2002

Crop Tree Growth and Quality Twenty-five Years after Precommercial Thinning in a Northern Conifer Stand

Leah M. Phillips

CROP TREE GROWTH AND QUALITY TWENTY-FIVE YEARS AFTER PRECOMMERCIAL THINNING IN A NORTHERN CONIFER STAND

By

Leah M. Phillips

B.S. Colorado State University, 1999

A THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

(in Forestry)

The Graduate School

The University of Maine

December, 2002

Advisory Committee:

Robert S. Seymour, Curtis Hutchins Professor of Forest Resources, Advisor

Laura S. Kenefic, Assistant Research Professor; Research Forester, USDA Forest Service, Northeastern Research Station

Alan J. Kimball, Associate Professor of Forest Resources

CROP TREE GROWTH AND QUALITY TWENTY-FIVE YEARS AFTER PRECOMMERCIAL THINNING IN A NORTHERN CONIFER STAND

By Leah M. Phillips

Thesis Advisor: Dr. Robert S. Seymour

An Abstract of the Thesis Presented
in Partial Fulfillment of the Requirements for the
Degree of Master of Science
(in Forestry)
December, 2002

Growth characteristics of selected *Picea rubens* Sarg. (red spruce) and *Abies balsamea* (L.) Mill. (balsam fir) crop trees were studied in a northern conifer forest to determine the effects of precommercial thinning (PCT) 25 years after initial treatment. Two measures of growth efficiency (GE, growth per unit of growing space) were examined: stemwood increment (dm^3) per unit of projected leaf area (PLA) (m^2) and stemwood increment (dm^3) per unit of crown projection area (CPA) (m^2).

Stem form differences were evaluated by comparing stem taper between species and treatments. Branch diameters were measured between 1.0 - 2.0 meters above breast height (BH, 1.37 m (4.5 ft)) for each crop tree, and the number and size of branches and the ratio of knots were determined. Volumes of all crop trees were calculated using Smalian's formula (Avery and Burkhart 1994) applied to different geometric forms of the tree to estimate total cubic foot volume from diameter measurements up the tree bole.

The efficacy of Honer's (1967) volume equation for estimating total cubic foot volume from diameter at BH (DBH) and total height (THT) was tested by comparing measured values to the estimated values. Differences in tree stability were determined by comparing height to diameter ratios (H/D) of all the crop trees by species and treatment.

GE did not differ between treatments using either definition, although average PLA and CPA per tree were higher in the spaced plots. As expected, balsam fir was more growth-efficient than red spruce using both GE definitions. There were no significant differences in average PLA between the two species, but red spruce had a larger average CPA than balsam fir. Crop trees in the spaced plots had more stem taper than the unspaced plots and a lower (H/D) ratio. Stem taper differed between species; red spruce crop trees had more stem taper than balsam fir. The crop trees in the spaced plots had significantly more volume than those in the unspaced; total stand volume including non-crop trees was not measured. Balsam fir trees contained significantly more volume than red spruce in both treatments. Crop trees in the spaced plots had more and larger branches and also a higher percentage of knot volume than in the unspaced plots. There were no differences in the number and size of branches between balsam fir and red spruce, although red spruce crop trees had a greater knot volume than balsam fir trees. Results of this study are important for managers wanting to use PCT as a silvicultural tool to increase volume growth of selected crop trees without losing value or productivity.

ACKNOWLEDGMENTS

First of all I would like to thank my advisor Bob Seymour for having the confidence in me, for his patience and support and sharing his extensive knowledge of silviculture with me. Thanks to Laura Kenefic for her help in every aspect of my thesis, her never ending patience and for a wonderful friendship. Thanks to Al Kimball for being a part of my committee and for his never ending words of wisdom. Thank you to all of the professors that I have had contact with and have learned so much from. Thanks to John Brissette from the USDA Forest Service for allowing me to conduct research on the plots of the precommercial thinning study. Thanks also to Rick Dionne and Tim Stone from the USDA Forest Service for providing me the data from Study 58.

Thanks to all of the graduate students who have made this experience exceptionally enjoyable, especially: Andrew Moores, Dawn Opland, Julie Swisher, Megan Fries, Isaac Annis, and Mandy Farrar. Thanks to Howard Daggett for all of the SYSTAT tutorials. Thank you to Ben Povak for climbing the crop trees for this study.

Thanks to my family for understanding and standing behind me while I pursue this degree. Thanks to my nephew Shawn Phillips for always being my best buddy and sharing my enthusiasm for trees and the outdoors.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Maine is the most heavily forested state in the United States. Almost 90 percent of the total land is forested, and 46 percent is occupied by the spruce-fir cover type (Seymour 1992). *Picea rubens* Sarg. (red spruce) and balsam fir *Abies balsamea* (L.) Mill. (balsam fir) are shade-tolerant trees that dominate this forest type and are found on sites with moderately coarse, somewhat poorly drained, acid soils (Seymour 1995). Red spruce and balsam fir trees are an important commodity in Maine forests. In the year 2000, a total of approximately 724,600,000 (board feet) of spruce-fir sawlogs and 675,000 cords of pulpwood were harvested in Maine (Maine Dept. of Conservation 2002). It is thus imperative to mange these forests to maintain healthy growing stock for the future. Precommercial thinning (PCT) is one silvicultural option that fosters uniformly stocked stands of crop trees optimally spaced with high potential future value.

PCT is a thinning made as an investment in the future growth of a young stand where none of the stems removed are utilized (Smith *et al.* 1997) (p. 113). PCT is usually done early in the life of a stand when the capability still exists for the renewal of leaf area and for crown expansion into the growing space made available. PCT is often important for the elimination of competitors and enhanced growth of the residual crop trees. Many young stands in the Acadian Forest Region are densely overstocked with balsam fir due to repeated selective logging and outbreaks of the spruce budworm (*Choristoneura fumiferana*) (Seymour 1995). PCT is an important tool for controlling the competition and growth in these stands, since it allows foresters to favor longer-lived species such as red spruce. Increased individual tree growth from PCT may lead to better quality and greater individual tree volumes. PCT early in the life of a dense stand can shorten the time to reach merchantability and reduce the costs of subsequent harvesting by taking out unmerchantable trees that may hinder future logging. Treatments that alter stand structure and the distribution of growing space affect stem growth and tree vigor, which are significant components of productivity.

Tree productivity is a function of both the amount and efficiency of leaf area (LA). LA is the surface area of all the foliage and is measured as either all-sided, or more commonly, projected (one-sided) leaf area (PLA). Growth efficiency (GE) is an expression of the amount of stemwood volume production per unit of LA. This study calculates GE on a per-tree basis to evaluate PCT effects on selected crop trees. Two factors that determine GE are the amount of carbon fixed by the foliage and the proportion of carbon allocated to stemwood growth (Roberts *et al.* 1993). Both factors are affected by stand structure, which in turn can be altered by silvicultural treatments such as PCT. Determining the GE of individual crop trees allows managers to assess the continued productivity of trees following PCT treatments and to base future decisions on the growth and productive potential of precommercially thinned trees.

Thinning reduces stand density, thus creating more favorable growing conditions for the residual trees. As a result there is an increase in crown size and thus stem taper. Increased crown size from thinning results in a shift of growth lower on the stem and a concomitant increase in stem taper. Conversely, as the crown base recedes due to unfavorable growing conditions, growth is concentrated near the crown base and trees exhibit a more cylindrical form (Larson 1963). Added growing space also allows the retention of lower branches and subsequently increases the branchiness of the tree bole. Branches on trees create knots that may decrease its value at the mill. This study gives managers insight on changes in the degree of stem taper and branchiness of selected red spruce and balsam fir trees resulting from PCT treatments.

Estimating the volume of trees for timber production assessment is an important aspect of managing a forest. An overestimation or underestimation of volume could result in a loss of money for the landowner selling the logs to the mill. Therefore, a check on volume estimation models is appropriate to confirm their validity for a particular area. Volumes were computed directly from upper-stem diameter measurements for each crop tree in the study, and compared to those estimated by Honer's (1967) standard total cubic foot volume equation.

Silvical Characteristics of Red Spruce and Balsam Fir

Balsam fir is an important component of the northeastern forest and is found in Canada in Newfoundland, west through northern Quebec through north-central Manitoba to portions of Alberta, and south to southern Manitoba. In the United States it is found in northern Minnesota into southeast Iowa, east to central Wisconsin and central Michigan, into New York and Pennsylvania, and northeast into all of the New England states. It is also found in the mountains of Virginia and West Virginia. It is a major component in 3 forest cover types and occurs in association with other species in 22 eastern and 4 western forest cover types. Balsam fir occurs on a wide range of shallow soils originating from glaciation with a wide range of acidity. Balsam fir is a prolific seeder with longevity of 70-150 years, but its susceptibility to heart-rot fungi and windthrow often limits its lifespan (Frank 1990). Balsam fir is the preferred host of the spruce budworm, which may further limit its lifespan to 40-70 years (Seymour 1992). Balsam fir is classified as very shade tolerant and can become established and grow in the understory (Frank 1990).

Red spruce is another important component of the northeastern forest and is found from the Maritime Provinces of Canada west to Maine, southern Quebec and southeastern Ontario, and south into central New York, Pennsylvania, New Jersey, and Massachusetts. It is found in western Maryland, eastern West Virginia, Virginia, western North Carolina, and eastern Tennessee. Red spruce is a major component in 6 forest types and a minor component in 13 forest types. It grows on shallow, fairly acidic soils developed from glacial till. Red spruce is an infrequent seeder and lives 250-400 years (Blum 1990). It is very shade tolerant and can persist as advance regeneration in the understory and respond to release after several decades (Seymour 1992). The spruce-fir forest type comprises 21 percent of the northeastern forests, and dominates the highest elevations and low elevation softwood flats (Seymour 1995). Though spruce and fir occur naturally throughout Maine, stands dominated by spruce and fir are found primarily in the northern and eastern parts of the state (Seymour 1992).

Objectives

There are two components of this study, each with its own objectives. The first component was assessed crop tree productivity as determined by GE between treatments and species, and between treatments for each species. The hypotheses were:

(H_1): GE differs between treatments and species;

(H_2): GE differs between treatments for each species; and

(H_3): GE is unaffected by crown size.

The null hypothesis was that GE is equivalent across species, treatments, and crown sizes.

The second component evaluated the stem form of crop trees between treatments and species and between treatments for each species; determined efficacy of Honer's (1967) volume equation by comparing measured versus estimated volumes of crop trees; and quantified the extent of branchiness between treatments and species and its effect on wood quality. The hypotheses tested were:

(H_1): There are significant stem form differences between species and treatments;

(H_2): The derived and estimated volumes differ between species and treatments; and

(H_3): There are significant differences in branch characteristics between species and treatments.

CHAPTER 1. EVALUATION OF GROWTH EFFICIENCY FOR (*PICEA RUBENS* SARG. (RED SPRUCE) AND *ABIES BALSAMEA* (L.) MILL. (BALSAM FIR)) CROP TREES IN PRECOMMERCIALLY THINNED STANDS

ABSTRACT

Growth of individual *Picea rubens* Sarg. (red spruce) and *Abies balsamea* (L.) Mill. (balsam fir) crop trees was studied to evaluate precommercial thinning (PCT) effects 25 years after initial treatment. PCT effects were investigated by evaluating growth efficiency (GE, stemwood growth per unit of leaf area) and individual tree leaf area (PLA, projected one-sided leaf area). GE was calculated per unit of PLA and crown projection area (CPA) to compare crop tree growth between treated and untreated plots. GE did not differ between treatments using either definition, although PLA and CPA per tree were larger in the spaced plots. Crop tree diameter and crown length were also greater in the spaced plots than in the unspaced plots. PCT increased stemwood volume for all trees, and as expected, balsam fir crop trees contained larger volumes than red spruce crop trees. Overall, balsam fir was more growth efficient than red spruce using both GE definitions. There were no differences in average PLA between the two species, but red spruce crop trees had a larger average CPA than balsam fir crop trees.

INTRODUCTION

Thinning creates a temporary reduction in stand density in order to improve individual tree growth. The removal of individuals from a stand reallocates growing space for the competitive benefit of the residual trees. Thinning a stand increases growing space for the selected trees and subsequently increases stemwood production per tree. Trees that are given adequate growing space intercept more sunlight and therefore have higher photosynthetic capacity and consequently more carbon production for stemwood growth. Precommercial thinning (PCT) is an investment in the future growth of a young stand where none of the stems removed are utilized (Smith *et al.* 1997, p.113). PCT is usually employed when trees are young and vigorous and can take full advantage of available growing space through crown expansion. PCT early in the life of a dense stand can shorten the time to reach merchantability and reduce the costs of subsequent harvesting by taking out unmerchantable trees that may hinder future logging. In order to assess the effects of silvicultural treatments such as PCT on growth, a measure of individual tree production must be studied. Treatments that alter stand structure and enhance available growing space affect stem growth and tree vigor, which are significant components of productivity.

Leaf Area and Growth Efficiency

Tree productivity is a function of both the amount and efficiency of leaf area (LA). LA is the surface area of all the foliage and is measured as either all-sided, or more commonly, one-sided (projected) leaf area (PLA). Light interception, photosynthesis, and carbon allocation processes all occur in the foliage. Growth efficiently (GE) is a term used to express how much stemwood volume a tree is producing per unit of LA. Both the amount of LA per individual tree and stand-level LA both influence GE and total stand production. GE depends on two factors: the amount of carbon fixed by the foliage, and the quantity allocated to stemwood growth (Roberts *et al.* 1993), both of which can be affected by stand structure. The balance between the rate at which a tree fixes carbon and the pattern of carbon allocation determines GE (Roberts *et al.* 1993).

Photosynthate production is a function of the amount of LA and the rate of photosynthesis per unit of LA (Brix 1982). At the stand level, as leaf area increases a greater proportion of the foliage is in deeper shade and thus contributing less to the overall net production of photosynthate. Therefore, one would expect a lower efficiency of growth in stands with high LAs (Kimmins 1997; Waring 1981 and 1983). Waring (1981) found that as the canopy increased in density, there were subsequent decreases in individual tree basal area growth, volume growth, and net assimilation rates. Some studies have found an increase in stand level efficiency with increasing canopy density up to a point and then a subsequent decrease in GE with any additional increases in LA (Roberts and Long 1992 and 1993). Other studies have found no relationship between increased stand level LA and GE (Binkley and Reid 1984; Waring 1981; O'Hara 1989).

At the tree-level, some studies have found that an increase in PLA per tree results in more carbon allocation to the respiration of living tissues and less to stemwood production and thus a lower GE (Roberts *et al.* 1993; Long and Smith 1990; Smith and Long 1989). A larger crown results in an increase in the ratio of non-photosynthetic to photosynthetic tissues and therefore is associated with an increase in the production and maintenance requirements from the larger amount of woody structures. Since stemwood growth is lower priority than respiration, the renewal of foliage and fine roots and height growth on the scale of biological activity, anything that reduces photosynthesis will decrease stemwood growth (Oliver and Larson 1996, p. 75; Smith *et al.* 1997, p. 48).

Crown Projection Area and Growth Efficiency

Crown projection area (CPA), a surrogate for PLA in the GE equation is a measure of crown size and reflects the amount of space an individual tree crown occupies. CPA, unlike PLA assumes unlimited aboveground growing space, with limitations on horizontal growing space only (O'Hara 1988). O'Hara (1988) found sapwood basal area (an approximation to LA) to be a better measure of growing space than CPA, although both measures of growing space were useful. CPA is a useful measure of growing space occupancy, but PLA provides a better evaluation of crown size and productivity (O'Hara 1988).

PCT – Red Spruce and Balsam Fir

Several studies have looked at the effects of PCT on various aspects of tree growth for *Picea rubens* Sarg. (red spruce) and *Abies balsamea* (L.) Mill. (balsam fir). Eighteen years after PCT in the northern conifer forest in east central Maine that was used in this study, Brissette *et al.* (1999) found that crop trees in the spaced plots had larger crowns and greater diameter and height growth than those in unspaced plots. Treated plots had a greater proportion of conifers, which is important for maintaining longer-lived and more insect resistant species, i.e. red spruce, or faster growing species, i.e. balsam fir, both economically valuable in this area. Lavigne and Donnelly (1989) also found that mean diameter, height, and volume of balsam fir trees was greater in spaced than in unspaced plots. In other studies, the volumes of individual balsam fir trees were found to increase following spacing treatments (Ker 1987; Piene 1981; Piene and Anderson 1987). Spacing had no significant effects on heights of balsam fir trees in several studies (Ker 1987; Piene and Anderson 1987; Piene 1981), although Barbour *et al.* (1991) found that red spruce trees 15 years after PCT were taller and had longer live crowns than unspaced trees.

Purpose and Objectives

The purpose of this project was to study the effects of PCT on crop tree growth and the relationship between tree-level PLA and GE. By estimating crop tree PLA and calculating GE, a thorough understanding of the effects of PCT on tree-level production can be attained. Two forms of GE were tested: one using average volume increment (AVINC) per unit of PLA (Gilmore and Seymour 1996; Maguire *et al.* 1998), and one using AVINC per unit of CPA (Assman 1970; Gilmore and Seymour 1996; O'Hara 1988).

The objectives of the study were to (1) compare crop tree GE between treatments and species; (2) determine if crop tree PLA differs by treatment and/or species, and if so; (3) whether this has a positive or negative effect on GE. The hypotheses tested were:

(H_1): GE differs between treatments and species;

(H_2): GE differs between treatments for each species; and

(H_3): GE is unaffected by crown size.

The null hypothesis was that GE is equivalent across species, treatments, and crown sizes.

METHODS

Study Area

The Penobscot Experimental Forest (PEF) is located in the towns of Bradley and Eddington in Penobscot County, Maine at 44°52'N, 68°38'W. The PEF is a 1540-ha tract of land donated to the University of Maine in 1994 by industrial landowners with one of the stipulations being the continued long-term cooperative research with USDA Forest Service scientists, University researchers, and professional forest managers in Maine. The PEF is included in the Acadian Forest Region, which is a transition zone between the boreal forests to the north and the broadleaf forests to the south. Conifers with an admixture of hardwoods dominate the study area. Dominant conifers include: balsam fir, red spruce, *Picea glauca* (Moench) Voss. (white spruce), *Pinus strobus* L. (eastern white pine), *Tsuga canadensis* (L.) Carr. (eastern hemlock), and *Thuja occidentalis* L. (northern white cedar). Hardwoods commonly found in the area include: *Acer rubrum* L. (red maple), *Betula papyrifera* Marsh. (paper birch), *Betula populifolia* Marsh. (gray birch), *Betula alleghaniensis* Britt. (yellow birch), *Populus tremuloides* Michx. (quaking aspen), and *Populus grandidentata* Michx. (bigtooth aspen). Soil types on the PEF range from well-drained loams and sandy loams to poorly drained loams and silt loams with parent material primarily consisting of glacial till (Brissette *et al.* 1999). The soil series on the study area is a Monarda-Burnham stony fine sandy loam on a 0-8% slope, developed from deep till parent material.

Background

Research was conducted in an area of the PEF where there is an ongoing study (Study 58) on the effects of different PCT regimes and fertilizer applications on species composition and the growth and yield of selected crop trees. The PCT study was conducted in an even-aged stand regenerated by a two-stage shelterwood method between July 1957 and October 1967. In 1957, 46% of the overstory was removed in an establishment harvest, and then the remaining merchantable overstory was removed in 1967. The PCT study was initiated in 1976, at which time all residual submerchantable trees > 12.7 cm diameter breast height (DBH) from the parent stand were removed. Prior to treatment application, densities of the 32 experimental units ranged from approximately 27,500 to 79,000 trees per ha with an overall mean of 42,736 trees per ha (Brissette *et al.* 1999).

Experimental Design

The completely random design of the initial PCT experiment was utilized in the present study. The initial experimental design was a factorial arrangement with three different PCT treatments, one unthinned control, and two levels of fertilization, each replicated four times. PCT treatments were applied between April and August of 1976, and included: (1) Unspaced: no PCT; (2) Row-No Release: a 1.5 m (5 ft) row removal with no crop tree release in 0.9 m (3 ft) wide residual strips; (3) Row-Release: a 1.5 m (5 ft) row removal with crop tree release at about 2.4 m (8 ft) intervals within the 0.9 m (3ft) residual strips; and (4) Spacing: selected crop trees were uniformly spaced at about 2.4 x 2.4 m (8 x 8 ft) intervals. Treatments were applied randomly to 24 x 24 m (79 x 79 ft) experimental units and then 19.5 x 19.5 m (64 x 64 ft) measurement plots were established within each experimental unit (Brissette *et al.* 1999). A total of 32 experimental units was established in the PCT study, and 9 of those were utilized for this study. Samples were taken from 4 of the spaced plots and 5 unspaced plots. The row-no release and row-release treatments were not sampled. Two of the unspaced plots selected were initially fertilized, but no effect on subsequent crop tree growth was detected (Brissette *et al.* 1999).

Data Collection

In the summer of 2001, a subsample of 80 crop trees from the original study were selected and marked. The samples consisted of 21 balsam fir and 16 red spruce in the unspaced plots, and 20 balsam fir and 23 red spruce in the spaced plots. The Forest Service has remeasured crop tree DBH, total height (THT), crown length (CL), crown width (CW), and stump diameter (SD) on these plots periodically from 1976 to 1994. The last inventory was taken in 2001 and the CL, CW, and SD were not measured and height to the live crown base and the crown radii in all four cardinal directions were measured. Crop trees selected for subsampling in this study were a spruce or fir tree: (1) in the 12.7 cm (5 inch) DBH class or larger; and (2) growing in the upper level of the canopy, designated as (D) dominant or (CD) codominant as described by Smith *et al.* (1997, p. 29). Some (I) intermediate and/or smaller diameter trees were chosen in order to obtain a sample size of 80 crop trees. The overall sample consisted of 56 CD, 2 D, and 22 I trees. Most of the (I) trees were red spruce, due to the fact that there were more balsam fir than red spruce trees in upper canopy positions. DBH was recorded for each crop tree to 0.1 cm using a diameter tape. Each crop tree was climbed using tree climbing ladders and/or climbing gear for diameter measurements up the tree bole. Height to the lowest live branch and height to the live crown base (defined as at least 3 live branches extending halfway around the bole) were recorded to the nearest 0.01 m for each crop tree using a logger's tape fastened at DBH. All living branches in whorls between the live crown base and the lowest live whorl were measured to the nearest 1.0 m using a small caliper. THT of each tree was measured to 0.1 m using a Vertex III hypsometer made by Haglöf. The crown class of each tree was recorded as D, CD, or I.

Projected Leaf Area (PLA)

Because Forest Service protocol prevented coring for sapwood on permanent plots, PLA (projected one-sided) leaf area of each crop tree was determined using non-sapwood based equations based on the model proposed by Valentine *et al.* (1994) and used by Gilmore (1996) and Kenefic (2000) (Table 1.1). Gilmore *et al.*'s (1996) PLA prediction model for balsam fir uses the lowest live whorl as the definition of the live crown base. In order to have a consistent live crown base definition for PLA estimates across species and inventories, the published Gilmore *et al.* (1996) PLA model was refitted to the data using lowest live branch as the definition of crown base (Table 1.1). The red spruce PLA model used was fit to the Maguire *et al.* (1998) dataset by Kenefic (2000) for application in a nearby study on the PEF. Average projected leaf area (AVEPLA) over a seven-year growth period, was calculated by averaging the PLA predicted from the 1994 Forest Service measurements of DBH and CL and the PLA based on our 2001 data.

Table 1.1 PLA equations with coefficients and citations.

Species	Model	Citation
Balsam Fir	$PLA = b_1(BA \times Mlcr)^{b2}$ $b_1 = 0.3031$ and $b_2 = 0.9746$	Seymour (unpublished), from Gilmore *et al.* (1996) dataset.
Red Spruce	$PLA = b_1 BA^{b2} \times mLCR^{b3}$ $b_1 = 0.5553$, $b_2 = 0.8532$ and $b_3 = 0.4925$	Kenefic (2000) from Maquire *et al.* (1998) dataset.

PLA = projected leaf area (m^2); BA = basal area (cm^2); CL = crown length (m); mLCR = modified live crown ratio, (CL/tree height – 1.3) (Valentine *et al.* 1994).

This required a minor adjustment to the 1994 Forest Service estimate of the live crown base, which was based on a different definition than that used in this study (2001). The Forest Service determined the base of the live crown as the lowest live branch with at least two additional live branches at or below it. Because we measured all living branches in the lower crown, we could reconstruct the Forest Service definition for 2001 and relate it to the standard lowest-branch definition. The following equation was derived:

$$CLLLB = b_0 * (CL94)^{b1}, \quad (1)$$

where CLLLB is the CL with the standard lowest-branch definition and CL94 is CL as defined by the Forest Service in 1994, and $b_0 = 1.3051$, $b_1 = 0.9057$, and $R^2 = 0.94$ for balsam fir and $b_0 = 1.0615$, $b_1 = 1.0190$ and $R^2 = 0.95$ for red spruce. Equation (1) was applied to the 1994 crown base measurements made by the Forest Service to predict the 1994 height to the lowest live branch. This adjusted crown base was then used to compute PLA for all crop trees, using the equations in Table 1.1.

Crown Projection Area (CPA)

Crown projection area (CPA) is a two-dimensional measurement of the growing space occupied by an individual tree. CPA of each crop tree was estimated as a function of DBH and CL using a subsample of CPA's calculated from the four radii (r_i) measurements taken by the Forest Service in 2001.

$$CPA = \sum (\pi r_i^2)/4 \quad \text{(Gregoire and Valentine 1995).} \tag{2}$$

The model used in the prediction of CPA was:

$$CPA = b_0 + b_1*(DBH + CL)^2, \tag{3}$$

where $b_0 = 2.9768$, $b_1 = 0.0336$, and $R^2 = 0.81$ for n = 67 balsam fir; and $b_0 = 2.6360$, $b_1 = 0.0623$, and $R^2 = 0.84$ for n = 68 red spruce.

Volume Growth Calculations

Honer's (1967) volume equation was used to determine total tree volume of each crop tree. Honer's volume equation estimates total tree volume inside bark from diameter (outside bark) and total height, where D is DBH (outside bark), H is total tree height, and b_0 and b_1 are regression coefficients (Honer 1965) (Table 1.2).

$$VIB\ (ft^3) = D^2/(b_0 + b_1*1/H) \tag{4}$$

Total stem volume was determined in ft^3 and converted to m^3 using the conversion factor 0.02832.

Table 1.2 Total cubic foot volume regression coefficients from Honer (1967)

	Balsam Fir	Red Spruce
b_0	2.139	1.226
b_1	301.634	315.634

Average Volume Increment (AVINC)

Average annual volume growth was determined for years 1994-2001 using Forest Service data (1994) and data from this study (2001). Volume was calculated as described above for both years, subtracted to get the volume growth and then divided by the number of intervening years. Total stem volume was determined in ft^3 and converted to dm^3 using the conversion factor 28.32.

$$\text{AVINC} = (\text{Volume 2001} - \text{Volume 1994})/7 \quad (5)$$

Growth Efficiency Calculations

GE is defined as stemwood volume growth per unit of PLA. GE was calculated for each tree by dividing AVINC by AVEPLA:

$$\text{GEPLA } (dm^3/m^2) = \text{AVINC/AVEPLA} \quad (6)$$

GE as a function of CPA was also calculated for each crop tree in the study:

$$\text{GECPA } (dm^3/m^2) = \text{AVINC/CPA} \quad (7)$$

Statistical Analyses

All analyses were made using SYSTAT (version 10), with $\alpha = 0.05$. A general linear model (GLM) using analysis of variance (ANOVA) was used to test for mean differences in GE, PLA, and CPA between species, treatments, and species by treatment interactions. ANOVA was also used to test for differences in DBH, THT, CL, and total tree volume between species and treatments. The relationships of GE and AVINC to PLA and CPA were examined using linear regression and scatter plots. Nonlinear equations were tested if the fit of a linear model was determined to be inadequate. Coefficient of determination (R^2) and Furnival's (1961) index of fit (FI) were used to compare model forms.

RESULTS

Crop Tree Characteristics

Crop trees in the spaced plots were larger in diameter and had longer live crowns than those in the unspaced plots (Tables 1.3 and 1.4). Overall, balsam fir crop trees had significantly more volume than red spruce crop trees (Table 1.5). There was more volume per crop tree in the spaced plots than in the unspaced plots (Tables 1.4, 1.6 and 1.7). As expected, balsam fir was significantly taller than red spruce in both treatments, since most of the balsam fir were in subordinate crown positions and half of the red spruce were in intermediate crown positions (Table 1.5). There were no significant treatment differences in heights of the crop trees (Table 1.3). However, balsam fir crop trees were significantly taller in the spaced plots than in the unspaced (Table 1.6), but this was a marginal result and red spruce did not differ between treatments (Table 1.7). Balsam fir crop trees also had a significantly larger average DBH and a longer average CL than red spruce crop trees (Table 1.5). There was a species x treatment interaction for CL, indicating that species and treatment differences were not independent of each other.

Table 1.3 ANOVA output with probability values of each source for each dependent variable. An asterisk (*) denotes significance at ($\alpha = 0.05$).

	Species	**Treatment**	**Species x Treatment**
Dependent Variable			
DBH (cm)	0.0078*	< 0.0001*	0.2443
Total height (m)	< 0.0001*	0.3985	0.1440
Crown length (m)	< 0.0001*	< 0.0001*	0.0025*
CPA (m^2)	0.0003*	< 0.0001*	0.7591
Ave PLA (m^2)	0.5897	< 0.0001*	0.0908
GEPLA (dm^3/m^2)	< 0.0001*	0.5763	0.6879
GECPA (dm^3/m^2)	< 0.0001*	0.0736	0.1941
Tree volume (m^3)	0.0016*	< 0.0001*	0.1140

Table 1.4 Means comparison between spaced & unspaced treatments for selected 2001 measurements averaged over both species with standard errors, sample sizes and probability values of each. An asterisk (*) denotes significance at ($\alpha = 0.05$).

	Unspaced		**Spaced**		**P -Value**
Mean	**n = 37**	**SE**	**n = 41**	**SE**	
DBH (cm)	12.50	(0.420)	16.10	(0.356)	< 0.0001*
Total height (m)	12.00	(0.255)	12.03	(0.239)	0.3985
Crown length (m)	5.34	(0.198)	6.89	(0.219)	< 0.0001*
CPA (m^2)	18.77	(1.681)	30.83	(1.307)	< 0.0001*
Ave PLA (m^2)	21.40	(1.613)	40.68	(1.683)	< 0.0001*
GEPLA (dm^3/m^2)	0.19	(0.009)	0.18	(0.007)	0.5763
GECPA (dm^3/m^2)	0.22	(0.017)	0.24	(0.014)	0.0736
Tree volume (m^3)	0.08	(0.007)	0.12	(0.007)	< 0.0001*

Table 1.5 Means comparison between both species for selected 2001 measurements averaged over both treatments, with standard errors, sample sizes and probability values of each. An asterisk (*) denotes significance at ($\alpha = 0.05$).

	Balsam Fir		Red Spruce		P -Value
Mean	**n = 41**	**SE**	**n = 39**	**SE**	
DBH (cm)	14.97	(0.473)	13.87	(0.474)	0.0078*
Total height (m)	12.97	(0.117)	11.01	(0.219)	< 0.0001*
Crown length (m)	6.71	(0.252)	5.62	(0.200)	< 0.0001*
CPA (m^2)	21.06	(1.216)	29.67	(1.984)	0.0003*
Ave PLA (m^2)	31.58	(2.327)	31.96	(0.474)	0.5897
GEPLA (dm^3/m^2)	0.20	(0.008)	0.16	(0.006)	< 0.0001*
GECPA (dm^3/m^2)	0.30	(0.015)	0.17	(0.006)	< 0.0001*
Tree volume (m^3)	0.12	(0.008)	0.09	(0.007)	0.0016*

Table 1.6 Means comparison for balsam fir between treatments for selected 2001 measurements with standard errors, sample sizes and probability values of each. An asterisk (*) denotes significance at ($\alpha = 0.05$).

	Unspaced		Spaced		P -Value
Balsam Fir					
Mean	**n = 21**	**SE**	**n = 20**	**SE**	
DBH (cm)	12.85	(0.499)	17.21	(0.421)	< 0.0001*
Total height (m)	12.66	(0.244)	13.29	(0.183)	0.0480*
Crown length (m)	5.51	(0.246)	7.96	(0.218)	< 0.0001*
CPA (m^2)	15.27	(1.064)	27.14	(1.152)	< 0.0001*
Ave PLA (m^2)	20.21	(1.94)	43.50	(2.13)	< 0.0001*
GEPLA (dm^3/m^2)	0.21	(0.012)	0.20	(0.010)	0.9202
GECPA (dm^3/m^2)	0.27	(0.025)	0.32	(0.016)	0.0907
Tree volume (m^3)	0.09	(0.008)	0.15	(0.009)	< 0.0001*

Table 1.7 Means comparison for red spruce between treatments for selected 2001 measurements with standard errors, sample sizes and probability values of each. An asterisk (*) denotes significance at ($\alpha = 0.05$).

	Unspaced		Spaced		P -Value
Red Spruce					
Mean	**n = 16**	**SE**	**n = 23**	**SE**	
DBH (cm)	12.04	(0.721)	15.15	(0.479)	0.0006*
Total height (m)	11.11	(0.405)	10.94	(0.249)	0.7096
Crown length (m)	5.12	(0.326)	5.97	(0.229)	0.0329*
CPA (m^2)	23.37	(3.348)	34.04	(2.023)	0.0064*
Ave PLA (m^2)	22.96	(2.744)	38.22	(2.469)	0.0002*
GEPLA (dm^3/m^2)	0.16	(0.010)	0.15	(0.007)	0.4310
GECPA (dm^3/m^2)	0.16	(0.011)	0.17	(0.007)	0.5057
Tree volume (m^3)	0.07	(0.011)	0.10	(0.007)	0.0192*

In contrast with all other findings, the species differences detected were due to treatment effects. In this case, the live crown of balsam fir crop trees increased relatively more than the live crown of red spruce crop trees from spacing.

Growth Efficiency and Projected Leaf Area

As expected, there is a positive relationship between AVINC and AVEPLA for the crop trees (Figure 1.1A-B). Statistically, there is a significant linear relationship ($p < 0.0001$), with AVEPLA explaining 80% of the variation in AVINC for balsam fir and 79% for red spruce crop trees across treatments, using the equation:

$$AVINC = b_0 + b_1*(AVEPLA), \qquad (8)$$

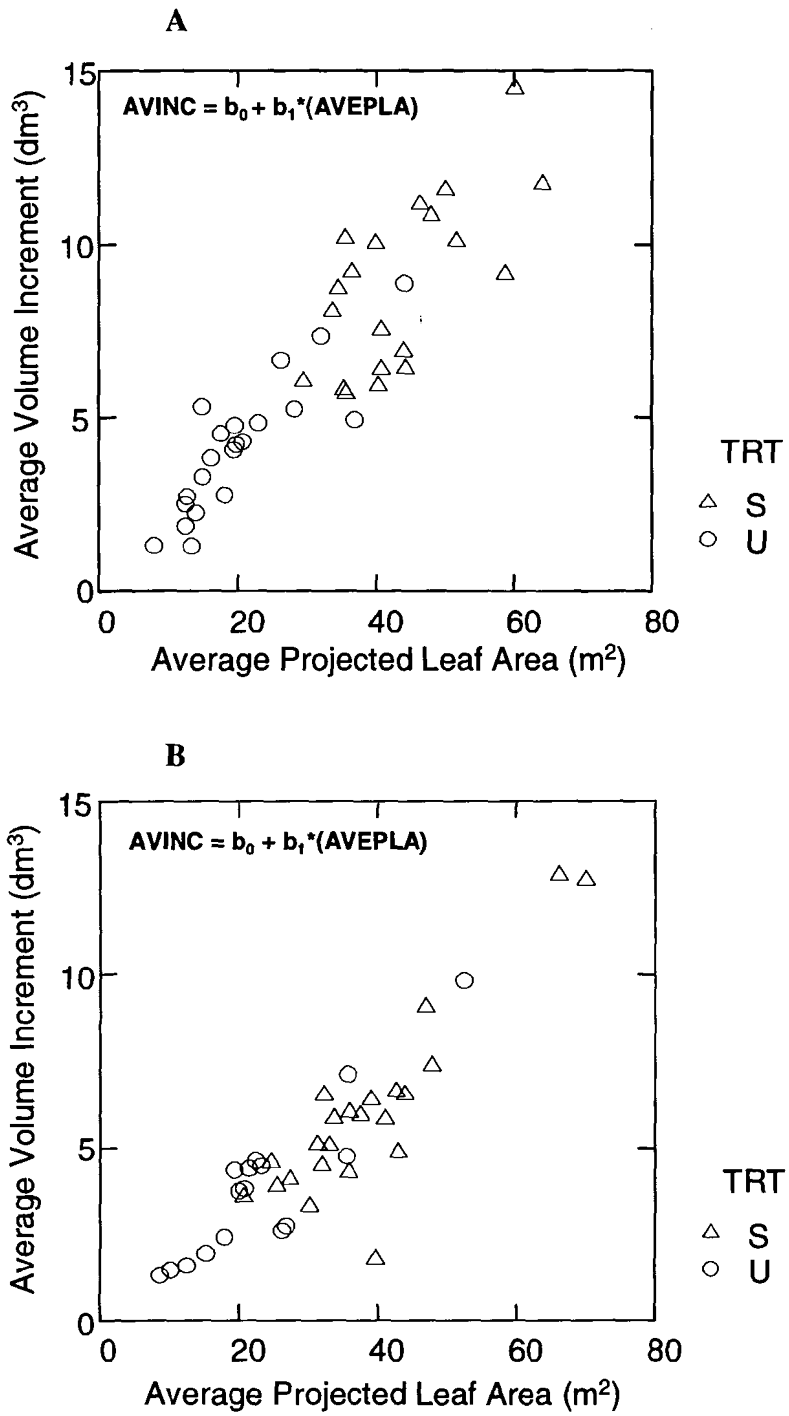


Figure 1.1 Average volume increment (AVINC dm^3) in relation to average projected leaf area (AVEPLA m^2) for 80 crop trees by treatment. A. Balsam fir B. Red spruce. S = Spaced and U = Unspaced.

where $b_0 = 0.3465$, $b_1 = 0.1921$ for balsam fir, and $b_0 = -0.4610$ and $b_1 = 0.1735$ for red spruce. There was no apparent trend in GE with increasing PLA for balsam fir ($p = 0.7239$) or red spruce ($p = 0.7524$) (Figure 1.2A-B). Additionally, while GE of balsam fir crop trees was significantly greater than GE of red spruce, there were no treatment differences for either species (Tables 1.5-1.7). Mean crop tree AVEPLA was significantly greater in the spaced plots than in the unspaced plots, although crop tree GE did not differ by treatment (Tables 1.3 and 1.4). There were no significant differences in AVEPLA between species (Tables 1.3 and 1.5).

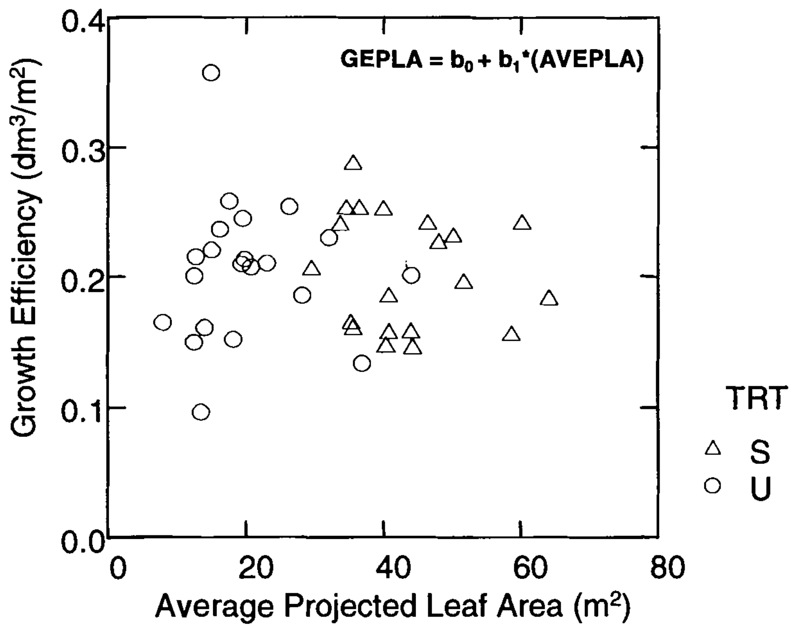
Growth Efficiency and Crown Projection Area

Average crown size, as expressed by CPA (a two-dimensional measure of growing space occupancy), was significantly greater in the spaced plots than the unspaced (Tables 1.3 and 1.4). However, there was no significant difference in GECPA between the spaced and unspaced plots (Tables 1.3 and 1.4). There was no significant trend in GECPA with increasing CPA for balsam fir ($p = 0.2531$) or red spruce ($p = 0.0846$) (Figure 1.3A-B). Overall, red spruce crop trees had a significantly larger average CPA than balsam fir, and balsam fir had significantly larger GECPA (Table 1.5). There was no significant difference in GECPA for either species between treatments (Table 1.6 and 1.7).

DISCUSSION

Twenty-five years after PCT, both red spruce and balsam fir had more PLA per crop tree in the spaced plots than in the unspaced plots. The crop trees in this study showed no

A



B

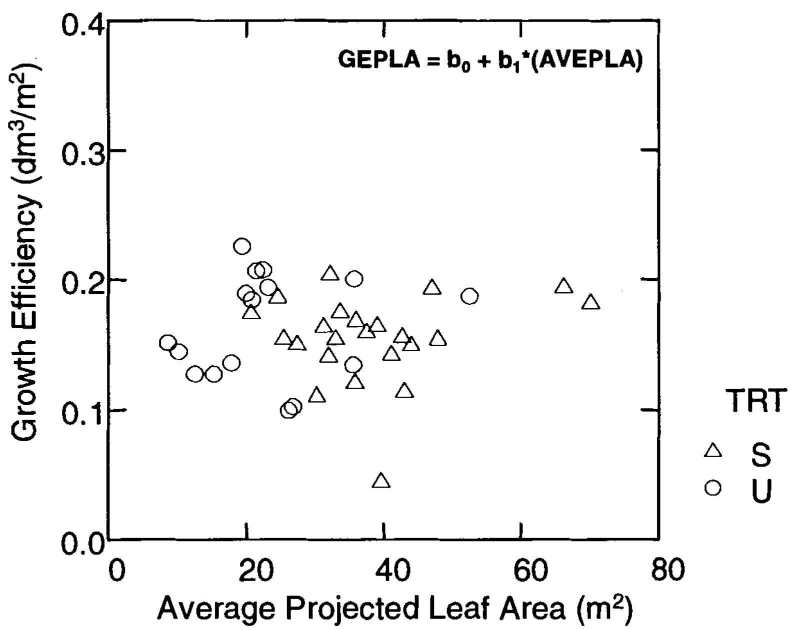
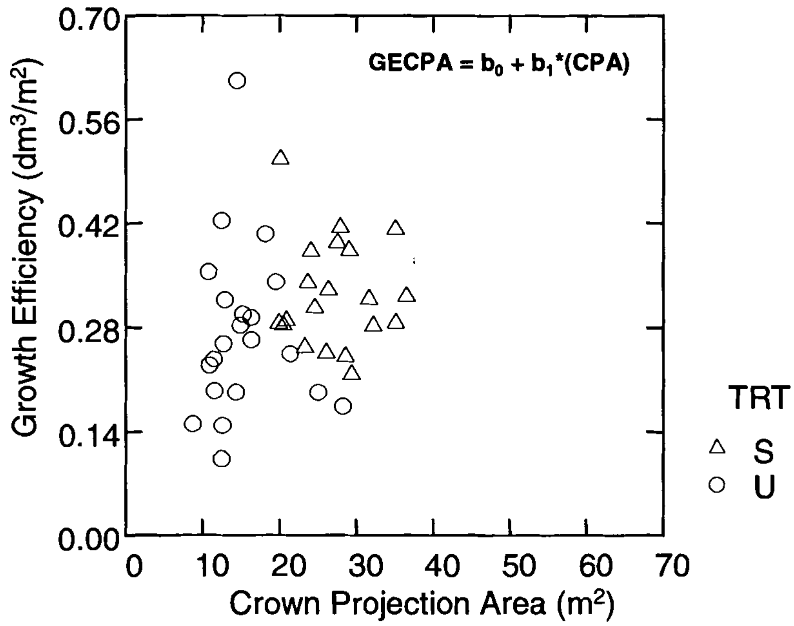


Figure 1.2 Growth efficiency (GEPLA, AVINC dm^3/AVEPLA m^2) in relation to average projected leaf area (AVEPLA m^2) for 80 crop trees by treatment. A. Balsam fir (b_0 = 0.2102, b_1 = -0.0002 and R^2 = 0.003). B. Red spruce (b_0 = 0.1538, b_1 = 0.0001 and R^2 = 0.003). S = Spaced and U = Unspaced.

A



B

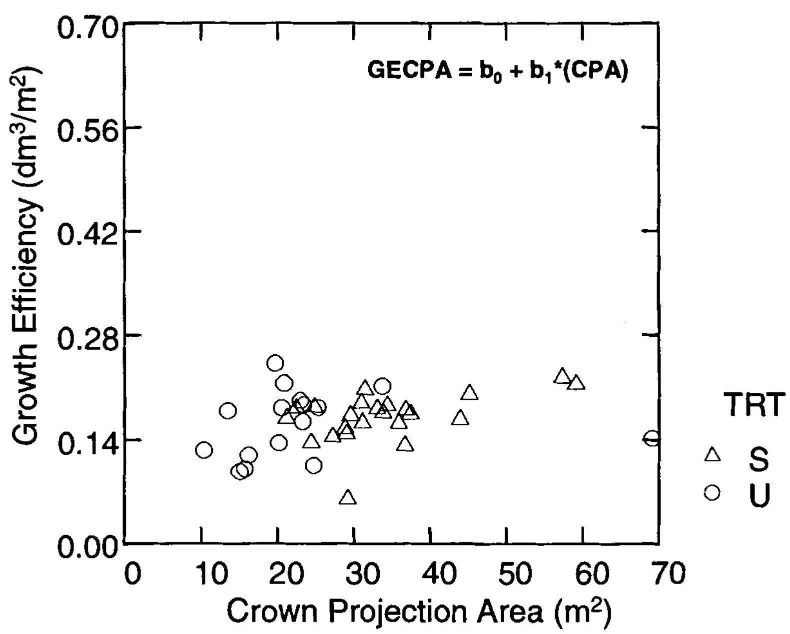


Figure 1.3 Growth efficiency (GECPA, AVINC dm^3/CPA m^2) in relation to crown projection area (CPA m^2) for 80 crop trees by treatment. A. Balsam fir ($b_0 = 0.2494$, $b_1 = 0.0023$ and $R^2 = 0.033$). B. Red spruce ($b_0 = 0.1415$, $b_1 = 0.0009$ and $R^2 = 0.078$). S = Spaced and U = Unspaced.

indication of a change in GE with a subsequent increase in PLA: spacing at 2.4 x 2.4 m (8 ft) intervals did not change GE when compared to unspaced stands. Furthermore, there was no optimum crown size at which an increase or decrease in PLA would affect GE as found in other studies (Assman 1970; Roberts and Long 1992; Roberts *et al.* 1993). Other studies have found that trees with greater amounts of LA were less growth efficient than trees with lower amounts of LA (Waring *et al.* 1981; Kaufmann and Ryan 1986; Smith and Long 1989; Long and Smith 1990; Roberts *et al.* 1993; Maguire 1998). In general, as tree size increases there is a concomitant increase in the proportion of respiring biomass relative to photosynthesizing tissues. GE is thought to decline because of increased carbon allocation to maintenance respiration (Roberts *et al.* 1993). Larger crowns are presumed to be less growth efficient because there are larger costs associated with the production and maintenance of the structure (more and larger branches) and these costs must be met before carbohydrates are allocated to stemwood growth (Smith and Long 1989). Other factors, such as canopy position, age, and shade tolerance of the trees also influence this GE/PLA relationship (O'Hara 1988; Roberts *et al.* 1993; Seymour and Kenefic (2002).

The crop trees sampled in this study are all shade tolerant trees residing in mid to upper canopy positions; overtopped trees were not sampled. Because they are already in the upper level of the stand, increases in PLA do not improve light conditions, since they are already growing in a saturated light environment. Also, with ample amounts of sunlight for photosynthesis, these trees must have enough carbohydrate production to meet both their basic respiratory requirements and allocate carbohydrates to branch and stem growth, thus offsetting any negative effects from increased PLA.

The crop trees in this study are on the lower end of the range of PLA values (8-70 m^2), and GE (1.0-0.23 dm^3/m^2) is still very high in comparison to trees in other studies. Increased tree-level PLA may not have resulted in a decrease in GE because the crop trees were young (≈ 40-50 years old) and have not yet accumulated sufficient PLA to show a declining GE. As trees grow older and consequently larger, the ratio of photosynthesis to respiration is thought to decrease and subsequently, GE declines (Long and Smith 1992). Also, there is a resultant change in carbon allocation from stemwood production to maintenance of other structures i.e., foliage and fine roots (Smith and Long 2001). Barker (unpublished) for example, found that upper canopy *Pinus strobus* L. (eastern white pine) trees showed an increase in GE up to ages 40-50, at which time there was a peak followed by a decline. Other studies have found that medium-sized codominants are the most GE (Assman 1970; Gilmore *et al.* 1996; O'Hara 1988). This supports our findings, since the majority of the crop trees in the present study are medium-sized codominants.

As a comparison, Maguire *et al.* (1998) found PLA values for red spruce to be between 23-400 m^2, where our largest PLA was barely over 70 m^2. They found that GE declined monotonically with increases in PLA. However, on the lower end of PLA their trees did not seem to exhibit any sort of relationship, which is consistent with our results. At the lower end of PLA, their trees appear to have the same growth efficient values as our red spruce crop trees for both treatments. Gilmore *et al.* (1996) found that balsam fir trees follow a sigmoid pattern, where there is a peak followed by a decline in GE with increasing PLA. Balsam fir trees in their study have comparable GE values (0.08-0.30 dm^3/m^2) to this study (1.0-0.35 dm^3/m^2), but the PLA values (0.8-167 m^2) extend much higher than in this study (8-64 m^2). The decline in GE appears to begin in trees with PLA higher than the trees in this study. Furthermore, most of the inefficient trees were suppressed, small-crowned trees growing in the understory. There were no such trees in our sample. Seymour and Kenefic (2002) found a peak GE of red spruce trees in a multi-aged stand on the PEF, at PLA of approximately 100 m^2, and a very gradual decline above that value. Again, the red spruce trees in this study have PLA values (8-70 m^2), which are smaller than the peak found by Seymour and Kenefic, suggesting the tree crowns in this study are too small to affect GE. Kenefic (2000) found that the maximum GE of balsam fir trees (0.17 dm^3/m^2) occurred at 55 m^2 of PLA, with no real decrease thereafter with increasing PLA. Kenefic also found the maximum GE values for red spruce (0.12 dm^3/m^2) to occur at 70 m^2 of PLA and found little change from 50-100 m^2, with a slight decline thereafter. Again, in this study there was no peak in GE and our largest PLA value was slightly above 70 m^2, where Kenefic found a peak GE.

CPA is two-dimensional horizontal measure of growing space that assumes full occupancy of vertical growing space (Assman 1970). Growth per unit of CPA is a useful gauge of the efficient use of growing space per tree, but is less directly linked to photosynthetic potential and resource allocation than LA (O'Hara 1988). In this study, when GE was expressed as stemwood volume growth per unit of CPA, results were essentially identical to those derived from PLA. This finding is supported by O'Hara (1988) who found a peak within the medium-sized codominants (e.g. CPA about 20-40 m^2) in a (*Pseudotsuga menziesii* (Mirb.) Franco) Douglas-fir thinning study. He found the large-crown trees in the unspaced plots, which were comparable to the medium-sized trees in the spaced plots, to be the most growth efficient in the study. The mean CPA for the current study in both treatments combined (25 m^2) falls within the range of O'Hara's most efficient trees. In the present study, GE did not change for individual trees in the treated plots when the amount of growing space occupied increased. This again could be because the increase in CPA was not substantial enough to cause decreased tree growth efficiencies.

Balsam fir crop trees were more growth-efficient, using both measures of growing space, than red spruce crop trees. There were no significant differences in AVEPLA between the two species, although red spruce had a larger average CPA. Kenefic (2000) also found balsam fir trees to be more growth efficient than red spruce trees in nearby multi-aged stands. Thus, balsam fir trees in the present study have the same average PLA as red spruce trees, but are using the space more efficiently.

Additionally, Maguire *et al.* (1998) found roughly the same GE values for red spruce trees as Gilmore *et al.* (1996) found for balsam fir trees in north central Maine. However, the red spruce trees had a much larger range of PLAs, but on the lower end of PLA, the red spruce trees exhibited smaller GE values than the balsam fir trees. Furthermore, Maguire *et al.* (1998) found a monotonically declining pattern of GE with increased PLA for red spruce, whereas Gilmore *et al.* (1996) found a peak followed by a declining pattern for GE with increased PLA for balsam fir. One difference in the patterns found could be that the red spruce trees sampled by Maguire *et al.* (1998) were much larger and the study did not include small, suppressed trees as did Gilmore *et al.* (1996). Increased red spruce LA in Maguire *et al.* (1996) study may not have corresponded with increased height and crown position since they are probably larger trees in favorable crown positions.

CONCLUSIONS

Findings from this study indicate that PCT at 2.4 x 2.4 m (8 x 8 ft) spacing to favor red spruce and balsam fir crop trees had no effect on the efficiency of growth per unit of average PLA and growth per unit of CPA 25 years after treatment. Although there were no significant differences in GE between treatments, PLA and CPA per tree were greater in the treated plots, signifying there is no loss in individual tree GE by opening up the canopy and allowing crowns to expand. Species did differ in GE using two measures of growing space efficiency, but this was not due to treatment effects. In both cases balsam fir was more growth-efficient than red spruce.

PCT is an important silvicultural tool for managing spruce-fir stands in this area due to the prolific regeneration and competition for growing space. PCT with crop tree selection allows favoring of the better quality trees and desirable species with the potential of increased growth for timber production. Most studies of the effects of PCT do not involve measures of LA, so GE has not often been addressed. Quantifying GE allows one to demonstrate that increasing the amount of growing space per tree early in the life of the stand does not reduce growth rates per unit of LA.

CHAPTER 2. THE EFFECTS OF PRECOMMERCIAL THINNING ON STEM FORM CHARACTERISTICS OF SELECTED (*PICEA RUBENS* SARG. (RED SPRUCE) AND *ABIES BALSAMEA* (L.) MILL. (BALSAM FIR)) CROP TREES

ABSTRACT

Stem form differences were quantified to determine the effects of precommercial thinning (PCT) on selected *Picea rubens* Sarg. (red spruce) and *Abies balsamea* (L.) Mill. (balsam fir) crop trees 25 years after treatment. Stem diameters were measured from the stump to the crown base on 80 crop trees. Stem taper was greater on crop trees in the spaced plots than in the unspaced plots ($p = 0.0006$), and they had a lower height/diameter ratio ($p < 0.0001$). There was barely a significant difference in stem taper between species ($p = 0.0561$), and both red spruce and balsam fir exhibited greater stem taper in the spaced plots than the unspaced plots. Volume, crown length, knot volume ratio, average branch size and the number of branches were compared to determine the effects of PCT on crop trees, and were all significantly greater for crop trees in the spaced plots than in the unspaced plots. Total height did not differ between treatments ($p = 0.3985$), but balsam fir crop trees had significantly taller trees in the spaced plots compared to the unspaced plots ($p < 0.0480$). The efficacy of Honer's (1967) volume equation was tested, but volume comparisons between Honer's (1967) estimated volume and measured volume differed depending on what statistical test was used. Refitting Honer's volume equation with the data from this study resulted in differences in volumes for unspaced red spruce crop trees.

INTRODUCTION

Precommercial thinning (PCT) is a thinning made as an investment in the future growth of a young stand where none of the stems removed are utilized (Smith *et al.* 1997, p. 113) PCT is often important for the maintenance of the desired species composition and enhanced growth of the residual trees. Young stands in the Acadian region are densely overstocked with balsam fir *Abies balsamea* (L.) Mill. (balsam fir) due to historic selective logging, outbreaks of the spruce budworm, and prolific regeneration (Seymour 1995). PCT is an effective means of reducing stand density and enhancing future development. PCT early in the life of a dense stand can shorten the time to reach merchantability and reduce the costs of subsequent harvesting by taking out unmerchantable trees that may hinder future logging. PCT has a pronounced effect on stand development and its goal is to maintain a profitable forest over the entire rotation (Pettersson 1993). PCT increases growth on an individual tree basis, with fewer trees and less volume at the stand level (Zeide 2001). Increased individual tree growth from PCT leads to trees of larger size and thus, lowers harvesting costs. A potential drawback of thinning and improving individual tree growth is the potential for greater stemwood taper and branchiness.

Thinning reduces stand density and the residual trees have more room to grow and can expand horizontally and laterally. As a result, there is an increase in crown size and stem taper. Stem taper is the rate of change in stem diameter with increasing tree height (Larson 1963). Increased crown size from thinning results in a shift of growth to lower on the stem and an increase in stem taper. A large degree of stem taper would result in less total volume on trees with the same DBH and height, instead of more, which is the desired end result of PCT. Conversely, as the crown base recedes and there is more bole area, stem growth concentrates near the crown base, creating a more cylindrical stem form (Larson 1963).

Branch characteristics are important components of wood quality (DeBell and Gartner 1997; Pape 1999). Less dense stands result in an increase in the number and size of branches compared to trees growing in less dense stands (DeBell *et al.* 1994; Baldwin, Jr. *et al.* 2000). Branches on trees create knots that may decrease value at the mill. All of these factors contribute to a decrease in wood quality with respect to timber production. Unfortunately, there has been little work on the increased branchiness of balsam fir and red spruce from thinning and its effect on wood quality. Some work has been done in the western United States on *Tsuga heterophylla* (Raf.) Sarg. (western hemlock) (DeBell *et al.* 1994), *Thuja plicata* (Donn) ex D. Don (western redcedar) (DeBell and Gartner 1997), and in Sweden on *Picea abies* (L.) Karst. (Norway spruce) (Johansson 1992; Pape 1999). Knowing the extent to which branchiness reduces tree quality and value is important when considering PCT regimes to favor larger crop trees that will reach merchantable size faster.

Volume equations are estimates of individual tree volumes based on diameter at breast height (DBH), total or merchantable height (THT), and sometimes a measure of stem form (Honer 1965). In the Acadian Forest Region, the most popular volume estimation is the one derived by T.G. Honer (1967). This volume formula estimates total cubic foot volume of individual trees from DBH and THT. Comparisons were made between measured volumes and Honer's (1967) estimated volumes. The efficacy of the model for this area is important for managing balsam fir and red spruce forests, which are important economic components in this region.

OBJECTIVES

The objectives of this study were to evaluate differences in stem form between treatments and species; determine the efficacy of Honer's (1967) volume equation for red spruce and balsam fir in our area by comparing measured versus estimated volumes of crop trees; and to determine the differences in branchiness between treatments and its effect on wood quality. The hypotheses tested were:

(H_1): There are significant stem form differences between species and treatments;

(H_2): The measured and estimated volumes differ between species and treatments;

(H_3): There are significant differences in branch characteristics between species and treatments.

METHODS

Study Area

The Penobscot Experimental Forest (PEF) is located in the towns of Bradley and Eddington in Penobscot County, Maine at 44°52'N, 68°38'W. The PEF is a 1540-ha tract of land donated to the University of Maine in 1994 by industrial landowners with one of the stipulations that continued long-term cooperative research would be conducted by

USDA Forest Service scientists, University researchers, and professional forest managers in Maine. The PEF is included in the Acadian Forest Region, which is a transition zone between the boreal forests to the north and the broadleaf forests to the south. Conifers with an admixture of hardwoods dominate the study area. Dominant conifers include: balsam fir, red spruce, *Picea glauca* (Moench) Voss. (white spruce), *Pinus strobus* L. (eastern white pine), *Tsuga canadensis* (L.) Carr. (eastern hemlock), and *Thuja occidentalis* L. (northern white cedar). Hardwoods commonly found in the area include *Acer rubrum* L. (red maple), *Betula papyrifera* Marsh. (paper birch), *Betula populifolia* Marsh. (gray birch), *Betula alleghaniensis* Britt. (yellow birch) *Populus tremuloides* Michx. (quaking aspen), and *Populus grandidentata* Michx. (bigtooth aspen). Soil types on the PEF range from well-drained loams and sandy loams to poorly drained loams and silt loams with parent material primarily consisting of glacial till (Brissette *et al.* 1999). The soil series on the study area is a Monarda-Burnham stony fine sandy loam on a 0-8% slope, developed in a deep till parent material.

Background

Research was conducted in an area of the PEF where a PCT study (Study 58) was established by the Forest Service. The purpose of Study 58 was to investigate the effects of different PCT regimes and fertilizer applications on species composition and the growth and yield of selected crop trees. The PCT study was conducted in an even-aged stand regenerated by a two-stage shelterwood method between July 1957 and October 1967. In 1957, 46% of the overstory was removed in an establishment harvest, and then the remaining merchantable overstory was removed in 1967. The PCT study was initiated in 1976, at which time all residual submerchantable trees > 12.7 cm from the parent stand were removed. Prior to treatment application, densities of the 32 experimental units ranged from approximately 27, 500 to 79, 000 trees per ha with an overall mean of 42, 736 trees per ha (Brissette *et al.* 1999).

Experimental Design

The completely random design of the initial PCT experiment was utilized in the present study. The initial experimental design is a factorial arrangement with three different PCT treatments, one unthinned control, and two levels of fertilization, each replicated four times. PCT treatments were applied between April and August of 1976 and included: (1) Unspaced: no PCT; (2) Row-No Release: a 1.5 m (5 ft) row removal with no crop tree release in 0.9 m (3 ft) wide residual strips; (3) Row-Release: a 1.5 m (5 ft) row removal with crop tree release at about 2.4 m (8 ft) intervals within the 0.9 m (3ft) residual strips; and (4) Spacing: selected crop trees were uniformly spaced at about 2.4 x 2.4 m (8 x 8 ft) intervals. Treatments were applied randomly to 24 x 24 m (79 x 79 ft) experimental units and then 19.5 x 19.5 m (64 x 64 ft) measurement plots were established within each experimental unit (Brissette *et al.* 1999). A total of 32 experimental units was established in the PCT study and 9 of those 32 were utilized for this study. Samples were taken from 4 of the 2.4 x 2.4 m (8 x 8 m) spaced plots and 5 unspaced plots. The row-no release and row-release treatments were not sampled. Two of the unspaced plots selected were initially fertilized, but fertilization had no significant effects on subsequent crop tree growth (Brissette *et al.* 1999).

Data Collection

In the summer of 2001, a subsample of 80 crop trees from the initial study were selected and marked. The samples consisted of 21 balsam fir and 16 red spruce in the unspaced plots, and 20 balsam fir and 23 red spruce in the spaced plots. The Forest Service has remeasured crop tree DBH, THT, crown length (CL), crown width (CW), and stump diameter (SD) on these plots periodically since the start of the study. The last inventory was taken in 2001, and the CL, CW, and SD were not measured and height to the live crown base and the crown radii in all four cardinal directions were recorded. Crop trees selected for subsampling were a spruce or fir tree: (1) in the 12.7 cm (5 inch) DBH class or larger; and (2) growing in the upper level of the canopy, designated as (D) dominant or (CD) codominant as described by Smith *et al.* 1997 (p. 29). To obtain the intended sample size of 80 crop trees, some (I) intermediate trees and/or smaller diameter trees were chosen. The overall sample consisted of 56 CD, 2 D, and 22 I trees. Most of the (I) trees were red spruce, due to the fact that there were more balsam fir than red spruce trees in upper canopy positions.

Each crop tree was climbed using tree climbing ladders and/or climbing gear to make stem form measurements up the tree bole; the heights up the tree bole were measured with a loggers tape. Measurements on each tree included: DBH; diameter 1.0 m below breast height (BH); and diameter at 1.0 m intervals above BH to the crown base. All of these were measured to 0.1 cm with a diameter tape. When a 1.0 m interval was a branch whorl, then diameter was measured 0.1 dm directly above or below, whichever had a clearer bole area. Bark thickness for each of the bole sections was estimated using a model developed from red spruce and balsam fir trees as described in the next section. Height to the lowest live branch and height to the crown base (defined as at least 3 live branches extending halfway around the bole) were measured to the nearest 0.01 m. Total height of each tree was measured to 0.1 m using a Vertex III hypsometer, made by Haglöf. The crown class of each tree was recorded as D, CD, or I. The branch diameters of each branch between 1.0-2.0 meters above BH (2.37-3.37 m) were measured to the nearest 1.0 mm using a small caliper. Branch diameters were measured just far enough from the bole of the tree to avoid the branch collar.

Volume Calculations

Bark Thickness Estimates

Smalian's formula (Avery and Burkhart 1994) can be used to compute tree bole segment volume (m^3) from diameter (cm) measurements and segment length (m). To determine total tree inside bark volume of the crop trees using Smalian's formula, bark thickness was estimated for each tree using regression equations fitted to Maquire's *et al.* (1998) red spruce dataset (n = 65) and a subsample of Gilmore's *et al.* (1996) balsam fir dataset (n = 39). All data for their studies were collected from the PEF and the University of Maine Dwight B. Demeritt Forest in Orono, Maine. Both areas are in close proximity to the area used in this study. First, single bark thickness (SBT) (mm) was calculated from the data provided by Gilmore *et al.* (1996) and Maguire *et al.* (1998):

$$SBT = (DOB-DIB/2)*10, \qquad (1)$$

where DOB is diameter outside bark (cm) and DIB is diameter inside bark (cm).

Next, a model was developed to predict SBT as a factor of DOB and applied to the crop trees.

$$SBT = b_0 + b_1 * (DOB), \quad (2)$$

where $b_0 = 0.9937$, $b_1 = 0.2549$, and $R^2 = 0.65$ for balsam fir, and

$$SBT = b_0 * (DOB)^{b1}, \quad (3)$$

where $b_0 = 1.1401$, $b_1 = 0.5917$, and $R^2 = 0.66$ for red spruce.

Measured Volume

Smalian's formula was applied to each bole segment of each crop tree and then summed for total tree volume (Table 2.1). The stem of any tree is considered a composite of a geometrical solid (Husch *et al.* 1972) (Figure 2.1). The tip of a tree is considered to resemble a cone or paraboloid, the central section a frustum of a paraboloid and the butt log a cylinder. The stump section and butt log were both calculated using the formula for the volume of a cylinder.

Table 2.1 Cubic foot volume equations of geometric solids.

Geometric Solid	Equation for Volume (V) (m^3)
Cylinder	$V = A_b h$
Paraboloid Frustum	$V = h/2(A_b + A_u)$ (Smalian's formula)
Cone	$V = 1/3(A_b h)$

h = height (length of segment) (m); A_b = cross-sectional area at base (cm^2); A_u = cross-sectional area at top (cm^2).

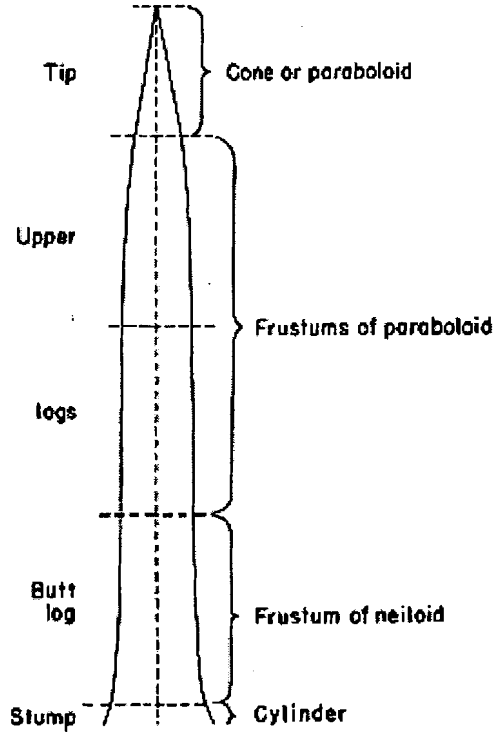


Figure 2.1 Geometric forms assumed by portions of a tree stem (from Husch et al. 1972).

Honer's Volume Equation

Honer's (1967) volume equation was used to estimate total inside bark volume of each crop tree. Honer's volume equation estimates total tree volume inside bark from diameter (outside bark) and THT, where D is DBH (outside bark), H is total tree height, and b_0 and b_1 are regression coefficients (Honer 1965) (Table 2.2). Total stem volume was determined in ft^3 and converted to m^3 using the conversion factor (0.02832) for comparison to measured volume.

$$VIB\ (ft^3) = D^2/(b_0 + b_1 * 1/H) \qquad (4)$$

Table 2.2 Total cubic foot volume regression coefficients from Honer (1967).

	Balsam Fir	Red Spruce
b_0	2.139	1.226
b_1	301.634	315.634

Stem Form Measurements

A form quotient is the ratio of some upper stem diameter to DBH (outside bark). For the same tree species, form quotients are lowest for open-grown trees with longer live crowns and higher for trees growing in denser stands with shorter crowns (Avery and Burkhart 1994). The most widely used form quotient in the United States is the Girard Form Class (Avery and Burkhart 1994). This form quotient uses the top of the first log as the height for the upper stem diameter measurement (17.3 ft, 5.27 m above the ground).

For this study upper stem diameter measurements were taken at an average height of 4.39 m (14.40 ft) (SE = 0.0092), a reasonable approximation to the Girard Form Class.

$$FC = DIB/DBH, \tag{5}$$

where DIB is upper stem diameter inside the bark at an average of 4.39 m above ground. One crop tree was excluded because diameter measurements were not made at that height.

Branch Volume Calculations

Knot volume ratio, a proportion of the volume of knots to total volume of a 1.0 m bole segment located between 1.0 and 2.0 meters above BH (the butt log) (2.37-3.37 m) was calculated for each crop tree. The cubic volume of each branch from pith to bark was calculated using the formula for a cone:

$$1/3*A_bh, \qquad (6)$$

where A_b is the cross-sectional area (cm^2) of the branch and h is the height (inside tree length, cm) of the branch. The length of each branch was determined by estimating the radius at the midpoint of each 1.0 m section where branch measurements were taken. Therefore, all branches of each 1.0 m section of all crop trees were considered the same length. Individual branch volumes were added together for each section to determine the total volume of knots for each section. The volume of the 1.0 m segment was calculated using Smalian's cubic volume formula (Avery and Burkhart 1994) for all solids:

$$(B + b)/2*L, \qquad (7)$$

where B is the cross-sectional area (cm^2) at the large end of the segment; b is the cross-sectional area (cm^2) at the small end of the segment; and L is the length (cm) of the segment.

Statistical Analyses

Volume Comparisons

All analyses were made using SYSTAT (version 10), with $\alpha = 0.05$. Volumes of each crop tree were calculated using Smalian's formula and predicted using Honer's (1967) volume equation and compared using scatterplots, paired T-Tests, and both linear and nonlinear regression. Regression analysis was used to predict Honer's (1967) volume from our measured volume, and then test for differences by comparing the slope and the intercept of the equation for each species between treatments. No significant differences existed if the 95% confidence interval of the slope (b_1) of the model included (1) i.e., the expected slope if the two volumes are equal, or if the intercept (b_0) included (0) i.e., no differences in the elevation of the line. The model used for volume predictions was:

$$\text{Honer's volume } (m^3) = b_0 + b_1*(\text{measured volume } (m^3)). \quad (8)$$

Honer's (1967) volume equation was fit to the measured volumes to test for overlap between his coefficients and our 95% confident interval to verify differences or similarities found with the previous statistical tests.

Stem Taper and Volume Analysis

A general linear model (GLM) using analysis of variance (ANOVA) was used to test for mean differences in stem taper between species, treatments, and each species and treatment combination. Trends in stem taper across species and treatments were evaluated with scatterplots. The relationship between crop tree volume and DBH was tested using regression analysis by predicting tree volume at the same DBH for each species between treatments. The model uses a dummy variable (1 or 0) to distinguish between treatments (i.e., 1 = spaced and 0 = unspaced), and tests for significant treatment effects on the DBH and volume relationship for each species. If a significant treatment difference was detected from the model, then DBH was added to the model to determine whether treated plots had more or less volume at a given DBH. The model used to detect differences was:

$$\text{Measured Volume } (m^3) = b_0 + b_1*(DBH) + b_2*(DBH*TRT), \quad (9)$$

where DBH is multiplied by 0 for untreated plots and 1 for treated plots.

Height:Diameter Relationship (H/D)

The H/D relationship was evaluated by a GLM using ANOVA to test for mean differences between species, treatments, and for each species between treatments.

Branch Analysis

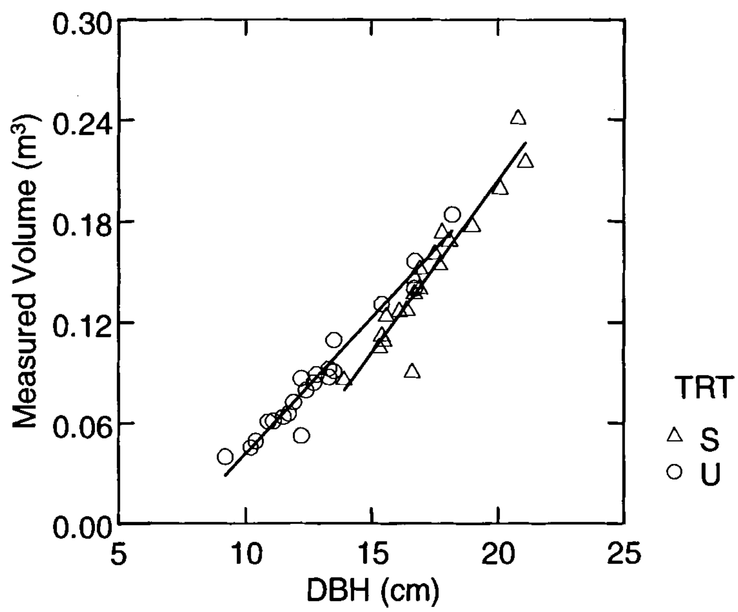
A GLM using ANOVA was used to test for mean differences in branch numbers and sizes between species, treatments, and for each species and treatment combination. Differences in the number of branches, branch sizes, and the knot volume ratio between species and treatments were evaluated using both SYSTAT and Microsoft Excel (2002).

RESULTS

At a given DBH, crop trees in the spaced plots had more stem taper, less volume and were shorter than in the unspaced (Figures 2.2-2.4). However, crop trees in the spaced plots had on average significantly larger DBH and volume than the crop trees in the unspaced plots (Tables 2.3 and 2.4). In general, there were no species x treatment interactions; therefore the results were pooled for each species and for each treatment. Balsam fir crop trees contained significantly more volume than red spruce and because there was no species x treatment interaction it may be concluded that the differences between species are independent of treatments (Tables 2.3 and 2.5). As expected, crop trees of both species had more volume in the spaced plots than in the unspaced plots (Tables 2.6 and 2.7).

Equation (9), testing for a significant relationship between DBH and volume of crop trees between treatments, resulted in a significant difference for both balsam fir ($p = 0.0070$) and red spruce ($p = 0.0027$). However, there was one unspaced red spruce outlier that had a much larger volume than the rest of the crop trees; when this tree was removed from the regression analysis, results changed to a non-significant relationship (p =

A



B

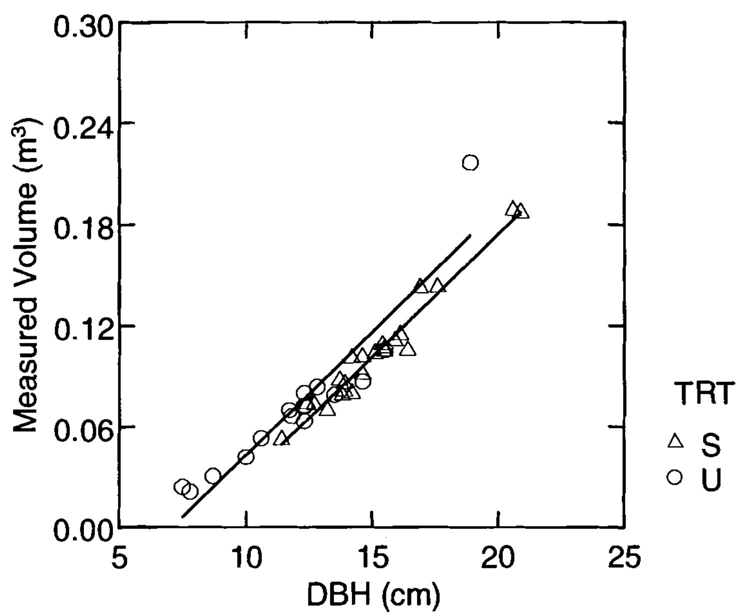


Figure 2.2 Total tree volume (m^3) in relation to diameter at breast height (DBH, cm) for 80 crop trees. Line represents linear regression for the model: $b_o+b_1*(DBH)$. A. Balsam fir. B. Red spruce. S = Spaced and U = Unspaced.

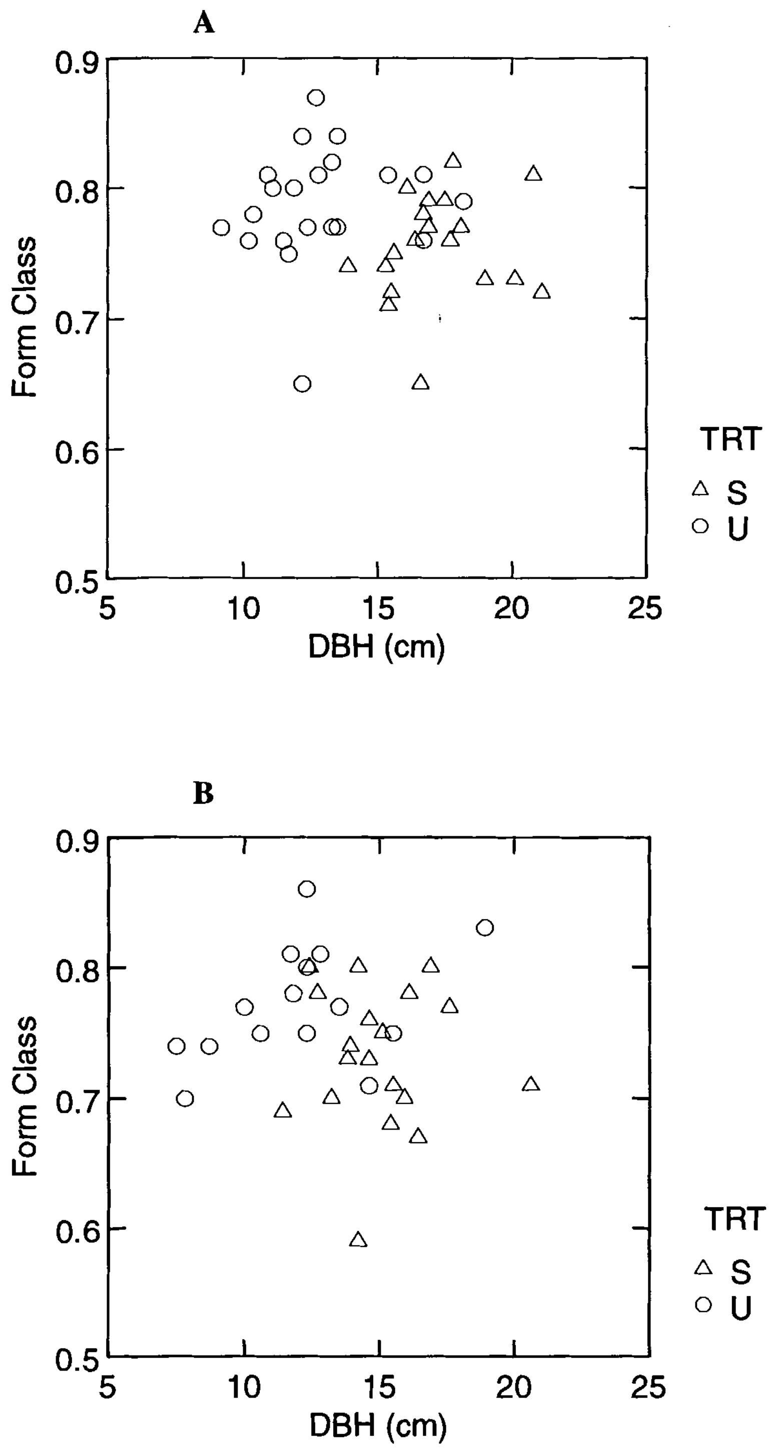
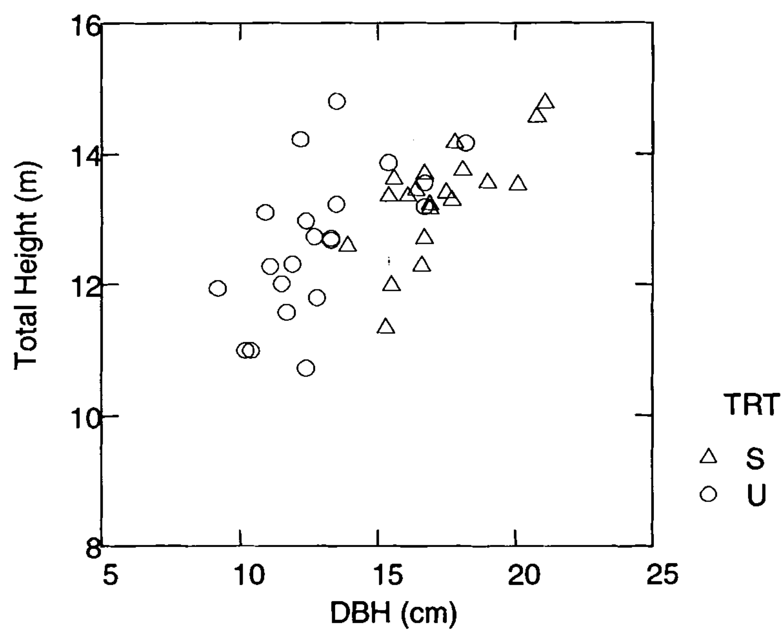


Figure 2.3 Form class (stem taper) in relation to DBH (diameter at breast height, cm) for 78 crop trees. A. Balsam fir. B. Red spruce. S = Spaced and U = Unspaced.

A



B

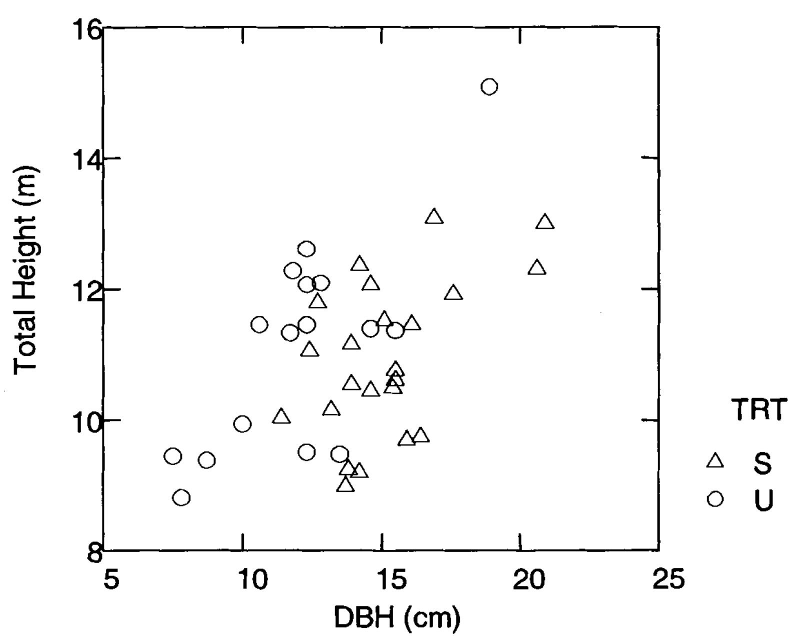


Figure 2.4 Total height (m) in relation to DBH (diameter at breast height, cm) for all 80 crop trees A. Balsam fir. B. Red spruce. S = Spaced and U = Unspaced.

Table 2.3 ANOVA output with probability values for each source for each dependent variable. An asterisk (*) denotes significance at ($\alpha = 0.05$).

	Species	Treatment	Species x Treatment
Dependent Variable			
DBH (cm)	0.0078*	< 0.0001*	0.2443
Total height (m)	< 0.0001*	0.3985	0.1440
Crown length (m)	< 0.0001*	< 0.0001*	0.0025*
Tree volume (m^3)	0.0016*	< 0.0001*	0.1140
Knot volume ratio	0.0077*	< 0.0001*	0.1842
Ave. branch size (cm)	0.0913	< 0.0001*	0.2092
# branches	0.4726	< 0.0001*	0.1196
Height/diameter ratio	0.0637	< 0.0001*	0.9025
Form factor	0.0561*	0.0006*	0.5944

Table 2.4 Means comparison between spaced and unspaced treatments for selected 2001 measurements averaged over both species with standard errors, sample sizes and probability values of each. An asterisk (*) denotes significance at ($\alpha = 0.05$).

	Unspaced		Spaced		P- Value
Both Species					
Mean	**n = 37**	**SE**	**n = 43**	**SE**	
DBH (cm)	12.50	(0.420)	16.10	(0.356)	< 0.0001*
Total height (m)	12.00	(0.255)	12.03	(0.239)	0.3985
Crown length (m)	5.34	(0.198)	6.89	(0.219)	< 0.0001*
Tree volume (m^3)	0.08	(0.420)	0.12	(0.007)	< 0.0001*
Knot volume ratio	0.002	(0.0002)	0.005	(0.0003)	< 0.0001*
Ave. branch size (cm)	1.08	(0.043)	1.48	(0.041)	< 0.0001*
# branches	12.16	(0.598)	16.88	(0.571)	< 0.0001*
Height/diameter ratio	98	(2.383)	75	(1.308)	< 0.0001*
	n = 37		**n = 41**		
Form factor	0.78	(0.007)	0.74	(0.007)	0.0006*

Table 2.5 Means comparison between both species for selected 2001 measurements averaged over both treatments with standard errors, sample sizes and probability values of each. An asterisk (*) denotes significance at ($\alpha = 0.05$).

	Balsam Fir		Red Spruce		P -Value
Mean	n = 41	SE	n = 39	SE	
DBH (cm)	14.97	(0.473)	13.87	(0.474)	0.0078*
Total height (m)	12.97	(0.117)	11.01	(0.219)	< 0.0001*
Crown length (m)	6.71	(0.252)	5.62	(0.200)	< 0.0001*
Tree volume (m^3)	0.12	(0.008)	0.09	(0.007)	0.0016*
Knot volume ratio	0.003	(0.0002)	0.004	(0.0004)	0.0077*
Ave. branch size (cm)	1.22	(0.042)	1.37	(0.060)	0.0913
# branches	14.80	(0.694)	14.59	(0.696)	0.4726
Height/diameter ratio	89	(2.415)	82	(2.653)	0.0637
	n = 41		n = 37		
Form factor	0.77	(0.007)	0.75	(0.009)	0.0561*

Table 2.6 Means comparison for balsam fir between treatments for selected 2001 measurements with standard errors, sample sizes and probability values of each. An asterisk (*) denotes significance at ($\alpha = 0.05$).

	Unspaced		Spaced		P -Value
Balsam Fir					
Mean	n = 21	SE	n = 20	SE	
DBH (cm)	12.85	(0.499)	17.21	(0.421)	< 0.0001*
Total height (m)	12.66	(0.244)	13.29	(0.183)	0.0480*
Crown length (m)	5.51	(0.246)	7.96	(0.218)	< 0.0001*
Tree volume (m^3)	0.09	(0.008)	0.15	(0.009)	< 0.0001*
Knot volume ratio	0.002	(0.0002)	0.004	(0.0002)	< 0.0001*
Ave. branch size (cm)	1.08	(0.053)	1.38	(0.043)	< 0.0001*
# branches	11.86	(0.688)	17.90	(0.757)	< 0.0001*
Height/diameter ratio	100	(2.929)	78	(1.369)	< 0.0001*
	n = 21		n = 20		
Form factor	0.78	(0.010)	0.76	(0.009)	0.0221*

Table 2.7 Means comparison for red spruce between treatments for selected 2001 measurements with standard errors, sample sizes and probability values of each. An asterisk (*) denotes significance at ($\alpha = 0.05$).

	Unspaced		Spaced		P -Value
Red Spruce					
Mean	**n = 16**	**SE**	**n = 23**	**SE**	
DBH (cm)	12.04	(0.721)	15.15	(0.479)	0.0006*
Total height (m)	11.11	(0.405)	10.94	(0.249)	0.7096
Crown length (m)	5.12	(0.326)	5.97	(0.229)	0.0329*
Tree volume (m^3)	0.07	(0.011)	0.10	(0.007)	0.0192*
Knot volume ratio	0.003	(0.0003)	0.005	(0.0005)	0.0002*
Ave. branch size (cm)	1.09	(0.072)	1.56	(0.062)	< 0.0001*
# branches	12.56	(1.068)	16.00	(0.810)	0.0130*
Height/diameter ratio	95	(3.931)	73	(2.062)	< 0.0001*
	n = 16		**n = 21**		
Form factor	0.77	(0.011)	0.73	(0.011)	0.0115*

0.3855). (This tree did not appear to be an outlier for other analyses in the study). Furthermore, by inserting specific diameters into equation (9) for both balsam fir and red spruce, it was possible to see that both unspaced balsam fir and unspaced red spruce crop trees had significantly more volume at a given DBH than spaced crop trees (Figure 2.2).

Crown length was significantly longer on spaced trees than unspaced trees (Table 2.4). Balsam fir crop trees had significantly longer crowns than red spruce crop trees and there was a treatment x species interaction (Tables 2.3 and 2.5). This indicates that the differences in crown length between species are influenced by spacing. The spaced balsam firs had much longer crowns than unspaced balsam firs, whereas spaced red spruce crowns were only marginally longer than the unspaced red spruce crowns (Tables 2.6 and 2.7). Overall, balsam fir trees were significantly taller than red spruce, but there was no treatment effect, nor any interactions (Table 2.3). However, spaced balsam firs were marginally taller than the unspaced balsam firs, and red spruce crop tree height did not differ significantly between treatments (Tables 2.6 and 2.7).

Stem Form

Stem taper, expressed as a form class, differed significantly between treatments and between species (Table 2.3). As expected, spaced crop trees had more stem taper than unspaced crop trees (Table 2.4; Figure 2.3). Red spruce trees had only marginally more stem taper than balsam fir trees, although this was a significant difference (Table 2.5). There was no species x treatment interaction, indicating that red spruce trees in this study have more stem taper independent of treatment (Table 2.3). Both red spruce and balsam fir crop trees had significantly more stem taper in the spaced plots compared to the unspaced plots, as indicated by the smaller form class for the spaced trees (Tables 2.6 and 2.7; Figure 2.3).

Height:Diameter (H/D) Relationship

The crop trees in the spaced plots had much lower H/D values compared to the unspaced trees, indicating more stability with spacing (Tables 2.3 and 2.4). There were no significant differences in H/D values between species, although this was marginally non-significant (Table 2.3). Both species had significantly larger H/D values for the unspaced crop trees than the spaced crop trees (Tables 2.6 and 2.7).

Branch Characteristics

The ratio of knots (encased branch volume) to lower bole area differed significantly between treatments (Tables 2.3). As expected, the crop trees in the spaced plots had higher knot volume ratios than trees in the unspaced plots (Table 2.4). Average crop tree branch size was larger for the spaced plots compared to the unspaced plots (Tables 2.3 and 2.4). Overall, the spaced plots had a larger average number of branches per crop tree than the unspaced plots (Table 2.4). Red spruce crop trees had a significantly larger knot volume ratio than balsam fir, although there were no significant differences in the number or size of branches between the species (Tables 2.3 and 2.5). This is because the segment volume of balsam fir crop trees is on average larger than red spruce crop trees. Both balsam fir and red spruce crop trees had significantly more branches, larger average branch sizes, and a larger knot volume ratio in the spaced plots than in the unspaced plots (Tables 2.6 and 2.7). Maximum branch diameter was 2.6 cm (1.02 in.) for the unspaced crop trees and 3.4 cm (1.34 in.) for the spaced crop trees (Table 2.8 and 2.9).

Volume Comparison

In general, stemwood volumes predicted using Honer's equations agreed closely with measured volumes. This is reflected in (Figures 2.5 and 2.6), indicating a general overlap of data points between the volumes, but slight deviations on larger trees. There were small, but statistically significant departures from the expected 1:1 regression line found for unspaced balsam fir and spaced red spruce crop trees (Table 2.10). Figures 2.7A and 2.8B illustrate that Honer's (1967) equation underestimates volumes of the unspaced

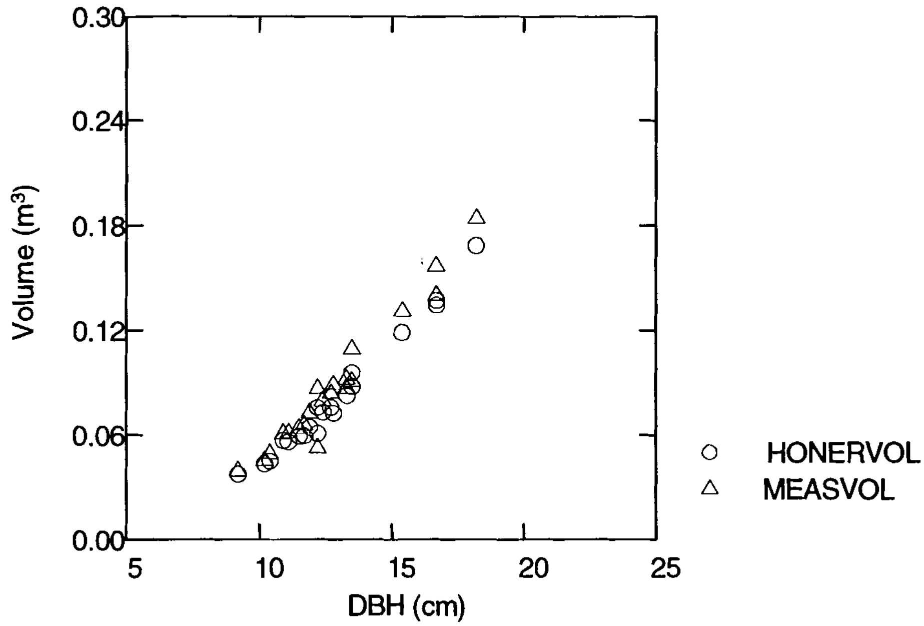
Table 2.8 The number and percentage of trees with specific maximum branch diameters for balsam fir between treatments.

BALSAM FIR UNSPACED				**BALSAM FIR SPACED**			
Maximum branch size		# Trees	% of trees	Maximum branch size		# Trees	% of trees
(cm)	(inches)			(cm)	(inches)		
1.0	0.39	1	4.8	—	—	—	—
1.1	0.43	4	19.0	—	—	—	—
1.2	0.47	1	4.8	—	—	—	—
1.3	0.51	5	25	—	—	—	—
1.4	0.55	1	4.8	1.4	0.55	2	10
1.6	0.63	3	14.3	1.6	0.63	1	5
1.7	0.67	1	4.8	1.7	0.67	1	5
—	—	—	—	1.8	0.71	4	20
1.9	0.75	1	4.8	1.9	0.75	1	5
2.0	0.79	1	4.8	2.0	0.79	5	25
2.1	0.83	1	4.8	2.1	0.83	2	10
—	—	—	—	2.2	0.87	2	10
2.3	0.91	2	9.5	2.3	0.91	1	5
—	—	—	—	2.6	1.02	1	5
Total		21	100	Total		20	100

Table 2.9 The number and percentage of trees with specific maximum branch diameters for red spruce between treatments.

RED SPRUCE UNSPACED				RED SPRUCE SPACED			
Maximum branch size		# Trees	% of trees	Maximum branch size		# Trees	% of trees
(cm)	(inches)			(cm)	(inches)		
1.1	0.43	2	12.5	–	–	–	–
1.2	0.47	2	12.5	–	–	–	–
1.3	0.51	2	12.5	–	–	–	–
1.4	0.55	1	6.3	–	–	–	–
1.5	0.59	2	12.5	1.5	0.59	1	4.3
1.6	0.63	1	6.3	1.6	0.63	1	4.3
1.7	0.67	1	6.3	1.7	0.67	2	8.7
2.0	0.79	2	12.5	2.0	0.79	3	13.0
–	–	–	–	2.1	0.83	1	4.3
2.2	0.87	2	12.5	2.2	0.87	3	13.0
–	–	–	–	2.3	0.91	3	13.0
–	–	–	–	–	–	–	–
2.6	1.02	1	6.3	–	–	–	–
–	–	–	–	2.7	1.06	1	4.3
–	–	–	–	2.8	1.10	1	4.3
–	–	–	–	2.9	1.14	1	4.3
–	–	–	–	3.0	1.18	2	8.7
–	–	–	–	3.1	1.22	1	4.3
–	–	–	–	3.2	1.26	1	4.3
–	–	–	–	3.3	1.30	1	4.3
–	–	–	–	3.4	1.34	1	4.3
Total		16	100	Total		23	100

A



B

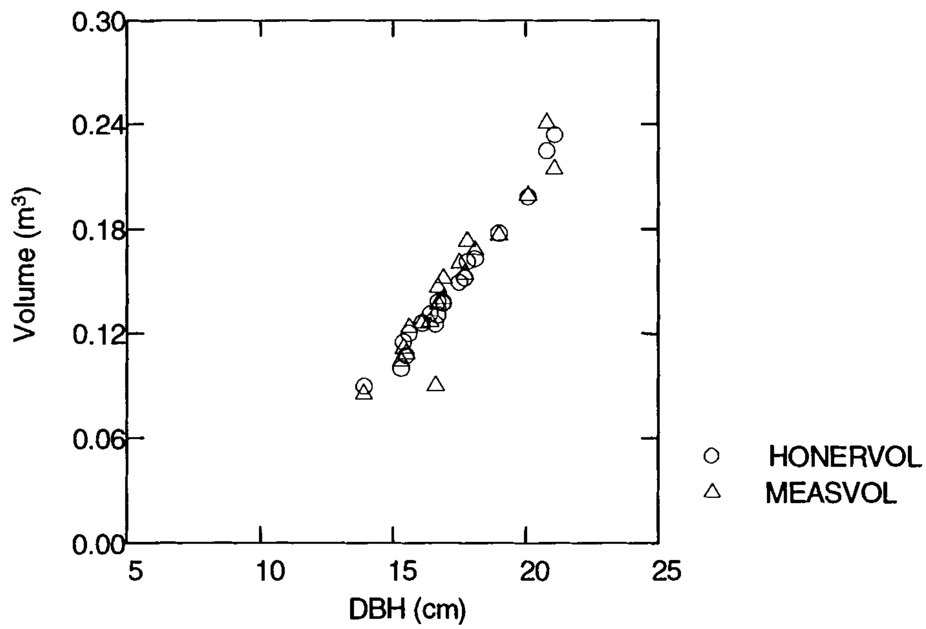


Figure 2.5 Honer's (1967) estimated volume and measured volume (m^3) in relation to DBH (diameter at breast height, cm) for 41 balsam fir trees. A. Balsam fir unspaced. B. Balsam fir spaced.

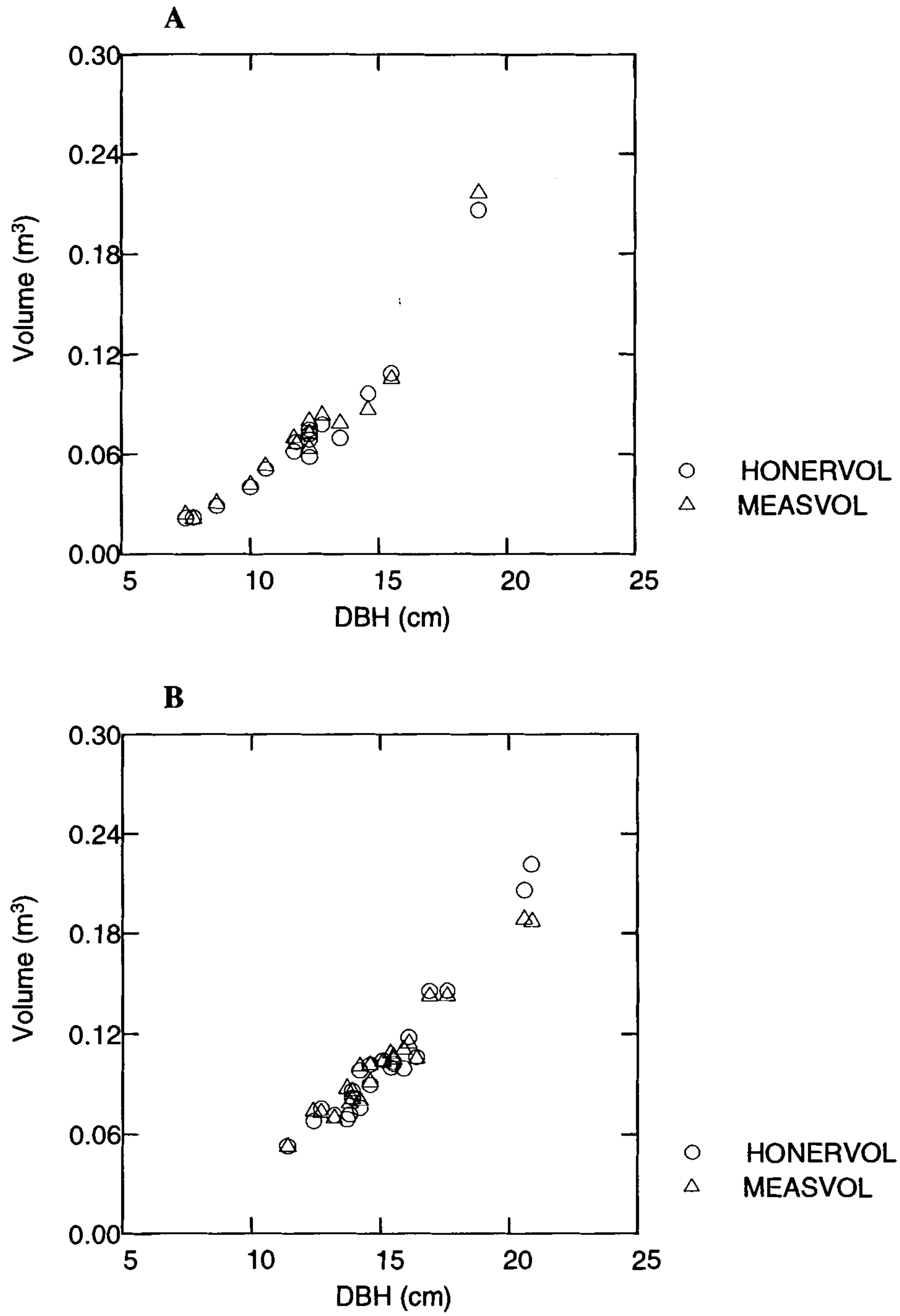


Figure 2.6 Honer's (1967) estimated volume and measured volume (m^3) in relation to DBH (diameter at breast height, cm) for 39 red spruce trees. A. Red spruce unspaced. B. Red spruce spaced.

Table 2.10 Comparison of Honer's (1967) estimated volumes and measured volumes for both species by treatment. Coefficients and 95% confidence intervals are presented for the slope and constant of the model: Honer's volume (m^3) = $b_0 + b_1$*(measured volume (m^3)). An asterisk (*) denotes a rejection of the hypothesis. P-values for the paired T-test are presented in the last column for all species and treatment combinations. An asterisk (*) for the paired T-test denotes significance at ($\alpha = 0.05$).

CONSTANT H_0: $b_0 = 0$		**95% Confidence Interval**		
	Coefficient	**Lower**	**Upper**	**T-Test**
Balsam fir unspaced	0.0028	-0.0024	0.0080	< 0.0001*
Balsam fir spaced	0.0129	-0.0073	0.0332	0.7302
Red spruce unspaced	0.0001	-0.0050	0.0052	0.0652
Red spruce spaced	-0.0206	-0.0313	-0.0099*	0.9322

SLOPE H_1: $b_1 = 1$		**95% Confidence Interval**	
	Coefficient	**Lower**	**Upper**
Balsam fir unspaced	0.8851	0.8305	0.9397*
Balsam fir spaced	0.9059	0.7728	1.0390
Red spruce unspaced	0.9646	0.9049	1.0243
Red spruce spaced	1.1997	1.1017	1.2976*

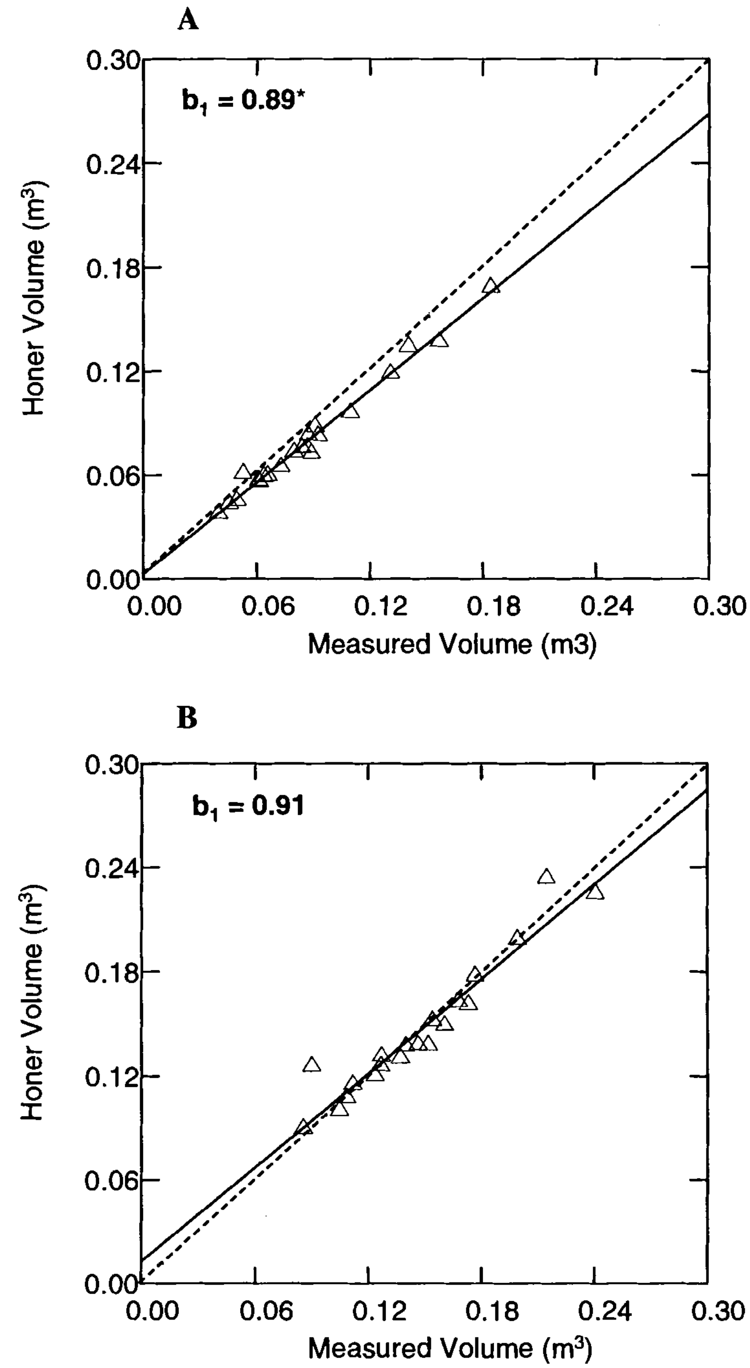


Figure 2.7 Honer's (1967) volume (m^3) versus measured volume (m^3) for 41 balsam fir trees. Solid line represents linear regression and dotted line represents 1:1 relationship. Asterisk (*) indicates a significant difference between the two volumes. A. Balsam fir unspaced. B. Balsam fir spaced.

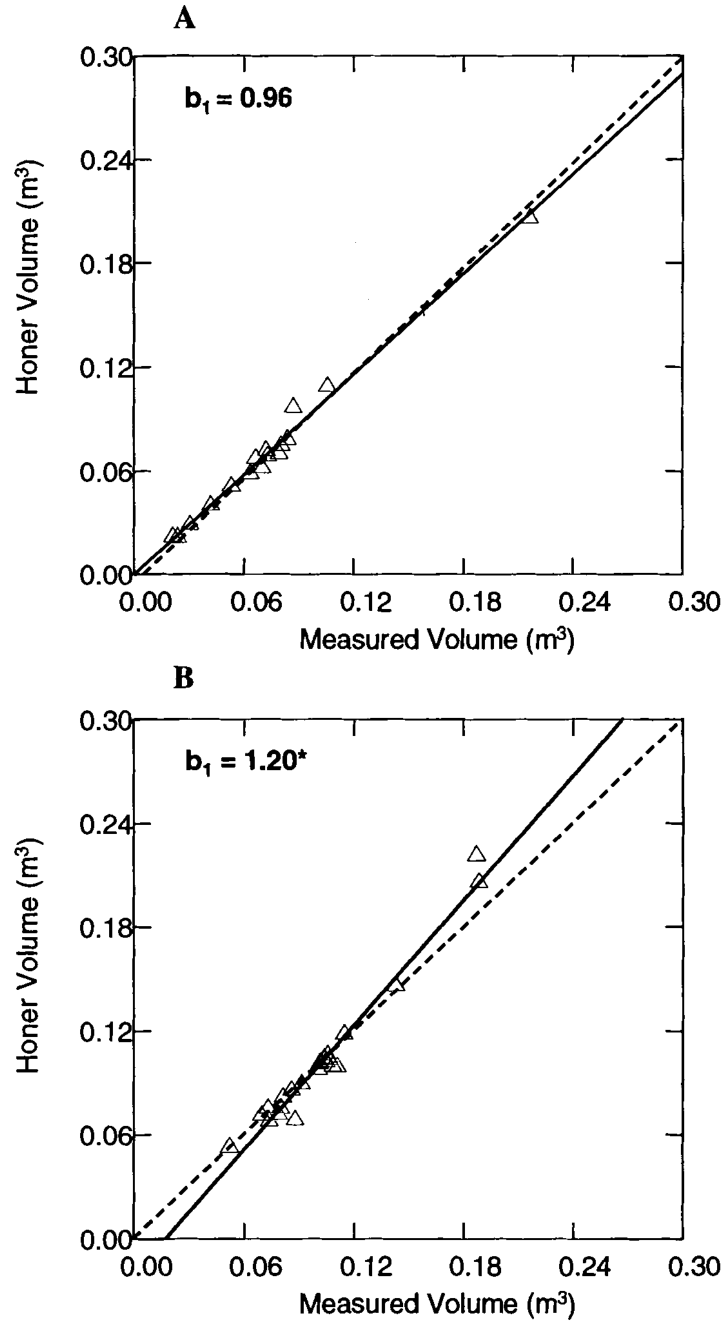


Figure 2.8 Honer's (1967) volume (m^3) versus measured volume (m^3) for 39 red spruce trees. Solid line represents linear regression and dotted line represents 1:1 relationship. Asterisk (*) indicates a significant difference between the two volumes. A. Red spruce unspaced. B. Red spruce spaced.

balsam fir and smaller spaced red spruce, and overestimates volumes of the larger spaced red spruce trees.

In contrast to the results of the regression analysis, paired T-test results indicate the estimated and measured volumes for the red spruce crop trees in the spaced plots are not significantly different and the only differences detected were for the unspaced balsam fir crop trees (Table 2.10, last column). The discrepancy between the two statistical tests is probably because the T-test is testing the overall mean differences between the two volumes, whereas the regression is evaluating the specific patterns over the entire range of data. For spaced red spruce crop trees, the paired T-test indicates the average difference between volumes is not significantly different than zero, likely because under predictions for the low-volume trees are offset by the over predictions of the larger volume trees, and thus causing a non-significant outcome. However, the slope of the regression line is significantly greater than one, revealing this outcome bias. For unspaced balsam fir, the predicted volumes are slightly but consistently lower than measured volumes over the entire range of data (Figure 2.7A).

Honer's (1967) cubic foot volume equation was refitted to the data from this study to further compare the volume estimates with measured volumes. Differences in volumes were found for spaced red spruce crop trees (Table 2.11). No differences were found for unspaced or spaced balsam firs or for unspaced red spruce trees (Table 2.11). Although there were no differences found between volumes for all but the spaced red spruce trees, empirically the intercepts from these data varied substantially from Honer's (1967) cubic

Table 2.11 Estimates and 95% confidence intervals for measured tree volumes using Honer's (1967) volume equation: VIB (ft^3) = $D^2/(b_0 + b_1 * 1/H)$. An asterisk (*) denotes Honer's coefficient (right column) does not fall within the 95% confidence interval of the model.

			95% Confidence Interval		
	Parameter	**Estimate**	**Lower**	**Upper**	**Honer's Coefficients**
Balsam fir unspaced	b_0	0.3512	-2.0725	2.7750	2.139
	b_1	302.4967	196.5488	408.4446	301.634
Balsam fir spaced	b_0	1.4264	-3.4098	6.2626	2.139
	b_1	282.8836	66.5183	499.2490	301.634
Red spruce unspaced	b_0	0.7383	-0.9589	2.4355	1.226
	b_1	320.9739	248.9204	393.0274	315.832
Red spruce spaced	b_0	7.0907*	4.9780	9.2034	1.226
	b_1	103.7765*	25.2975	182.2555	315.832

volume equation. However, since Honer's (1967) confidence intervals are not compared in this study, no statistical conclusions can be inferred from these comparisons.

DISCUSSION

Stem Form and Volume

Trees conform to known patterns of stem growth and stem form, which can be altered by environmental factors and various silvicultural practices. In this study, stem taper and crown size increased due to spacing. Although spacing increased stem taper of the crop trees in this study, tree volume was also larger simply due to increased diameters, because tree heights did not differ between treatments. There have not been many spacing studies evaluating stem taper changes in balsam fir and red spruce trees in the Acadian Forest Region. Most studies reported here were conducted in Sweden with Norway spruce trees. However, Barbour *et al.* (1991) in Nova Scotia studied stem form in a precommercially thinned red spruce stand, and Muhairwe (1994) in British Columbia studied tree form and stem taper over time in interior *Pinus contorta* var. *latifolia* Engelm. (logdepole pine) trees.

Consistent with the findings in this study, Barbour (1991) found red spruce trees in PCT treatments had, on average, longer crowns and greater stem taper. McClain *et al.* (1994) found increases in crown lengths of all *Picea mariana* (Mill.) B.S.P. (black spruce), white spruce, and *Pinus resinosa* Ait. (red pine) trees with wider spacings. Other studies have found that trees subjected to heavy thinnings, had greater stem taper than those in unthinned or lightly thinned stands (Piene 1981; Pape 1999; Karlsson 2000). Thinning affected stem taper on the spaced crop trees in this study because there was an increase in growing space and a concomitant increase in crown size, resulting in greater allocation of growth lower on the tree stem (Larson 1963; Muhairwe 1994; Karlsson 2000). In denser stands similar to the unspaced plots in this study, shading is known to cause live tree crowns to recede and consequently more growth is concentrated higher on the stem resulting in more cylindrical stems (Larson 1963; Karlsson 2000). Increased wind velocity in less dense (spaced) stands, can also cause increased stem taper. Wind pressure results in allocation of growth to trunks and root systems (Piene 1981).

Vigorously growing trees with longer live crowns such as the spaced crop trees in this study, have a greater proportion of diameter to height growth and therefore have a more pronounced diameter decrease up the tree bole relative to trees in lower crown classes or in denser stands (Larson 1963). In fact the spaced trees in this study had a lower H/D ratio, indicating they had much larger diameters in relation to total tree height and greater stability, than those in unspaced plots. The H/D ratio of a tree is an expression of stability under wind and snow pressures with higher values indicating less stability, and lower values indicating increased stability (Wilson and Oliver 2000). This is because trees growing in open conditions have more photosynthate available and can allocate carbohydrates to diameter growth, whereas trees growing in denser and more limiting environments have fewer resources left over for diameter growth. Height growth, in contrast, is less affected by increasing stand density because the carbohydrates necessary for the lateral extension of the leader shoot are supplied when stored carbohydrates are at a peak. Extreme fluctuations in height growth do not occur with the addition of growing space and resource availability, because the carbohydrates needed for leader shoot growth will have already been met and are therefore available elsewhere in the tree (Lanner 1985).

Consistent with this study, Ker (1987) and Piene and Anderson (1987) found no significant height differences between PCT plots and the unthinned plots. However, even though there were no overall treatment differences in total height of the crop trees in this study, balsam fir trees were marginally significantly taller in the spaced plots compared to the unspaced plots. Consistent with the findings for balsam fir in this study, Baskerville (1965) found that the average height of balsam fir trees increased with decreasing stand density, though the relationship between diameter and height was similar throughout all spacings. McClaine *et al.* (1994) however, found all trees were successively shorter with increased spacing. Other studies have found that precommercially thinned trees were taller than the unthinned trees (Curtis and Reukema 1970; Lavigne and Donnelly 1989; Barbour *et al.* 1991; Brissette *et al.* 1999). Furthermore, Brissette *et al.* (1999) found that 18 years after treatment, crop trees in PCT plots were 32 percent taller than crop trees in the unthinned plots.

In this study, we only looked at individual crop tree volumes and not total stand volume. Thinning and spacing have been found to increase individual tree volumes in other studies (Piene 1981; Ker 1987; Lavigne and Donnelly 1989; McClain *et al.* 1994). However, we also found that at the same DBH, the unspaced crop trees had more volume for both species than the spaced crop trees (refer to Figure 2.2). This is primarily due to the concomitant increase in stem taper without a height increase in the spaced plots, resulting from the reduction in stand density from PCT. The average diameters of trees in the spaced plots are larger than the unspaced, so over all diameters, the crop trees in the treated plots would have larger volumes, consistent with what we found in this study.

Branch Characteristics

In this study, PCT was found to increase both the number and size of branches on individual trees. When trees have more room to grow, they not only increase in diameter, but there is an associated increase in crown size, which determines branching patterns.

Knots are the product of branches formed on trees and have a marked affect on wood quality and they are a key factor in determining log and lumber grades. Studies which assess the extent of branchiness associated with different silvicultural treatments provide critical information to forest managers who wish to increase individual tree volumes without sacrificing wood quality.

The knot volume ratio in the butt log was significantly greater for the spaced plots relative to the unspaced plots (Table 2.4). This is consistent with the fact that with increased growing space, crowns are longer and thus will have more branches and concomitantly a larger number of knots. The number and average size of branches were also significantly greater on the trees in the spaced plots than the unspaced plots (Table 2.4). Baldwin *et al.* (2000) found a significant increase in the number and size of branches with heavier thinnings and unthinned plots always had smaller branch diameters than the thinned plots. In contrast, DeBell and Gartner (1997) concluded that the number of branches was not affected by spacing. Increased initial spacing was found to increase branch diameters in the butt log of Norway spruce trees (Johansson 1992). DeBell *et al.* (1994) found an increase in branch size as spacing increased over a range of PCT intensities in young western hemlock stands. Even at the widest spacing (6.6 m, 21.8 ft), the largest hemlock branch diameter did not exceed 5.1 cm (2 in). This did not affect the log grade to be achieved with the size logs produced at the particular rotation age. In this study, the largest branch diameter did not exceed 1.3 in (3.4 cm), with the average branch size of the spaced plots being 1.48 cm (0.58 in.). DeBell and Gartner (1997) also found an increase in branch diameter with increased spacing, but their largest individual branch diameter did not exceed 3.8 cm (1.5 in.).

Usually, the presence of knots causes a loss in value. Knots cause a distortion in the grain of wood around the knot and influence the strength of the wood. Knots are harder, denser, and more resinous than the adjacent tissues and therefore shrink differently (Panshin and Zeeuw 1980). There are no universal log grades for spruce and fir in the region where this study was conducted, and each mill has its own specifications. Therefore, for this study the knot size of crop trees was compared with structural lumber grades for the Northeast (NELMA 1991). Most spruce and fir is bought for structural lumber and the appearance of knots is not as important as the strength of the lumber (James Contino pers. commun.). The grade rules for structural lumber require downgrading if the knots are above a certain percentage of the board face. Also, if the knot is large and part of a big cluster then a downgrade is common (James Contino pers. commun.).

The Northeastern Lumber Manufacturers Association (NELMA) establishes and monitors grade rules for the sawmill industry in Maine and has specific guidelines for grading lumber. Knots are characterized by form, size, quality and occurrence in lumber. There are eight categories for grading dimension lumber in the Northeast with a maximum knot size allowable for each grade (NELMA 1991); (Table 2.12). All of the crop trees in both spaced and unspaced plots in this study meet the grades of all categories except for "Select Structural" for producing 2 inch thick x 4 inch wide boards. Crop trees which

Table 2.12 NELMA standard grading rules for softwood dimension lumber that is 2-4" thick and 4" wide. Included are the categories with grade names and maximum knot size allowable for each grade.

Grades	Maximum Knot Size
I. Light Framing	
1-Construction	1 ½" (3.81 cm)
2-Standard	2" (5.08 cm)
3-Utility	2 ½" (3.81 cm)
II. Studs	
Stud	2 ½" (3.81 cm)
III. Structural Light Framing	
1-Select structural	7/8" (2.22 cm)
2- No.1	1 ½" (3.81 cm)
3- No.2	2" (5.08 cm)
4- No.3	2 ½" (3.81 cm)

would not make the "Select Structural" lumber grade are: 2 unspaced balsam fir (9.5%); 1 unspaced red spruce (6.3%); 2 spaced balsam fir (10%); and 12 spaced red spruce (52%) (Tables 2.8 and 2.9). This lumber is used for light framing and the highest strength and stiffness is required. More than half of the red spruce spaced trees in this study had maximum branch sizes that exceeded the maximum allowed for this lumber grade. However, even though maximum branch size was larger for balsam fir crop trees in the spaced plots compared to unspaced, most were not larger than the requirement for the most stringent grade of dimension lumber.

Knots do not make very good pulp and are sometimes removed from the pulping process. More commonly, they are ground up with the clear wood that is coming out of the debarker and therefore deductions are not usually made for knots in this process (James Contino Pers. commun.). This is based on logs coming from natural stands and not PCT stands as in this study. However, in this study, there were significantly more and larger average branch sizes on trees in the spaced plots than in unspaced plots. Also, crop trees in spaced plots had a larger percentage of knots in the butt log. How this will affect the prices of logs being pulped is unclear. Since knots do not make the same grade as the rest of the wood, excessively knotty wood may decrease the quality of pulp. PCT to release crop trees to create larger and better quality trees does affect the number, size, and percentage of knots produced per tree, but the extent to which this affects pulp quality is not reflected in the market for pulpwood at this time.

Volume Comparisons

Most research conducted to study the effects of silvicultural practices on individual tree volumes does not involve cutting down trees to collect the data, nor do they have the means to climb trees to collect the appropriate measurements. The majority use published volume tables to predict individual tree volumes from field measurements. There is always a question of whether volume equations will be biased when applied to a population outside the initial sample. This study had the necessary data to calculate volumes and compare to a known volume equation to test its validity for red spruce and balsam fir trees in this area. By testing the slope and the intercept of the model predicting Honer's (1967) estimated volume from measured volume, no differences were found for unspaced red spruce and spaced balsam fir, but volumes differed for spaced red spruce and unspaced balsam fir trees. If one were to use Honer's (1967) model to estimate volumes of unspaced balsam fir, a slight underestimation of individual tree volume would occur. On the other hand, if the equation were applied to spaced red spruce trees, a slight overestimation of individual tree volume would occur. The largest overall percent difference between volumes for all treatment and species combinations did not exceed 8% (Appendix). This significant difference may not be very large, but could possibly become a problem when applied to a larger sample size.

The paired T-tests verified the volume differences for unspaced balsam fir, but did not reveal the overestimation of the model for spaced red spruce trees. The underestimation of the smaller trees seemed to offset the overestimation of the larger trees, and no overall differences were detected. We can only speculate the reason for the underestimation of volumes because we do not know the type of site or the stand history of Honer's sample trees. The diameter and height of the trees in this study overlap with Honer's sample trees. However, a tree with the same DBH and height could have dissimilar stem form and taper and consequently different volumes. Therefore, one reason for the differences in volumes could be that Honer's trees have more stem taper than the trees in this study. Since stem taper is known to increase in more open grown conditions, those trees may be growing in less dense stands than our trees. More stem taper would lead to an underestimation of total tree volume at a given DBH and THT. Another reason for the discrepancies found between the two volumes could be because Honer's volume equation is based on measured bark thickness, where bark thickness estimates were used for this study. An over or underestimation of bark thickness for the crop trees in this study could result in an over or underestimation of measured volume.

The only differences detected by refitting Honer's (1967) model with the data from this study were in spaced red spruce trees. This could be due to the high variability in the parameter estimates for the intercept of the model, as revealed by the large confidence intervals, which resulted in no differences between the volumes (Table 2.11). However, as noted earlier no statistical conclusions can be drawn using this test because the confidence interval of Honer's (1967) volume equation is unavailable. Based on the findings from this study, it is apparent that Honer's volume equation for estimating total tree volume from field measurements is accurate for unspaced red spruce and spaced balsam fir in this area, but is slightly biased for unspaced balsam fir and spaced red spruce crop trees.

CONCLUSIONS

Tree growth characteristics were altered for trees growing in PCT plots compared to trees growing in the untreated plots. Overall, the only measured variable that was not affected by PCT was THT. There were no differences in the average size of branches, the number of branches, or the H/D ratio between balsam fir and red spruce, but all other measured variables were significantly different. There were significant differences between Honer's (1967) volume estimation and our measured volumes for the unspaced balsam fir and spaced red spruce crop trees. However, there were inconsistencies with the statistical tests. The percent differences between the two volumes for all of the crop trees were minor, but may still present a problem when working with large acreages of trees with misrepresented volumes.

Additionally, the size of the knots on half of the precommercially thinned red spruce trees in this study precludes them from being used as select structural lumber. At this time, both species of crop trees in the treated plots can attain all other grades for dimension lumber. Implications of this study will enable managers to make better decisions about the appropriateness of PCT with regard to crop tree growth and stem quality as expressed in branchiness and stem taper.

CHAPTER 3. CONCLUSIONS

The primary objective of this study was to determine how PCT affects important growth characteristics of selected red spruce and balsam fir crop trees. PCT is beneficial for eliminating trees that inhibit growth of the selected crop trees, as well as creating additional growing space. Preferential cutting of mature spruce in the 18th and 19th centuries, coupled with episodic spruce budworm outbreaks have converted the spruce-fir forests in Maine from one dominated by a mixed-aged, old growth forest to one with a more uniform stand structure dominated by younger individuals (Seymour 1992). Therefore, PCT can be advantageous in reducing competition and increasing individual tree growth in these stands. PCT had no effect on the growth efficiency of selected balsam fir and red spruce crop trees 25 years after treatment. As expected, spacing increased average projected leaf area and crown projection area of the crop trees, but did not affect GE. At this point in the life of the stand, the trees are still growing efficiently and there is no indication of a decline in growth with increased crown sizes. Consistent with Kenefic (2000), balsam fir was found to be more growth efficient than red spruce.

PCT increased stem taper and the length of the live crown of selected crop trees. Trees in the spaced plots had more stem taper and more volume per tree, due to the concomitant increase in DBH from spacing. Thinning reduces stand density and allows trees to expand their crowns and increase the length of their live crown and take on a more conical shape. A longer live crown results in a change in the distribution of diameter growth along the stem and thus affects stem form. Consistent with other studies, PCT increased DBH (Johnstone 1982; Burns *et al.* 1996) and total tree volume of individual trees in the spaced plots compared to the unspaced plots (Piene 1981; Ker 1987; Lavigne and Donnelly 1989; McClain *et al.* 1994; Brissette *et al.* 1999). Total height was found to be unaffected by thinning or initial spacing, consistent with other studies (Piene 1981; Ker 1987; Piene and Anderson 1987; Burns *et al.* 1996), though some found an increase in THT from PCT (Barbour *et al.* 1991 and Brissette *et al.* 1999). PCT caused an increase in the number, average size, and knot volume ratio of selected crop trees, which ultimately affects lumber grades and pulping costs. The knot sizes were large enough to exclude half of the red spruce and two of the balsam fir crop trees from the select structural grade of dimension lumber for 2-inch thick x 4-inch wide boards for the Northeast. This is an important distinction between the two species. Despite non-significant differences in the number and average size of branches between the two species, the maximum branch diameters were greater for the red spruce crop trees. Additionally, though trees grown in spaced stands have more knots and thus poorer fiber quality, the extent to which this affects the pulpwood value is not known at this time.

Comparing individual volumes estimated with Honer's (1967) volume equation and measured volumes for all of the crop trees revealed differences for spaced red spruce and unspaced balsam fir crop trees. Honer's (1967) cubic volume equation underestimated the volumes for the unspaced balsam fir, and overestimated the volumes of the larger red spruce. No factual conclusions can be drawn from this result since Honer's (1967) dataset is unavailable. We can speculate that the trees used in his study had different stem taper and thus different volumes at a given diameter and height, than trees in the present study. These are important findings for landowners estimating the volume of trees on their property. The small differences per tree could amount to a large loss for the landowner or buyer when applied to a large tract of land.

Findings from this study are beneficial to private as well as industrial landowners wanting to increase the size of spruce and fir crop trees on their property and shorten the time to reach merchantable size, while knowing the extent to which tree growth and quality are affected.

REFERENCES

Assman, E. 1970. Principles of forest yield study: studies in the organic production, structure, increment, and yield of forest stands. Pergamon Press Ltd., Oxford. 506 p.

Avery, Thomas E. and H.E. Burkhart. 1994. Forest measurements, 4th ed. McGraw-Hill Inc., New York. 408 p.

Baldwin, C.V., K.D. Peterson, A.C. Clark III, R.B. Ferguson, M.R. Strub and D.R. Bower. 2000. The effects of thinning on stand and tree characteristics of 38-year-old loblolly pine. For. Ecol. and Manage. 137: 91-102.

Barbour, R.J., R.E. Bailey and J.A. Cook. 1992. Evaluation of relative density, diameter growth, and stem form in a red spruce (*Picea rubens*) stand 15 years after precommercial thinning. Can. J. For. Res. 22: 229-238.

Barker, A.A. 1998. Influences of age and canopy position on the growth efficiency of eastern white pine (Pinus strobus L.). M.S. Thesis, Univ. Maine. 92 p.

Baskerville, G.L. 1965. Dry matter production in immature balsam fir stands. For. Sci. Monogr. 9. 42 p.

Binkley, D. and P. Reid. 1984. Long-term responses of stem growth and leaf area to thinning and fertilization in a Douglas-fir plantation. Can. J. For. Res. 28: 1233-1240.

Blum, B.M. 1990. Red Spruce. *In*: R.M. Russell and B.H. Honkala, (eds.). Silvics of North America: Vol. 1, Conifers. Agric. Handbook 654. pp. 250-259. USDA, Washington D.C.

Brissette, J.C., R.M. Frank, T.L. Stone and T. Skratt. 1999. Precommercial thinning in a northern conifer stand: 18-year results. For. Chron. 75 (6): 967-972.

Brix, H. 1983. The effects of thinning and nitrogen fertilization on growth of Douglas-fir: relative contribution of foliage quantity and efficiency. Can. J. For. Res. 13: 167-175.

Burns, J., K.J. Puettmann and D. Perala. 1996. Strip thinning and spacing increases tree growth of young black spruce. North. J. Appl. For. 13 (2): 68-72.

Contino, J. 2002. Personal Communication.

Curtis, R.O. and D.L. Reukema. 1970. Crown development and site estimates in a Douglas-fir plantation spacing test. For. Sci. 16: 287-301.

DeBell, J. D. and B. L. Gartner. 1997. Stem characteristics on the lower log of 35-year-old western redcedar grown at several spacings. West. J. Appl. For. 12 (1): 9-14.

DeBell, J.D., J.C. Tappeiner II and R.L. Kramer. 1994. Branch diameter of western hemlock: effects of precommercial thinning and implications for log grades. West. J. Appl. For. 9 (3): 88-90.

Frank, R.M. 1990. Balsam fir. *In*: R.M. Burns and B.H. Honkala, (eds.). Silvics of North America: Vol. 1, Conifers. Agric. Handbook 654. pp. 26-35. USDA, Washington, D.C.

Furnival, G.M. 1961. An index of comparing equations used in constructing volume tables. For. Sci. 7: 337-341.

Gilmore, D.W. and R.S. Seymour. 1996. Alternative measures of stem growth efficiency applied to *Abies balsamea* from four canopy positions in central Maine, USA. For. Ecol. Manage. 84: 209-218

Gilmore, D.W., R.S. Seymour and D.A. Maguire. 1996. Foliage-sapwood area relationships for *Abies balsamea* in central Maine, U.S.A. Can. J. For. Res. 26: 2071-2079.

Gregoire, T.G. and H.T. Valentine. 1995. A sampling strategy to estimate the area and perimeter of irregularly shaped planar regions. For. Sci. 41: 470-476.

Honer, T.G. 1965 B. A new total cubic foot volume function. For. Chron. 41 (4): 476-493.

Honer, T.G. 1967. Standard volume tables and merchantable conversion factors for the commercial tree species of central and eastern Canada. Forest Management Research and Services Institute, Ottawa, Ontario. Information Report FMR-X-5. 21 p.

Husch, B., C.I. Miller and T.W. Beers. 1972. Forest mensuration, 2nd ed. John Wiley & Sons, NewYork. 410 p.

Johansson, K. 1992. Effects of initial spacing on the stem and branch properties and graded quality of *Picea abies* (L.) Karst. Scand. J. For. Res. 7: 503-514.

Karlsson, K. 2000. Stem form and taper changes after thinning and nitrogen fertilization in *Picea abies* and *Pinus sylvestris* stands. Scand. J. For. Res. 15: 621-632.

Kaufman, M.R. and M.G. Ryan. 1986. Physiographic, stand, and environmental effects on individual tree growth and growth efficiency in subalpine forests. Tree Physiol. 2: 47-59.

Kenefic, L.S. 2000. Leaf area and stemwood volume growth relationships for *Tsuga Canadensis*, *Abies balsamea*, and *Picea rubens* in mixed-species, multi-aged northern conifer stands. Ph.D Dissertation Chap.2, Univ. Maine. 50 p.

Kerr, M.F. 1987. Effects of spacing on balsam fir: 25-year results from the Green River spacing trials. *In*: T.S. Murray and M.D. Cameron, (eds.). Precommercial thinning workshop. pp. 58-75. Canadian Forestry Service, Maritimes Forest Research Centre, Fredericton, NB.

Kimmins, J.P. 1987. Forest ecology: a foundation for sustainable management, 2nd edition. Prentice Hall, Inc., New Jersey. 596 p.

Lanner, R.M. 1985. On the insensitivity of height growth to spacing. For. Ecol. Manage. 13: 143-148.

Larson, P.R. 1963. Stem form development of forest trees. For. Sci. Monogr. 5. 42 p.

Lavigne, M.B. and J.G. Donnelly. 1989. Early results of a spacing trial in a precommercially thinned balsam fir stand in western Newfoundland. Forestry Canada, Newfoundland and Labrador Region. Inf. Rep. N-X-269. 23 p.

Long, J.N. and F.W. Smith. 1990. Determinants of stemwood production in *Pinus contorta* var. *latifolia* forests: the influence of site quality and stand structure. J. Appl. Ecol. 27: 847-856.

Long, J.N. and F.W. Smith. 1992. Volume increment in *Pinus contorta* var. *latifolia*: the influence of stand development and crown dynamics. For. Ecol. Manage. 53: 53-64.

Maguire, D.A., J.C. Brissette and L. Gu. 1998. Canopy structure and growth efficiency of red spruce in uneven-aged, mixed species stands in Maine. Can. J. For. Res. 28: 1233-1240.

Maine Department of Conservation. Wood processor report (internet). Augusta, ME: (updated 2002 April 3; cited 2002 August 30). Maine Forest Service Publications. Available from: http://www.state.me.us/doc/mfs/pubs.htm.

McClaine, K.M., D.M. Morris, S.C. Hills and L.J. Buse. 1994. The effects of initial spacing on growth and crown development for planted northern conifers: 37 year results. For. Chron. 70 (2): 174-183.

Muhairwe, C.K. 1994. Tree form and taper variation over time for interior lodgepole pine. Can. J. For. Res. 24: 1904-1913.

Northeastern Lumber Manufacturers' Association. 1991. Standard grading rules for northeastern lumber. p. 53-63.

O'Hara, K.L. 1988. Stand structure and growing space efficiency following thinning in an even-aged Douglas-fir stand. Can. J. For. Res. 18: 859-866.

O'Hara, K.L. 1989. Stand growth efficiency in a Douglas-fir thinning trial. Forestry 62 (4): 409-418.

Oliver, C.D. and B.C. Larson. 1996. Forest stand dynamics. Wiley and Sons, New York. 520 p.

Panshin, A.J. and C. De Zeeuw. 1980. Textbook of wood technology, 4th ed. McGraw-Hill, Inc., New York. 722 p.

Pape, R. 1999. Effects of thinning regime on the wood properties and stem quality of *Picea abies*. Scand. J. For. Res. 14: 38-50.

Pettersson, N. 1993. The effect of density after precommercial thinning on volume and structure in *Pinus sylvestris* and *Picea abies* stands. Scand. J. For. Res. 8: 528-539.

Piene, H. 1981. Early growth responses to operational spacing in young balsam fir stand on the Cape Breton Highlands, Nova Scotia. Inf. Rep. M-X-125. Canadian Forestry Service, Maritimes Forest Research Centre, Fredericton, NB.

Piene, H. and W.F.A. Anderson. 1987. Ten-year growth response to spacing in young balsam fir stands, Cape Breton Highlands, Nova Scotia. *In*: T.S. Murray and M.D. Cameron, (eds.). Precommercial thinning workshop. pp. 76-85. Canadian Forestry Service, Maritimes Forest Research Centre, Fredericton, NB.

Roberts, S.D. and J.N. Long. 1992. Production efficiency in *Abies lasiocarpa*: influence of vertical distribution of leaf area. Can. J. For. Res. 22: 1230-1234.

Roberts, S.D., J.N. Long and F.W. Smith. 1993. Canopy stratification and leaf area efficiency: a conceptualization. For. Ecol. Manage. 60: 143-156.

Seymour, R.S. 1992. The red spruce-balsam fir forest of Maine: Evolution of silvicultural practice in response to stand development patterns and disturbances. Ch. 12 (p.217-244) *In*: M.J. Kelty, B.C. Larson and C.D. Oliver, (eds.). The ecology and silviculture of mixed-species forests. A festschrift for David M. Smith. Kluwer Publishers, Norwell, MA. 287 p.

Seymour, R.S. 1995. The northeastern region. *In*: J.W. Barrett, (ed.). Regional silviculture of the United States. 3rd ed. John Wiley & Sons, New York. pp. 31-79.

Seymour, R.S. and L.S. Kenefic. 2002. Influence of age on growth efficiency of *Tsuga Canadensis* and *Picea rubens* trees in mixed-species, multiaged northern conifer stands. Can. J. For. Res. 32: 2032-2042.

Smith, D.M., B.C. Larson, M.J. Kelty and P.M.S. Ashton. 1997. The practice of silviculture: applied forest ecology, 9th ed. John Wiley & Sons, New York. 537 p.

Smith, F.W. and J.N. Long. 1989. The influence of canopy architecture on stemwood production and growth efficiency of *Pinus contorta* var. *latifolia*. J. Appl. Ecol. 26: 681-691.

Smith, F.W. and J.N. Long. 2001. Age-related decline in forest growth: an emergent property. For. Ecol. and Manage. 144: 175-181.

Valentine, H.T., V.C. Baldwin Jr., T.G. Gregoire and H.E. Burkhart. 1994. Surrogates for foliar dry matter in loblolly pine. For. Sci. 40: 576-585.

Vose, J.M. and H.L. Allen. 1988. Leaf area, stemwood growth, and nutrition relationships in loblolly pine. For. Sci. 34 (3): 547-563.

Waring, R.H., K. Newman and J. Bell. 1981. Efficiency of tree crowns and stemwood production at different canopy leaf densities. Forestry 54: 129-137.

Waring, R.H. 1983. Estimating forest growth and efficiency in relation to canopy leaf area. *In*: A. Macfadyen and E.D. Ford, (eds.). Advances in Ecological Research. 1983. 13: 327-354.

Westveld, M. 1931. Reproduction on the pulpwood lands in the Northeast. USDA Tech Bull. 223. 52 p.

Wilson, J.S. and C.D. Oliver. 2000. Stability and density management in Douglas-fir plantations. Can. J. For. Res. 30: 910-920.

Zeide, B. 2001. Thinning and growth: a full turnaround. J. For. 99 (1): 20-25.

APPENDIX. Percent difference between total cubic foot volume and measured volume of each crop tree by treatment and species. (Honer's (1967) estimated volume equation and Smalian's formula applied to different geometric forms of the tree stem were used for calculations).

Plot #	Tree #	Spp	Trt	Dbh (cm)	Total height (m)	Calculated Volume (m^3)	Honer's Volume (m^3)	Difference	Percent Difference
1	2	BF	U	12.2	14.2	0.087	0.076	0.011	12.391
1	3	BF	U	13.3	12.7	0.087	0.083	0.004	5.032
1	5	BF	U	16.7	13.6	0.157	0.137	0.019	12.407
1	6	BF	U	9.2	11.9	0.040	0.038	0.002	5.017
5	2	BF	U	11.5	12.0	0.064	0.059	0.004	6.857
5	3	BF	U	11.7	11.6	0.066	0.060	0.006	9.397
5	4	BF	U	13.3	12.7	0.092	0.083	0.010	10.471
5	7	BF	U	12.8	11.8	0.089	0.072	0.016	18.487
5	9	BF	U	10.2	11.0	0.045	0.044	0.002	4.217
5	10	BF	U	10.4	11.0	0.049	0.045	0.004	8.381
13	1	BF	U	12.4	13.0	0.080	0.073	0.006	8.098
13	3	BF	U	11.9	12.3	0.073	0.065	0.008	11.018
13	4	BF	U	13.5	13.2	0.091	0.088	0.003	3.162
13	6	BF	U	18.2	14.2	0.184	0.169	0.016	8.461
13	7	BF	U	15.4	13.9	0.131	0.119	0.012	9.372
18	3	BF	U	16.7	13.2	0.140	0.134	0.006	4.134
18	4	BF	U	12.2	10.7	0.053	0.061	-0.008	-15.770
18	5	BF	U	10.9	13.1	0.061	0.057	0.004	6.445
18	6	BF	U	13.5	14.8	0.109	0.096	0.014	12.439
18	7	BF	U	11.1	12.3	0.061	0.056	0.005	8.138
30	4	BF	U	12.7	12.7	0.084	0.076	0.008	9.831
Total						**1.843**	**1.690**	**0.153**	**8.288**
8	6	BF	S	17.7	13.3	0.154	0.152	0.002	1.504
8	7	BF	S	15.3	11.3	0.105	0.100	0.004	4.110
8	8	BF	S	18.1	13.7	0.168	0.163	0.005	3.000
8	9	BF	S	16.4	13.4	0.127	0.131	-0.004	-3.542
8	10	BF	S	15.5	12.0	0.108	0.107	0.001	0.847
17	2	BF	S	17.8	14.2	0.173	0.161	0.012	6.789
17	4	BF	S	15.6	13.6	0.124	0.120	0.003	2.721
17	5	BF	S	16.6	12.3	0.090	0.126	-0.036	-39.397
17	7	BF	S	13.9	12.6	0.085	0.090	-0.004	-5.149
17	9	BF	S	16.7	13.7	0.146	0.138	0.008	5.580
19	1	BF	S	21.1	14.8	0.215	0.234	-0.019	-8.940
19	2	BF	S	19.0	13.6	0.177	0.178	-0.001	-0.614
19	3	BF	S	15.4	13.4	0.112	0.115	-0.004	-3.282
19	6	BF	S	16.9	13.2	0.140	0.137	0.002	1.757
19	7	BF	S	16.1	13.4	0.126	0.126	0.000	0.270
22	1	BF	S	20.1	13.5	0.199	0.199	0.001	0.327
22	2	BF	S	20.8	14.6	0.241	0.225	0.016	6.603

Plot #	Tree #	Spp	Trt	Dbh (cm)	Total height (m)	Calculated Volume (m^3)	Honer's Volume (m^3)	Difference	Percent Difference
22	3	BF	S	16.7	12.7	0.137	0.131	0.006	4.672
22	5	BF	S	16.9	13.2	0.152	0.138	0.014	9.092
22	6	BF	S	17.5	13.4	0.161	0.149	0.011	6.911
Total						**2.939**	**2.921**	**0.018**	**0.617**
1	1	RS	U	18.9	15.1	0.216	0.206	0.010	4.730
1	4	RS	U	10.6	11.5	0.053	0.051	0.002	3.477
5	1	RS	U	12.3	12.6	0.080	0.075	0.005	6.505
5	5	RS	U	15.5	11.4	0.106	0.109	-0.003	-3.008
5	6	RS	U	12.3	11.5	0.073	0.069	0.004	5.263
5	8	RS	U	12.8	12.1	0.084	0.078	0.005	6.420
5	11	RS	U	10.0	9.9	0.042	0.040	0.002	3.910
13	2	RS	U	14.6	11.4	0.087	0.097	-0.010	-11.211
13	5	RS	U	11.8	12.3	0.066	0.067	-0.001	-1.541
13	8	RS	U	12.3	9.5	0.063	0.059	0.005	7.833
13	9	RS	U	7.8	8.8	0.021	0.022	-0.001	-3.258
18	1	RS	U	12.3	12.1	0.072	0.072	0.000	0.068
18	2	RS	U	8.7	9.4	0.031	0.029	0.002	5.501
30	1	RS	U	11.7	11.3	0.070	0.062	0.008	11.666
30	2	RS	U	7.5	9.4	0.024	0.022	0.002	9.437
30	3	RS	U	13.5	9.5	0.079	0.070	0.009	11.116
Total						**1.168**	**1.128**	**0.039**	**3.375**
8	1	RS	S	14.6	10.5	0.091	0.090	0.002	1.858
8	2	RS	S	15.5	10.8	0.107	0.104	0.003	2.783
8	3	RS	S	15.5	10.6	0.105	0.102	0.003	2.389
8	4	RS	S	15.9	9.7	0.111	0.099	0.012	10.369
8	5	RS	S	13.7	9.0	0.088	0.069	0.019	21.274
8	11	RS	S	11.4	10.0	0.052	0.053	-0.001	-1.022
8	12	RS	S	13.8	9.2	0.079	0.072	0.007	9.066
8	13	RS	S	13.9	10.5	0.081	0.082	-0.001	-0.760
8	14	RS	S	14.2	9.2	0.080	0.076	0.004	5.168
17	1	RS	S	14.6	12.1	0.101	0.102	0.000	-0.343
17	3	RS	S	14.2	12.4	0.101	0.098	0.002	2.480
17	6	RS	S	16.9	13.1	0.143	0.146	-0.003	-2.226
17	8	RS	S	12.4	11.1	0.074	0.068	0.006	7.959
17	10	RS	S	13.9	11.2	0.086	0.086	0.000	-0.238
17	11	RS	S	13.2	10.1	0.070	0.071	-0.002	-2.609
19	4	RS	S	20.9	13.0	0.187	0.221	-0.034	-18.320
19	5	RS	S	16.1	11.5	0.115	0.118	-0.004	-3.081
19	8	RS	S	16.4	9.8	0.105	0.106	-0.001	-0.964
22	4	RS	S	20.6	12.3	0.188	0.206	-0.017	-9.275
22	7	RS	S	15.4	10.5	0.109	0.100	0.009	7.837
22	8	RS	S	15.1	11.5	0.103	0.104	-0.001	-0.999
22	9	RS	S	17.6	11.9	0.143	0.146	-0.003	-2.239
22	10	RS	S	12.7	11.8	0.073	0.075	-0.002	-3.263
Total						**2.392**	**2.396**	**-0.004**	**-0.173**

BIOGRAPHY OF AUTHOR

Leah M. Phillips was born in Towson, Maryland on December 3, 1969 and grew up in Parkton, Maryland. Upon graduation from Hereford High School in 1987 she worked at Hillcrest Nursery, a wholesale plant nursery located in Millers, Maryland. Though she enjoyed working in the plant nursery business, her admiration of trees and the outdoors drove her to Colorado where she attended college. She graduated from Colorado State University in 1999 with a B.S. in Natural Resource Management and a minor in Forestry. Despite her love of Colorado, an interest and need for further education in Forest Ecosystems and Silviculture brought her to the most heavily forested state in the United States and the University of Maine in Orono, Maine. She is currently a student and a national member of the Society of American Foresters. Leah is a candidate for the Master of Science degree in Forestry from The University of Maine in December, 2002.