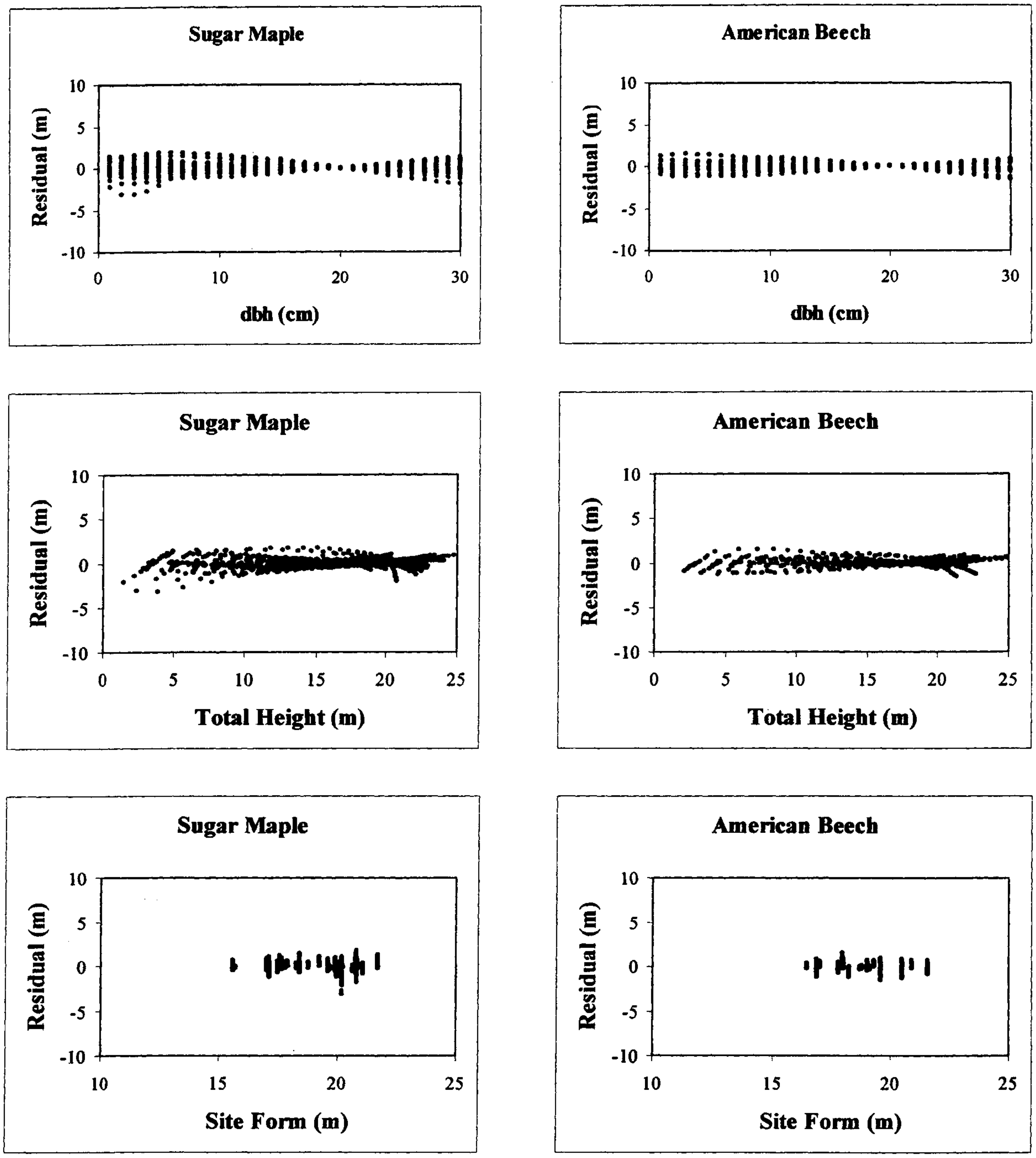

Figure 4.1: Residuals (m) plots for equation [4.2] for sugar maple and American beech against dbh (cm), total height (m) and site form (m).

(continued on next page)

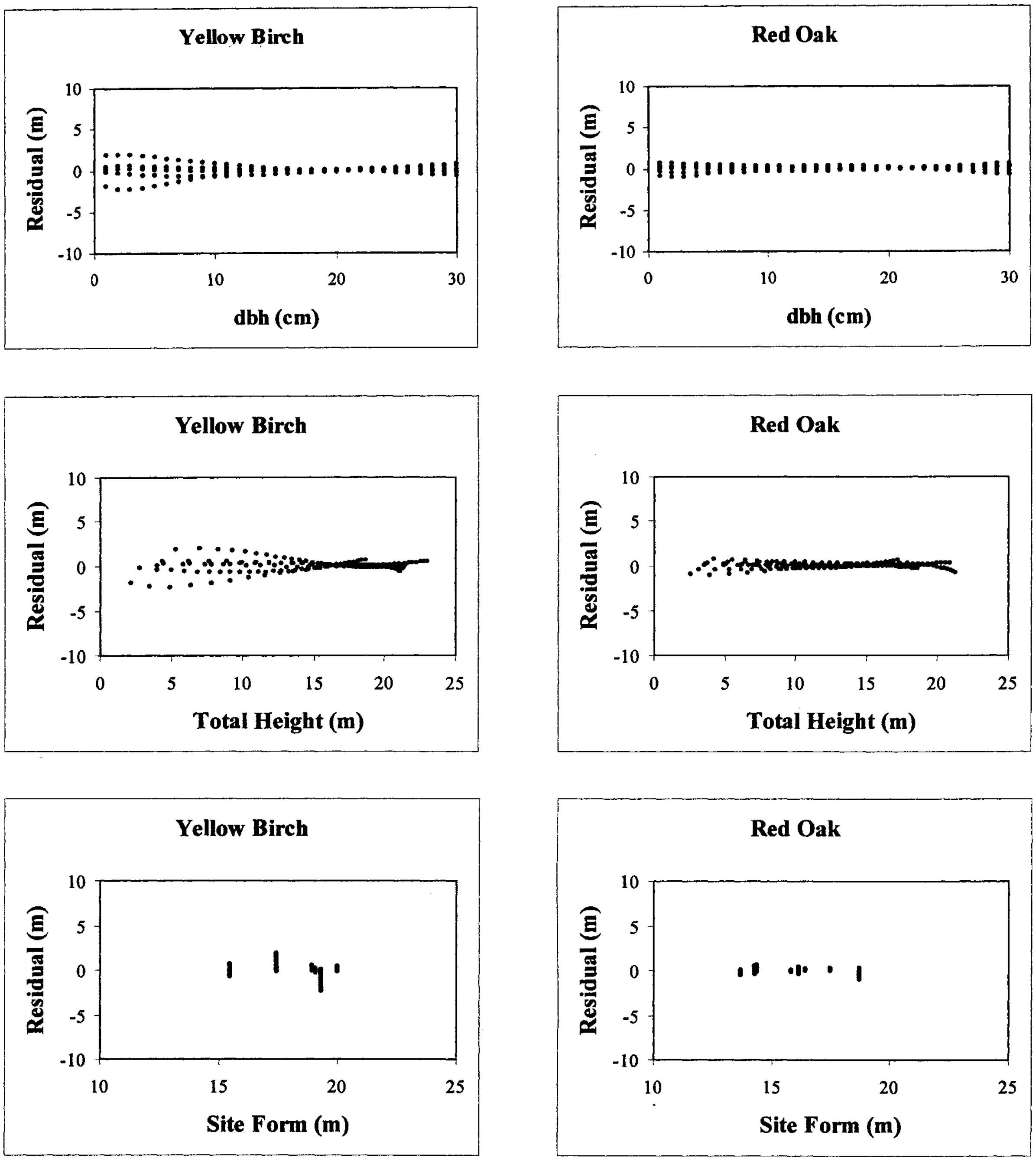

Figure 4.1 (continued): Residuals (m) plots for equation [4.2] for yellow birch and red oak against dbh (cm), total height (m) and site form (m).

4.5.3 Validation of Site Form as a Measure of Tolerant Hardwood Forest Site Quality

Results of the correlation analyses for site form and the various stand and soil variables are summarized in Table 4.6. Sugar maple site form was shown to be correlated

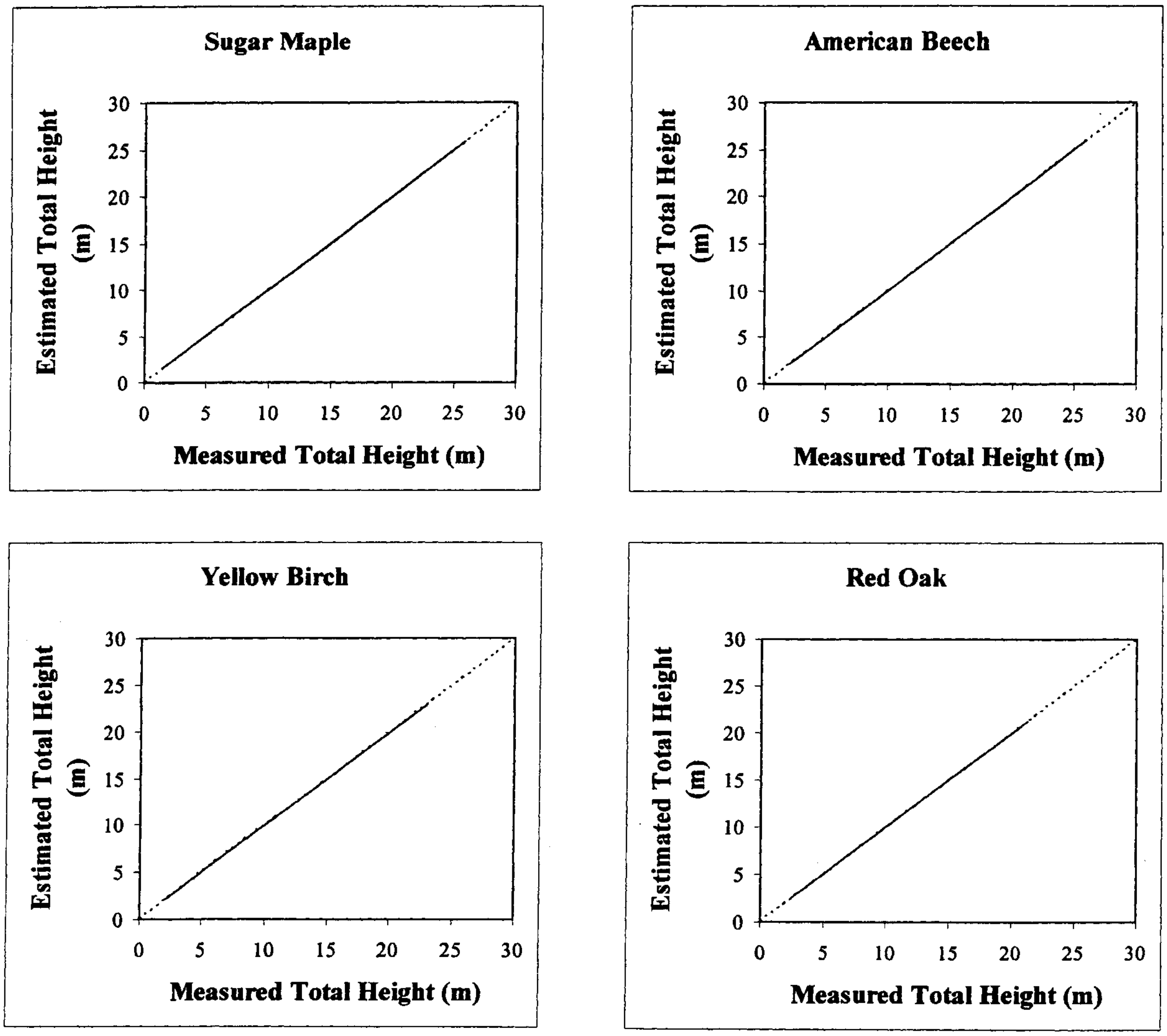

Figure 4.2: Results of the regression lines for estimated versus observed total height for equation [4.2]. The regression lines are solid; dashed lines represent $y = x$. No significant differences between the two lines were detected ($p > 0.05$ level) for any of the four species.

with total F nitrogen ($r = 0.377$, $p = 0.040$), but no other soil variables known to be related to sugar maple height growth (Rahi 2004). In addition, sugar maple site form was shown to be unrelated to site index ($r = 0.327$, $p = 0.090$).

Sugar maple taper was shown to have a strong positive correlation with site index ($r = 0.581$, $p = 0.001$). Taper for this species was also correlated with the percentage of coarse fragments in the B horizon ($r = 0.455$, $p = 0.009$). Finally, sugar maple taper was negatively

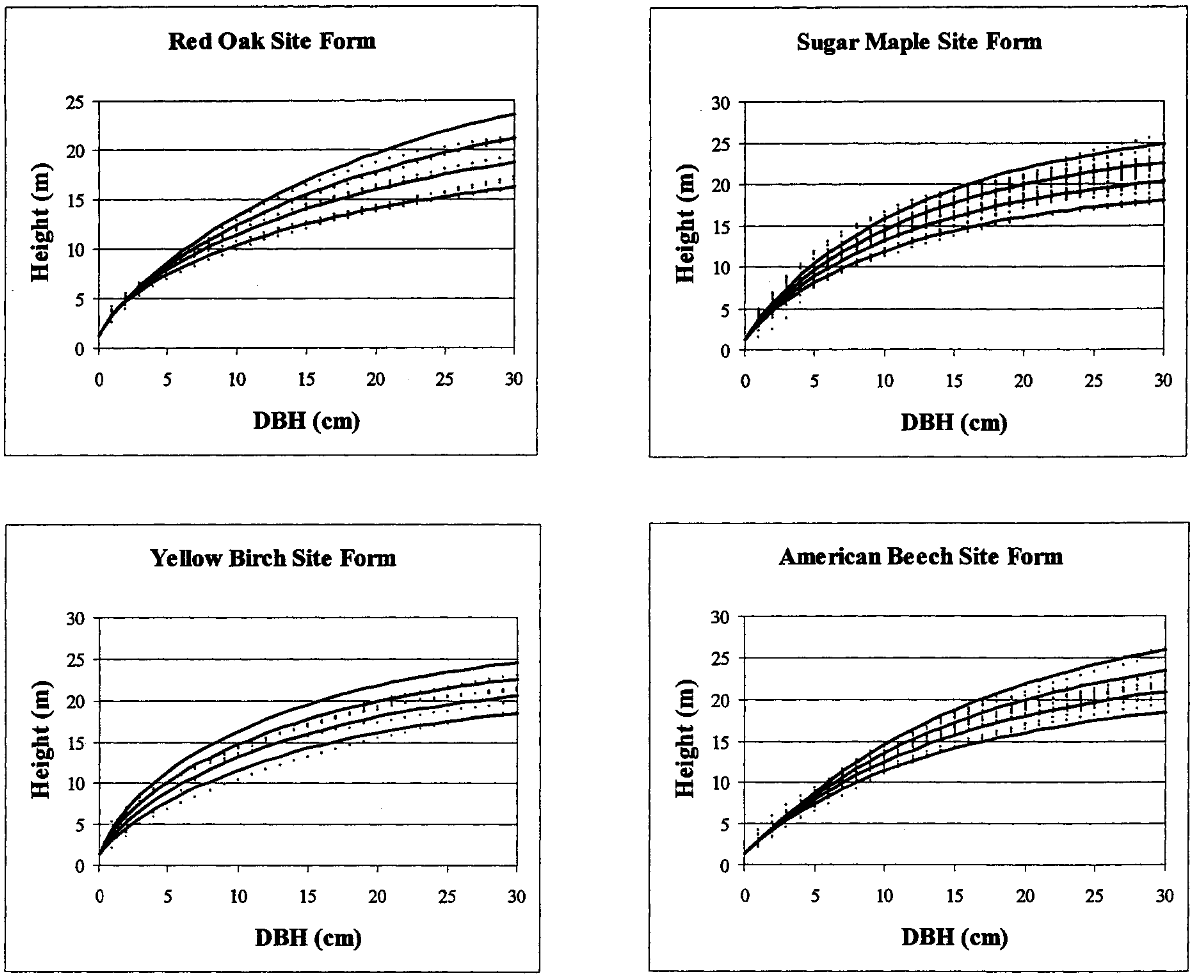

Figure 4.3: Preliminary site form curves based on equation [4.2] plotted against observed data from central Ontario for sugar maple, American beech, yellow birch and red oak.

correlated to site form (p = -0.398, r = 0.026).

American beech was not significantly correlated ($p > 0.05$) with site index, nor to any soil variables known to affect height growth of American beech in central Ontario (Rahi 2004). A positive correlation ($r = 0.590$, $p = 0.026$) was observed between American beech taper and site index.

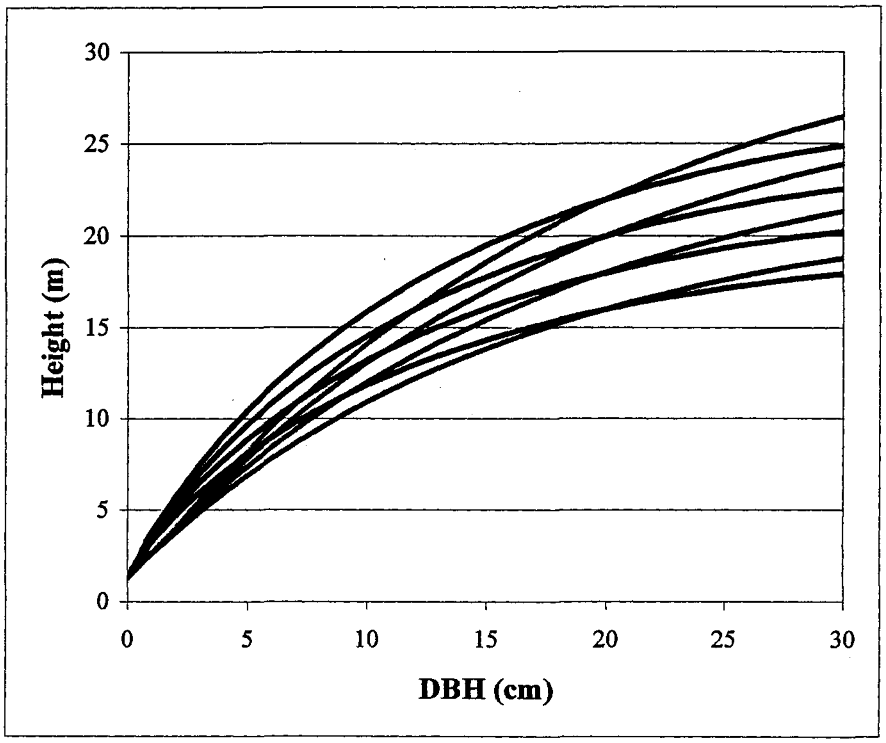

Figure 4.4: Site form curves developed in this study (black lines) plotted against the provisional curves developed by Woods *et al.* (1998) (red lines) for sugar maple.

4.6 DISCUSSION

4.6.1 Height-Growth Models

There is currently no common ground in the literature for the choice of a particular function form to be the most appropriate for developing site-form curves (Huang and Titus 1993). The model proposed by Huang and Titus (1993) and tested for tolerant hardwoods in central Ontario (equation [4.1]) was shown to be a poor fit for these species, despite the authors' successful application of it for boreal forest tree species in Alberta. In addition, none of the published site-form curves (e.g. Stout and Shumway 1982; Vanclay and Henry 1988; Huang and Titus 1993) to date have been subjected to the same stringent validation and accuracy assessment procedures afforded their height-age and site-index corollaries (e.g.

Table 4.6: Results of site form correlation analyses for stand and soil variables by species.

	Site Form		Taper		
Variable	r	p	r	p	n
Sugar Maple					
Site Index	0.327	0.090	0.581	0.001*	28
Total F Nitrogen	0.377	0.040*	-0.244	0.179	30
F Potassium Concentration	0.206	0.740	-0.257	0.156	30
Total A Magnesium	0.047	0.804	-0.088	0.630	30
A Nitrogen Concentration	-0.041	0.830	0.051	0.784	30
B Horizon Coarse Fragments	-0.242	0.198	0.455	0.009*	30
Basal Area	0.368	0.239	0.040	0.896	13
Taper	-0.398	0.026*			31
Site Form			-0.398	0.026*	31
American Beech					
Site Index	-0.194	0.525	0.590	0.034*	13
Total F Nitrogen	-0.146	0.603	0.215	0.408	15
F Potassium Concentration	-0.178	0.525	0.258	0.317	15
Total A Magnesium	-0.127	0.651	0.038	0.885	15
A Nitrogen Concentration	0.081	0.774	-0.107	0.683	15
B Horizon Coarse Fragments	-0.353	0.196	0.187	0.763	15
Basal Area	-0.169	0.785	0.237	0.361	5
Taper	-0.272	0.309			16
Site Form			-0.272	0.309	16

*significant correlation (0.05)

Nigh and Sit 1996; Nigh 1998; Chen *et al.* 1998; Chen and Klinka 2000). Neither an equation nor any information about the data from which the Ontario site-form curves were derived is offered in publication (Woods *et al.* 1998). No validation or accuracy assessment beyond mean square error and coefficient of determination is presented for equation [4.1] in a previous study either (Huang and Titus 1993). It is possible these may have been misleading interpretations as they were for this study where residuals plots and further regressions revealed a poor fit to the data, despite high R^2 and mean square error values for the model.

One possible reason for the lack of fit of the Huang and Titus (1993) model when applied to hardwoods in Ontario is that the model lacks sufficient shape parameters to adequately describe height growth patterns for these species. A faintly sigmoid growth pattern was observed for the height-dbh curves plotted for individual trees in this study, and equations that describe such patterns accurately typically require three parameters to describe at minimum the slope, asymptote and shape or inflection point (e.g. Richards 1959; Schnute 1981). Three-parameter sigmoid-type models were shown to be most suitable for describing height-diameter growth patterns for Ontario tree species (Peng *et al.* 2001).

The Chapman-Richards (1959) model was superior in describing height-dbh relationships for Ontario tree species (Peng *et al.* 2001); this coincides with results in Chapter 2 where it fits height-diameter data well for data from central Ontario on the basis of mean square error and coefficient of determination. Accordingly, this model or some derivation of it would likely be most suitable for developing site-form curves for these species. Despite no prior precedent in the literature, the analogue to the height versus age and site index model used by Hahn and Carmean (1982) was used to describe the site form relationships in this study (equation [4.2]); it was deemed far superior to the Huang and Titus (1993) model and proved to fit the data well in this study – likely for the reasons outlined above.

There is no doubt that sample sizes - particularly for American beech, yellow birch and red oak - in this study limit these site-form curves to preliminary approximations of true relationships for these species in central Ontario. Funding and time constraints limited the collection of data for these species. The curves for sugar maple were based on a sufficiently large number of samples, and so can be considered more reliable.

Validation procedures and accuracy assessments for these models were carried out as for height-age and site-index models in Chapter 3 and other studies (e.g. Nigh and Sit 1996; Nigh 1998; Nigh and Courtin 1998; Chen and Klinka 2000), and so should be interpreted with the same considerations as outlined in the discussion in Chapter 3.

Briefly, the models in this study are a reflection of the data from which they were derived, as for height-age models (Nigh and Sit 1996) and so should be interpreted accordingly. Errors in precision and bias could reflect errors in the dataset rather than the models themselves, such as those observed for equation [4.1]. The superior precision and unbiasedness of equation [4.2] in this study probably indicates that such errors were more likely a result of equation [4.2] not accurately reflecting local height-growth patterns in this study.

Unfortunately, the small number of samples in this study did not afford the luxury of testing the models against an independent dataset, known to be a superior method of validating nonlinear models (Neter *et al.* 1996).

4.6.2 Validation of the Provisional Site-Form Model for Sugar Maple in Ontario

The provisional sugar maple site-form model Woods *et al.* (1998), as interpreted and developed in this study, was shown to be biased and inaccurate in application to the dataset from samples in this study. Aside from the obvious potential for considerable error when guessing the form of and fitting a suitable model to the tabular data provided in OMNR (1998), reasons for this difference in site form curves could be attributed to differences in data sets between the two studies.

The Woods *et al.* (1998) models are stated to be applicable to uneven-aged hard maple stands based on Ontario conditions (Woods *et al.* 1998). No information about the sample size, region, or type of data used in developing the model is provided. It is possible that differences between the two sets of curves arise as a result of local stand conditions in central Ontario differing slightly from the provincial patterns on average.

It is also important to note that the models developed in this study included samples in uneven-aged and mixed-species stands, stand conditions which may have an effect on site-form relationships despite proponents' claims to the contrary (Stout and Shumway 1982; Vanclay and Henry 1988; Huang and Titus 1993; Wang 1998). Presumably the Woods *et al.* (1998) models were derived solely from uneven-aged sugar maple stands since that is their stated range of application. Accordingly, differences between the two sets of curves for sugar maple could be expected if such conditions do affect site form. Further research is needed to evaluate whether or not this is the case for sugar maple and other species.

4.6.3 Site Form as an Adequate Measure of Forest Site Quality

Site form has been shown to be an inadequate measure of forest site quality for even-aged, mixed-species stands in British Columbia (Wang 1998). Its use in uneven-aged mixed-species stands has been questioned (Wang 1998), despite strong theoretical validation by its proponents (Stout and Shumway 1982; Vanclay and Henry 1988; Huang and Titus 1993). The assumptions of site form as outlined by Huang and Titus (1993) have yet to be explicitly tested (Wang 1998). These assumptions are: (1) decreasing tree taper is associated with increasing site productivity and (2) stand density does not affect the height-diameter relationship of the dominant and codominant trees in uneven-aged or mixed-species stands Huang and Titus (1993).

The results from the preliminary investigation in this study using methods adapted from Wang (1998) suggest such assumptions may be invalid. In general, site form for sugar maple and American beech was found to be unrelated to site index and soil variables known to affect height growth of these species (Rahi 2004). Sugar maple site form was the exception, shown to be correlated to total nitrogen in the F horizon; but not the other four variables known to affect height growth of sugar maple.

In addition, there is evidence in this study to suggest the site form/taper relationship to site quality may change with time. Taper in this study, as with Wang (1998), was calculated as dbh divided by total height for the sample trees in the study at 50 years breast height age. This was accomplished through linear interpolation of stem analyses data, and in most cases resulted in a different ratio than would have been calculated for the same trees at the time of sampling, since most sample trees were greater than 50 years of age at breast height. Site form was determined in a similar manner, though was developed based on a reference diameter of 20 cm, and this may or may not have coincided with the interpolated diameter of a given tree at breast height-age 50 years. It could therefore be stated that taper and site-form estimates were often representative of different ages for a given tree.

Taper for sugar maple was correlated with site form (American beech had no correlation for these two variables), which suggests a relationship between these variables as well. Since taper for both species was positively correlated with site index, and since site form was not, it is possible taper-site index and hence site form-site index relationships are affected by time (age), and so site form may not be as age-independent a measure of forest site quality as is accepted.

Since site form and taper were generally not related to the ecological measures of site quality (soil variables) in this study, were not related to site index (an accepted measure of forest site quality), and were unrelated to a stand growth parameter (basal area) it is likely an unreliable measure of forest site quality for uneven-aged, mixed-species, tolerant hardwood stands in central Ontario.

While these findings coincide with those for even-aged, mixed-species, boreal forest stands in British Columbia (Wang 1998), they are limited to the data in this study due to small sample sizes and should be considered preliminary at best. Further work is needed in assessing the relationships of site form to forest site quality and whether or not it is a valid method of site quality evaluation in Ontario's hardwood forests.

At present, site form is probably best applied in a more qualitative context, to assist foresters in making broad assessments of the quality of a given site, in conjunction with other site-quality estimation tools such site-index curves and overall site and stand conditions, relative to the silvics of a given species.

The best solution to evaluating forest site quality in the types of stands occurring in central Ontario and other regions potentially lies in ecosystem-based approaches that incorporate vegetative and environmental factors in site-quality models (Huang and Titus 1993). Due to the enormous complexity and expense involved in these types of quantitative studies, it is unlikely they will be developed for hardwoods in Ontario for some time to come since funding for growth and yield research is scarce in the province.

4.7 CONCLUSIONS

The height-growth models and respective site-form curves developed in this study for four hardwood species were shown to be reasonably precise and were unbiased estimators of tree height. Models for all four species should be considered preliminary approximations of their height-dbh relationships in central Ontario, particularly for yellow birch and red oak where sample sizes were small. The models for all four species could be improved and verified by additional samples at larger diameter classes and by being validated with an independent dataset.

The provisional sugar maple site-form curves (Woods *et al.* 1998), despite challenges due to lack of information about the methods used in developing them, and their precision and reliability, were shown to be biased estimators of sugar maple height growth in this study. The Woods *et al.* (1998) curves differed substantially from those in this study. Their use should therefore remain provisional until more information is available and until further validation work is carried out.

Preliminary results have indicated that site form is unrelated to site index, basal area or ecological variables known to affect forest site quality and the height growth of sugar maple and American beech in uneven-aged, mixed-species stands. In addition, it is possible site form (taper) relationships to site quality change over time. These findings agree with results of a similar study for even-aged, mixed-species stands. Accordingly, site form at present should be considered a more qualitative site-quality evaluation tool. Further work is needed to verify these results.

At present, neither site index nor site form appears to be a superior method of forest site-quality evaluation for the predominant stand conditions in central Ontario. Foresters should utilize both tools in making stand level growth and yield decisions in the region, bearing in mind the limitations of each in the region.

CHAPTER 5: CONCLUSIONS

5.1 SITE-INDEX

Preliminary investigations into height-age and height-dbh curves in Chapter 2 revealed qualitative differences in height-growth curves for central Ontario hardwoods between species and different levels of site quality. This highlights the need for species-specific and site-specific height-growth curves for these species. Since curves for all study species varied with site quality, both height-age and height-dbh curves have potential applications in forest site-quality evaluation for hardwoods in central Ontario.

Sugar maple height-age curves were similar around 50 years breast-height age in both pure and mixed stands. Site index should theoretically be used in pure or single-species dominated stands. Since site index in Ontario normally refers to height at an age of 50 years at breast height, effects on sugar maple site index may be minimal in mixed stands. It is likely site index remains a valid method of site-quality evaluation for sugar maple occurring in mixed stands, and that direct comparisons of site index could be made between the two stand types for sugar maple. This idea was further verified in Chapter 3 where no significant differences were detected between pure stands of sugar maple and mixtures with American beech and yellow birch on the same site type.

In Chapter 2, sugar maple height-age curves did not appear to differ qualitatively between even- and uneven-aged stands, are were very close at breast-height age 50 years. As with pure vs. mixed stands, this would suggest site index is relatively unaffected by stand age structure and remains a valid method of site quality evaluation for both even- and uneven-aged sugar maple stands.

Care must be taken to ensure trees selected for site-index estimation in all stand types meet the requirements of "site" trees, and that they are free from suppression in particular. Height-age curves developed for both sugar maple and American beech both showed dramatic differences between suppressed and free-growing trees. These differences were most pronounced around 50 years breast-height age for both species. This agrees with traditional site-index guidelines that recommend the use of free-growing trees exclusively for estimation of site index.

The site-index curves developed in this study suffer from small sample sizes, particularly for red oak and yellow birch. Accordingly, these curves should be considered preliminary until further validation work is carried out against a larger sample and the models themselves can be refined. Still, these curves represent the only locally-derived models in the region to date, and are a good first approximation of any future models for the region. There use is preferable to those currently in use from the Lake States region, which were shown to be inadequate in describing height-age relationships for hardwoods in central Ontario without local calibration.

Future work on applying site index to central Ontario hardwoods could examine methods of utilizing suppressed trees for obtaining site index estimates. Though it is challenging to work with in Ontario hardwood stands, site index is favourable since age is one of its components. This makes estimates of future stand qualities such as volume and yield possible when site-index curves are used in conjunction with normal yield tables. The development of these yield tables should also be the focus of future work in the region.

Utilizing suppressed trees for site-index estimates is questionable. It will only succeed if methods are developed to correct various levels of suppression in sample trees.

Such methods might include mathematical “suppression corrections”, or separate index curves for suppressed and free-growing trees. Of course, there will be a limit to these possibilities, and it may be necessary to consider alternate methods of site quality evaluation such as site form, or indirect methods of site-index estimation for sites not supporting free-growing trees.

5.2 SITE FORM

Height-dbh relationships in Chapter 2 were unaffected by species mixture and stand age structure, as with height-age curves. In addition, height-dbh curves appeared similar for both suppressed and free-growing sugar maple and American beech trees, whereas height-age curves were not. Like height-age curves, height-dbh curves changed relative to differences in site quality. This would suggest height-dbh relationships, such as site-form curves, have potential as site-quality evaluation tools.

Site form was shown to be unrelated to a number of variables known to affect or be related to forest site quality of central Ontario hardwoods; this coincided with a previous study in British Columbia in even-aged stands. Accordingly, its use as a method of forest site quality evaluation is questionable in central Ontario despite its apparent success in other regions and with other species. Further work is needed to validate the preliminary site form models presented in this thesis, and verify the adequacy of site form as a method of forest site-quality evaluation.

Despite these suspicions, site form may have potential as a secondary method of site quality evaluation in situations where site index is challenging or impossible to apply, such as in heavily high-graded stands or stands where all trees show signs of suppression.

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Appendix 1:

Summary tables and descriptive statistics by plot, total trees and species.

Table A2.1. Total number of trees and descriptive statistics by species and site quality class. Min is the minimum observed value, Max is the maximum observed value, Mean is the average of the observations and SD is the sample standard deviation.

	Site		Age (years)				Height (m)				DBH (cm)			
Species	Quality	n	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
	Good	27	50	123	82	16	15.4	25.1	21.3	2.3	12.8	33.8	24.1	4.8
Maple	Medium	46	67	160	97	20	15.1	24.6	19.8	2.6	17.0	34.7	25.9	4.7
	Poor	14	79	161	131	21	17.4	24.8	21.7	2.0	16.5	37.7	29.9	6.2
	Good	5	56	105	75	21	16.7	21.6	19.6	2.0	17.4	36.5	25.0	7.6
Beech	Medium	18	50	181	107	32	19.0	23.8	21.4	1.4	19.7	36.7	27.8	4.9
	Poor	20	99	168	127	23	17.8	25.0	21.3	2.0	14.6	34.7	26.1	5.8
	Good	11	52	156	64	31	14.9	22.6	20.5	2.2	11.2	34.8	25.3	6.6
Birch	Medium	6	75	102	88	14	16.4	20.7	18.9	1.5	17.3	29.8	22.3	4.6
	Poor	5	84	120	99	15	13.8	21.0	17.1	3.0	12.7	25.6	19.8	4.8
	Good	12	60	84	69	9	16.6	21.0	18.8	1.2	19.3	37.7	27.5	5.7
Oak	Medium	15	77	142	95	21	15.3	21.3	18.2	1.6	20.4	35.3	27.3	4.6
	Poor	6	97	115	107	6	15.3	17.4	16.1	0.8	22.5	38.4	29.4	5.7

Table A2.2. Total number of plots and trees and descriptive statistics for sugar maple-American beech height growth comparisons and for sugar maple growing in pure versus mixed stands. Min is the minimum observed value, Max is the maximum observed value, Mean is the average of the observations and SD is the sample standard deviation.

		Plots	Trees	Age (years)				Height (m)				DBH (cm)			
		n	n	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
Same Site	Mh	12	31	61	160	11	28	18.7	24.8	21.9	1.5	17.0	37.7	28.7	4.8
	Be	12	31	76	181	20	28	17.8	25.0	21.4	1.8	14.6	36.7	26.8	5.5
Pure vs Mixed	Mh Pure	21	57	50	134	91	17	15.1	25.1	19.8	2.7	12.8	34.6	24.7	5.0
	Mh Mixed	10	30	54	161	110	32	18.9	24.5	21.9	1.4	17.0	37.7	28.3	5.1

Table A2.3. Total number of plots and trees and descriptive statistics for sugar maple growing in even-aged and uneven-aged stands and for free-growing versus suppressed trees. Min is the minimum observed value, Max is the maximum observed value, Mean is the average of the observations and SD is the sample standard deviation.

		Plots	Trees	Age (years)				Height (m)				DBH (cm)			
		n	n	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
Age Structure	Even	15	41	50	160	96	23	15.1	25.1	20.4	2.6	12.8	36.2	25.5	5.0
	Uneven	18	47	61	161	110	39	17.0	23.9	22.1	1.0	14.0	37.7	27.5	4.8
Canopy Position	Free	N/A	65	50	149	91	22	15.1	25.1	20.4	2.6	12.8	37.7	25.4	5.1
	Suppressed	N/A	22	68	161	116	25	16.1	24.5	21.1	2.5	16.5	37.6	27.7	5.6

Table A2.4. Results of fitting equation [2.2] to height growth for each species at different levels of forest site quality. R^2 is the corrected coefficient of determination, MSE is the mean square of error and DFE is the degrees of freedom from error.

Height (m) vs. Age $_{BH}$ (years):

	Site	Parameters					
Species	Quality	b_1	b_2	b_3	R^2	MSE	DFE
Mh	Good	23.948	0.024	1.311	0.817	8.424	2151
	Medium	23.438	0.017	1.342	0.857	5.305	4486
	Poor	45.170	0.004	0.996	0.901	3.914	1957
Be	Good	26.065	0.016	1.178	0.807	7.440	377
	Medium	20.908	0.017	1.374	0.712	11.959	2098
	Poor	23.776	0.016	1.898	0.820	7.585	2541
By	Good	18.863	0.059	1.653	0.885	4.253	708
	Medium	18.730	0.021	0.942	0.770	6.348	608
	Poor	37.724	0.005	0.938	0.866	3.032	495
Or	Good	19.703	0.033	1.246	0.951	1.403	836
	Medium	20.558	0.015	0.879	0.895	2.522	1431
	Poor	Insufficient observations, model would not converge					

Height (m) vs. DBH (cm):

	Site	Parameters					
Species	Quality	b_1	b_2	b_3	R^2	MSE	DFE
Mh	Good	25.755	0.058	0.811	0.957	1.957	2151
	Medium	26.783	0.038	0.716	0.935	2.429	4486
	Poor	23.510	0.061	0.825	0.957	1.692	1957
Be	Good	22.216	0.059	0.815	0.952	1.835	377
	Medium	22.611	0.076	1.010	0.958	1.759	2098
	Poor	23.551	0.070	1.050	0.942	2.459	2541
By	Good	23.840	0.050	0.677	0.968	1.175	708
	Medium	24.871	0.043	0.761	0.929	1.943	608
	Poor	18.540	0.090	1.109	0.850	3.401	495
Or	Good	20.380	0.060	0.807	0.969	0.903	836
	Medium	74.518	0.003	0.607	0.907	2.228	1431
	Poor	21.120	0.024	0.569	0.938	1.058	644

Table A2.5. Results of fitting equation [2.2] to height growth data for sugar maple and American beech growing on the same sites, for sugar maple growing in pure vs. mixed stands, and for sugar maple growing in even- vs. uneven-aged stands. R^2 is the corrected coefficient of determination, MSE is the mean square of error and DFE is the degrees of freedom from error.

		Parameters					
	Species	b_1	b_2	b_3	R^2	MSE	DFE
Maple and beech on the same sites:							
Height vs.	Mh	23.556	0.016	1.327	0.798	9.011	3590
Age	Be	23.070	0.015	1.591	0.777	9.239	3650
Height vs.	Mh	23.157	0.070	0.846	0.955	2.007	3590
DBH	Be	22.851	0.073	1.010	0.950	2.090	3650
Maple in pure vs mixed stands:							
Height vs.	Pure	22.965	0.019	1.251	0.831	6.313	5261
Age	Mixed	23.670	0.015	1.184	0.761	10.710	3336
Height vs.	Pure	27.798	0.037	0.725	0.935	2.415	5261
DBH	Mixed	22.802	0.073	0.867	0.950	2.225	3336
Maple in even versus uneven-aged stands:							
Height vs.	Even	22.965	0.019	1.251	0.831	6.313	5261
Age	Uneven	23.670	0.015	1.184	0.761	10.710	3336
Height vs.	Even	27.798	0.037	0.725	0.935	2.415	5261
DBH	Uneven	22.802	0.073	0.867	0.950	2.225	3336

Table A2.6. Results of fitting equation [2.2] to free growing and suppressed trees by species for height vs. age and height vs. dbh. R^2 is the corrected coefficient of determination, MSE is the mean square of error and DFE is the degrees of freedom from error.

		Parameters					
	Species	b_1	b_2	b_3	R^2	MSE	DFE
Height (m) vs. Age $_{BH}$ (years):							
Mh	Free	21.232	0.024	1.358	0.816	7.263	6015
	Supp.	30.200	0.010	1.318	0.875	5.232	2582
Be	Free	21.197	0.025	1.705	0.835	6.967	1995
	Supp.	28.082	0.011	1.656	0.831	6.849	3024
By	Free	14.699	0.052	1.431	0.610	11.940	1603
	Supp.	19.161	0.033	1.056	0.868	4.516	211
Or	Free	16.809	0.028	1.046	0.813	4.504	2778
	Supp.	33.803	0.006	1.062	0.996	0.100	136
Height (m) vs. DBH (cm):							
Mh	Free	24.997	0.050	0.745	0.937	2.493	6015
	Supp.	24.859	0.054	0.847	0.949	2.144	2582
Be	Free	22.953	0.076	1.008	0.962	1.618	1995
	Supp.	23.457	0.064	0.987	0.942	2.360	3024
By	Free	27.485	0.036	0.751	0.904	2.937	1603
	Supp.	22.222	0.069	0.774	0.986	0.494	211
Or	Free	22.849	0.032	0.672	0.902	2.348	2778
	Supp.	Model would not converge.					

Appendix 2:

Various model accuracy assessment results and summary tables for Chapter 3.

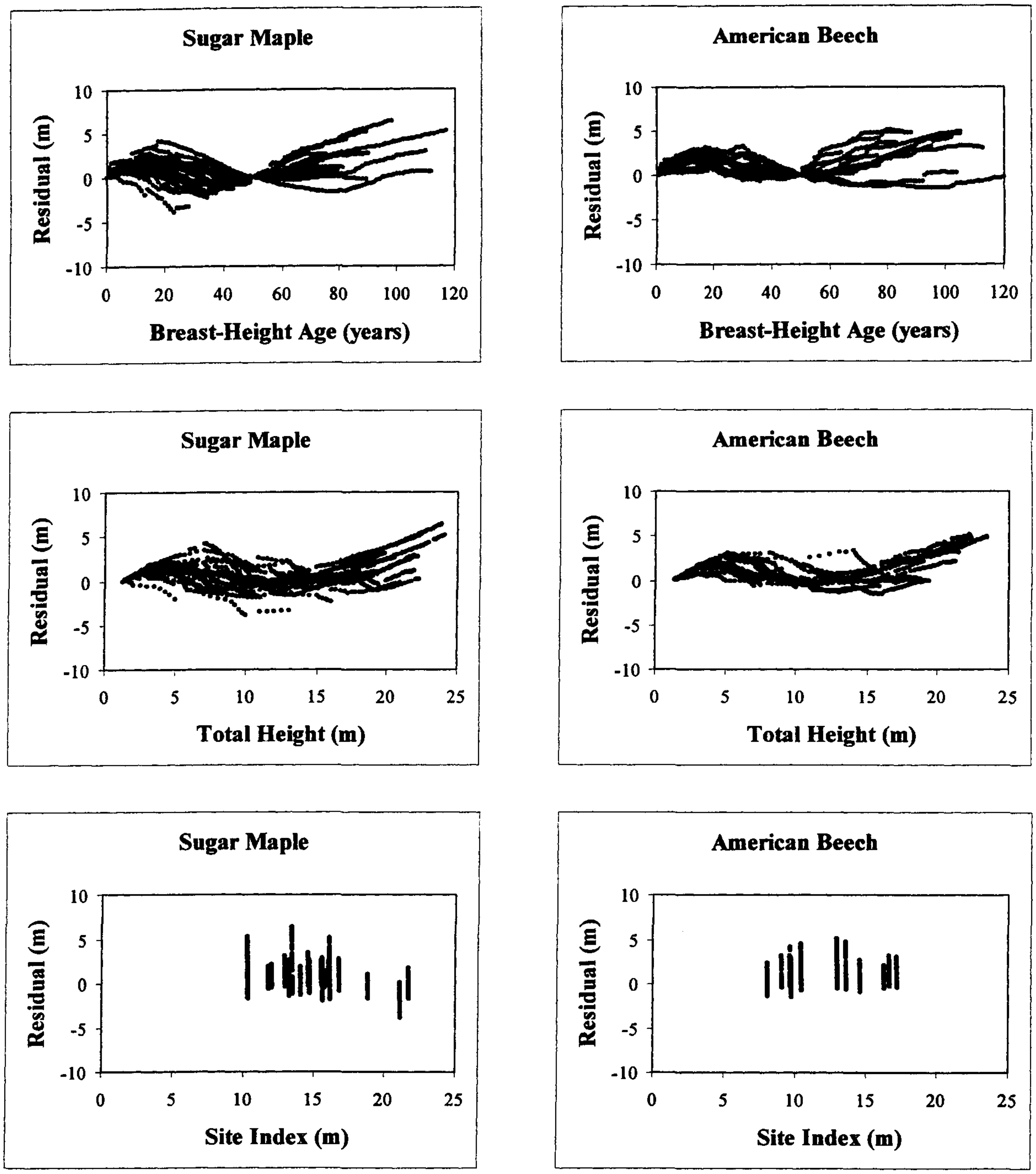

Figure A3.1. Residuals of logistic height-growth model [3.1] versus breast-height age (years), total height (m) and site index (m) for sugar maple and American beech.

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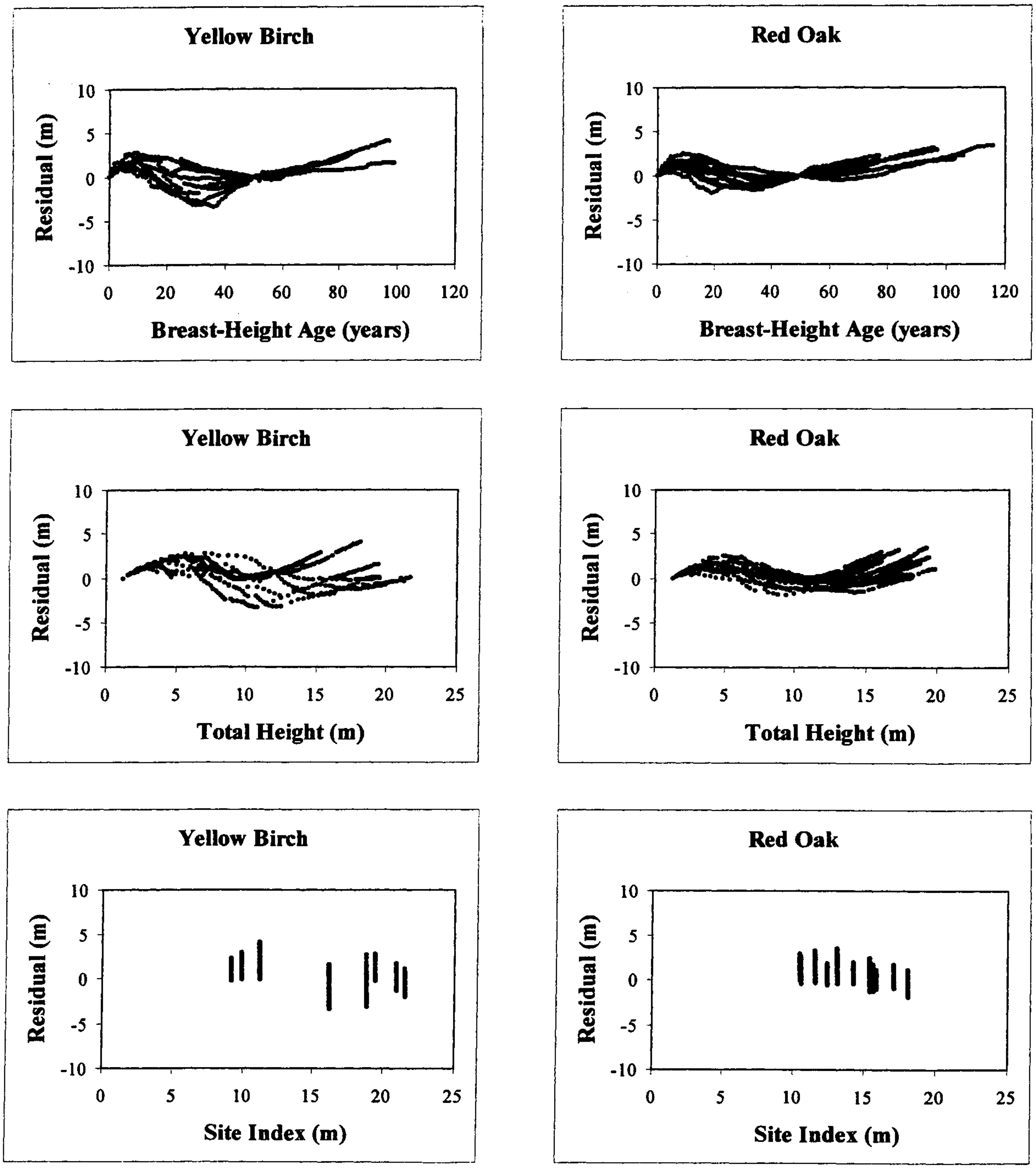

Figure A3.1 (continued). : Residuals of logistic height-growth model [3.1] versus breast-height age (years), total height (m) and site index (m) for yellow birch and red oak.

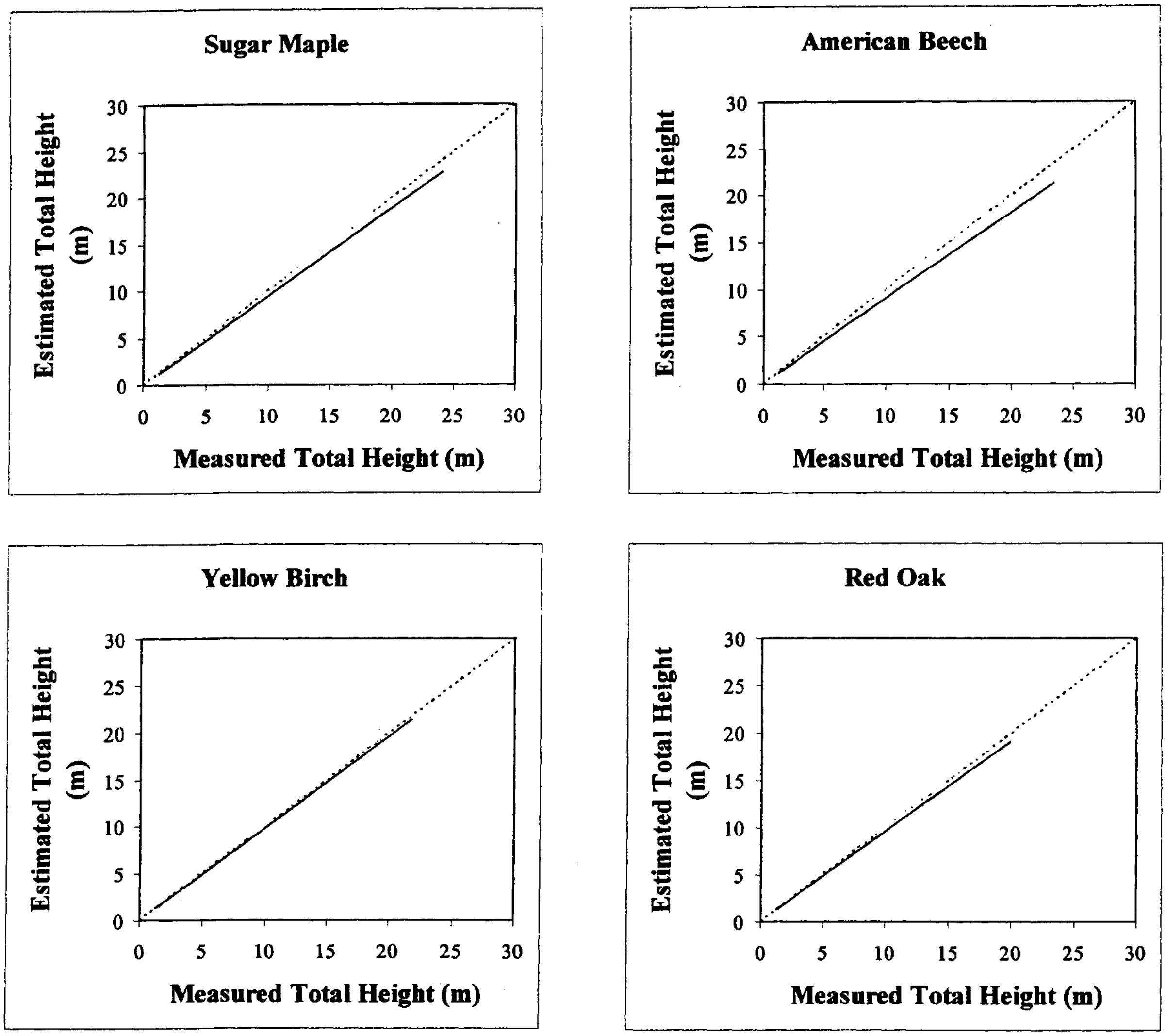

Figure A3.2. Graphical results of regression of measured total height (m) versus total height predicted by equation [3.1] by species. Solid lines are regression lines and dashed lines represent y = x. Regression models for sugar maple, American beech and red oak were shown to be significantly different ($p > 0.05$) from the line y = x in a two-tailed t-test comparing slopes.

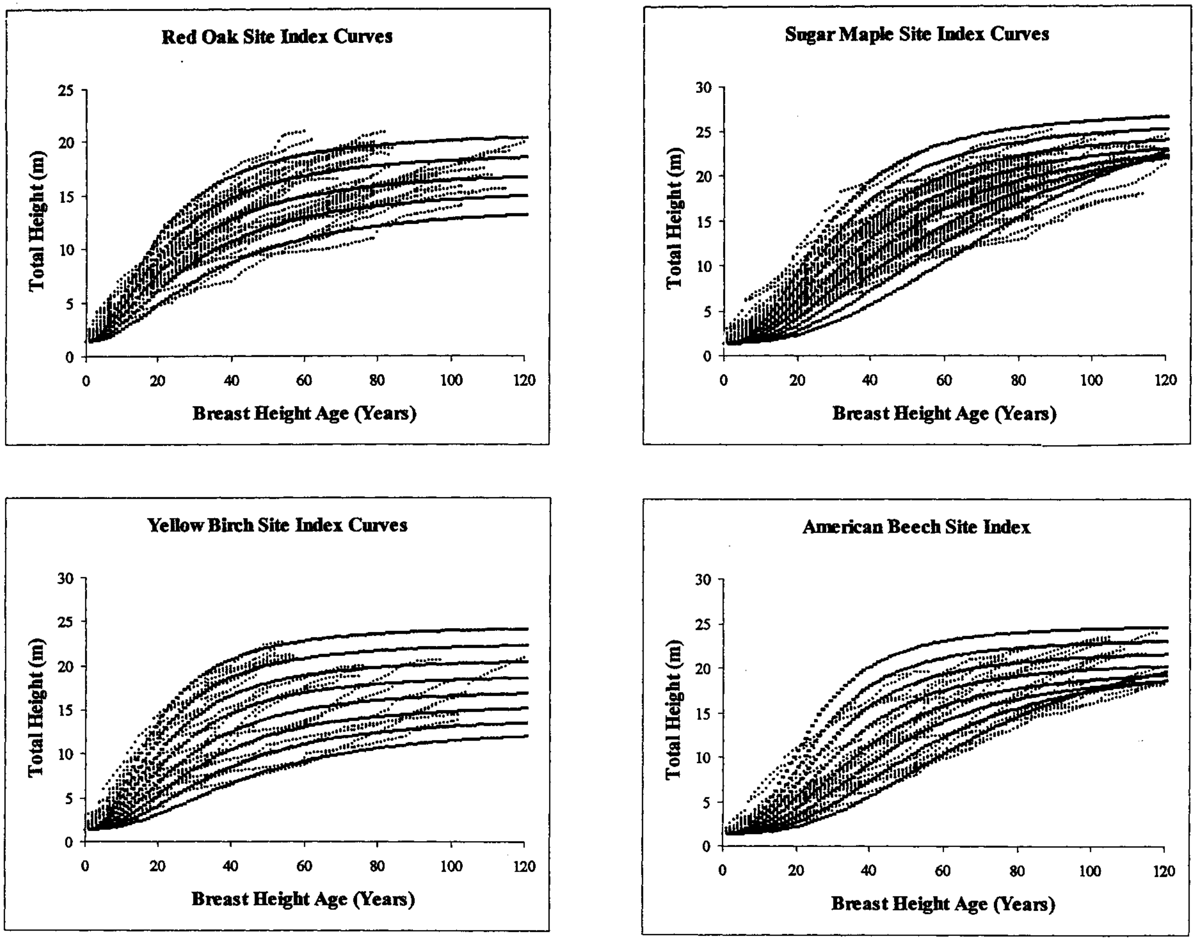

Figure A3.3. Site index curves based on equation [3.1] for each species, plotted against data used in developing them. Clearly they are not a good fit to the height-age data in this study.

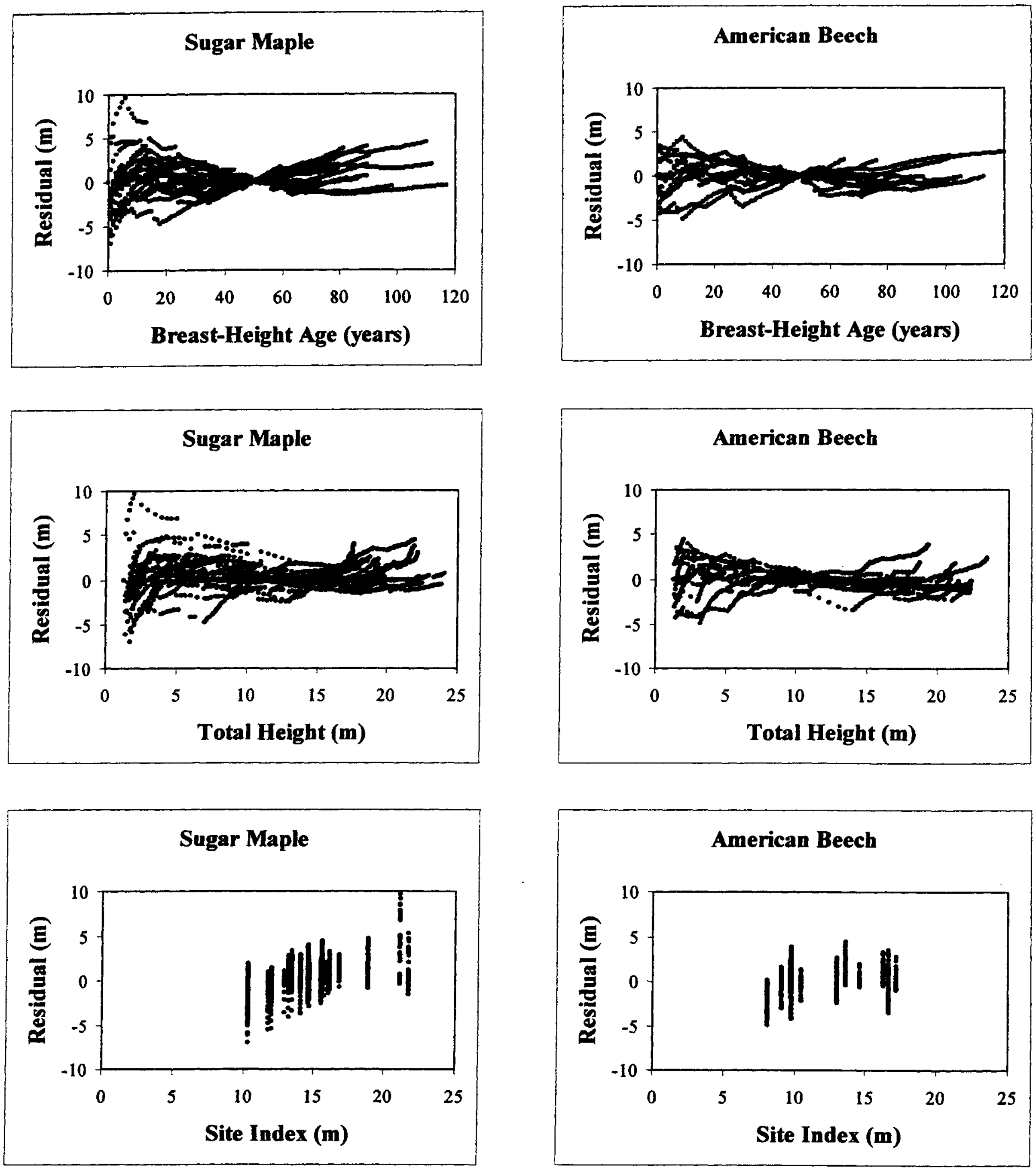

Figure A3.4. Residuals of logistic site-index model [3.3] versus breast-height age (years), total height (m) and site index (m) for sugar maple and American beech.

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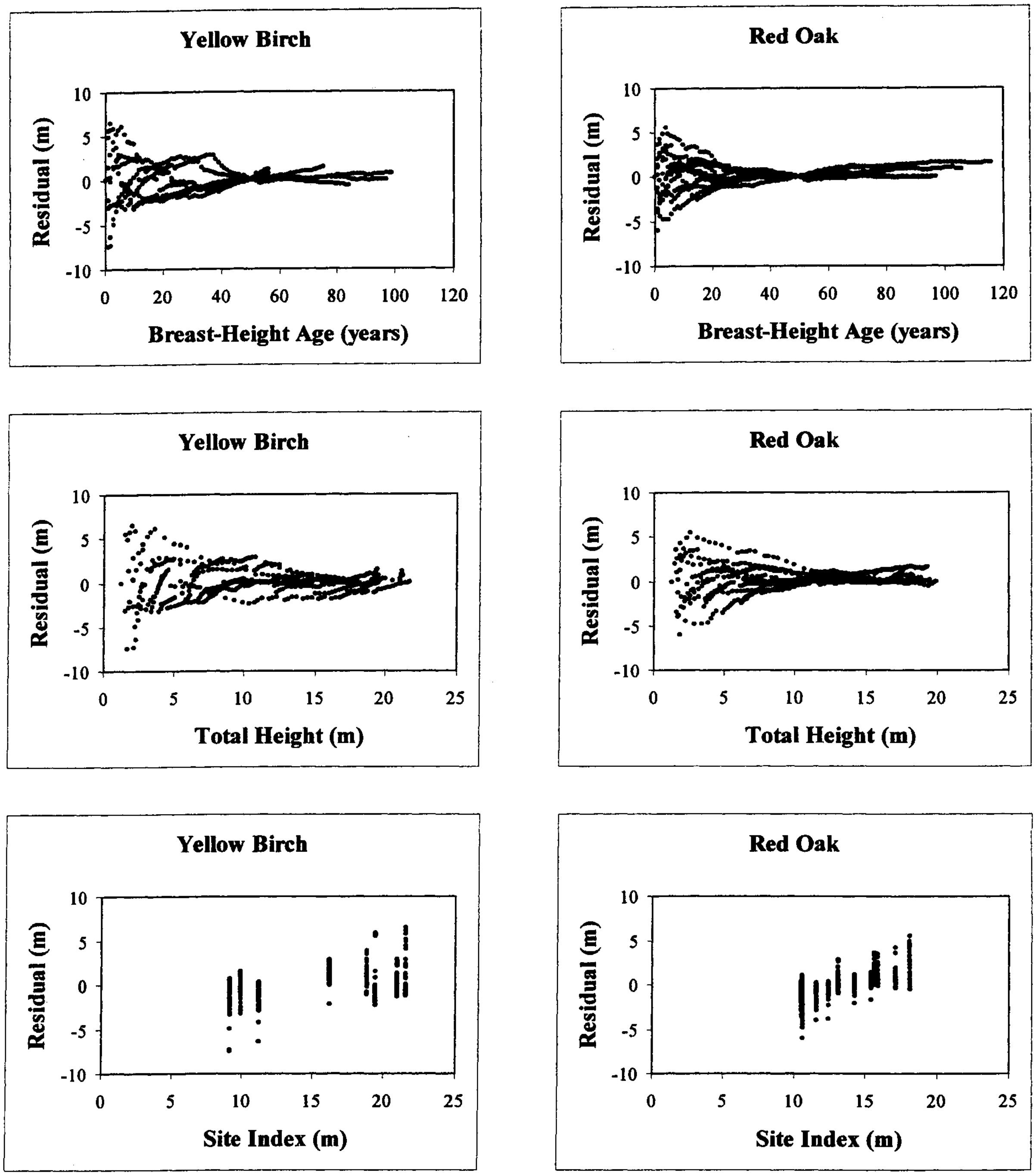

Figure A3.4 (continued). Residuals of logistic site-index model [3.3] versus breast-height age (years), total height (m) and site index (m) for yellow birch and red oak.

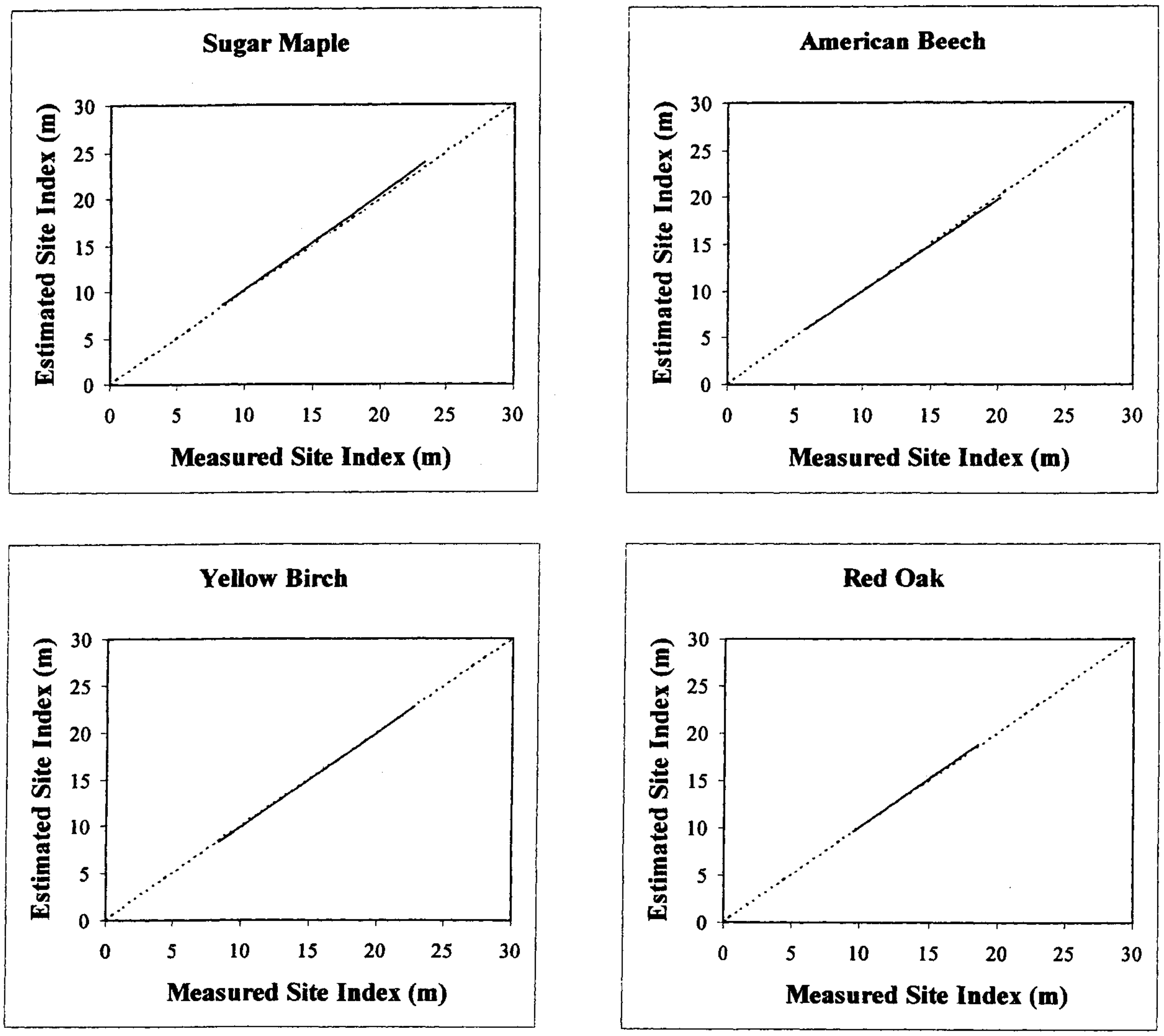

Figure A3.5. Graphical results of regression of measured total height (m) versus total height predicted by equation [3.3] by species. Solid lines are regression lines and dashed lines represent $y = x$. Regression models for all four species were not shown to be significantly different ($p > 0.05$) from the line $y = x$ in a two-tailed t-test comparing slopes.

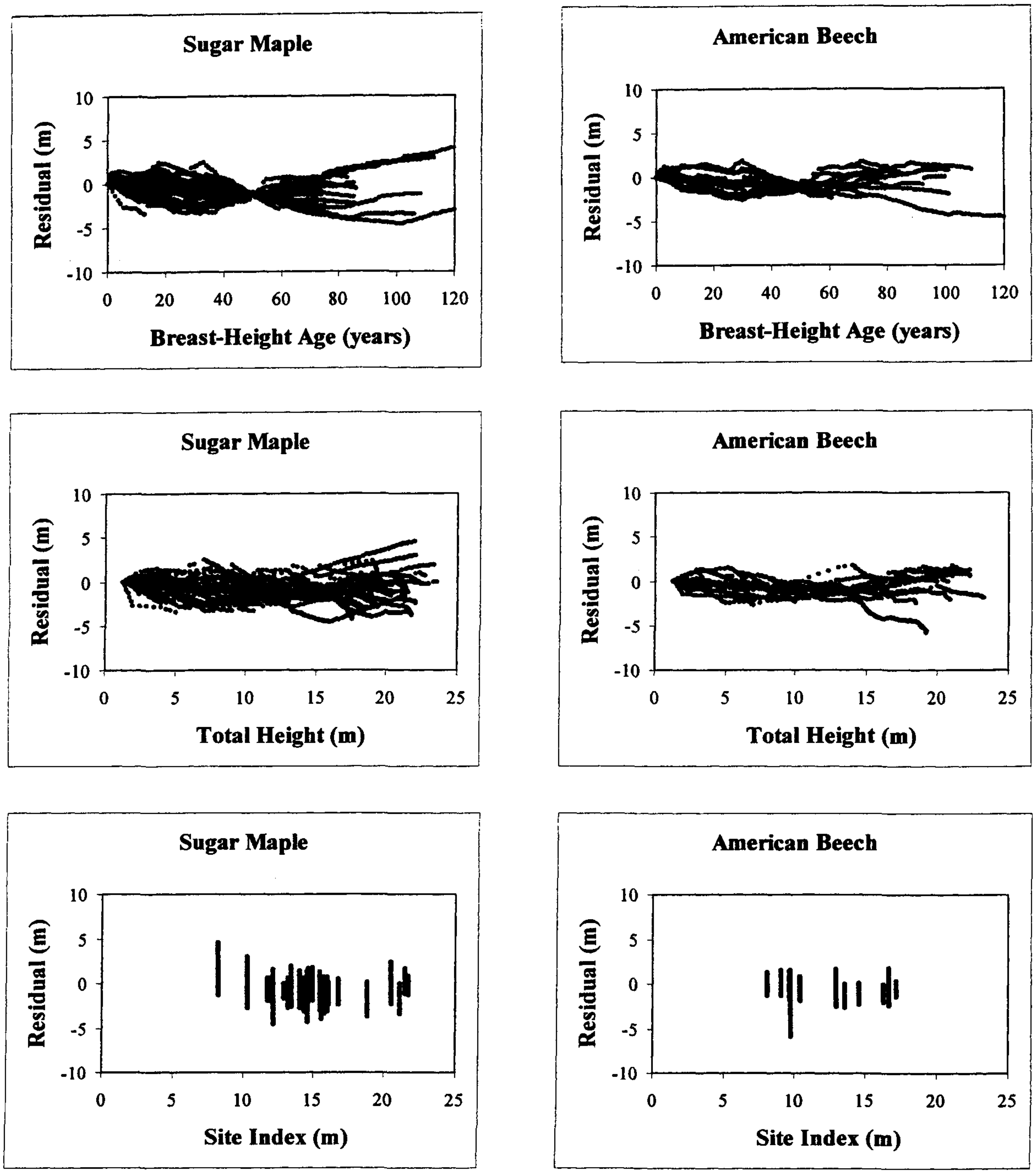

Figure A3.6. Residuals plots from Hahn and Carmean's (1982) equations against breast-height age (years), total height (m) and site index (m) for sugar maple and American beech.

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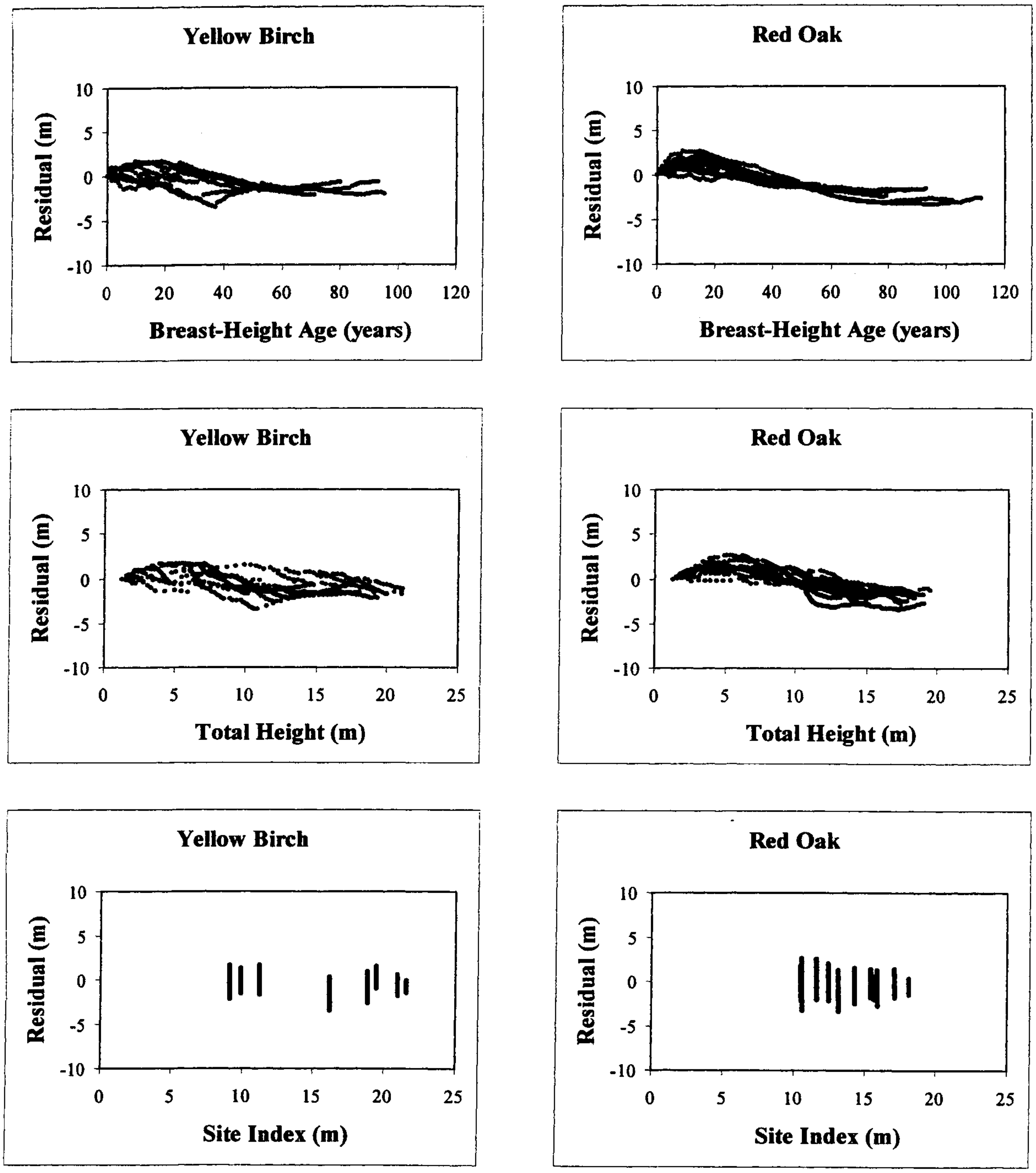

Figure A3.6 (continued). Residuals plots from Hahn and Carmean's (1982) equations against breast-height age (years), total height (m) and site index (m) for yellow birch and red oak.

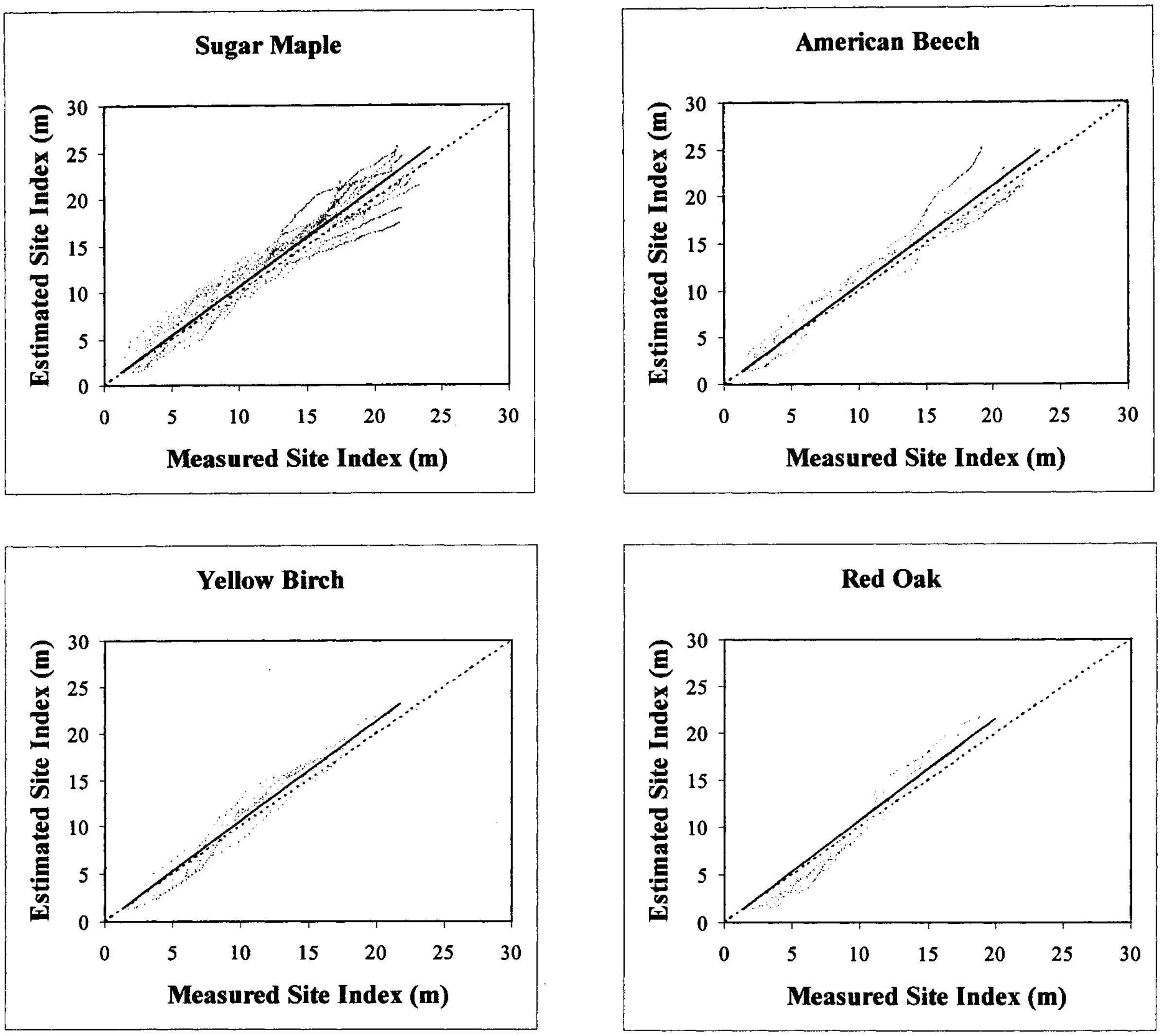

Figure A3.7. Graphical results of regression of measured total height (m) versus total height predicted by Hahn and Carmean's (1982) equations by species. Solid lines are regression lines and dashed lines represent y = x. Regression models for all four species were shown to be significantly different ($p > 0.05$) from the line y = x in a two-tailed t-test comparing slopes.

Table A3.2. Summary of descriptive statistics for forest floor variables tested for differences between stand types.

F Horizon Variable	Min	Max	Mean	SD
Sugar Maple				
pH	4.4	5.8	4.8	0.5
Total Ca (kg/ha)	129.6	463.6	255.1	112.0
Total Mg (kg/ha)	15.1	58.5	26.8	15.3
Total K (kg/ha)	19.4	70.4	34.9	18.6
Total P (kg/ha)	5.9	15.2	10.1	3.7
C:N Ratio	21.6	49.4	28.0	9.7
Sugar Maple-American Beech				
pH	4.4	4.7	4.6	0.1
Total Ca (kg/ha)	167.1	537.2	288.9	153.6
Total Mg (kg/ha)	14.7	55.1	28.2	16.5
Total K (kg/ha)	18.4	97.4	43.0	30.5
Total P (kg/ha)	5.9	21.9	10.7	5.8
C:N Ratio	15.8	38.0	24.4	8.3
Sugar Maple-American Beech-Yellow Birch				
pH	4.5	5.0	4.8	0.2
Total Ca (kg/ha)	189.9	515.5	305.2	144.9
Total Mg (kg/ha)	21.4	27.7	24.5	3.2
Total K (kg/ha)	24.9	39.1	29.9	6.4
Total P (kg/ha)	5.8	9.3	7.1	1.5
C:N Ratio	20.8	27.0	22.7	2.9

Appendix 3:

Chapter 4 site-form model accuracy assessment results and descriptive statistics for soil variables.

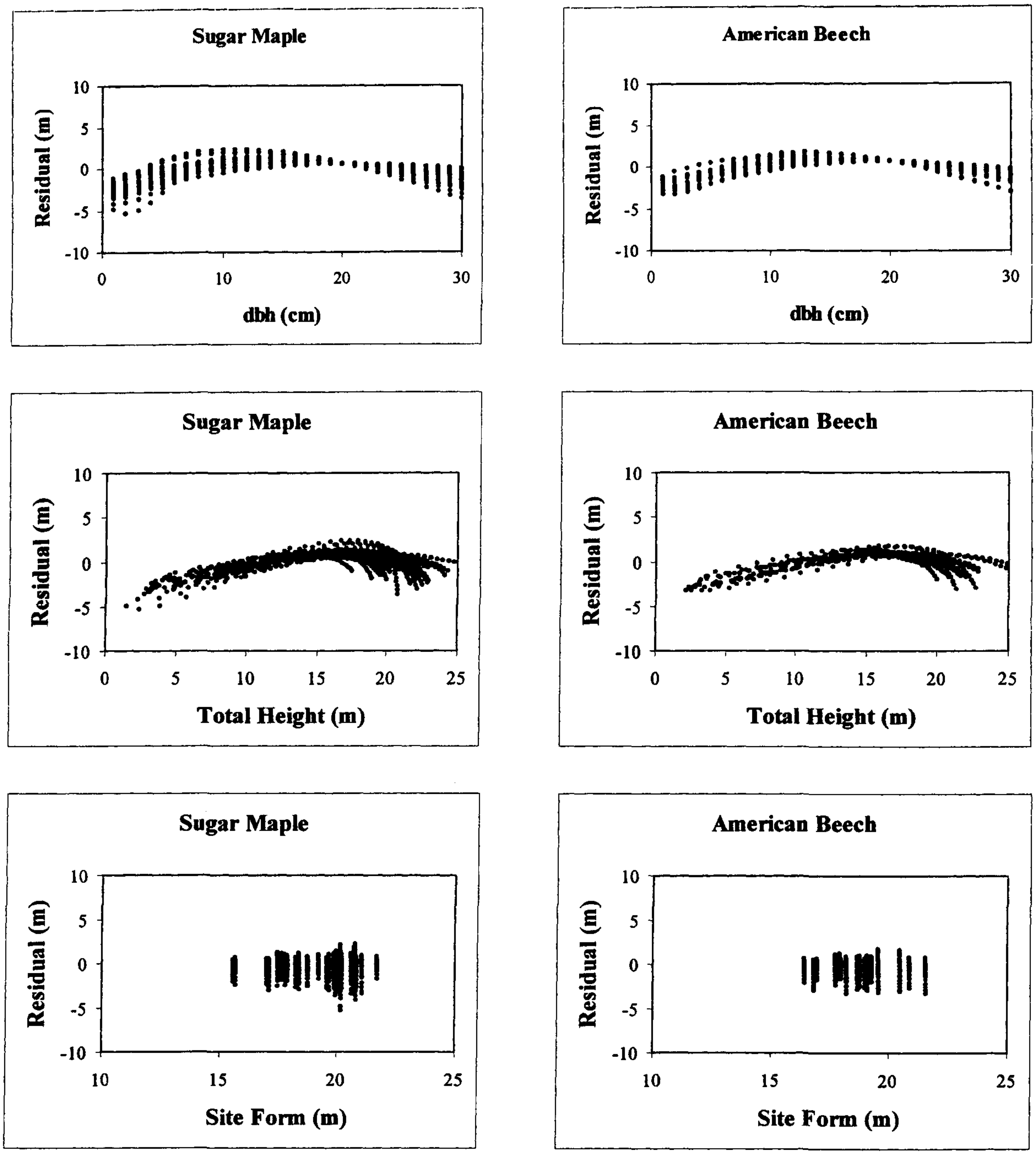

Figure A4.1. Residuals plots for height as function of dbh and site form using equation [4.1] for sugar maple and American beech.

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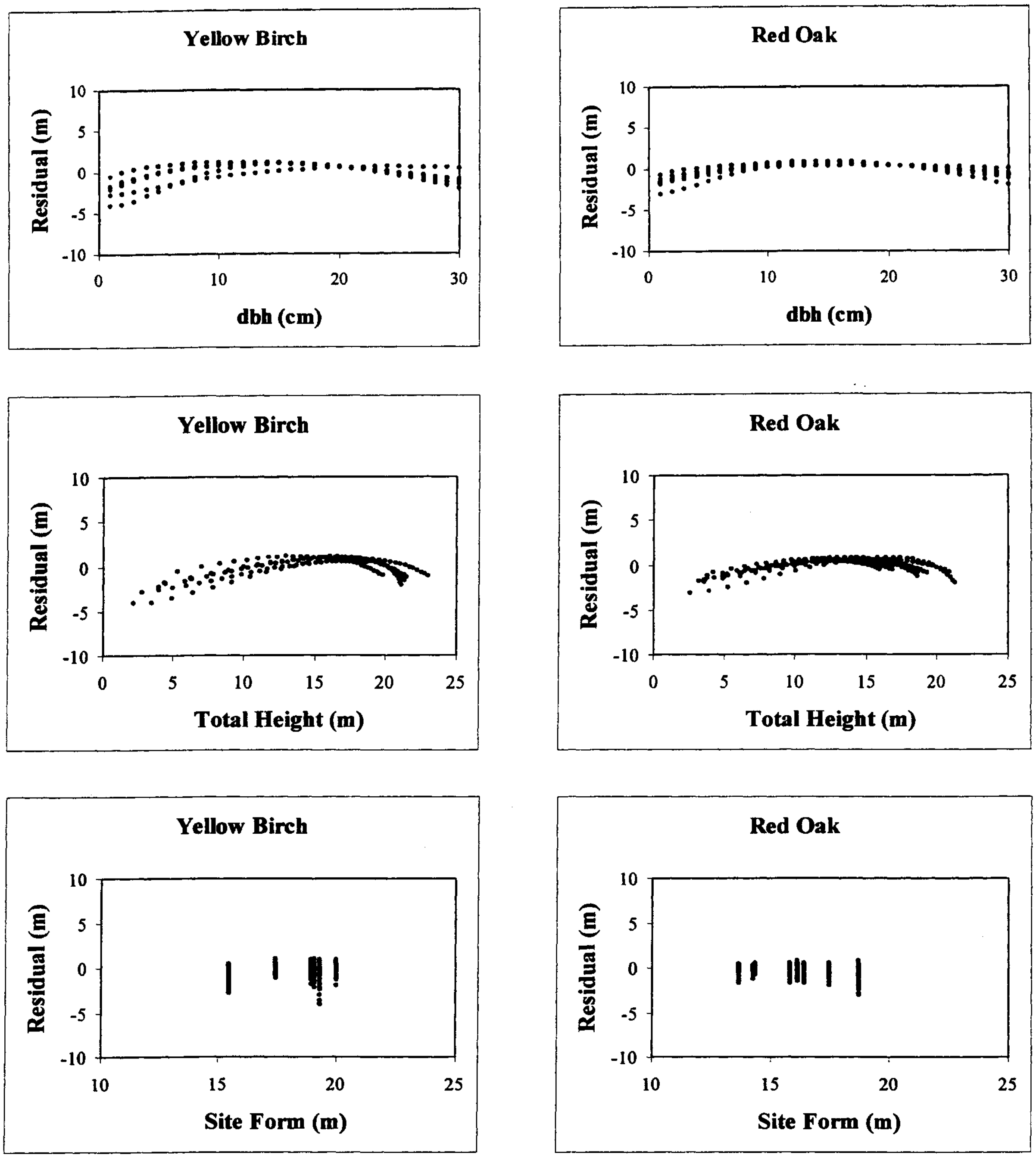

Figure A4.1 (continued). Residuals plots for height as function of dbh and site form using equation [4.1] for yellow birch and red oak.

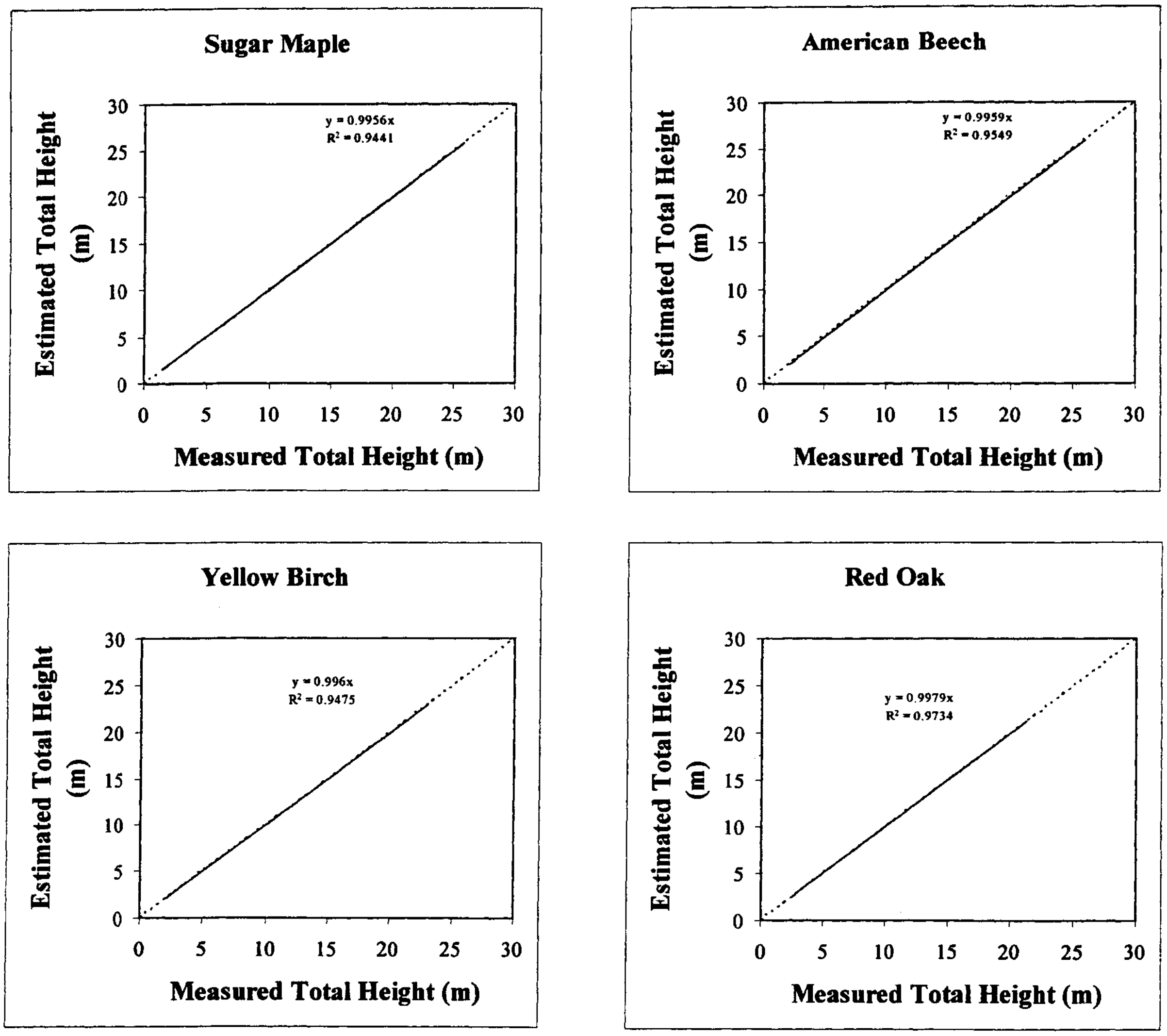

Figure A4.2. Graphical results of regression of measured total height (m) versus total height predicted by equation [4.1] by species. Solid lines are regression lines and dashed lines represent y = x. Regression models for all four species were shown to be similar ($p > 0.05$) from the line y = x in a two-tailed t-test comparing slopes.

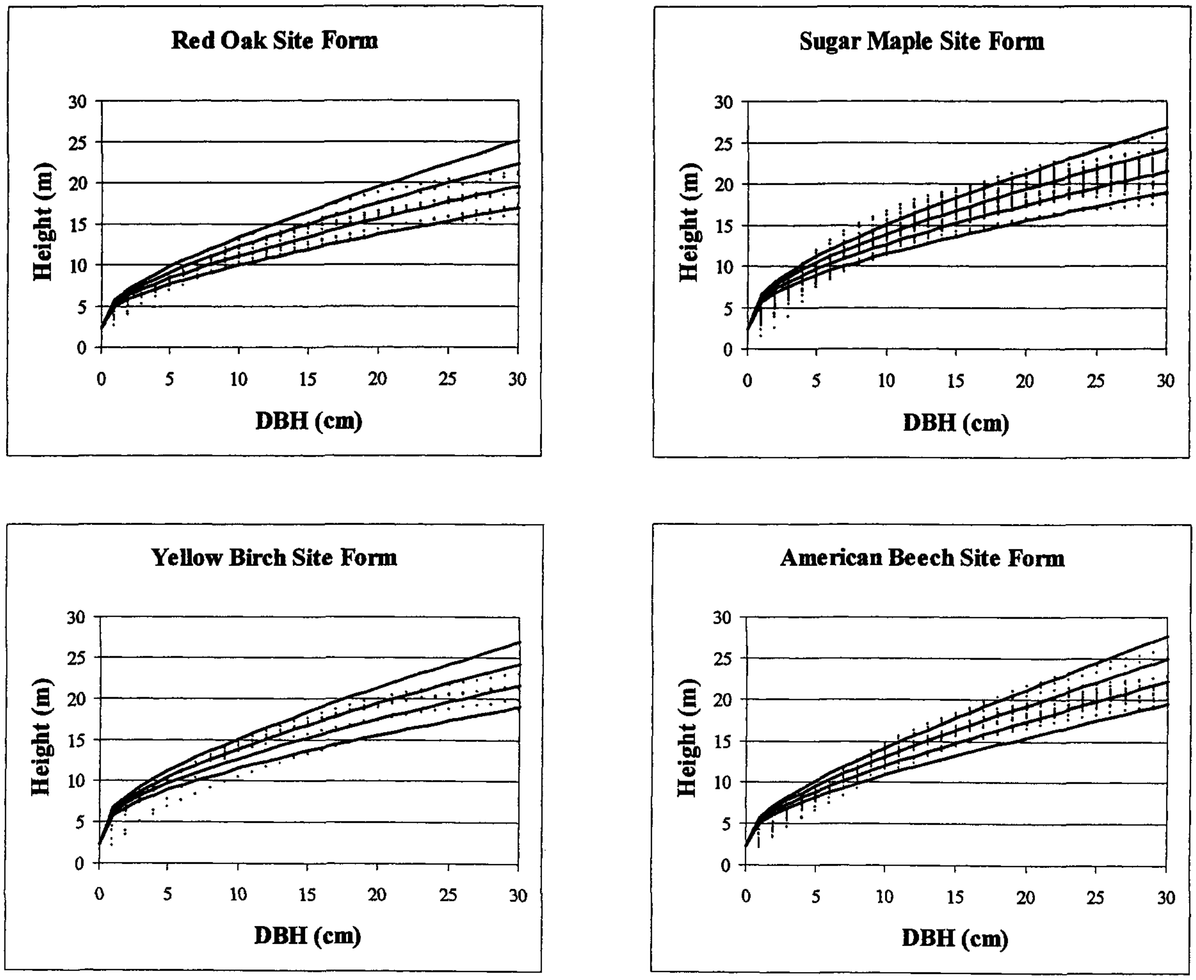

Figure A4.3. Site form curves for based on equation [4.1] and plotted against observed data for sugar maple, American beech, yellow birch and red oak.

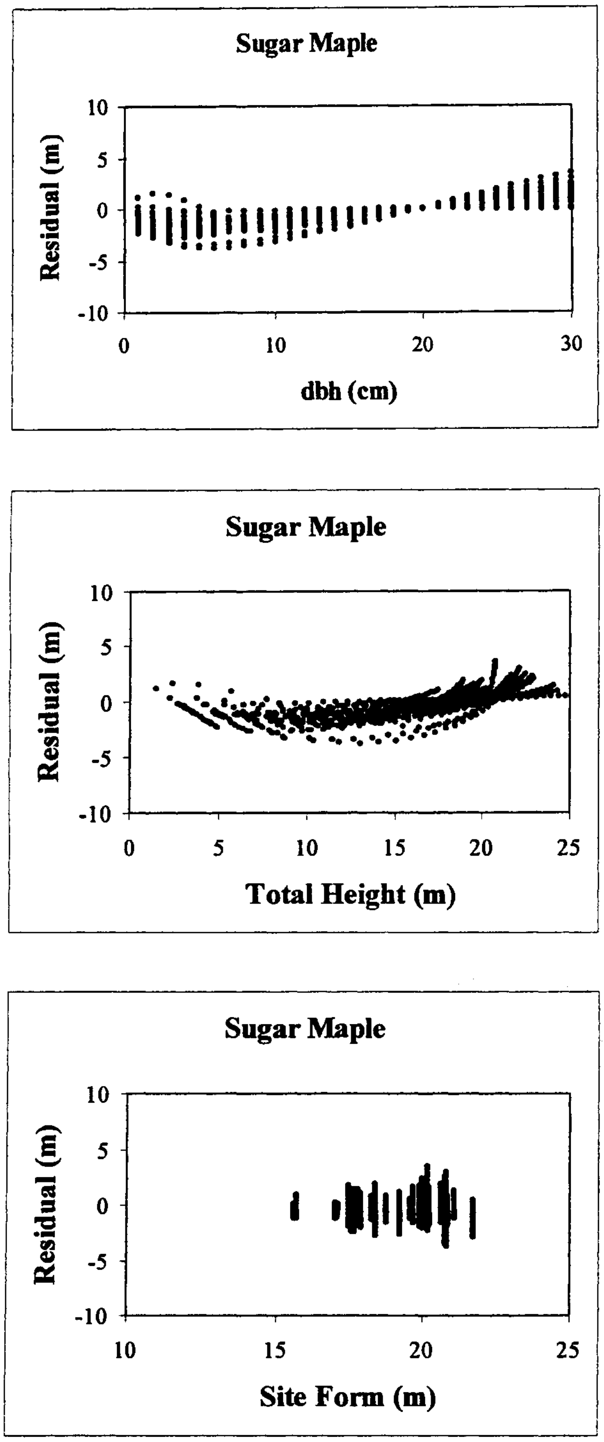

Figure A4.4. Residuals (m) plots for Woods *et al.* (1998) accuracy assessment model against dbh (cm), total height (m) and site form (m).

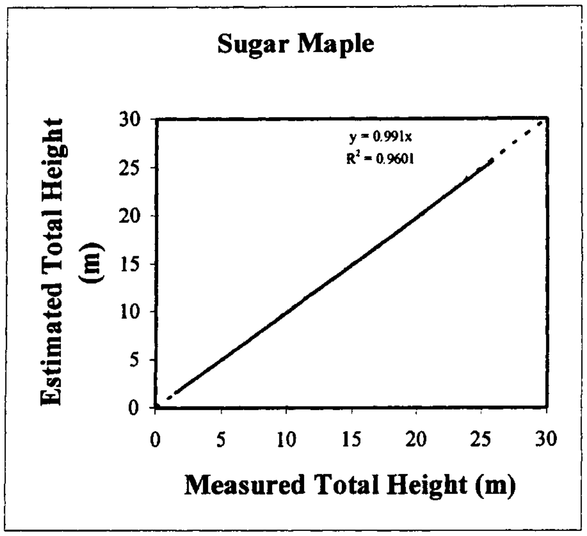

Figure A4.5. Graphical results of regression of measured total height (m) versus total height predicted by Woods *et al.* (1998) model for data in this study. The solid line is the regression line and the dashed line represents the line $y = x$. The regression model was shown to be significantly different ($p > 0.05$) from the line $y = x$ in a two-tailed t-test comparing slopes.

Table A4.1. General Statistics for soil variables used in correlation analyses for site form.

Site Variable	Min	Max	Mean	SD
Sugar Maple				
Total F Nitrogen (kg/ha)	472	2575	1149	503
F Potassium Concentration (ppm)	155	922	430	153
Total A Magnesium (kg/ha)	9	79	27	17
A Nitrogen Concentration (ppm)	411	7947	3839	1864
% B Horizon Coarse Fragments	0	44	9	9
American Beech				
Total F Nitrogen (kg/ha)	719	2720	1415	600
F Potassium Concentration (ppm)	268	922	434	159
Total A Magnesium (kg/ha)	10	68	25	15
A Nitrogen Concentration (ppm)	1772	7037	3834	1226
% B Horizon Coarse Fragments	0	28	8	8