

**DEVELOPING ECOREGION-BASED HEIGHT-  
DIAMETER MODELS AND REFERENCE-AGE  
INVARIANT POLYMORPHIC HEIGHT AND SITE INDEX  
CURVES FOR BLACK SPRUCE AND JACK PINE IN  
MANITOBA**

**BY**

**WENLI XU**

**A thesis  
Submitted to the Faculty of Graduate Studies  
in Partial Fulfillment of the Requirements  
for the Degree of**

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University of Manitoba  
Winnipeg, Manitoba  
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## Abstract

Eight different height-diameter models, five height prediction models with stand variables as predictors and six height and site index models were selected, examined, compared and developed for black spruce (*Picea mariana* [Mill.] B.S.P.) and jack pine (*Pinus banksiana* Lamb.) in Manitoba.

Eight different height-diameter models were fitted using nonlinear modeling techniques and compared in each of the five ecoregions in Manitoba: Churchill River Upland (Ecoregion 88); Hayes River Upland (Ecoregion 89); Lac Seul Upland (Ecoregion 90); Lake of the Woods (Ecoregion 91); Mid-Boreal Lowland (Ecoregion 148). Results suggested that the Weibull-type and Chapman-Richards models were the most suitable models. Differences of the height-diameter relationship among and between ecoregions were tested. Testing results suggested that height-diameter models significantly differed between ecoregions, indicating ecoregion-based or 'local' height-diameter models are needed for prediction purposes. The ecoregion-based height-diameter models developed in this study may provide more accurate information for developing forest growth and yield models.

Five height prediction models were examined with the addition of stand density variables into the base height-diameter model. Adding stand variable resulted in increased prediction accuracy.

Six height and site index models were examined and compared for black spruce and jack pine based on the provincial stem analysis data and the most suitable models were selected for Manitoba and the provincial height and site index prediction tables were produced.

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# CHAPTER 1. INTRODUCTION AND LITERATURE REVIEW

## 1.1 Introduction

Both jack pine (*Pinus banksiana* Lamb) and black spruce [*Picea mariana* (Mill.) B.S.P.] are among the most widely distributed and economically important tree species in Manitoba. The total merchantable volume of black spruce is 196.1 million m<sup>3</sup> and that of jack pine is 140.5 million m<sup>3</sup> (Manitoba Conservation, 2001)

Black spruce (*Picea mariana* (Mill.)B.S.P.) is a main tree species in the boreal forests of Canada, and its geographic range includes much of Canada and the North-eastern United States. The northern boundary of black spruce follows the tree line, extending east from the west coast of Alaska, through British Columbia to the Atlantic coast of Labrador. The southern boundary includes central British Columbia, Alberta, Saskatchewan, Manitoba, Minnesota, Wisconsin (Viereck and Johnston 1990, Farrar 1995).

Black spruce is commonly found in pure stands on lowland or wet organic soils, but it can also be found in mixed stands on a variety of mineral soils (Viereck and Johnston 1990) with jack pine (*Pinus banksiana* Lamb) and trembling aspen (*Populus tremuloides* Michx.). Because of the lateral growth of root systems, black spruce can survive in very shallow soils or in soils with shallow oxygenated zones. The majority root biomass of black spruce is located within the upper 20 cm of a soil profile (Viereck and Johnston 1990). Black spruce is an important resource for the pulp wood industry and it is also used for lumber (Viereck and Johnston 1990).

The mean height of black spruce is 12 to 20 meters at maturity on relatively high quality sites. On poor quality sites, the mean height is somewhat lower at about 8 to 12

meters (Viereck and Johnston 1990). The character of shade tolerance allows black spruce to develop under a closed canopy, although growth is better under open canopy (Farrar 1995).

Jack pine (*Pinus banksiana* Lamb) is also a very widely distributed tree species in North America. It is an important source of pulpwood, lumber, and round timber (Rudolph and Laidly 1990). The form of jack pine is quite variable, depending on soil and crown conditions (Hosie 1979). In open conditions, it has a conical open crown of ascending and arching branches and a tapered trunk. In the closed stand, the live-crown becomes reduced, usually covering less than 1/5 of the length of the tree; the trunk is slender, straight, and with little taper. On the poor soils and rocky sites, jack pine tree is often short and twisted. The root systems are usually widespread and moderate in depth (Hosie 1979).

Jack pine is a boreal forest tree species and usually grows in pure stands or in mixture with black spruce. It can also be found with white spruce, balsam fir, trembling aspen, balsam poplar and white birch in mixed stands. Usually, jack pine establishes and maintains even-aged pure stands after forest fires (Sweda et al. 1979).

The mean height of jack pine is 14 to 24 meters at maturity on relatively high quality sites (Hosie 1979). Jack pine is a pioneer, shade-intolerant species typically found on dry sandy soils. It survives well on poor soils such as rocky sites. The wood of jack pine is moderately hard and heavy, but not particularly strong, and is used for general construction, pulp, railway ties and mine timbers. When mature, even-aged stands of jack pine are commonly harvested by clear-cutting. Regeneration of jack pine often comes from natural seed-fall, direct seeding or by planting seedlings.

The provincial site index models and ecoregion-based height-diameter models developed in this study may provide more accurate information for forest stand productivity classifications, and improve the accuracy and precision of forest inventory projections and provincial wood supply analysis.

## **1.2 Height-diameter models**

Foresters often use height-diameter models to predict total tree heights based on observed diameter at breast height (DBH) for estimating tree or stand volume and site quality (e.g., Stout and Shumway 1982). Therefore, estimates of tree or stand volume and site quality heavily rely on the accuracy of height-diameter models. Many postulated height-diameter models have been developed for different species and regions since Meyer (1940) suggested the exponential height-diameter relationship.

Predicting total tree height based on observed diameter at breast height outside bark (DBH, 1.3 meters above ground) is routinely required in forest management and silvicultural research work (Arabatzis and Burkhart 1992; Huang et al. 2000). Examples include volume sampling programs, pre-harvest surveys. However, the height-diameter relationship of a given species heavily depends on local environmental conditions and varies within a geographic region (Huang et al. 2000; Zhang et al. 2002).

In Ontario, the Chapman-Richards growth function has been used to model jack pine (*Pinus banksiana* Lamb.) tree height-diameter relationships at provincial, regional, and ecoregional levels (Zhang, et al. 2002). Tree height-diameter relationships of jack pine are significantly different among the geographic regions of Ontario, reflecting a dependence on local climatic, soil, and ecological conditions. The provincial and regional height-diameter models are therefore not appropriate for predicting tree heights at the



ecoregional level (Zhang, et al. 2002). Applying a specific ecoregional model to other ecoregions resulted in significant biases in the prediction of local tree heights (Zhang, et al. 2002).

In order to increase prediction accuracy, the height-diameter base models which use DBH as a predictor are modified to include stand variables, such as stand density, basal area of a stand and species compositions using the parameter prediction approach (Clutter et al. 1983; Huang and Titus 1994; Staudhammer and LeMay 2000). Because of the cost of obtaining accurate age data, the tree or stand ages are typically not introduced as additional predictors in height-diameter base models (Huang and Titus 1994).

To select appropriate height-diameter models, Huang et al. (1992) plotted height against DBH for white spruce (*Picea glauca* Voss.) and aspen (*Populus tremuloides* Michx.). Height-diameter relationship for white spruce resembled a typical sigmoid or S-shaped curve with an inflection point occurring in the lower portion of the data points. The height-diameter relationship for aspen indicated a concave curve with no apparent inflection point. Based on these findings, Huang et al. (1992) proposed that functions generating concave shapes and sigmoid shapes should be considered in the process of model selection in order to obtain an accurate height-diameter model. They selected and compared 20 published, nonlinear height-diameter functions for 16 tree species in Alberta. Based on the t-statistics for significance of parameters, mean squared error values, and the plot of studentized residuals against the predicted heights, all the equations recommended for height-diameter relationships from their study produced S-shaped curves with inflection points. Fang and Bailey (1998) investigated 33 height-diameter equations, including S-shaped and concave-shaped curves, for tropical forests on

Hainan Island in southern China. They suggested the selection of height-diameter relationships should consider both data-related and reasonable biological criteria, such as monotonic increment, functional inflection point, and asymptotic value.

Lei (1998) suggested that the data for modeling the height-diameter relationship should include early height growth. In addition, functions rendering a concave curve cannot describe tree growth behaviours appropriately, especially for fast-growth tree species. However, if a data set includes only larger or older trees beyond the inflection point, then a model generating a concave curve will probably work best. Even though a sigmoid model is correct biologically, it may not provide a reasonable fit if the range of the data is beyond the point of inflection for the species and growing conditions (Lei 1998).

The Bertalanffy-Richards growth function (Richards 1959) and the Schnute (1981) model are probably the most flexible and versatile functions available for modeling height-diameter relationships (Lei 1998). Both models are able to assume various shapes with different parameter values, and they produce satisfactory curves under a wide range of biological and ecological conditions. The Schnute model is usually easy to fit and achieve convergence quickly (Lei 1998).

### 1.3 Site index models

In North America, site index has been commonly used as a measure of forest productivity (e.g., Carmean 1975; Monserud 1984; Huang, et al. 1994b; Wang et al. 2000) and is a 'driving' variable in many growth and yield models (e.g., Clutter et al. 1983; Davis and Johnson 1987) for even aged stands. Site index is usually defined as the mean height of the dominant and co-dominant trees 50 years after they reached breast height (1.3m) (Huang, et al. 1994b; Philip 1998; Carmean 2001). Breast height age was used because early height growth is erratic and does not necessarily reflect site productivity (Clutter et al. 1983). Site index is the mean height of dominant and co-dominant trees of a stand in Manitoba. Site index provides standardized comparisons of productive potential between sites, across a broad range of existing stand conditions.

Given a set of stem analysis data obtained from dominant and co-dominant trees, as site index proceeds from low to high, the shape of height-age curves will change as well as their magnitude. Usually, trees with the lowest site index display a flatter, more linear curve while trees with the highest site index approach the asymptote rapidly; thus the curves for different site classes diverge for young trees, then they tend to become parallel or converge at older ages. If individual curves are fit to relatively narrow classes of site index, most of the variability of curve shape across site will be recovered (Carmean 1972). However, if an equation is fit to data pooled across site index, the trend in curve shape across site index will be underestimated. Goelz and Burk (1992) indicated that this observation was a "regression towards the mean" phenomenon, although it is more appropriate to term it an "errors-in-variables" problem (Fuller 1987) as it results

from the assumption that height at base age (site index) is measured without error. This problem could become important when subsets of residuals based on age and site index are plotted. Goelz and Burk (1992) used an ad hoc procedure in an attempt to remove the errors-in-variables problem.

The potential statistical problem of heteroscedasticity and inherent dependence (autocorrelation of the tree sectioning data, caused by taking several measurements from the same trees at different locations) may render the usual regression hypothesis-testing procedures and interval estimations invalid. The problem can be solved by using appropriate generalized least squares techniques (Monseru 1984; Goelz and Burk 1992; Huang 1992). However, since the ordinary nonlinear least squares estimator of the parameters is asymptotically unbiased and consistent even if both heteroscedasticity and autocorrelation are present (Gallant 1987; Judge et al. 1988), the problem should not bias the coefficient estimates of the height growth and site index model. As a result, the estimated coefficients from ordinary nonlinear least squares techniques will still provide unbiased estimates of the predicted values for the dependent variable. The problem of autocorrelations is also ignored, mainly because it does not cause biased parameter estimates and result in biased predictions. This attitude towards autocorrelation has been widely accepted by many researchers in taper modeling, height growth and site index studies and is appropriate provided that only the point estimates are required (Curtis et al. 1974; Monserud 1984; Huang 1997; Kozak 1997).

#### **1.4 Overall research objectives**

This study has three objectives: (1) to quantify the relationship between height and DBH (diameter at breast height) of black spruce and jack pine, and to test if separate

height-diameter models are needed for different ecoregions in Manitoba; (2) to test if stand variables can be used, in addition to DBH, to improve height prediction when developing height-DBH models, and (3) to develop reference-age invariant polymorphic height growth and site index models for black spruce and jack pine in Manitoba .

The results of this research are reported in three, relatively independent chapters. Chapter 2 deals with objective (1). Chapter 3 deals with objective (2). Chapter 4 deals with objective (3).

## **CHAPTER 2. ECOREGION-BASED HEIGHT-DIAMETER MODELS DEVELOPMENT FOR BLACK SPRUCE AND JACK PINE**

### **2.1 Introduction**

The prediction of forest growth and yield is the basis for developing forest management plan, analyzing wood supply, and determining provincial annual allowable cut (AAC) to achieve sustainable forest management in Manitoba.

Predicting total tree height based on observed diameter at breast height outside bark (DBH, 1.3 meter above ground) is routinely required in practical management and silvicultural research work, such as volume sampling and pre-harvest surveys. Because data of tree heights are relatively more difficult and costly to obtain, measuring all sample trees for DBH and a portion of these trees for height is a common practice when collecting data from both permanent and temporary sample plots. Currently, foresters in Manitoba are using Alberta provincial black spruce and jack pine height-diameter models to estimate the total tree height because of the lack of locally developed models. As a result, the Manitoba growth and yield program has identified an urgent need to develop local tree height-diameter equations that can be used to estimate tree heights and consequently tree volumes.

A single height-diameter model developed for an entire province may not account for variation among different ecological regions. As a result, applying the provincial model to different ecoregions may result in biased predictions of tree heights (Huang et al. 2000; Peng et al. 2001). For example, the incorrect application of height-diameter models from one ecoregion to another resulted in tree height overestimations between 1.10% and 29.05%, or underestimations between 1.92% and 21.92% (Huang et al. 2000).

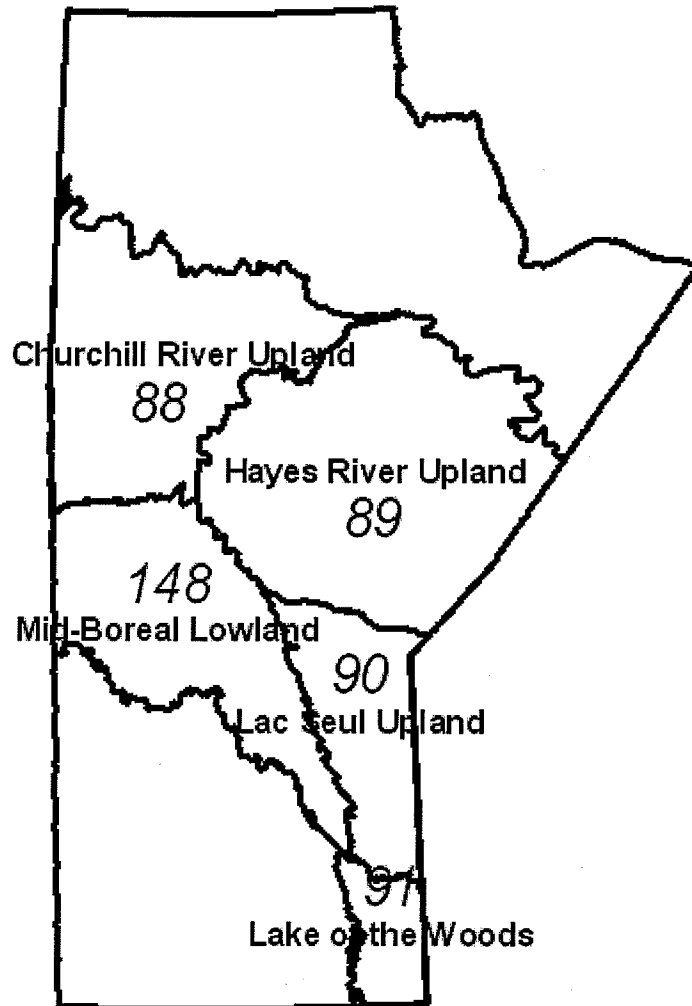
The objectives of the this study were (1) to quantify the relationship between height and DBH of black spruce and jack pine in Manitoba, (2) to test if separate height-diameter models are needed for different ecoregions in Manitoba, and (3) to develop ecoregion-based height-diameter models if necessary.

## 2.2 Study Area

The study included the following ecoregions in Manitoba (Smith et al 1998): Churchill River Upland (Ecoregion 88); Hayes River Upland (Ecoregion 89); Lac Seul Upland (Ecoregion 90); Lake of the Woods (Ecoregion 91); Mid-Boreal Lowland (Ecoregion 148) (Figure 2.1).

The Churchill River Upland Ecoregion is located on the southern edge of the Precambrian Shield. It is characterized by closed Boreal forest of black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*) and white spruce (*Picea glauca*) (Smith et al 1998). It has cool summers and very cold winters. The mean annual temperature is about  $-2.5^{\circ}\text{C}$ . The mean summer temperature is  $12.5^{\circ}\text{C}$  and the mean winter temperature is  $-18.5^{\circ}\text{C}$ . The mean annual precipitation ranges 400–500 mm (ESWG 1995). This ecoregion is classified as having a subhumid high boreal ecoclimate. It forms part of the continuous coniferous boreal forest that extends from northwestern Ontario to Great Slave Lake in the southern Northwest Territories. The predominant vegetation consists of closed stands of black spruce and jack pine with a shrub layer and a ground cover of mosses and lichens and black spruce is the climatic climax species (ESWG 1995). Permafrost is distributed throughout the ecoregion, but is only widespread in organic deposits. Exposed bedrock occurs throughout the ecoregion and is locally prominent. On level and in depressional areas, Gleysolic soils are associated with clayey sediments, whereas Mesisols and Organic Cryosols are associated with shallow to deep peatlands (ESWG 1995).





**Figure 2.1.** Distribution of the five studied ecoregion in Manitoba: Churchill River Upland (Ecoregion 88); Hayes River Upland (Ecoregion 89); Lac Seul Upland (Ecoregion 90); Lake of the Woods (Ecoregion 91); Mid-Boreal Lowland (Ecoregion 148).