COMPETITION AND JUVENILE GROWTH IN MIXED REGENERATION IN MANITOBA

by

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ABSTRACT

There is a need to quantify the effects of hardwood competition on the growth and free-to-grow status of commercial conifer species in regenerating mixedwood stands in Manitoba. This Canada-Manitoba agreement project was developed to provide some of that information. The major objective was to quantify competition levels using competition indices and identify at what stage the competition level becomes detrimental to conifer growth. This information was then used to evaluate the competition relationships for Free-to-Grow assessment in young stands in Manitoba.

This study used a "retrospective survey" approach, in which detailed conifer growth, vegetation competition and microsite measurements were collected from conifer tree-centred 2 m radius competition plots. Competition thresholds were determined which could be used for the development of free-to-grow assessment procedures. Results indicate that, in general, growth measurements based on radial increment are preferable to use when assessing response to competition levels. The most useful competition indices were based on relative hardwood:conifer height ratios and those that use distance-weighted root-collar diameter hardwood:conifer ratios. The ecological thresholds in terms of hardwood:conifer height ratios and distance were determined.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The increase in aspen density and shift from conifer to mixed regeneration after harvesting mixedwood and softwood stands has raised concerns about its potential impact on softwood production. Little is known in Manitoba about the competition thresholds affecting the growth of conifers, free-to-grow status and juvenile growth. It is important to quantify the effects of vegetation competition on the survival and growth of commercial conifer species, especially in regenerating stands. This information is essential for forest managers to improve their ability to plan the timing and intensity of release treatments.

There have been a number of methods developed for quantifying interspecific competition (between plants of different species). The effect of surrounding vegetation on conifer growth is often quantified by using competition indices (Alemdag 1978)[1]. Competition indices are based on empirical measurements of the competing vegetation and conifer tree growth. These interspecific competition indices are often simple, and are based on easily measured variables, although some researchers have developed more complex ones (e.g., Brand 1986). These indices are based on individual hardwood competitor and conifer tree measurements or stand characteristics. Individual conifer tree to competitor measurements may include: competitor distance and dispersion around the conifer tree or size ratios of competitor to conifer tree. Stand measures can include amount of overtopping by surrounding vegetation, density, percent cover, and light interference (Mugasha 1989, MacDonald et al. 1990, Salonius et al. 1991, DeLong 1991).

Competition indices have been a major component in this study, and were used to quantify the relationship between hardwood competition and conifer growth.

The major objectives of this study were:

a) To quantify competition levels using competition indices and identify at what stage the competition level becomes detrimental to conifer growth. Specifically, this required determining the relationship between competition indices, competition thresholds and growth of white spruce, black spruce and jack pine in mixed regeneration.

b) Application of the above in the design of Manitoba's Free-to-Grow standards. This involved evaluation of the implications of the competition relationships for free-to-grow design.

This report summarizes the analysis used to meet the first objective. It indicates the most important results from analysis of conifer growth in hardwood competition in juvenile stands for white spruce, black spruce and jack pine in several areas throughout Manitoba. Additional information will be presented in a Canadian Forest Service Information Report, to be published later in the 1995/96 fiscal year.

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[1] In competition studies, the conifer tree of interest is referred to as the "target", "crop" or "subject" tree.

FIELD METHODS

The overall field objective was to sample, across a geographic range, young coniferous blocks, from upland sites, with predominantly hardwood competition for several age classes, for the three conifer species studied (white spruce, black spruce and jack pine).

During 1991 to 1993, three areas of the province were sampled (Figure 1). These were:

1. Abitibi FML (1991) - east of Pine Falls for black spruce
2. Western Region (1992) - Porcupine Hills for white spruce; Duck Mts. for black spruce
3. Northern Region (1993) - north of The Pas for jack pine.

The choice of which conifer species to study in each region was based on three criteria: 1) sufficient number of regenerating blocks for study 2) regional differences in use and management of the species and 3) logistical concerns such as consolidated field work and accessability.

Block Selection

The criteria for block selection was sufficiently high stocking levels of both conifer and hardwoods (based on the regeneration survey information from the Manitoba Forestry Branch), reasonable access, and a sufficient range of aspen competition levels (density and cover) throughout the block (i.e., open and dense areas) to measure conifer tree response. Because the focus was on hardwood-conifer competition, blocks where the competition was mostly between conifers (i.e., high intraspecific competition) were avoided. Blocks which had been stand tended were also not selected for study.

For black and white spruce, planted blocks were selected, whereas for jack pine, blocks which had been scarified and then left for natural regeneration were used. The post-harvest ages of the sampled blocks ranged between 7 and 14 years.

Plot Establishment

As expected, hardwood regeneration was not uniform throughout most of the blocks, so specific portions of blocks which contained hardwood competitors were delineated for sampling. Placement of competition plots within these subareas was based on a uniform 20 m by 20 m grid, with a random starting point. If the subarea was small, a 20 m (between lines) by 10 m (between plots) grid was used. At each point on the grid, the closest conifer (target) tree was used for the plot centre. If a suitable target tree was not found within 5 m of the sampling grid, then there was no plot placed at that grid point. The plots had a fixed 2 m radius (12.56 m^2). Selected saplings were replaced with the next closest target tree if damage unrelated to competition pressure was noted. All sizes of conifer trees were used, subject to the following criteria.

Manitoba

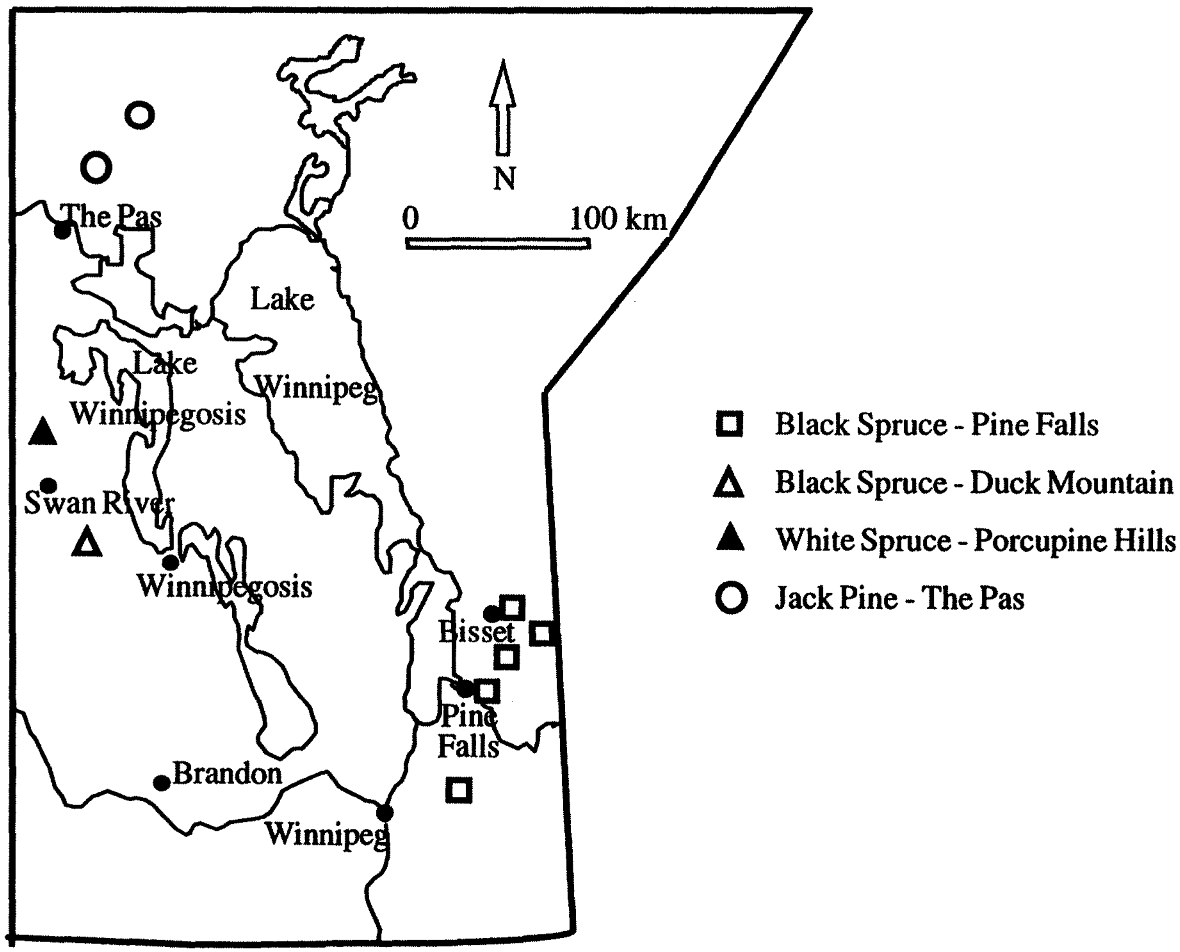

Fig. 1 Location of Sampling Areas

A conifer tree was selected as a target tree if it had at least five years of growth, and was not of advance regeneration origin. As well, it could not have major or recent damage due to mechanical agents (e.g., snow press, leader whip), herbivores, insects and/or disease. For a tree to be selected on jack pine sites, most of the competition around the conifer tree had to be hardwoods or shrubs, not other conifers.

Over the three summers, a total of 18 blocks and 1036 plots were sampled. A listing of the blocks, number of plots and harvest and silviculture information for each block is summarized in Table 1. Table 2 contains information on the stand composition from regeneration surveys in the chosen blocks. In Table 3, the age class distribution within each sampled block, based on tree ring analysis of the selected conifer trees, is provided.

Data Measurements

Detailed measurements were made in the 2 m radius conifer target-tree centred competition plots. Three types of measurements were taken:

1. Vegetation data collected on a plot-level basis. This included average heights, cover and density of different species.
2. Microsite variables estimated on a plot-level basis.
3. Vegetation data collected for individual trees and shrubs.

A schematic diagram of a competition plot is shown in Figure 2.

Average crown cover and height was estimated for each tree species, shrubs, broadleaf non-woody plants (forbs), and grasses. Stem counts were made of each tree species and shrub clump in the plot. Several other "categorical" variables were collected for each plot, including: etiolation (physical evidence of shading on the conifer tree), amount of crowding of the conifer tree by grasses and forbs, and browse damage to adjacent trees.

Microsite variables were also measured in each plot[1]. These included: moisture class, drainage class, slope position, slope, aspect, microtopography class, slash abundance, site quality class, and depth of humus. For most microsite variables, the classes were derived from Luttmerding et al. (1990).

The following measurements were collected for specific trees and shrubs:

a) Target tree:

- height, crown height, crown radius, percent overtopping, root collar diameter, five most recent height increments

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[1] Microsite variables were not measured in blocks in the Pine Falls area.

Table 1
Harvest and Silviculture Information

Block	Plots	Plantation Number	Harvest Year/Type	Site Preparation Year/Type	Planting Stock	Planting Year
Black Spruce - Pine Falls						
1	25	23-84	-[2] clear cut	1983 burn	408-paperpot	1984
2	66	10-85	1983 clear cut	TTS disk trench	2-0 can am	-
3	45	48-84	- clear cut	1983 burn	408-paperpot	1984
4	34	50-84	- clear cut	1983 burn	408-paperpot	1984
5	37	49-84	- partial cut	1983 burn	408-paperpot	1984
6	42	39-82	- clear cut	- -	-	1982
7	18	51-85	- clear cut	- -	408-paperpot	1985
8	8	3-81	- partial cut	- -	408-paperpot	1981
9	40	11-84	- partial cut	1983 shearblade	408-paperpot	1984
10	7	10-84	- partial cut	1983 shearblade	408-paperpot	1984
Total	321					
Black Spruce - Duck Mountains						
1	51	20-04	1985 clear cut	shearblade	408-paperpot	1985
White Spruce - Porcupine Hills						
1	86	02-01	1981 salvage cut	shearblade	-	1985
2	103	22-04	1981 salvage cut	1981 burn	bare root	1982
3	113	22-22	1981 salvage cut	1981 burn	bare root	1981
Total	302					
Jack Pine - The Pas						
1	78	04-33	1981 clear cut	none	natural	n/a[3]
2	97	33-41	1981 clear cut	none	natural	n/a
3	95	21-01	1985 clear cut	scarified	natural	n/a
4	91	20-01	1986 clear cut	scarified	natural	n/a
Total	361					
Grand Total	1035					

1. Block is in FMU 23 (Agassiz). The remainder are in the Abitibi FML.
2. Data not available.
3. Data not applicable.

Table 2
Regeneration Performance[1]

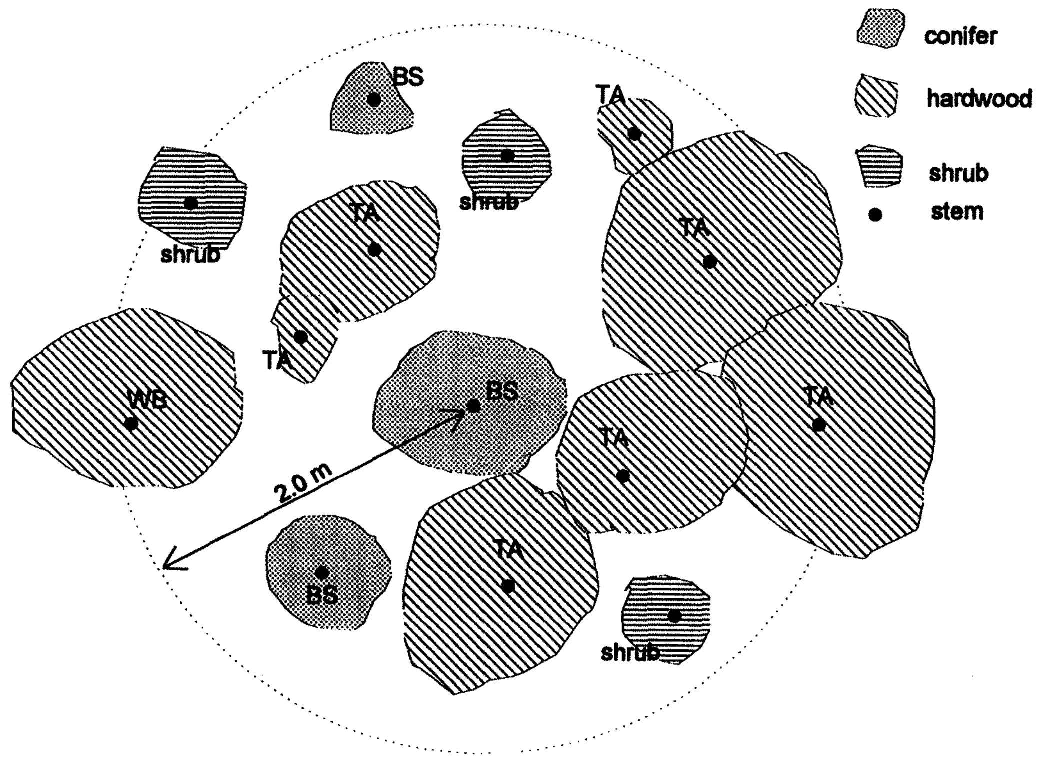
Location Block	Survey Year	Cutblock Size (ha)	Percent Stocking and Stem Density													
			BS		WS		JP		Total C		TA		BA		Total HW	
			%	st/ha	%	st/ha	%	st/ha	%	st/ha	%	st/ha	%	st/ha	%	st/ha
Pine Falls																
1	1988	9.7	64	7773	0	0	50	3045	75	10932	9	318	34	1795	52	4340
2	1988	7.6	63	3481	4	37	67	2481	85	5999	33	926	0	0	33	926
3	1989	33.0	77	1600	0	0	24	421	84	2021	76	4126	5	158	76	4295
4	1988	6.0	57	1857	0	0	86	7429	100	9286	57	3857	7	714	64	4571
5	1988	18.6	46	1917	0	0	25	667	54	2584	54	1042	12	500	62	1667
6	1989	13.0	56	1487	0	0	23	974	69	2794	44	1231	3	128	46	1359
7	1989	12.7	84	1789	0	0	16	237	84	2052	71	4632	8	263	74	4921
8	1988	8.5	47	822	27	311	0	0	71	1133	29	978	2	44	31	1022
9	1989	10.0	71	1464	0	0	0	0	71	1464	79	3536	14	429	89	3965
10	1989	22.7	62	1369	0	0	0	0	62	1369	66	4185	20	1138	69	5323
Porcupine Hills																
1	1988	76.3	52	1404	68	1684	15	316	76	2434	78	9921	47	2474	86	12395
2	1987	70.0	55	2881	50	1143	1	0	77	4024	96	12786	37	2571	98	17833
3	1987	144.7	2	80	54	954	33	1966	67	3000	90	13816	41	3011	95	16828
Duck Mnt																
1	1989	51.7	52	1404	20	191	10	128	75	2234	48	3255	24	1383	60	5043
The Pas																
1	1986	96.2	11	200	0	0	67	6280	69	6480	71	7860	5	240	73	8100
2	1986	72.6	19	1262	0	0	77	7595	81	8857	77	8119	1	0	78	8119
3	1990	27.7	2	74	5	37	89	11333	90	519	80	5481	12	444	81	5926
4	1990	123.0	9	187	1	8	70	11772	74	11984	75	5821	6	122	77	5992

1. Information from regeneration surveys, Manitoba Forestry Branch.

Table 3
Age Class Distribution of Target Trees

Species/Location	Total Blocks	Age Class	Plots	Total
Black Spruce Pine Falls	10	5-9	124	
		10	122	
		11-15	76	
				321
Black Spruce Duck Mountains	1	8-12	51	
				51
White Spruce Porcupine Hills	3	8-13	156	
		14-20	146	
				302
Jack Pine The Pas	4	6-8	211	
		9-12	148	
		-[1]	2	
				361
Total	18		1035	

1. Two tree disks were missing, so age not available for those plots.



Crown Cover of Woody Competitors in a 2 m Radius Competition Plot

Fig. 2 Diagram of Competition Plot

recent height increments

b) Tallest and closest hardwood and conifer in the plot:
- height, crown radius, stem-to-stem distance from target tree, stem-to-inside crown distance from target tree, azimuth or quadrant from target tree, root collar diameter, height increments (five most recent for conifer, three most recent for hardwood).

c) Other trees and shrubs in the plot:
- height, stem-to-stem distance from target tree, stem-to-inside crown distance from target tree, azimuth or quadrant from target tree

For jack pine blocks in The Pas area, individual trees and shrub clumps were not measured because analysis from the spruce data indicated that this information was not as critical as plot averages and data from closest and tallest tree competitors in predicting the observed conifer growth.

Descriptions of the measured variables is as follows:

a) Quadrant: location of the stem in one of four quadrants: N: 315-45 E: 45-135 S: 135-225 W: 225-315. This was used with the Pine Falls black spruce blocks.
b) Azimuth: (nearest 5^0) Bearing from target tree stem at ground level to the competitor stem at ground level. This was used with the blocks in the Western and Northern region.
c) Total Height: (nearest cm): total height, including current year's growth.
d) Crown Height: (nearest cm): measured from ground to first branch whorl (3 of 4 branches intact). Used to determine live crown length.
e) Crown Radius: (nearest cm): the average radius was recorded, average of widest and narrowest crown radii.
f) Percent Overtopping: (nearest 10%): percentage of the top ⅓ of the target tree that is overtopped by crown foliage of competing tree or shrub. (ie. the crown of top ⅓ is projected upwards as a cylinder).
g) Root Collar Diameter: (nearest mm): this was the basal diameter, taken at ground level, above the root collar swelling.
h) Stem-Stem Distance: (nearest cm): Measured from centre of target tree stem to centre of competitor tree stem. In the case of shrub clumps, it was to the centre of the clump.
i) Stem-Inside Crown Distance: Measured from centre of target tree stem to the nearest edge of the competitor foliage. (Nearest cm for closest and tallest, nearest 5 cm for other trees and shrubs).
j) Height Increments (nearest cm): Used 5 most recent increments for conifers and 3 most recent increments for hardwoods, starting with the current year.

As well, a basal disc was collected of the target tree and the tallest hardwood and conifer in the plot for determination of basal age and radial increments.

ANALYSIS METHODS

The methods presented here were those used to develop the analysis variables, and perform general tests on them. As well, the basic analytical methodology used throughout the analysis is presented here. The detailed analytical methods used to answer a particular question are presented in the appropriate section.

Development of Variables for Analysis

A literature review was completed on competition indices and on autecology of black spruce, white spruce and jack pine to choose appropriate dependant growth variables, to include more recent indices in the analysis, and check for appropriate indices. The autecology review was done to ensure that competition indices selected had some biological relevance.

Published Competition Indices

The amount of conifer:conifer (intraspecific) and hardwood:conifer (interspecific) competition on a plot-by-plot basis was calculated to determine if intraspecific competition indices should be used, and to determine if aspen was dominant enough in each area so that it could be used to approximate all the hardwood competition. Analysis of black spruce data from Pine Falls indicated that the majority of plots had some conifer competition (see Table 4) and so all the published competition indices were calculated twice, using different sets of competitors: a) including conifers and hardwoods (predominantly aspen) and b) including just hardwoods. The competition indices did not include shrubs, for two reasons: a) At the ages sampled, most shrubby competitors (e.g., raspberry, willow and alder) had relatively low stature and cover. b) In the analysis, there were other competition variables which incorporated shrubs. The formulas of the published competition indices, as used in this study, are in Appendix 1.

Growth Variables

A total of 22 conifer tree growth response variables were selected or developed for analysis. They included simple variables and ratios, both size-dependant and size-independent. Some of the more commonly-used variables were: height, height increment, mean 3 year periodic height increment, root collar diameter, radial increment, mean 3 year periodic radial increment, basal area, basal area increment, height:RCD ratio, crown length, and crown radius.

Three additional growth variables, based on basal area increment, were also developed. They were:

a) ratio of basal area increment:inside bark circumference
b) ratio of basal area increment:basal stem wood area
c) ratio of volume increment:basal stemwood

The last variable was modified from Waring et al. (1980) and is a good measure of tree vigour for some species. These variables were less size-dependant than more traditional growth response variables and they were more physiologically-based. They were derived from "pipe-model" theory, which states that sapwood area is important to tree vigour (Valentine 1988). For example, sapwood area is highly related to root collar basal area in young pine plantations in the southern U.S. (Bacon and Zedaker 1986, Blanche et al. 1985).

Competition Variables

Close to 100 competition and microsite variables were selected or developed for analysis. They included intensive and extensive competition variables (ratios and sums), published and unpublished inter- and intraspecific multivariable variables and microsite variables. Many of the competition variables incorporated not just tree competitors (both hardwoods and conifers) but also shrubs, forbs and grasses (either singly or in combination with trees).

They were categorized in the following groups: 10 based on stem density, 13 based on crown cover, 16 based on height, 9 based on distance, 10 based on shading or distribution of competitors around the target tree, 5 based on intraspecific competition, and 13 variables based on microsite conditions. In addition 22 extensive and intensive competition indices developed by Wagner and Radosevich (1987) were also tested.

The distribution of competitors around conifer trees may affect tree growth in some situations, and this potential effect has been tested by many researchers (e.g., Wagner and Radosevich 1987, MacDonald et al. 1990, Simard 1990). An index of angular dispersion (Zar 1984), based on the azimuth from the target tree stem to each competitor stem has been the most common method to measure dispersion (e.g., MacDonald et al. 1990). This quantifies how clumpy (i.e., all in one spot) the competitor stems are in relation to the target tree. This index was calculated for the white spruce and jack pine trees.

General Methods Used in Analysis

Prior to analysis, the statistical properties of each variable were analyzed and tests for normality were performed. The tests for normal distribution were based on a procedure outlined by Sabin and Stafford (1990). Much of the analysis was stratified on specific target tree age classes (Table 3). These age classes were assigned for two reasons: 1. Some of the variation in growth response was due to age (and thus size) differences in the trees, and not just to variable competition pressure. By restricting analysis within discrete age classes, this effect was reduced. 2. Vegetation dynamics operating in different age classes would become apparent in this analysis. Age class boundaries were chosen to have, as much as possible, similar sample sizes in each, to facilitate statistical analysis. In each location, the age spread of target trees was not large. For example, the Pine Falls black spruce, age 10, was deemed to be a separate age class, as lumping it with either of the adjacent classes would have caused a large discrepancy in age class frequency distribution.

In this study, the two main methods of analysis used were correlation analysis and regression (single and multiple linear and nonlinear). Spearman's Rank Order Correlation analysis was completed with the black spruce and white spruce data sets, for exploratory data analysis on all growth and competition variables. The analysis was also performed separately for each age class in each region, and then for all age classes combined. A ranking method modified from Mugasha (1989) was used to determine the overall best growth and competition variables for each species and location. This correlation analysis was not done for the 1993 jack pine data set, as the regression analysis, described below, was providing much of the same information.

Linear regression analysis was used extensively in this study in order to determine the relationships between competitor and conifer growth. Multiple regression analysis was conducted using all 117 competition variables (assumed for this study to be the "independent" variables). Models were developed using 1 to 7 competition variables. The analysis was repeated for all 22 target tree growth variables (assumed for this study to be the "dependant" variables). Regression analysis was used to select those competition variables which were associated with the highest coefficient of determination (r^2) (i.e., explained the most amount of observed variation in conifer tree growth), were most meaningful, and had operational potential due to ease of measurement.

Regression analysis was run to determine the variables with the highest r^2 using the following different groups of competition variables:

a) overall competition variables
b) competition variables that don't incorporate the size of the target tree
c) competition variables that are easy to measure

The competition-growth relationships which were the most promising in linear regressions were further analyzed using non-linear regression and multiple linear regression. This analysis on the selected competition-growth response variables was performed to better describe the relationship between growth and competition. Most of the regression analyses presented in this report are based on single variable linear regression; the results of multiple regression and non-linear regression will be presented more fully in a Canadian Forest Service Information Report to be published later in the 1995/96 fiscal year.

Most of the data development and analysis was performed using SAS for VMS, version 6 (SAS Institute Inc. 1990). This included Spearman's Correlation analysis, regression analysis (linear, multiple linear and non-linear), two mean t-tests and multiple means tests. Additional linear and non-linear regression analysis was performed with Tablecurve 2D and 3D for Windows (Jandel Scientific). Data summary and means were generated with QuattroPro for Windows (Borland Inc.).

RESULTS AND DISCUSSION

Vegetation Characteristics of the Surveyed Blocks

The selected blocks from all four areas were harvested in the early to mid 1980's, and some blocks in the Pine Falls and Porcupine Hills areas had been burned in the early 1980's. The spruce blocks were mostly planted, and the jack pine sites had natural regeneration (Table 1). The site preparation for these blocks was not severe. Most of the sampled areas were on moderately-well to well drained sites. Hardwood densities, estimated from regeneration surveys, were from 4,000 to 18,000 stems/ha (Table 2). Conifer densities ranged from 1,464 stems/ha in the black spruce sites to a high of 11,984 stems/ha in the jack pine sites near The Pas (Table 2).

Age classes used in analysis were based on tree ring counts of the target conifer trees and were developed for each species and location separately, as described previously (Table 3). The majority of trees were between 8 and 12 years old. Table 4 presents the conifer and hardwood densities and proportions as a percentage of all trees, as well as the percentage of target trees that were derived from advanced regeneration and ingress (recruitment) in each block. Most of the spruce blocks were planted within a few years of harvest or burn (Table 1), and the majority of the conifer target trees in these sites were from planted stock. For the spruce plots, between 8 and 23 percent of the target trees were advanced regeneration (tree more than one year older than the block), whereas there were no jack pine advanced regeneration trees (Table 4). Seven percent of the white spruce and pine trees were deemed to be recruitment (more than three years younger than the block age); for black spruce the recruitment was 27%. In terms of growth modelling, it was appropriate that the majority of the target trees were about the same age as the block, as hardwood and conifer growth would have proceeded simultaneously. Overall, the pine tree ages were more uniform within a block, while the spruce age spread was greater.

Tables 4 and 5 provide information on the tree growth and competition for each location. In all locations, the majority of the plots had some conifer competition around the target tree. This is especially evident in The Pas, where almost 50% of the plots had more than 10 jack pine trees (Table 4), and the average tree to competitor conifer stem distance was less than the other sites (Table 5). In the Pine Falls area only 17% of the black spruce plots had the target tree as the only conifer in the plot.

Aspen was the most abundant hardwood competitor in all locations. It was the only hardwood competitor in a majority of plots in the Pine Falls area (66%) and The Pas area (92%). In the Western Region, there was a greater mix of hardwood species, with aspen the only hardwood competitor in only 22% and 37% of the plots in the Duck Mountain and Porcupine Hills, respectively. Even though aspen was the dominant hardwood in all sites, all hardwoods were included in the development of competition indices, as the purpose of the study was to analyze mixedwood regeneration, not simply aspen-conifer competition. In all areas, hardwoods were a major competitor in terms of cover, density and height. There were, however, regional differences in the proportion of hardwood competition to other competitors. For black spruce blocks in the

Table 4
Conifer and Hardwood Densities and Proportions and Conifer Regeneration

	Pine Falls BS	Duck Mt BS	Porcupine Hills WS	The Pas JP
<u>Conifer Competition</u> (including target tree)				
Plots with target tree the only conifer in the plot	17%	8%	12%	3%
Plots with greater than 5 conifer (same species as target tree)	8%	10%	20%	68%
Plots with greater than 5 conifer (all species)	21%	12%	29%	74%
Plots with greater than 10 conifers (same species as target tree)	2%	0%	5%	47%
Plots with greater than 10 conifer (all species)	9%	2%	11%	56%
Plots with target tree species as only conifer species	64%	88%	77%	64%
<u>Hardwood Competition</u>				
Plots with more than 10 aspen stems	28%	73%	52%	68%
Plots with more than 10 hardwood stems	32%	90%	70%	69%
Plots with aspen as the only hardwood	66%	22%	37%	92%
Plots with other hardwoods more numerous than aspen	10%	20%	16%	0%
Plots with more hardwood stems than conifer stems	56%	100%	91%	46%
<u>Advanced Regeneration and Recruitment</u>				
Plots where target tree is advanced regeneration[1]	13%	8%	23%	0%
Plots where target tree is ingress	27%	6%	7%	7.5%
Number of Plots Used for Analysis	321	51	302	359

1. Target tree is more than one year older than cutblock.

Table 5
Tree Growth and Competition Characteristics for Each Location[1]

	Black Spruce[2] Pine Falls	Black Spruce[3] Duck Mountain	White Spruce[4] Porcupine Hills	Jack Pine[5] The Pas
Target Tree				
Height (cm)	98.3 (2.7)	112.5 (4.9)	169.1 (4.1)	223.2 (3.6)
Diameter (cm)	1.2 (0.04)	1.4 (0.07)	2.4 (0.06)	2.3 (0.04)
Age (years)	9.7 (0.1)	10.0 (0.1)	13.1 (0.1)	8.1 (259,0.1)
Ht/RCD	77.2 (0.0)	80.9 (2.3)	102.9 (8.8)	86.8 (0.9)
Height increment (cm)	17.8 (0.6)	18.7 (1.3)	25.4 (0.7)	32.5 (0.7)
Radial increment (mm)	1.0 (0.0)	1.1 (0.1)	1.6 (0.0)	1.9 (259,0.0)
Basal Area incr. (cm^2)	0.5 (0.0)	0.3 (0.0)	1.7 (0.2)	1.3 (0.0)
Cover (%)				
Conifer cover	9.7 (317,0.5)	5.9 (0.7)	5.3 (0.3)	7.2 (0.3)
Hardwood cover	15.3 (308,0.8)	34.4 (2.8)	27.3 (1.1)	19.3 (0.6)
Aspen cover	12.1 (319,0.8)	27.1 (2.8)	21.3 (1.0)	19.1 (0.6)
Shrub cover	21.3 (1.0)	14.3 (1.7)	12.5 (0.7)	7.1 (0.2)
Forb cover	18.5 (0.9)	18.2 (2.1)	17.4 (0.9)	8.6 (0.5)
Grass cover	6.5 (0.7)	12.8 (2.6)	8.9 (0.6)	1.8 (0.2)
Overtopping	26.6 (1.7)	21.6 (3.7)	28.3 (1.8)	25.1 (1.6)
Density (stems/plot)[6]				
Conifer count	3.5 (0.3)	2.1 (0.2)	3.3 (0.2)	12.0 (0.6)
Hardwood count	6.7 (0.4)	24.1 (1.8)	13.5 (0.6)	13.4 (0.4)
Aspen count	5.3 (0.3)	18.0 (1.7)	10.7 (0.6)	13.2 (0.4)
Shrub count 1	-[7] -	8.7 (1.3)	5.0 (0.3)	- -
Shrub count 2	13.2 (0.6)	18.5 (3.0)	15.2 (1.2)	- -
Height (cm)				
Average conifer height	119.8 (278,3.7)	106.3 (47,5.8)	121.1 (264,3.9)	147.4 (344,2.9)
Average hardwood height	288.0 (289,7.5)	230.4 (11.3)	288.4 (298,7.0)	313.3 (359,6.7)
Average Shrub height	98.5 (318,2.7)	68.0 (4.9)	58.5 (1.9)	60.0 (325,1.3)
Average Forb height	38.0 (321,1.1)	28.3 (1.8)	39.3 (1.1)	27.2 (0.6)
Average Grass height	39.0 (221,1.3)	40.7 (3.1)	36.4 (0.7)	29.9 (341,1.3)
Distance (cm)				
Average stem-to-stem	132.1 (314,1.2)	136.4 (2.0)	137.4 (1.0)	104.1 (1.1)
Avg. conifer stem-to-stem	137.5 (116,3.1)	136.4 (6,23.8)	135.2 (232,4.4)	90.6 (28,11.3)
Avg.hardwood stem-to-stem	128.8 (292,1.6)	134.9 (2.0)	135.5 (298,1.1)	109.0 (1.3)
Avg. aspen stem-to-stem	128.5 (257,1.8)	134.6 (2.4)	135.2 (287,1.3)	109.0 (1.3)

1. Mean values followed in brackets, by number of plots (when sample size less than full number of plots) and standard error of the mean.
2. n=322, except where noted.
3. n=51, except where noted.
4. n=302, except where noted.
5. n=361, except where noted.
6. Density was measured in the field in 2 m radius plots (12.57 m^2). In this table, the density values are converted to 10 m^2 (millhectare plot) equivalents.
7. Dash indicates data not recorded for that variable for that location.

Pine Falls area, while hardwoods were a significant competitor (32% of plots had more than 10 aspen stems (Table 4)), the shrubs were more abundant (in terms of cover) than hardwoods. In fact, the average shrub and target tree height were similar. For jack pine blocks in The Pas area, there was a lot of intraspecific competition, as only 46% of the plots had more hardwood stems than conifer stems in the plot. Grasses and forbs were not dominant on any of the sites, in terms of both cover and height (Table 5).

Exploratory Correlation and Linear Regression Analysis to Select Significant Growth and Competition Variables

An initial series of Spearman's rank order correlations and multiple linear regressions were performed on the black spruce data from the Pine Falls area (results not shown) to determine which variables were most useful in further analysis. In general, those growth variables that included radius had a greater absolute (negative) Spearmans' correlation (r_s) and higher regression coefficients of determination (r^2) than those that did not. As well, the more complex, size-independent variables did not have greater r_s values than the more simple growth variables. The competition variables with the largest absolute r_s values were those based on average competitor tree height, and the ratio between average competitor tree height and target tree height. A distance weighted basal area of the tallest and closest competitors (MACD1 in Appendix 1), was the best published competition index that didn't include the size of the target tree. Other competition indices with high r^2 were: distance weighted root collar diameter of the competitor (STENECK in Appendix 1) and ratio of root collar diameter of largest hardwood versus target tree (BDRATIO1 in Appendix 1). *In general, competition indices which included root collar diameter ratios had the highest r^2.*

These initial regression results were compared, through correlation analysis, with black and white spruce data in the Western Region. The results indicate the same trends for black spruce and white spruce from a different region. For both spruce species, in two regions, growth variables based on radius were more responsive to changes in competition levels than those based on height. In other words, the conifers were responding to competition stress through changes in radial growth rather than height growth. However, the competition variables with the highest r_s were the *ratio of average competitor tree height to the target tree height* and *ratio of tallest competitor tree height to target tree height.* Interestingly, age of the target tree alone did not have a high r_s value. In most regressions described in this section the r^2 values were less than 0.5 and an r^2 of 0.4 would be considered "high". This may be partly explained by the high variability in growth response at low competition levels (see Figure 3).

In summary, from the exploratory correlation and multiple regression results, *conifer growth was most responsive to changes in competition indices such as relative heights of competing and target trees and those based on root collar diameter.* The relatively high r^2 was partly due to changes in target tree size. This was a concern, and analysis to remove this effect is described later.

The Effect of Including and Excluding Conifers as a Component in Competition Indices

The initial analyses had used competition indices which were based on hardwood and conifer competitors. This was because statistical analysis indicated there was a significant amount of conifer competition within the plots. There were three reasons why testing of competition indices which only include hardwood competitors would be preferable to those which include conifers: 1) While there were appreciable amounts of conifers in the plots, the main competitor in all the sites were hardwoods, especially aspen. 2) Traditionally, competition indices developed for stand tending decisions in juvenile stands are based on intraspecific brush competition and do not include conifers. 3) Competition indices based on only hardwoods would be simpler to apply operationally.

Regression analysis was used to determine the effect of removing conifers from the competition indices. In general, the r^2 values were very similar for hardwoods alone as for hardwoods and conifers (Table 6). In a few cases, it even increased. For this reason, and the three stated earlier, *subsequent analysis used only hardwoods in the calculation of competition indices.*

As shown in Table 4, the jack pine sites in The Pas had significant amounts of intraspecific competition. It would be expected that the regression r^2 would be higher when conifers were included compared to hardwood alone, however, Table 6 indicates minimal effect of excluding conifers. This may be because, based on the jack pine selection criteria described in the methods section, target trees tended to be relatively isolated from adjacent jack pine, thus reducing effects of intraspecific competition.

Other Competition Variables Which Add Significantly to the Competition-Conifer Growth Models

Linear regression results of conifer growth versus competition variables (not including competition indices) was completed. There were five types of competition variables tested: density, cover, height/relative height, distance, and shading/dispersion/relative age. The competition variables based on relative height had, by far, the highest r^2 values, for all species and locations, with the r^2 of the best variables ranging from 0.25 to 0.76. The ratio of average height of hardwood and conifer competitors versus target tree height was the best overall. Other important competition variables included hardwood cover, and hardwood density, however, the r^2 were all less than 0.20. These could be considered as "secondary" variables. They were different for each conifer species and growth variable, and they did improve the predictive ability of the growth-competition relationships.

Since relative height variables explained the greatest amount of the conifer growth response, the ratio between the average height of all tree competitors versus target tree height was regressed with the other best competition indices from earlier analyses along with hardwood cover and density variables (Table 7). In general, the inclusion of other variables in the model resulted in a

Table 6
Comparison of Published Competition Indices Using
Hardwood & Conifer Competitors Versus Only Hardwood Competitors

Species/ Location	Growth Variable	Highest r^2 in Linear Regression		Two Competition Indices with Highest r^2 in Linear Regression	
		HW+C	HW	HW+CON	HW Alone
Black Spruce Pine Falls	Height	0.26	0.26	BDRATIO1 MARTIN	LORIMER MARTIN
	Diameter	0.28	0.28	BDRATIO1 MARTIN	LORIMER BDRATIO1
	Radial Inc.	0.3	0.30	BDRATIO1 BDRATIO2	BDRATIO1 LORIMER
	Height Inc.	0.24	0.26	BDRATIO1 MARTIN	MARTIN LORIMER
Black Spruce Duck Mountain	Height	0.28	0.32	BRAATHE BDRATIO2	MARTIN LORIMER
	Diameter	0.32	0.39	BRAATHE BDRATIO2	LORIMER BDRATIO2
	Radial Inc.	0.42	0.40	BRAATHE COMEAU	BRAATHE MARTIN
	Height Inc.	0.24	0.24	BRAATHE COMEAU	MARTIN BRAATHE
White Spruce Porcupine Hills	Height	0.09	0.08	COMEAU BRAATHE	COMEAU BRAATHE
	Diameter	0.12	0.12	BRAATHE COMEAU	BRAATHE COMEAU
	Radial Inc.	0.16	0.15	COMEAU BRAATHE	COMEAU BRAATHE
	Height Inc.	0.10	0.09	COMEAU BRAATHE	COMEAU BRAATHE
Jack Pine The Pas	Height	0.15	0.14	LORIMER BDRATIO2	LORIMER BDRATIO1
	Diameter	0.38	0.36	LORIMER MARTIN	LORIMER MARTIN
	Radial Inc.	0.45	0.45	MARTIN LORIMER	MARTIN LORIMER
	Height Inc.	0.07	0.09	BDRATIO2 RELVOL	BRAATHE BDRATIO2

1. Definitions and formulas for the competition indices are in Appendix 1.

Table 7
Linear Regression of Conifer Growth Versus
Relative Competitor Height in Combination With Other Competition Variables

Loc	Age Class	Growth Variable	r^2 for RELHT1 Alone[1]	Other Competition Variables that have High r^2	Max r^2 for 3 Var Model
PF	5 -9	Height	0.37	HARDWCOV MARTIN LORIMER	0.42
		Height Inc.	0.34	HARDWCNT MARTIN STSTCLOS	0.35
		Diameter	0.46	HARDWCNT LORIMER STSTCLOS	0.50
		Radial Inc.	0.39	STSTCLOS BDRATIO2 OT	0.41
PF	10	Height	0.38	HARDWCOV MARTIN LORIMER	0.48
		Height Inc.	0.34	HARDWCOV MARTIN LORIMER	0.43
		Diameter	0.36	HARDWCOV BDRATIO2 BDRATIO1	0.45
		Radial Inc.	0.38	HARDWCOV BDRATIO2 BDRATIO1	0.47
PF	11 -15	Height	0.40	STSTCLOS BDRATIO2 BDRATIO1	0.46
		Height Inc.	0.45	HARDWCNT MARTIN BDRATIO1	0.50
		Diameter	0.53	STSTCLOS BDRATIO2 BDRATIO1	0.57
		Radial Inc.	0.49	STSTCLOS BDRATIO1 BDRATIO2	0.53
PH	8 -13	Height	0.21	HARDWCNT HARDWCOV STSTCLOS	0.32
		Height Inc.	0.14	HARDWCNT HARDWCOV STSTCLOS	0.20
		Diameter	0.21	HARDWCNT HARDWCOV STSTCLOS	0.32
		Radial Inc.	0.33	HARDWCNT STSTCLOS HARDWCOV	0.41
PH	14 -20	Height	0.01	HARDWCOV STSTCLOS LORIMER	0.10
		Height Inc.	-	STSTCLOS MARTIN BDRATIO2	0.10
		Diameter	0.09	HARDWCOV STSTCLOS BDRATIO2	0.24
		Radial Inc.	0.08	HARDWCOV STSTCLOS OT	0.23
DM	8 -12	Height	0.63	HARDWCOV HARDWCNT STSTCLOS	0.67
		Height Inc.	0.53	BDRATIO1 BDRATIO2 OT	0.55
		Diameter	0.67	HARDWCNT BDRATIO1 OT	0.69
		Radial Inc.	0.68	HARDWCNT BDRATIO2 BDRATIO1	0.72
TP	6 - 8	Height	0.29	HARDWCOV MARTIN HARDWCNT	0.35
		Height Inc.	0.15	OT MARIN HARDWCNT	0.20
		Diameter	0.42	HARDWCOV MARTIN OT	0.55
		Radial Inc.	0.31	STSTCLOS MARTIN LORIMER	0.48
TP	9 -12	Height	0.57	HARDWCNT HARDWCOV BDRATIO1	0.64
		Height Inc.	0.07	STSTCLOS BDRATIO1 OT	0.09
		Diameter	0.53	STSTCLOS LORIMER HARDWCNT	0.71
		Radial Inc.	0.42	STSTCLOS LORIMER MARTIN	0.62

1. RELHT1 = average competitor height/target tree height, where average competitor height is based on all conifer and hardwood competitors, from individual height measurements.
2. Dash indicates that RELHT1 was not one of the best seven individual competition variables in the linear regression for the particular growth varianble.

greater r^2 than in models using the relative height ratio alone, but in some cases not by very much. *The additional variables that added most significantly to the model included hardwood cover, hardwood density and stem-to-stem distance of the closest competitor.*

In a series of single variable linear regressions, simplified relative height ratios based on the average aspen competitor had higher r^2 values than those based on the tallest aspen competitor (Table 8), however, both showed weaker regression relationships compared to the height ratios based on all tree competitors (Table 7). The strength of the linear regression results for aspen cover, density and target tree overtopping was much weaker still; in many cases there was no significant relationship at all. The more significant result of the height ratios compared to hardwood competition variables is partly explained by the fact that target tree size is incorporated in the relative height variables. While the r^2 values were lower, hardwood cover, hardwood count and overtopping showed significant relationships in some age classes, with maximum r^2 values of 0.18, 0.22 and 0.16, respectively. Non-linear regression did not improve the regression very much for the aspen variables. As with relative height using average trees, there was a large variation in results between age classes. In some locations, regression analysis stratified by block yielded higher r^2 values; this indicates there may be a block effect not accounted for when analysis is performed on a species and location basis (all blocks pooled together).

Linear and Non-Linear Regression was done to test the effect of target tree age on the growth variables. This was done with age as the single independent variable, and also age in combination with several relative height and competition variables (Table 9). Results indicate that age alone is a significant factor in predicting conifer growth, with r^2 values as high as 0.31. The inclusion of age and one other competition variable in non-linear models yielded significant r^2 values, up to 0.69 for relative average tree competitor-conifer height ratio versus radial increment.

From the results of correlation and regression analysis, the following five groups of competition variables were selected for use in much of the subsequent analysis:

1. Four relative height ratios.
   They are the ratio of target conifer tree height and the height of: a) tallest tree, b) tallest aspen c) average tree and d) average aspen. These variables were selected because they showed the best response in exploratory analysis, and provided the basis of the distance and height competition threshold analysis.

2. Competition indices based on RCD ratios and which (in some cases) included competitor stem to target stem distance.
   These indices were: MARTIN, LORIMER, BDRATIO1 and BDRATIO2 (Appendix 1). They were selected because they were the best competition indices in the analyses and were relatively easy to measure

3. Recently Developed Indices For Young Stands in B.C. and Ontario
   These indices were: COMEAU, DELONG, TOWILL (Appendix 1). They were selected

Table 8
Linear Regression of Conifer Growth Versus
Relative Aspen Height and Hardwood Cover, Density and Overtopping

Loc	Age Class	N	Growth Variable	RELHT3[1]	RELHT4[2]	Hardwood Cover	Hardwood Density	Over-topping
PF	5 -9	111	Height	0.24	0.13	-	-[3]	-
			Height Inc.	0.24	0.13	-	-	-
			Diameter	0.36	0.23	0.06	-	0.09
			Radial Inc.	0.28	0.18	0.05	-	0.10
PF	10	99	Height	0.45	0.29	-	-	0.06
			Height Inc.	0.44	0.29	-	-	0.06
			Diameter	0.44	0.32	-	-	0.07
			Radial Inc.	0.38	0.24	-	-	0.09
PF	11 -15	67	Height	0.19	0.12	0.09	-	0.10
			Height Inc.	0.21	0.16	0.18	0.18	-
			Diameter	0.35	0.26	0.11	-	0.16
			Radial Inc.	0.37	0.27	0.14	-	0.16
DM	8-12	51	Height	0.53	0.40	-	-	-
			Height Inc.	0.48	0.28	-	-	0.05
			Diameter	0.55	0.46	0.05	-	-
			Radial Inc.	0.56	0.43	0.07	-	0.08
PH	8 -13	153	Height	0.12	0.10	-	-	-
			Height Inc.	0.10	0.07	-	-	-
			Diameter	0.15	0.14	-	0.09	0.06
			Radial Inc.	0.26	0.25	-	0.07	0.09
PH	14 -20	142	Height	-	-	-	-	-
			Height Inc.	-	-	-	-	-
			Diameter	0.05	-	-	-	0.07
			Radial Inc.	0.05	-	-	0.07	0.10
TP	6-8	211	Height	0.22	0.15	-	-	-
			Height Inc.	0.12	0.09	-	-	0.05
			Diameter	0.33	0.25	-	-	0.09
			Radial Inc.	0.27	0.21	0.09	-	0.10
TP	9-12	147	Height	0.56	0.44	-	0.11	0.08
			Height Inc.	0.05	-	-	-	0.05
			Diameter	0.45	0.40	-	0.22	-
			Radial Inc.	0.35	0.31	0.18	-	-

1. RELHT3 = average aspen height/target tree height, where average aspen competitor height is based on all individual aspen height measurements.
2. RELHT4 = tallest aspen height/target tree height.
3. Dash indicates that the competition variable was not significant and had an r^2 of less than 0.05.

Table 9
Linear and Non-Linear Regression of the Most Significant Conifer Growth and Competition Variables

Species/ Location	Growth Variable	Competition Variable	Linear Regression r^2	Non-Linear Regression Including Age		
				r^2	Std	Fstat
Black Spruce Pine Falls	Radial Inc.	Age alone	0.13	-	-	-
	Radial Inc.	Relht1[1]	0.41	0.46	0.47	132.7
	Diameter	Relht1	0.39	0.55	4.61	187.31
	Radial Inc.	Overtopping	0.12	0.23	0.56	48.6
Black Spruce Duck Mountain	Radial Inc.	Age alone	0.21	-	-	-
	Radial Inc.	Total veg cover	0.12	0.32	0.42	11.63
	Radial Inc.	Relht1	0.68	0.69	0.28	54.83
	Radial Inc.	Weighted cover[2]	0.19	0.41	0.39	16.8
White Spruce Porcupine Hills	Radial Inc.	Age alone	0.31	-	-	-
	Radial Inc.	Relht2[3]	0.30	0.51	0.54	155.85
	Radial Inc.	Relht1	0.22	0.49	0.55	142.45
	Radial Inc.	Closest stem-to-stem distance	0.12	0.37	0.61	88.41
	Height	Relht2	0.20	0.64	42.83	269.72
Jack Pine The Pas	Radial Inc.	Age alone	0.02	-	-	-
	Radial Inc.	Hardwood cover	0.11	0.14	0.62	29.54
	Radial Inc.	Overtopping	0.11	0.17	0.61	35.48
	Ht_RCD	Weighted cover	0.13	0.15	15.69	31.1

1. RELHT1 = average competitor tree height/target tree height, where average aspen competitor height is based on all individual tree height measurements.
2. Weighted cover is the sum of height-weighted cover for all trees, shrubs, forbs and grass.
3. RELHT2 = tallest competitor tree height/target tree height.

because they had recently been developed for (in some cases) similar vegetation types to the Manitoba sites

4. Competition Indices Which Do Not Incorporate The Size of The Target Tree
   These indices were: DELONG, MACD1, MACD2, MACD3, MACD4 and STENECK (Appendix 1). They were selected because these indices had large r_s and r^2 values in the analysis than those variables developed by Radosevich and Wagner (1987)

5. Simple Hardwood Competition Variables
   These variables included: hardwood cover, hardwood density and overtopping. They were selected because they were easy to measure and widely used in silvicultural research

Competition variables related to non-tree competitors, and shading variables based on competitor dispersion were not investigated further. This was because they did not explain a significant amount of the observed target tree growth response, neither in single variable models, nor in combination with other competition variables.

Based on the correlation and regression analyses, four conifer seedling growth variables were used in subsequent analyses. They were radial increment(based on previous growing season), root collar diameter, total height and height increment(based on previous growing season). They were selected because they were easy to measure, more commonly used in silviculture research, and had stronger correlations and regression relationships with competition variables than did the more complex growth variables. Radial increment consistently showed the best correlation with competition variables, while height increment usually showed less significant relationships with competition. This may be partly because height increment is more directly affected by year-to-year changes in microclimate, insect and disease condition than is radial increment.

Other seedling growth variables were discarded for the following reasons:

1. Had weak correlations or low predictive ability in regression analyses.
2. Were error prone in measurement and harder to measure objectively (e.g., crown height).
3. Too complex to measure. While some of these growth variables were less affected by the size of the target tree, they were too complex to use in an operational setting (e.g., ratio of volume increment:basal stemwood).
4. Were not superior to similar, but simpler, variables. For example, three year mean periodic height and radial increment were not better than radial and height increment based on the previous growing season.

How Conifer Tree Size Influences Relationship Between Competition Indices, Relative Height Ratios, and Competition Variables

Competition indices which include the size of the target tree, such as those tested in this study, have seen widespread development and use (e.g., Martin and Ek 1984, MacDonald et al. 1990, Comeau 1991) and have been defended in the literature (e.g., Lorimer 1983). They have, however, been criticized as not appropriate by others (e.g., Mitchell-Old 1987, Burton 1993) because large growth may not so much be due to competition as it is to size in the current year. The problem is that their highly predictive results can give the reader unwarranted confidence in the results. For this reason, other indices which do not include target tree size were included in the analysis. For the most part, there was not a strong relationship the target tree size and these indices (see indices MACD1, MACD2, MACD3, MACD4, STENECK and DELONG in Tables 10 and 11). The best index which does not incorporate target tree size is the distance weighted basal area of the tallest and closest competitors (MACD1), with a best r^2 of only 0.11. This finding is corroborated by recent publications. For example, Wagner and Radosevich (1987, 1991a,b) presented a competition index for Douglas fir-red alder in which the growth-competition index had an r^2 of only 0.11.

There are several approaches to remove or lessen the effect of target tree size on the relationship between target tree growth and competition indices. One approach was to use less size-dependant growth variables in the analysis, as was done for this study. A second approach was to stratify the plots into 5 mm RCD classes (Table 10) and 33 cm height classes (Table 11), so that changes in competition indices which incorporate competitor:target conifer tree competition ratios would be primarily due to changes in competitor size. Regression analysis was then run with the most important competition indices and relative height ratios versus target tree radial increment. The latter was chosen because it was the best performing growth variable. As well, a dynamic growth response variable such as radial increment is preferable to a cumulative growth variable such as height or RCD, because the response of cumulative growth variables would be constrained by the RCD classes.

In all cases, the r^2 values were lower than for comparable analysis with target tree size not controlled; however, the relative ranking was similar to previous regressions (Tables 10 and 11). *The relative height of average conifer to hardwood and conifer competitors to the target tree was still the best index to use with radial increment for conifers stratified by RCD size classes* (Table 10). *For trees stratified by height classes, the distance weighted RCD ratio of competitors versus target tree (Martin) was the best competition index* (Table 11).

The regression analyses described in the preceding sections show surprisingly weak relationships between what could be considered major competition variables (e.g., hardwood density and cover in Table 8) and conifer growth response. This is also the case with a number of competition indices (e.g., Tables 10 and 11). Figure 3 describes why this occurs. It illustrates the regression of hardwood competition, as described by Delong's 1991 Competition Index versus conifer radial increment for jack pine in The Pas. The best non-linear regression model has an r^2 of only 0.09.

Table 10

Target Tree Radial Increment vs All Published Competition Indices[1] and Relative Height Ratios Stratified by 5 mm Target Tree RCD Classes

Variable	Overall Average[2] r^2	Average Linear Regression r^2 (range in brackets)			
		Black Spruce Pine Falls	Black Spruce Duck Mountain	White Spruce Porcupine Hills	Jack Pine The Pas
No. Classes[3]		5	2	9	7
Size Classes with Highest r^2		10-15 mm	15-20 mm	5-10 mm to 15-20 mm	25-30 mm
<u>Most Significant</u>					
Relht1[4]	0.16	0.15 (0.10-0.23)	0.33 (0.21-0.46)	0.18 (0.00-0.47)	0.15 (0.09-0.33)
Relht2[5]	0.14	0.11 (0.04-0.23)	0.37 (0.28-0.45)	0.19 (0.00-0.61)	0.11 (0.01-0.24)
Relht3[6]	0.14	0.14 (0.01-0.27)	0.40 (0.27-0.53)	0.12 (0.00-0.46)	0.17 (0.06-0.38)
Lorimer	0.13	0.09 (0.01-0.14)	0.01 (0.00-0.01)	0.09 (0.00-0.18)	0.21 (0.10-0.32)
Martin	0.12	0.07 (0.00-0.12)	0.01 (0.00-0.02)	0.07 (0.00-0.24)	0.23 (0.14-0.39)
Relvol	0.12	0.14 (0.05-0.19)	0.06 (0.01-0.11)	0.07 (0.00-0.29)	0.14 (0.07-0.24)
<u>Others</u>					
Comeau	0.12	0.08 (0.02-0.12)	0.48 (0.14-0.67)	0.11 (0.01-0.35)	0.16 (0.11-0.23)
Relht4[7]	0.11	0.09 (0.00-0.22)	0.32 (0.29-0.34)	0.13 (0.00-0.76)	0.11 (0.02-0.29)
BDRatio2	0.10	0.13 (0.00-0.23)	0.01 (0.00-0.01)	0.06 (0.00-0.23)	0.10 (0.01-0.17)
Braathe	0.10	0.06 (0.03-0.12)	0.33 (0.20-0.45)	0.10 (0.00-0.27)	0.15 (0.04-0.38)
Towill	0.10	0.08 (0.00-0.14)	0.42 (0.17-0.66)	0.10 (0.00-0.34)	0.16 (0.06-0.37)
Macd1	0.09	0.07 (0.02-0.10)	0.01 (0.00-0.01)	0.03 (0.00-0.09)	0.18 (0.01-0.30)
Delong	0.09	0.04 (0.00-0.11)	0.29 (0.06-0.52)	0.06 (0.00-0.21)	0.17 (0.13-0.27)
BDRatio1	0.08	0.09 (0.00-0.17)	0.02 (0.01-0.02)	0.05 (0.00-0.15)	0.11 (0.04-0.17)
Daniels	0.08	0.04 (0.00-0.08)	0.01 (0.00-0.01)	0.03 (0.00-0.12)	0.18 (0.07-0.34)
Brande	0.08	0.06 (0.00-0.12)	0.30 (0.01-0.59)	0.05 (0.00-0.22)	0.14 (0.03-0.25)
Steneck	0.08	0.02 (0.00-0.06)	0.01 (0.01-0.01)	0.03 (0.00-0.12)	0.18 (0.07-0.27)
Macd3	0.07	0.03 (0.00-0.06)	0.23 (0.02-0.41)	0.05 (0.00-0.20)	0.14 (0.04-0.25)
Macd4	0.07	0.03 (0.00-0.06)	0.21 (0.02-0.40)	0.04 (0.00-0.18)	0.15 (0.02-0.22)
Macd2	0.06	0.04 (0.00-0.09)	0.13 (0.02-0.24)	0.03 (0.00-0.09)	0.12 (0.00-0.17)

1. Definitions and formulas for the competition indices are in Appendix 1.
2. Average from all size classes for each species at each location.
3. Number of size classes. Only those size classes with n greater than 9 are used in the analysis.
4. RELHT1 = average competitor tree height/target tree height, where average competitor height is based on all individual tree height measurements.
5. RELHT2 = tallest competitor tree height/target tree height.
6. RELHT3 = average aspen height/target tree height, where average competitor height is based on all individual aspen height measurements.
7. RELHT4 = tallest aspen height/target tree height.

Table 11
Target Tree Radial Increment vs All Published Competition Indices[1] and Relative Height Ratios Stratified by 33 cm Target Tree Height Classes

Variable	Overall Average[2] r^2	Average Linear Regression r^2 (Range in Brackets)			
		Black Spruce Pine Falls	Black Spruce Duck Mountain	White Spruce Porcupine Hills	Jack Pine The Pas
No. Classes[3]		5	2	8	8
Size Classes with Highest r^2		169-199 cm	66-99 cm	66-99 cm to 133-166 cm	300-333 cm
<u>Most Significant</u>					
Martin	0.24	0.17 (0.04-0.33)	0.17 (0.12-0.22)	0.13 (<0.01-0.35)	0.42 (0.21-0.70)
Lorimer	0.23	0.17 (0.15-0.31)	0.17 (0.10-0.24)	0.13 (0.01-0.43)	0.39 (0.21-0.70)
BDRatio1	0.20	0.19 (0.07-0.36)	0.19 (0.14-0.24)	0.13 (<0.00-0.44)	0.28 (0.07-0.57)
BDRatio2	0.19	0.21 (0.05-0.47)	0.22 (0.20-0.24)	0.10 (0.03-0.31)	0.27 (0.07-0.65)
Daniels	0.19	0.14 (0.03-0.31)	0.03 (0.01-0.04)	0.08 (<0.01-0.27)	0.34 (0.08-0.58)
Relht1[4]	0.17	0.11 (0.04-0.23)	0.33 (0.28-0.37)	0.18 (<0.01-0.36)	0.24 (0.02-0.39)
<u>Others</u>					
Relht3[5]	0.17	0.13 (0.03-0.33)	0.29 (0.28-0.29)	0.16 (<0.01-0.31)	0.22 (<0.11-0.41
Revol	0.17	0.13 (0.07-0.27)	0.12 (0.06-0.18)	0.10 (<0.01-0.27)	0.28 (0.03-0.74)
Braathe	0.16	0.13 (0.06-0.33)	0.21 (0.08-0.34)	0.17 (<0.01-0.34)	0.19 (<0.01-0.64)
Comeau	0.16	0.13 (0.05-0.30)	0.19 (0.09-0.28)	0.14 (<0.01-0.28)	0.22 (0.03-0.63)
Delong	0.15	0.11 (0.03-0.30)	0.11 (0.03-0.30)	0.12 (<0.01-0.24)	0.22 (0.01-0.61)
Relht2[6]	0.13	0.09 (0.01-0.21)	0.37 (0.32-0.42)	0.12 (<0.01-0.24)	0.13 (0.02-0.36)
Relht4[7]	0.13	0.10 (0.01-0.30)	0.43 (0.41-0.45)	0.14 (0.03-0.30)	0.16 (<0.13-0.37)
Macd3	0.13	0.04 (0.02-0.06)	0.16 (0.01-0.31)	0.12 (<0.01-0.25)	0.24 (0.11-0.43)
Macd4	0.13	0.05 (0.03-0.09)	0.43 (0.41-0.45)	0.11 (<0.01-0.22)	0.22 (0.09-0.40)
Towill	0.13	0.12 (0.05-0.27)	0.20 (0.12-0.16)	0.11 (<0.01-0.23)	0.17 (<0.01-0.62)
Steneck	0.12	0.08 (0.03-0.21)	0.08 (0.03-0.21)	0.02 (<0.01-0.08)	0.26 (0.04-0.57)
Macd2	0.12	0.08 (<0.01-0.16)	0.08 (<0.01-0.16)	0.09 (<0.01-0.23)	0.20 (0.05-0.38)
Brande	0.10	0.08 (<0.01-0.31)	0.08 (<0.01-0.31)	0.08 (<0.01-0.18)	0.14 (<0.01-0.46)
Macd1	0.10	0.08 (<0.01-0.24)	0.08 (<0.01-0.24)	0.02 (<0.01-0.07)	0.21 (0.04-0.65)

1. Definitions and formulas for the competition indices are in Appendix 1.
2. Average from all size classes for each species at each location.
3. Number of size classes. Only those size classes with n greater than 9 are used in the analysis.
4. RELHT1 = average competitor tree height/target tree height, where average competitor height is based on all individual tree height measurements.
5. RELHT3 = average aspen height/target tree height, where average competitor height is based on all individual aspen height measurements.
6. RELHT2 = tallest competitor treeheight/target tree height.
7. RELHT4 = tallest aspen height/target tree height.

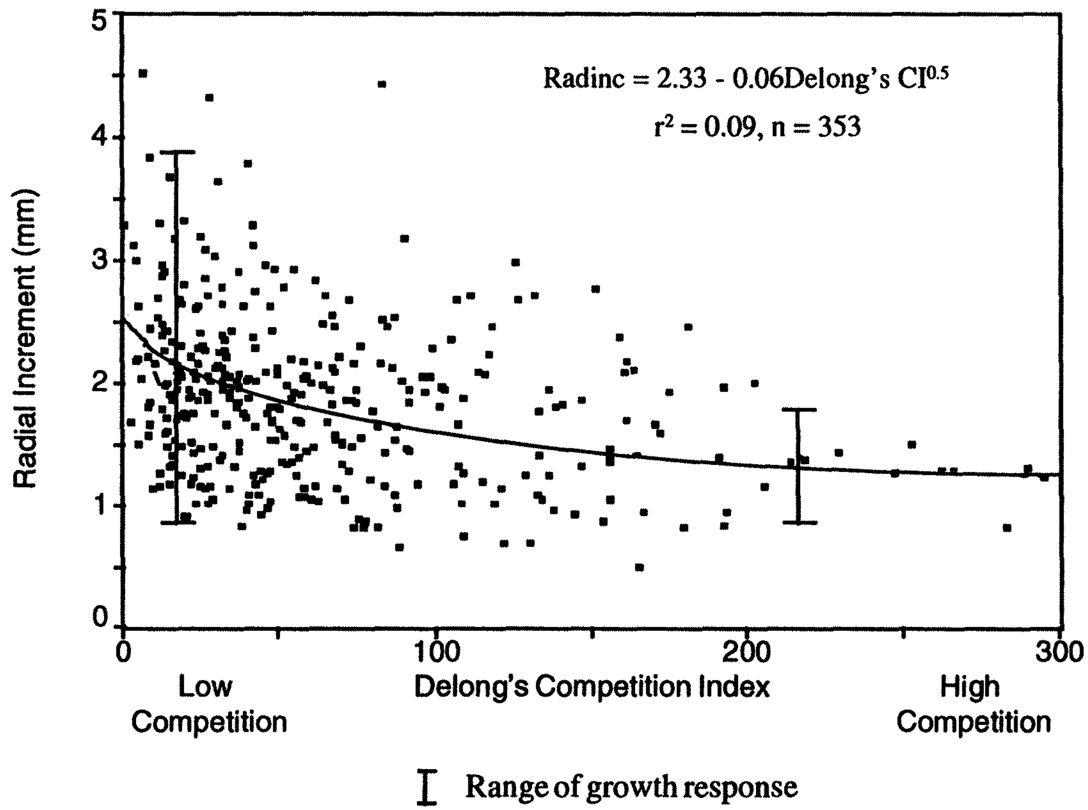


Fig. 3 Relationship Between Jack Pine Radial Increment and Hardwood Competition - The Pas

This is caused by the wide degree of variation in growth response at low to moderate competition levels. The widely-accepted explanation is that at lower competition levels, microsite conditions and other factors contribute to variations in growth response. The use of data transformations and inclusion of additional variables in the regression models often does not improve the model's explanatory power very much.

Non-linear regression was completed to duplicate most of the linear regression performed in the preceding sections (Tables 6-8, 10-11) because some of the exploratory analysis had indicated non-linearity between competition and growth response. In almost all non-linear regression analyses, the r^2 values increased relative to the linear regression. However, the relative ranking of the results, based on the r^2 values did not change. These analyses will be presented in the Canadian Forest Service information report to be published later in the 1995/96 fiscal year.

Test to Determine If Larger Target Trees are Associated with Lower Competition Levels

A direct approach was used to test if there was a significant difference in average competition levels around target trees larger and target trees smaller than the average target tree size for a specific location and tree age. A series of t-tests (with correction for unequal variances) were used, and tested a variety of competition variables. The following questions were addressed:

1. Is the average competition around the target trees significantly different for target trees which have a larger RCD than average versus those target trees that have a smaller RCD than average (where average is defined as the mean RCD for that particular location, species and tree age)? This test was repeated for 25 different competition variables.

2. Is the average competition around the target trees significantly different for target trees which have a taller height than average versus those target trees that have a smaller height than average (where average is defined as the mean height for that particular location, species and tree age)? This test was repeated for 25 different competition variables.

The tests indicated that in fact, for both height and RCD, there were different levels of competition associated with larger than average and smaller than average target trees (results not shown). There were significant differences ($P< 0.05$) for a variety of competition variables that did not include target tree size, such as hardwood and conifer competitor cover and density, average and closest competitor stem and foliage distance. In most cases, smaller target trees had greater amounts of hardwood cover, density, and closer competitor stems. For shrubs, grasses and forbs, the results were not as clear. In some cases, larger target trees were associated with more abundant and taller forbs, grasses and shrubs. This would be due to microsite effects, where conditions were good for growth of all plant types. It may also partly explain why shrubs, forbs and grass factor negligibly in the regression models. In the sites studied, only the hardwoods exert enough shading effect to reduce the conifer growth. In summary, *there is evidence that significantly different levels of tree competition are associated with trees growing faster and* *slower than the average tree.*

Determination of Competitor Distance and Height Thresholds

Previous analysis in this study had shown, very clearly, that competitor height relative to target tree height was one of the best competition variables in "predicting" conifer growth, and that some of the competitor distance measurements were useful as "secondary" variables. From these results, a comprehensive series of tests were conducted. This analysis investigated the effect on target tree size (e.g., height or RCD) and growth rate (e.g., radial increment or height increment) with hardwood and shrub competitors at various distances and heights relative to the target tree.

Two questions were addressed:

1. At what distance from the conifer do hardwood trees begin to significantly affect conifer growth (Figure 4)? In other words, what is the required growing space around a conifer seedling to ensure growth potential is met?
2. For a given intertree distance, at what relative hardwood competitor-target tree height difference do hardwood trees begin to significantly affect conifer growth (Figure 5)?

Table 12 presents the matrix of the distance and height competition thresholds which were tested. It could be considered as a type of two-way factorial design as shown below:

Factor	Levels	Description of Levels
Relative Competitor:Target Tree Height Ratio	6	0.5, 0.66, 0.75, 1.0, 1.25, 1.5[1]
Competitor Distance (cm) (target tree growing space)	7	25, 50, 75, 100, 125, 150, 175

In each test, a specific combination of competitor height ratio and distance was used to group the target trees from each plot into free-to-grow (FTG) and not free-to-grow (NFTG) categories. For example, in one test a target tree would be considered NFTG if it had hardwoods taller than 100% of the target tree height (i.e., height ratio of 1.0), with stems within 75 cm of the target tree. In another test, the target tree would be considered NFTG if it had hardwoods taller than 66% of the target tree height (i.e., height ratio of 0.66), with stems within 125 cm of the target tree. Only a subset of the possible competitor distance-height threshold combinations was tested,

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[1]For example, a relative height ratio of 0.66 meant that the competitor was 66% (⅔) the height of the target conifer tree. A relative height ratio of 1.25 meant that the competitor was 125% (25% larger than) the height of the target tree.

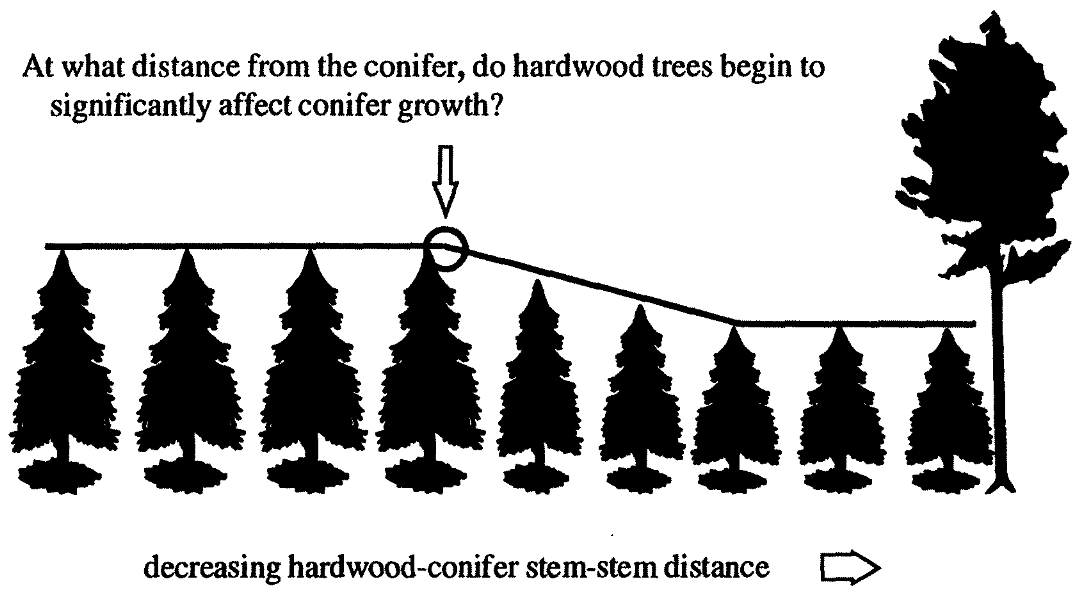
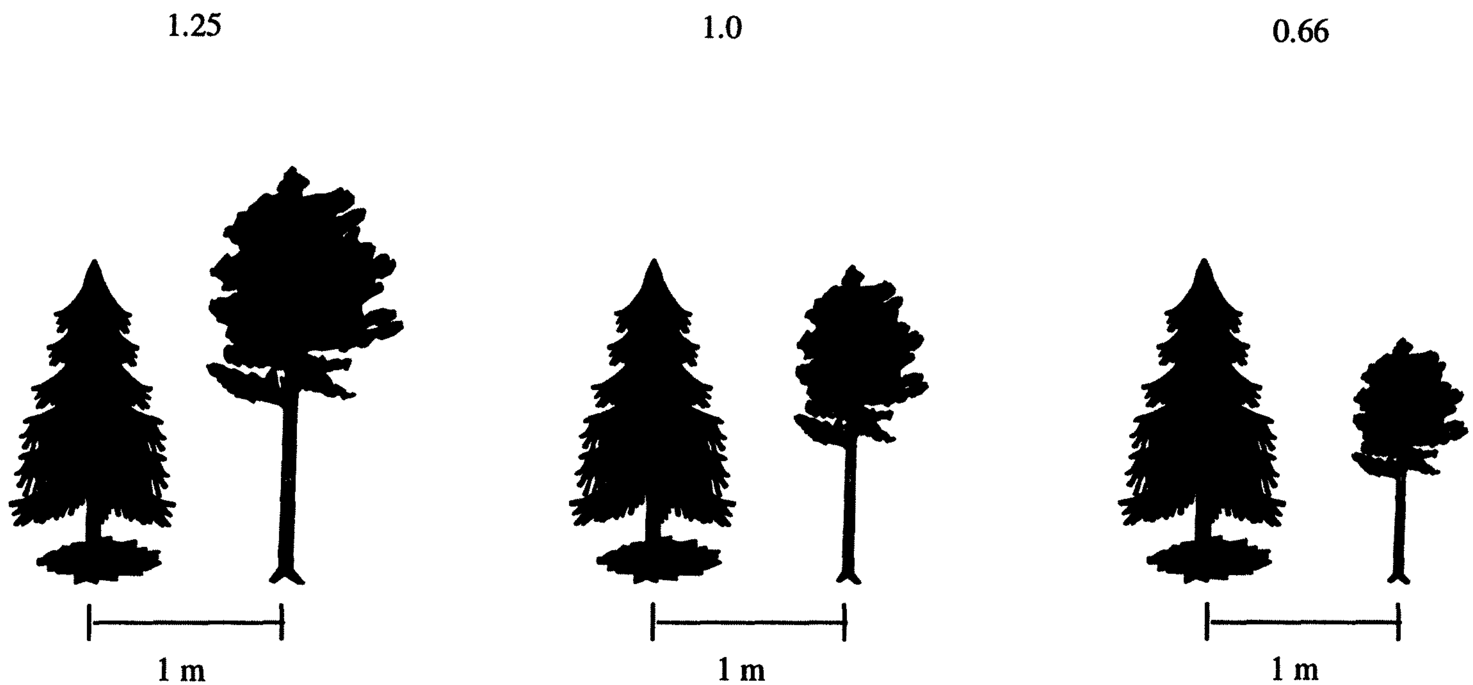


Fig. 4 Determination of hardwood-conifer inter-tree distance thresholds.

Different hardwood: conifer height ratios.



At what relative hardwood:conifer height is conifer growth significantly affected?

Fig. 5 Determination of hardwood-conifer height ratio thresholds as shown in Table 12. Each test was run independent of the others. In other words, the grouping of target trees into FTG and NFTG sets was based on the unique combination of competition height ratio and distance thresholds; a tree could be defined as FTG in one test and NFTG in the next.

In each separate test (based on the unique combination of competitor distance and height factors), a t-test (with correction for unequal variances) was used to test for significant differences in growth of target trees designated as FTG versus target trees designated as NFTG. Four growth variables were tested: total tree height, height increment, radial increment and root collar diameter. The tests were done separately for each species, location and age class[1]. Analysis was stratified by target tree age class to control for target tree size in the analysis. There were two components of the tests which were of interest. The probability value (P-value) of the t-test indicated the consistency of the difference in growth between target trees designated as FTG versus target trees designated as NFTG. The relative difference between FTG and NFTG tree growth indicated the strength of the difference. A specific combination of factors could be considered important in defining competition thresholds when they resulted in the lowest P-value with the greatest growth difference between FTG and NFTG trees.

These tests were repeated using two definitions of competition: hardwoods alone and hardwoods plus shrubs. In the latter case, shrub competitors were considered (along with hardwoods) when determining if a target conifer was free-to-grow. These tests were also repeated with distance measurements based on stem-to-stem distance and based on stem-to-competitor-foliage (inside crown) distance. These replications were used to determine what was more important in competition thresholds: hardwoods or hardwoods and shrubs, and stem-to-stem distance or stem-to-competitor-foliage distance.

Overall results indicate that *competition thresholds using hardwoods alone with stem-to-stem distance yielded the overall lowest P-values and the highest growth difference between FTG and NFTG trees.* This result was consistent for jack pine in The Pas and white spruce in the Porcupine Hills. However, results for black spruce in Pine Falls indicate that hardwoods and shrubs yielded the most significant results, perhaps due to the greater proportion of shrubby sites in those locations (see Table 5).

Distance Thresholds

Figure 6 illustrates how the output of the distance threshold t-tests is interpreted graphically. The top diagram shows the trend in actual size or growth (e.g., RCD or radial increment) of FTG and NFTG trees based on FTG definitions using different hardwood-conifer intertree distances. This can be shown by one t-test which determines, for example, the effect of a 75 cm competition distance threshold on tree size. FTG trees (defined as having no competitors above a certain

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[1] Analysis was performed on black spruce in the Duck Mountains, but not shown in graphical output as results in that location are based only on one block.

Table 12
Matrix of Tested Distance and Height Thresholds

Competitor:Target (Conifer) Tree Height Ratio	Competitor:Target (Conifer) Tree Distance (cm)						
	25	50	75	100	125	150	175
0.5				x[1]			
0.66	x	x	x	x	x	x	x
0.75				x			
1.0	x	x	x	x	x	x	x
1.25				x			
1.5				x			

1 For a particular plot, the target tree is deemed to be free-to-grow if there was no hardwood taller than x% of the target tree, within y cm of the target tree (based on stem-to stem distance).

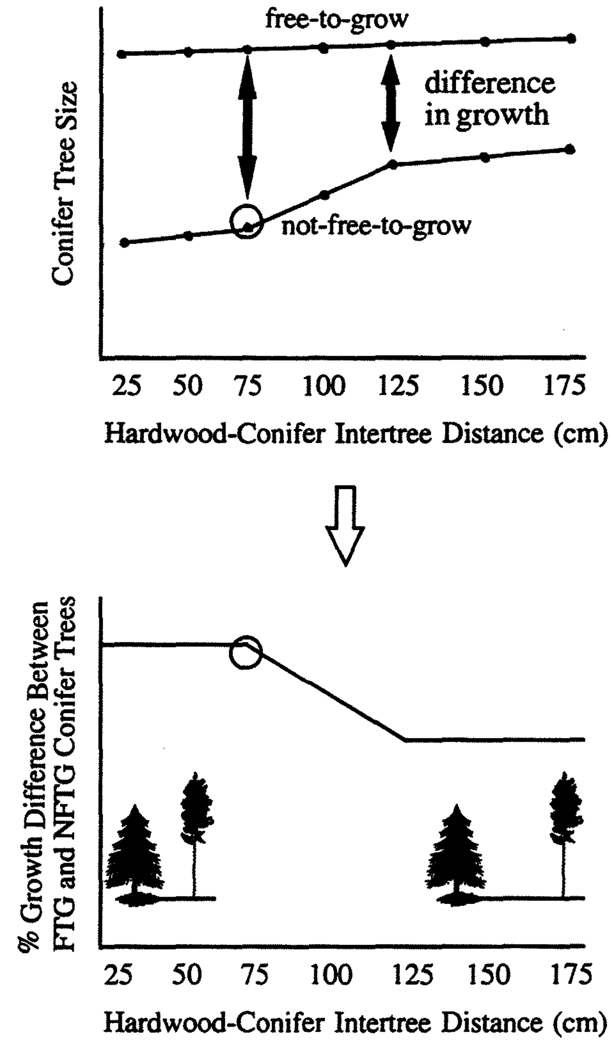

Fig. 6 Graphical representation of methodology used to determine hardwood-conifer competition distance thresholds. The dots on the lines in the top diagram illustrate the average tree sizes for FTG and NFTG trees for each distance threshold, based on the individual t-test results. The circles in the diagrams represent the critical distance thresholds. The trees in the lower diagram represent the stem distances associated with the x-axis values and a consistent competitor-target tree height ratio of 0.66. Note: growth difference is defined as ((FTG size - NFTG size)/FTG size)*100.

relative height within 75 cm of the target tree) have an average tree size. This average size is plotted as the value on the top line at the 75 cm point along the x-axis (competitor distance). Those trees designated as NFTG in the same test (defined as having at least one competitor above a certain relative height within 75 cm of the target tree) would also have an average size. This average is plotted as the bottom line value, at the 75 cm point along the x-axis.

The separate average FTG and NFTG tree sizes (or growth rates) for each t-test at each competitor distance are plotted and joined to create the FTG and NFTG lines in the top diagram, thus yielding the *trend* in FTG versus NFTG tree size over all distance thresholds. In general, it is expected that the average size of a FTG tree will increase (for a constant relative height ratio) at larger competitor-tree distance thresholds. This is because for a tree to be defined as FTG at the 150 cm distance threshold, it requires more growing space than a FTG tree based on a 50 cm distance threshold.

It is important to note that the series of tests described above present only one factor in the two factor design. The second factor of relative competitor height would be set, in this example, at a certain ratio over all the distance tests. One way to describe this effect would be to add the relative competitor height along a third axis on the top diagram in Figure 6.

The difference between the FTG and NFTG lines as described above is then combined in the lower diagram in Figure 6 to illustrate changes in the growth *difference* between the FTG and NFTG trees. The diagram also includes small silhouettes of hardwood and conifers to illustrate the intertree distance associated with the values on the x-axis. Note that while the lower diagram in Figure 6 looks superficially like the diagram in Figure 4, *they are not synonymous*. Figure 4 is based on a single target tree size response while Figure 6 shows a growth difference between FTG and NFTG target trees.

There are three distinct parts to the bottom diagram in Figure 6:

Small Distance (25-75 cm growing-space distance thresholds)

Relative to the FTG trees, NFTG trees are strongly suppressed by competition. For a given competitor-target tree height ratio, changes in the competition-free growing space around the target tree have no effect on the target tree growth. In other words, at that range of competitor distances, the NFTG target trees are always suppressed by the competitors.

Medium Distance (75-125 cm growing-space distance thresholds)

This is the distance range where, for a given competitor-target tree height ratio, there are large changes in the growth suppression of NFTG trees, relative to FTG trees. Inclusion of competitors in the definition of growing space of FTG trees at increasing distances causes less and less suppressed NFTG trees.

Large Distance (125-175 cm growing-space distance thresholds)

Relative to the FTG trees, NFTG trees are not strongly suppressed by competition. For a given competitor-target tree height ratio, changes in the area of the competition-free growing space around the target tree does not have an effect on the target tree growth. In other words, at that range of competitor distances, the NFTG target trees are not suppressed by the competitors.

From a management perspective, in Figure 6, the critical competitor-target conifer intertree distance is the point where the *difference* in FTG versus NFTG tree growth *starts to decrease.* This is because a definition of growing space for trees defined as FTG should yield the greatest growth difference between FTG and NFTG trees. A definition of a FTG tree which yields a smaller difference in FTG versus NFTG tree growth would not be desirable.

The distance threshold tests were duplicated using a hardwood:conifer height ratio of 0.66 and 1.0 (Table 12). *In these distance threshold tests, the overall lowest P-value and height growth difference was achieved using the 0.66 height ratio.* Figures 7-9 graphically represent the t-test results for differences in size and growth rate between FTG and NFTG trees based on FTG definitions using different distance criterion, and a relative hardwood:conifer height ratio of 0.66.

The overall results for black spruce in Pine Falls, and white spruce in Porcupine Hills indicate, quite clearly, critical competitor distance thresholds of 75 cm and 100 cm respectively (Figures 7 and 8). These were based on overall averages for all age classes and growth variables combined. The P-values for these tests was less than 0.10 for most of the distances tested. For the jack pine data in The Pas, the growth differences based on the combined results of the four growth variables was less clear. However, when results were plotted for certain age classes based on the average of all growth variables with height increment excluded, a threshold of 125 cm becomes obvious (Figure 9).

Of the four growth variables used in the distance tests, radial increment had the lowest P-value (consistently < 0.10) and greatest growth differences between FTG and NFTG trees. However, the *trend* in growth differences between FTG and NFTG trees versus distance thresholds were the same for all growth variables. Differences in radial increment growth of FTG versus NFTG trees is shown separately for each age class for each tree species and location in Appendix 2. These support the distance thresholds based on all data combined. (Figures 7-9).

Height Thresholds

Most of the concepts presented in the discussion on critical distance thresholds from the previous section, also apply to this section on relative competitor-target tree height thresholds. The underlying theoretical approach to presentation and interpretation of the critical height threshold is shown in Figure 10. In these series of t-tests, the growing space around the target tree is fixed while the relative competitor-target tree height ratio is varied.

In the distance thresholds analysis, two series of t-tests were performed, based on relative height ratios of 0.66 and 1.0. With the height threshold analysis, one series of t-tests were performed,

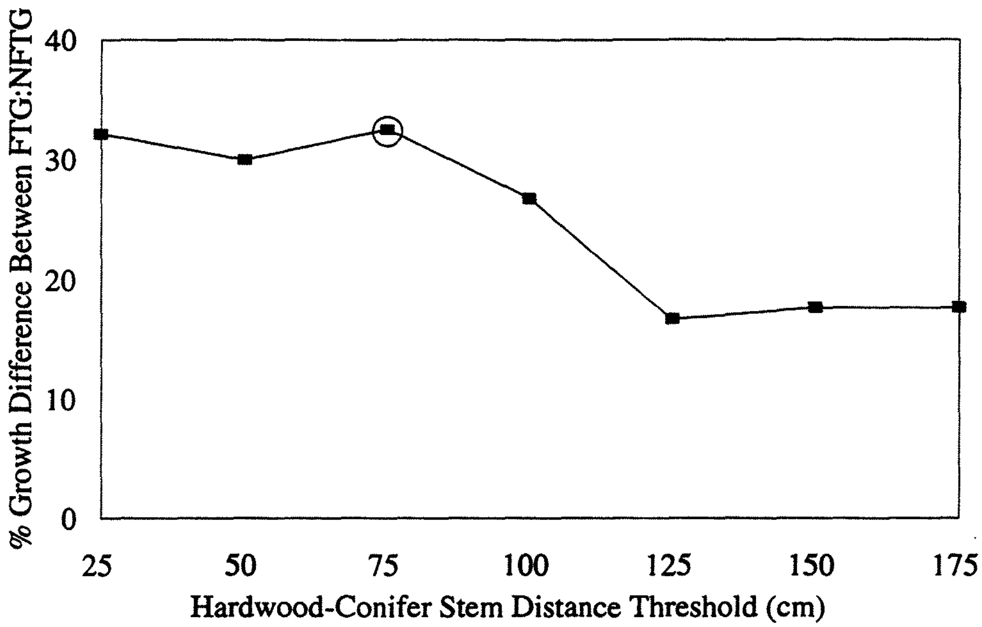

Fig. 7 Effect of hardwood-conifer stem distance on growth response between free-to-grow and not-free-to-grow black spruce in Pine Falls. Based on overall average of separate t-tests performed for each age class and growth variable (radial increment, RCD, height and height increment). The critical distance threshold is circled on the line. Tests based on hardwood-conifer height ratio of 0.66.

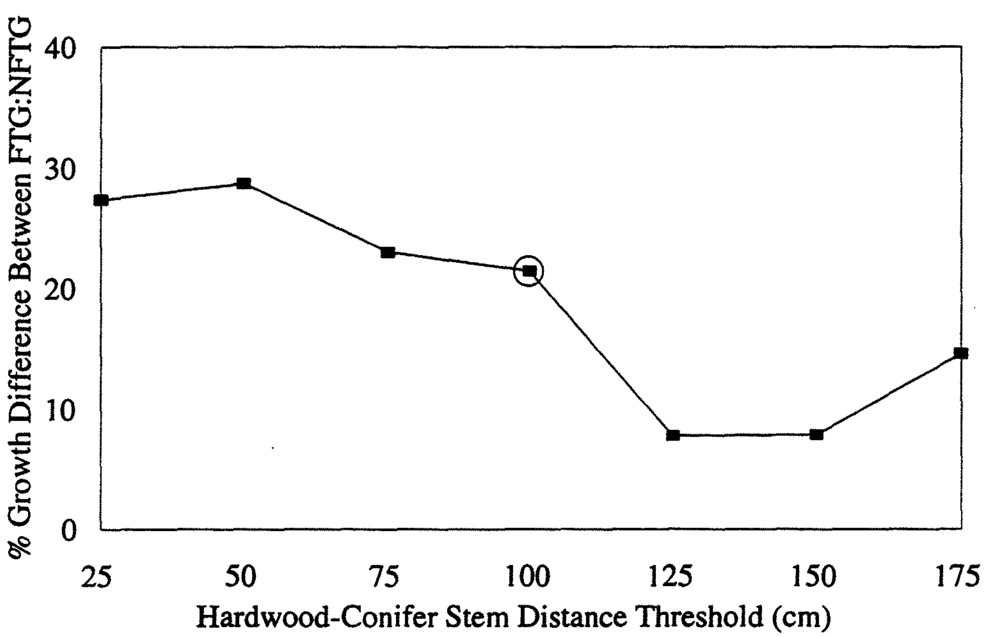

Fig. 8 Effect of hardwood-conifer stem distance on growth response between free-to-grow and not-free-to-grow white spruce in Porcupine Hills. Based on overall average of separate t-tests performed for each age class and growth variable (radial increment, RCD, height and height increment). The critical distance threshold is circled on the line. Tests based on hardwood-conifer height ratio of 0.66.

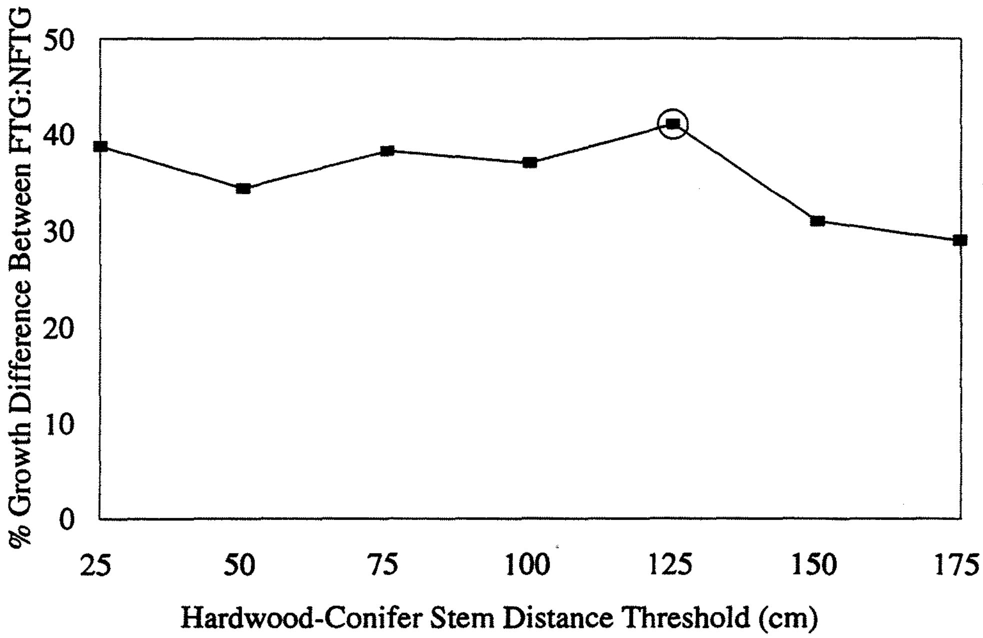

Fig. 9 Effect of hardwood-conifer stem distance on growth response between free-to-grow and not-free-to-grow jack pine in The Pas for age class 9-12. Based on overall average of separate t-tests performed for each growth variable (radial increment, RCD and height). The critical distance threshold is circled on the line. Tests based on hardwood-conifer height ratio of 0.66.

based on a fixed 1 m competitor-hardwood growing space used in the FTG definition (Table 12).

In contrast to the distance threshold, *the critical relative height threshold is the point where the growth difference between FTG trees and NFTG trees starts to increase.* This can be explained as follows, using Figure 10. For a given competitor-target tree distance threshold, changes in relative competitor-target tree height at low height ratios (e.g., 0.5-0.75) do not result in a significant change between FTG and NFTG tree growth. This is because the competitors are small compared to the target tree, throughout that range of height ratios. Likewise, for a given competitor-target tree distance threshold, changes in relative competitor-target tree height at high height ratios (e.g., 1.25-1.75) do not result in significant changes between FTG and NFTG tree growth. This is because the competitors are already large compared to the target tree, throughout that range of height ratios. The range of relative height ratios between 0.75 and 1.75 is the zone associated with significant changes in the difference between FTG and NFTG tree growth. In Figure 6, moving to the right along the distance axis means better growing conditions for a tree defined as FTG, because the FTG tree would be defined as having more growing space. In Figure 10, moving to the right along the height ratio axis means poorer growing conditions because a tree designated as FTG could have taller competitors. It is when this gradient of growing conditions starts to have an effect on the FTG-NFTG size differences that the critical height threshold occurs.

Figures 11-13 graphically present the t-test results for differences in size and growth rate between FTG and NFTG trees, based on FTG definitions using different relative height criteria, and a distance (growing-space) threshold of 1 m. The overall results for the three species indicate consistent critical height thresholds of 0.66, based on results averaged for all age classes and growth variables. The P-values for these tests were less than 0.10 over most of the relative height ratios tested. For the white spruce in the Porcupine Hills, RCD results were not as conclusive, so the overall average is based on radial increment, height and height increment for all age classes (Figure 12).

Of the four growth variables used in the height ratio tests, radial increment had the lowest P-value (consistently < 0.10) and the greatest growth difference, however, the *trend* in growth difference between FTG and NFTG trees versus height ratio was the same for all growth variables. Differences in radial increment growth of FTG versus NFTG trees is shown separately for each age class for each tree species and location in Appendix 2. They support the distance thresholds based on the overall results for all age classes and growth variables combined (Figures 11-13).

The critical height thresholds were validated through non-linear regression, in which conifer radial growth was regressed against height of the closest competitor. In most, cases, the place on the curve where the conifer growth started to decline was between 66% and 100 % of the relative target tree to competitor height (results not shown).

A second approach to determine the height competition thresholds involved correlation analysis with competitors above and below specific relative height levels. The analysis of competition thresholds for black spruce from the Pine Falls area indicated that competing trees and shrubs that

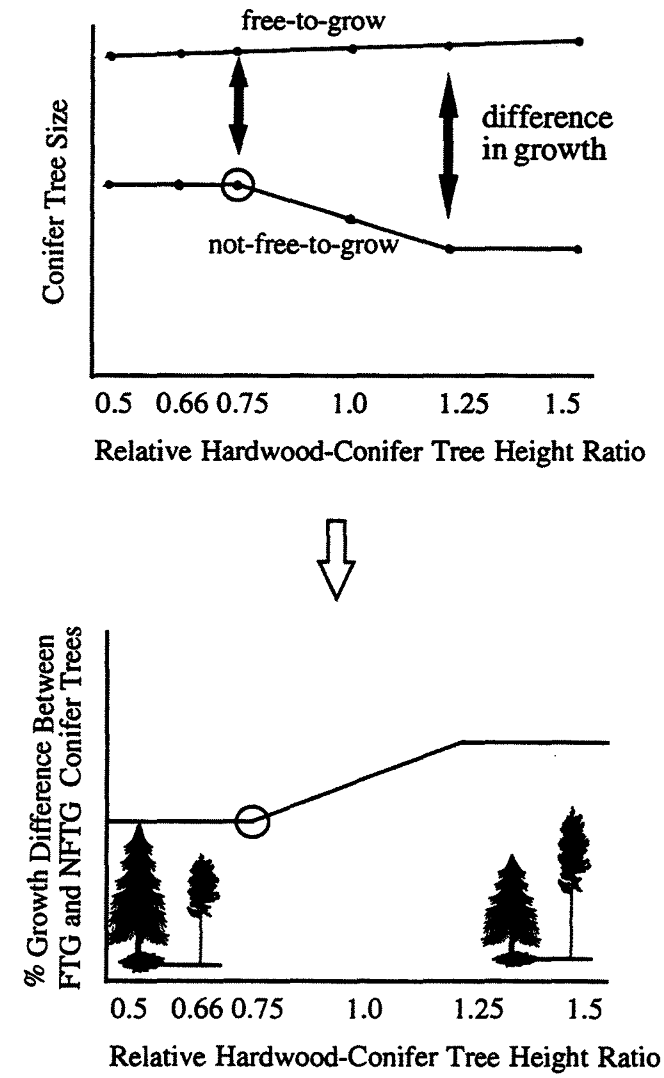

Fig.10 Graphical representation of methodology used to determine hardwood-conifer competition height thresholds. The dots on the lines in the top diagram illustrate the average tree size for FTG and NFTG trees for each height threshold based on individual t-test results. The circles in the diagrams represent the critical relative height thresholds. The trees in the lower diagram represent the relative sizes associated with the x-axis values and a consistent competitor-target tree distance threshold of 100 cm. Note: Growth difference is defined as ((FTG size - NFTG size)/FTG size)*100.

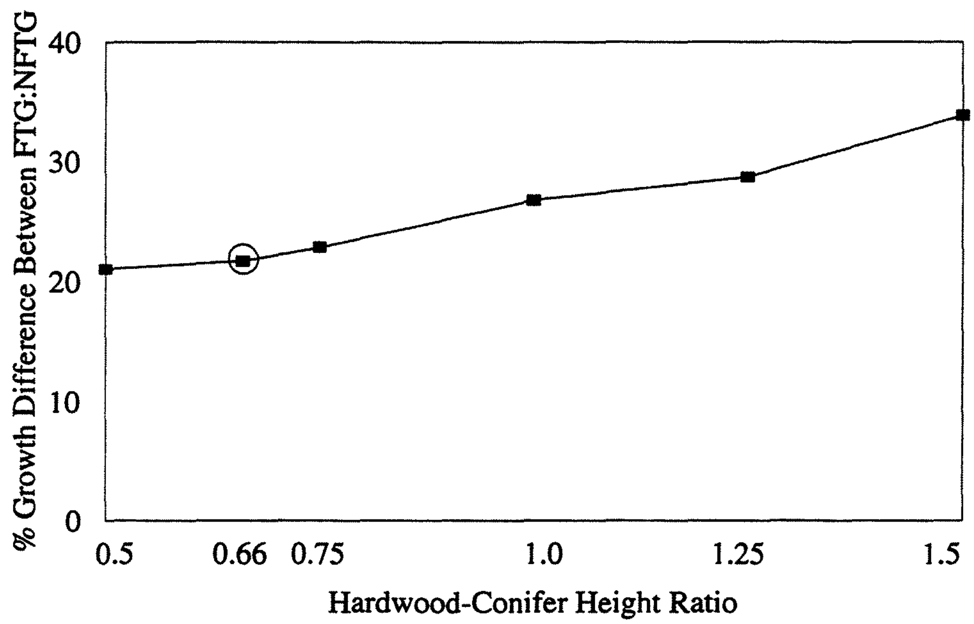

Fig. 11 Effect of relative hardwood-conifer height ratio on growth response between free-to-grow and not-free-to-grow black spruce in Pine Falls. Based on overall average of separate t-tests performed for each age class and growth variable (radial increment, RCD, height, height increment). The critical relative height threshold is circled on the line. Tests based on hardwood-conifer stem distance of 1 m.

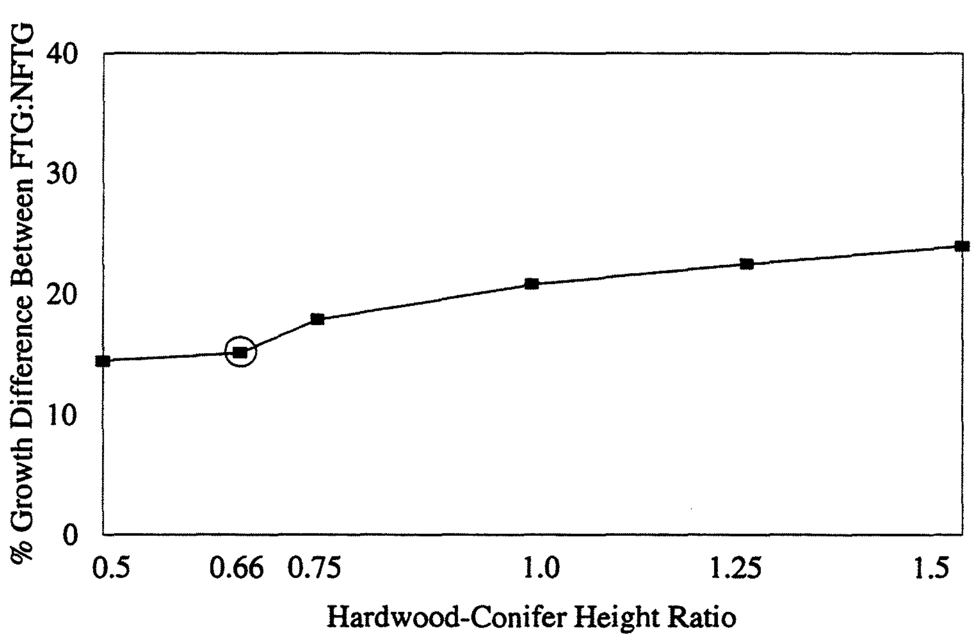

Fig. 12 Effect of relative hardwood-conifer height ratio on growth response between free-to-grow and not-free-to-grow white spruce in Porcupine Hills. Based on overall average of separate t-tests performed for each age class and growth variable (radial increment, RCD, height, height increment). The critical relative height threshold is circled on the line. Tests based on hardwood-conifer stem distance of 1 m.

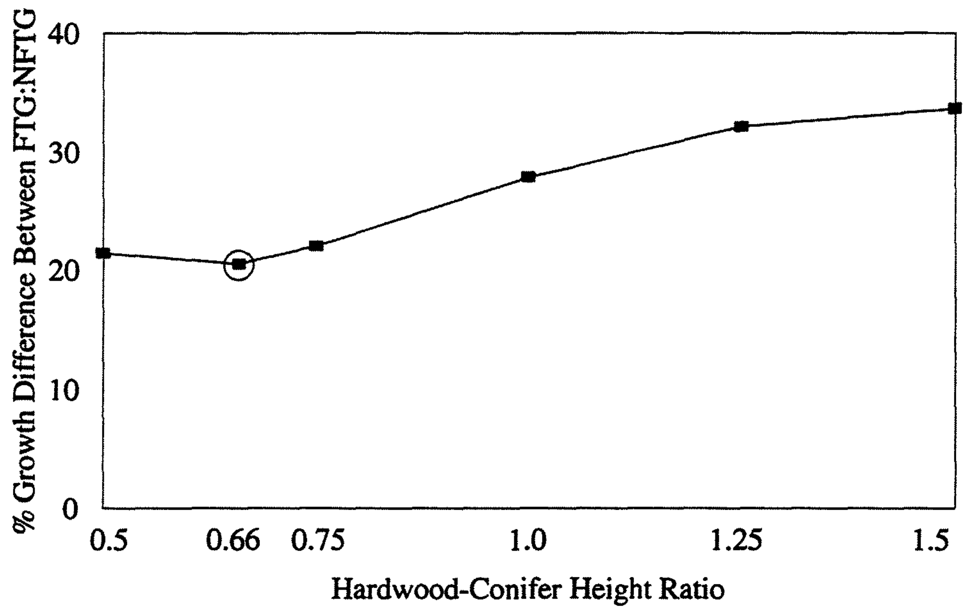

Fig. 13 Effect of relative hardwood-conifer height ratio on growth response between free-to-grow and not-free-to-grow jack pine in The Pas. Based on overall average of separate t-tests performed for each age class and growth variable (radial increment, RCD, height, height increment). The critical relative height threshold is circled on the line. Tests based on hardwood-conifer stem distance of 1 m.

were between 75% and 150% of the target tree height had the most effect on conifer growth (results not shown). Shorter competitors presumably do not shade enough of the conifer foliage to affect conifer growth (and in the sites studied, competition for nutrients and moisture were not deemed to be as important a factor as light competition). Competitors greater than two times the height of the target tree did not appear to exert any additional negative effects on conifer growth. In fact, there is some evidence that these taller competitors may have a positive effect on conifer form. This may be because taller competitors have fewer low branches, with less chance for physical damage, while still providing some nurse crop benefits.

From the preceding analyses, height and distance thresholds used in a definition of a FTG tree can be estimated for each conifer species (Table 13). They are as follows:

Black Spruce	- 0.66 relative competitor tree:target tree height ratio, 75 or 100 cm hardwood stem-to-conifer stem distance
White Spruce	- 0.66 relative competitor tree:target tree height ratio, 100 cm hardwood stem-to-conifer stem distance
Jack Pine	- 0.66 relative competitor tree:target tree height ratio, 125 cm hardwood stem-to-conifer stem distance

Competition and Growth Relationships for Trees Seven Years and Younger

While most of the target trees surveyed in the study were from 8-12 years old (Table 3), there were a number of younger trees, especially in the Pine Falls area. Regression analysis was performed to determine if the competition-growth relationships deemed to be important in the older blocks were similar for the younger blocks (7 years or younger). Grass competition could be a major influence rather than hardwoods. Separate linear regression analysis was performed on plots with target trees seven years or younger. As well, age classes 5-9 for black spruce in Pine Falls and age class 6-8 for jack pine in The Pas were analyzed separately in earlier analysis. Tables 7 and 8 indicate that results for the younger age classes are similar as for the older age classes.

Non-linear regressions were performed separately for trees aged 6 years, 7 years and 8 years for black spruce in Pine Falls and jack pine in The Pas. Analysis included regression of hardwood and non-tree competitors (grass, shrub and forb) versus target tree growth. The regression relationships were similar to previous analysis, although stronger. *Aspen was shown to be the major competitor influencing conifer growth in these younger stands.* This may be partly because these sites had been selected specifically for their high aspen component. While radial increment had high r^2, analysis of target tree height and three year periodic height increment versus MARTIN showed r^2 values of less than 0.10.

Table 13
Distance and Height Hardwood Competition Threshold For Free-to-Grow Trees

Species/Location	Age Class	Hardwood-Conifer Distance (cm) Where Growth Difference Between FTG and NFTG Trees Starts to Decrease[1]	Relative Hardwood-Conifer Height Ratio Where Growth Difference Between FTG and NFTG Trees Starts to Increase[2]
Black Spruce Pine Falls	5-9	75	1.0
	10	75	0.5
	11-15	50	0.66
	All averaged	75	0.66
Black Spruce Duck Mt	8-12	75-100	0.66
White Spruce Porcupine Hills	8-13	100	0.66
	14-20	75	0.66
	All averaged	100	0.66
Jack Pine The Pas	6-8	125	0.66
	9-12	125	0.75
	All averaged	125	0.66

1. Free-to-grow tree defined as having no hardwoods taller than 66% of the target tree, within "x" cm of the target conifer tree(based on stem-to-stem distance).
2. Free-to-grow tree defined as having no hardwoods within 1 m of the target tree, taller than "x" % of the target conifer tree height.

Effect of Microsite Conditions on Conifer Growth

Regression analysis was used to test the combined effect of slope and aspect on target tree growth. For the white spruce and jack pine sites, where the microsite data was collected, slope and aspect had a significant effect ($P<0.05$) on the seedling growth in only four of a possible 56 location-block-species-growth variable combinations.

The effect of the other microsite conditions on tree growth was done with Hochberg's GT2 multiple means test (1974). Multiple means tests which tested the difference between growth of target trees, stratified by classes for each microsite variable were performed. For example, if a location had trees growing in four soil moisture classes, the multiple means test would compare if there was a difference in growth individually between all possible pairs of moisture classes. *Results indicated that moisture was the microsite variable which most often indicated significant growth differences between microsite classes. As well, the effect of specific microsite variables was not the same for the white spruce and jack pine sites.*

GENERAL DISCUSSION

In the black spruce, white spruce and jack pine blocks in the Duck Mountain, Porcupine Hills and The Pas areas, respectively, hardwoods were the major competitor in terms of cover and height. However, in the black spruce sites in Pine Falls, average shrub and target tree height were similar and the shrub stratum had more cover than the hardwoods. This was reflected in the overall height and distance threshold analysis averages based on location. For jack pine in The Pas and white spruce in the Porcupine Hills, stem-to-stem distance was more indicative of competition than stem-to-inside crown distance, and shrubs did not contribute much to improving the relationship. For black spruce in Pine Falls, however, for the 100% height threshold analysis, stem-to-inside crown distance was important as well. This indicates that species or competition composition differences can be important.

For each conifer species, different competition variables best explained conifer growth response. For black and white spruce, relative competitor:target tree height ratio was superior to the MARTIN and LORIMER competition indices, but for jack pine in The Pas, LORIMER and MARTIN were better than relative heights (Table 10). Jack pine was more affected by the proximity of the competitor than the spruces were. This is shown by the fact that the MARTIN index (which incorporates stem-to-stem distance) explained more of the conifer growth than did relative height. Also, multiple regression analysis indicated that average stem-to-stem distance is significant (although with a low r^2). Based on the competition distance thresholds, there was evidence that inclusion of shrubs in the stem distance analysis improved the regression relationship only slightly.

Delong (1991) and Comeau et al. (1993) present intraspecific competition indices which explain a significant amount of the variation of conifer seedling growth response. When these indices are applied to hardwood competition in Manitoba mixedwood sites, the relationship is not as strong. It may be, in part, because of the differences in the growth form of major competitors in young regenerating stands between the two provinces. For example, with indices developed in the Pacific Northwest and B.C. in very young stands, the competitors such as red alder, thimbleberry and fireweed have a high leaf area index; their crowns form overlapping solid patches. In the Manitoba sites, the competing trees and shrubs have a more diffuse crown than the BC species, with the exception of beaked hazel and green alder. However, these latter shrub species were only present in a minority of blocks surveyed in the study.

The asymmetric and open growth form of the aspen crowns presents problems when attempting to correlate conifer growth with the distance to a specific aspen competitor. The target tree stem to competitor stem distance measure performed better than the target tree stem to closest competitor foliage distance. The stem-to-stem distance is more easily defined and is recommended as the best distance measurement to quantify proximity of competitors.

The relationship between some apparently "simple" competition variables and conifer growth was more complex than first thought. One example is the amount of overtopping of the conifer seedling. It would seem logical, in a situation where the hardwood competitors are often much larger than the conifer seedlings, that overtopping of the seedling would be an important competition factor. However, analysis indicated that overtopping was not a useful variable in explaining conifer growth. This may be due to three reasons: 1) Overtopping is difficult to properly assess (wide discrepancy between observers). 2) Some overtopping may protect the conifer seedling against frost and weevil damage, and 3) Conifer seedlings that are overtopped by hardwoods may in fact receive a lot of sunlight if there is an opening to the south of the seedling. These three points illustrate how this relationship isn't simple. This may be why more easily measured and interpreted competition factors such as relative competitor height performed better in this analysis.

In summary, *relative competitor:target tree height ratios had the highest r^2 for black and white spruce, but for jack pine, the competition indices which are based on RCD (i.e., MARTIN and LORIMER) were better.* This may be because of a different sampling protocol for jack pine compared to the white and black spruce blocks. For the jack pine, individual tree heights were not recorded for all individuals in the plot, however, a larger set of root collar diameters were measured in the plot. The r^2 values were much improved with the non-linear regression. As well, age alone had a significant affect on the growth response.

Application for Free-To-Grow Guidelines

From this study, an empirically and biologically-based rationale for some components of a Manitoban free-to-grow assessment protocol were developed. The concept of incorporating relative height in a Free-to-Grow assessment was confirmed by the strong correlation of average tree competitor to target tree. More specific height thresholds for black spruce, white spruce and jack pine were determined. Stem-to-stem distance of the average and closest competitor was one of the more important competition variables. In terms of assessment of conifer tree growth response, radial increment or total root collar diameter were shown to be the most reliable. There are other components required in the development of a Free-to-Grow survey system that are not addressed in this study. They include: minimum height requirements, stocking and spacing, coniferous competition, and pest management concerns.

Based on the analysis, the following Free-to-Grow height and distance thresholds are recommended:
Black Spruce - 0.66 relative competitor:conifer height ratio, 75-100 cm stem-to-stem distance
White Spruce - 0.66 relative competitor:conifer height ratio, 100 cm stem-to-stem distance
Jack Pine - 0.66 competitor:conifer height ratio, 125 cm stem-to-stem distance

In development of free-to-grow guidelines, it may be appropriate to allow a tolerable amount of hardwood competition within the growing space determined as appropriate for the conifer seedling. Foresters throughout B.C. and the prairie provinces have attested to the ecological adaptation of white spruce in regeneration and growth in mixedwood stands. Of the conifers studied, white spruce has the greatest shade tolerance (low light adapted) (Sims et al. 1990). Maintaining some hardwoods on mixedwood sites has beneficial aspects in terms of reducing weevil damage, and modifying microclimate (e.g., reducing risk of frost damage) (Simard 1990).

It is important to note that the analysis was based on sites that were specifically selected to have hardwoods as the dominant competitor. This is reflected in the results, and at least partly explains why the competition effects for hardwoods were much greater than for grass, forbs and shrubs. The ecological relationships described in this report apply to those aspen-dominated vegetation complexes. In other sites, especially where the conifers are smaller, the competition dynamics could be much different. For example, it is well documented how significant marsh reed grass (*Calamagrostis canadensis*) can be in affecting conifer growth (e.g., Hogg and Lieffers 1991). The lack of grassy sites may have also been a factor of age, blocks 3-5 years old could very well have been grass dominated. For this reason, these results should not be extrapolated to areas outside the site types and competition types already sampled.

A wide variety of competition variables were tested in this study. In general, *the simpler variables often explained more of the conifer growth response than those that were more complex.* This is because the more complex ones were more difficult to quantify. It is important to realize that, in most cases, the best competition variables, used in single factor analysis only explained a minority of the observed growth. Notwithstanding the above, there were some consistent trends that were apparent from the analysis. A variety of analytical approaches, sometimes quite varied, often lead to the same conclusions.

This free-to-grow analysis indicated that shrubs are not important in the FTG thresholds. This may be due to: 1) the selection of blocks dominated by hardwood competition, 2) the analysis only capturing a minority of the variability observed in conifer growth, 3) the presence of shrubs may be overwhelmed by the rest of the unexplained variation. If the major competitors in a region are shrubs, the analysis should focus more closely on sites like Pine Falls black spruce where shrubs are relatively more dominant.

In a retrospective study such as this, the previous stand history has to be reconstructed from use of height and radial increments. It cannot determine the amount of ingress, or density dynamics in the previous years. To infer the stand dynamics at age 2, from a retrospective study at age 12 may result in error, as the competition dynamics at the two different ages may be quite different. At age 12, only the survivors are present. Attempting to merge the growth performance with tree survival may make interpretation difficult.

Application of Competition Indices to Mixedwood Management

There is a concern that competition indices can be over applied (e.g., Caza and Kimmins 1989, Burton 1993), and their use may be over-rated. Across the spectrum from detailed process models to mensurational empirically-based mathematical models, competition indices are very simplistic. They must be used with absolute caution. It is very important to evaluate the explanatory power of these indices by examining the *average* coefficient of determination (r^2), in using these indices in regression analysis to explain conifer growth, rather than the best r^2. It is also very important to state when part of the high r^2 from a regression model used to describe relationships between the competition index and conifer growth is due to variations in the size of the conifer. However, if an operationally-useful, simple competition index can be shown to have a high correlation with a more physiologically based measurement, and the regression analysis is satisfactory then the approach is valid. This was the approach used by Delong in the development of his Light Interception Index (1991). In spite of the drawbacks mentioned by Burton (1993), researchers and those involved in vegetation management continue to search for the proper index. No one competition index is universally applicable to the assessment of competition levels in all regenerating sites. To be most accurate, they must be developed for each combination of species, in each ecoregion.

In determining the appropriate levels of hardwoods to be maintained on mixedwood stands, a certain level of competition could, on some sites, be acceptable within the growing space of a conifer. This approach has been suggested for northeastern British Columbia (Richard Kabzems, pers. comm, 1994). From the analysis, it was difficult to determine what would be an appropriate amount of acceptable hardwood competition (in terms of crown cover or density), due to the wide range in conifer growth response at moderate to low competition levels (Fig. 3).

There may be some difficulty in using competition indices for stand tending decisions. For example, a graph of the competition index-conifer growth relationship usually indicates a lot of variability in growth response, particularly at low to moderate competition levels (e.g., Fig. 3). While there may a statistically-significant relationship, there is often difficulty in determining the competition threshold above which stand tending is required.

Most of the blocks in this study were 10-14 years old. However, stand release decisions would be made for regenerating stands, 3-7 years after harvest, where grass competition, in addition to hardwoods, would be a serious concern for the forest manager. Competition indices derived from this study, which are based solely on hardwoods, would be even less applicable in those young stands for release decisions. There has to be some other way to quantify the competition in those younger stands.

CONCLUSIONS

The results of this study provide background information for the development of Free-To-Grow assessment procedures. The recommendations on competition thresholds have been confirmed by a variety of analyses, which approached the problem from different perspectives (e.g., multiple regression analysis and t-tests for significant differences in mean growth). The best growth response variables (root collar diameter and radial increment), the best competition variable (relative height ratio of the average hardwood competitor:target tree), and the height and distance thresholds have been highlighted within this report. Other factors which were not as strong in explaining conifer growth response (e.g., overtopping, various competition indices), were mentioned but not presented in as much detail.

The competition thresholds derived in this report are being used by the Manitoba Forestry Branch to assist in the development of Free-to-Grow assessment procedures. In 1994, field tests of this procedure were undertaken. Analysis of this work is being used to validate the major competition thresholds suggested by this study.

From the analysis, there are several major conclusions.

1. On the sites sampled, the hardwood component was by far the most important competitor in determining conifer tree growth. The contribution by forbs and grasses was negligible. Shrubs had some effect but only for a few sites, and not nearly as much as aspen and balsam poplar. These results were applied to mostly hardwood competition areas for blocks aged 8-12 years old. At this point, increasing aspen crown closure had shaded out heavy grass cover.

2. Relative height is important to include in a Free-To-Grow designation. It was the competition variable which explained the greatest amount of the observed conifer growth. The best height variable was relative height using average of all trees based on individual tree measurements. However, relative height using the average of all aspen and relative height based on just the tallest aspen were also useful.

3. Stem-to-stem distance is also important to include in a Free-To-Grow designation. While not as highly correlated with growth as relative height, both stem-to-stem distance to the closest competitor and the average stem-to-stem distance were important in the analysis. For the

distance measurements, average stem-to-stem distance explained the greatest amount of target tree growth response.

4. Hardwood competitor stem distance and height thresholds were defined for each species. The distance from competitors and relative height of competitors to target trees recommended as competition thresholds are as follows: Black spruce: 75-100 cm,66% relative height, White spruce 100 cm, 66% relative height, Jack Pine: 125 cm, 66% relative height.

5. Growth variables which include radius or radial growth were more highly correlated with hardwood competition levels than those growth variables which included height or height growth. Radial increment from the previous growing season was consistently the best growth variable to use, however, it is difficult to incorporate this variable in an operational assessment.

6. "Secondary" variables, such as hardwood cover or hardwood density, did not explain a large degree of conifer growth, by themselves, but did improve the regression models for relative height and competition indices.

7. Age of the target conifer tree (between 5 and 20 years) was a significant factor in the observed growth rates.

8. Published competition indices which include target tree size explained a larger amount of target tree growth response than those that do not. The best indices used root collar diameter ratios (e.g., LORIMER, BDRATIO1 and BDRATIO2), and incorporate (in some indices), distance to the competitor (e.g., MARTIN). Overall, MARTIN was the best published competition index, as shown by size-controlled analysis for radial increment. Use of this index in an operational assessment program would be time consuming, as it requires distances and root collar diameter measurements of, at the very least, the closest and tallest competitor in the plot.

9. Indices based on extensive measurements performed as well as those based on more intensive measurements.

10. Comparative analysis of black spruce data from two locations indicated, that while there were some regional variations in growth relationships, the general trends were similar (e.g., the best growth response variables were the same in both areas).

11. Based on the sites sampled, competition relationships for young-aged trees less than eight years old, were similar in nature to those from older blocks .

12. Site variables did not add significantly to the competition models, except in a few cases.

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REFERENCES

Alemdag, I. 1978. Evaluation of some competition indices for the prediction of diameter increment in planted white spruce. Inf. Rep. FMR-X-108. Can. Dept. Env., Can. For. Serv., Forest Management Institute, Ottawa, Ont. 39 p.

Bacon, C.G.; Zedaker, S.M. 1986. Leaf area prediction equations for young southeastern hardwood stems. For. Sci. **32**:818-821.

Blanche, C.A.; Hodges, J.D.; Nebeker, T.E. 1985. A leaf area-sapwood ratio developed to rate loblolly pine tree vigour. Can. J. For. Res. **15**:1181-1184.

Braathe, P. 1989. Development of regeneration with different mixtures of conifers and broadleaves. II. Proc. IUFRO Conference on Treatment of Young Forest Stands. 19-23 June 1989. Dresden, GDR. IUFRO Working Party S 1.05-03.

Brand, D. 1986. A competition index for predicting the vigour of planted Douglas-fir in southwestern British Columbia. Can. J. For. Res. **16**:23-29.

Burton, P.J. 1993. Some limitations inherent to static indices of plant competition. Can. J. For. Res. **23**:2141-2153.

Caza, C.L.; Kimmins, J.P. 1989. Problems with the development and application of competition indices in complex, multispecies communities. Vegetation management: An integrated approach - Proceedings of the Fourth Annual Vegetation Management Workshop. Nov 14-16, 1989, Vancouver, B.C. Canada-BC FRDA Report 109., Victoria, BC.

Comeau, P. 1991. Light attenuation and competition by overtopping vegetation in the interior cedar helmock zone: project No. 3.48 Can-BC FRDA Memo 159.

Comeau, P.G.; Braumandl, T.F.; Xie, C.Y. 1993. Effects of overtopping vegetation on light availability and growth of Engelmann spruce (Picea engelmannii) seedlings. Can. J. For. Res. **23**:2044-2048.

Daniels, R. 1976. Simple competition indices and their correlation with annual loblolly pine tree growth. For. Sci. **22**:454-457.

Delong, S.C. 1991. The light interception index: a potential tool for assisting in vegetation management decisions. Can. J. For. Res. **21**:1037-1042.

DeLong, S.C. 1994. Survey procedure for making management decisions in young conifer stands. Pages 27-36 *in* C. Farnden, editor. Proceedings of Northern Interior Vegetation Management Association annual general meeting. 2-3 Feb. 1994. Prince George, B.C.

Hegyi, F. 1974. A simulation model for managing jack-pine stands. Pages 74-90 *in* J. Fries, editor. Growth models for tree and stand simulation. Royal College of Forestry, Stockholm, Sweden.

Hochberg, Y. 1974. Some generalizations of the T-method in simultaneous inference. J. Multivar. Anal. 4:224-234.

Hogg, E.H.; Lieffers, V.J. 1991. The impact of *Calamagrostis canadensis* on soil thermal regimes after logging in northern Alberta. Can. J. For. Res. **21**:387-394.

Lorimer, C. 1983. Tests of age-independent competition indices for individual trees in natural hardwood stands. For. Ecol. Manage. **6**:343-360.

Luttmerding, H.A., et al. 1990. Describing ecosystems in the field. 2nd ed. B.C. Ministry Env. Manual 11, Victoria, BC.

MacDonald, G.B.; Weetman, G.F. 1993. Functional growth analysis of conifer seedling responses to competing vegetation. For. Chron. **69**:64-70.

MacDonald, B.; Morris, D.M.; Marshall, P.L. 1990. Assessing components of competition indices for young boreal plantations. Can. J. For. Res. **20**:1060-1068.

Martin, G. L.; Ek, A.R. 1984. A comparison of competition measures and growth models for predicting plantation red pine diameter and height growth. For. Sci. **30**(3):731-743.

Mitchell-Olds, T. 1987. Analysis of local variation in plant size. Ecology **68**: 82-87.

Mugasha, A. 1989. Evaluation of simple competition indices for the prediction of volume increment of young jack pine and trembling aspen trees. For. Ecol. Manage. **26**:227-235.

Navratil, S.; MacIsaac, D.A. 1993. Competition index for juvenile mixed stands of lodgepole pine and aspen in west-central Alberta. Forest Mgmt. Note 57, Forestry Canada, Northern Forestry Centre, Edmonton, Ab.

Sabin, T.E.; Stafford, S.G. 1990. Assessing the need for transformation of response variables. Forest Research Lab Special Publication 20. Oregon State University, College of Forestry, Corvallis Oregon.

Salonius, P.O.; Baton, K.P.; Murray, T.S. 1991. How to estimate future competition stress to better spend herbicide dollars. For. Can., Marit. Reg., Tech. Note 251.

SAS Institute Inc. 1990. SAS/STAT User's Guide. Version 6. 4th ed. 2 vols. SAS Institute, Cary, NC.

Simard, S. 1990. A retrospective study of competition between paper birch and planted douglas-fir. FRDA Report 147. Forestry Canada and BC Ministry of Forests, Victoria, BC.

Sims, R.A.; Kershaw, H.M.; Wickware, G.M. 1990. The autecology of major tree species in the north central region of Ontario. COFRDA report 3302. NWOFTDU Technical Report 48. Ontario Ministry of Natural Resources Publication 5310, Thunder Bay, Ontario.

Steneker, G.; Jarvis, J. 1963. A preliminary study to assess competition in a white spruce-trembling aspen stand. For. Chron. **39**(3):334-336.(?)

Towill, W.D.; Archibald, D.A. 1991. A competition index methodology for Northwestern Ontario. Ont. Min. Nat. Res., Northwestern Ont. For. Tech. Dev. Unit, Rep No. TN-10.

Valentine, H.T. 1988. A carbon-balance model of stand growth: a derivation employing pipe-model theory and the self thinning-rule. Annals of Botany **62**:389-396.

Wagner, R.; Radosevich, S. 1987. Interspecific competition indices for vegetation management decisions in young Douglas-fir stands on the Siuslaw National Forest. Report No. 1. Dept. For. Sci., Oregon State Univ., Corvallis, OR. 108 p.

Wagner, R.; Radosevich, S.R. 1991a. Neighborhood predictors of interspecific competition in young Douglas-fir plantations. Can. J. For. Res. **21**:821-828.

Wagner, R.; Radosevich, S.R. 1991b. Interspecific competition and other factors influencing the performance of Douglas-fir saplings in the Oregon Coast Range. Can. J. For. Res. **21**:829-835.

Waring, R.H.; Thies,W.G.; Muscato, D. 1980. Stem growth per unit of leaf area: a measure of tree vigour. For. Sci. **26**:112-117.

Zar, J.H. 1984. Biostatistical analysis. Prentice-Hall, Englewood Cliffs, New Jersey.

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APPENDIX 1

Formulas for Published Competition Indices Tested in Analysis.

The formulas presented here are, in some cases, modifications of the original formulas. All indices are based on a 2 m radius (12.56 m^2) plot. For the black and white spruce blocks, all competing trees (hardwoods and conifers) were tallied. For the jack pine blocks, only the tallest and the closest hardwood in each quadrant and tallest and closest conifer in each plot was tallied, so the indices for those blocks are based on this subset of competitors. **In this study, these indices were calculated twice; once with all tree competitors (hardwoods and conifers) and once with hardwoods only.**

BDRATIO1: Navratil and MacIsaac (1993) - published index used a plot radius of 1.78 m.

$$BDRATIO1 = \frac{RCD\ of\ tallest\ competitior}{RCD\ of\ target\ tree} \qquad \text{... [1]}$$

BDRATIO2: Navratil and MacIsaac (1993) - published index used a plot radius of 1.78 m.

$$BDRATIO2 = \frac{RCD\ (avg\ of\ tallest\ plus\ closest\ competitor)}{RCD\ of\ target\ tree} \qquad \text{... [2]}$$

Note: includes only tallest and closest trees.

BRAATHE: Braathe (1989) pg 270 - published index used plot radius of 3 m.

$$Braathe = \sum_{i=1}^{n} \frac{ht\ of\ competitor_i\ -\ ht\ of\ target\ tree}{target\ stem\text{-}to\text{-}competitor_i\ stem\ distance} \qquad \text{... [3]}$$

Where: n = number of individual competing trees in the plot
Note: Heights and distances can be metres or centimetres since the units cancel out

BRAND: Brand (1986) pgs 25 & 26 - published index used plot radius of 1.41 m.

$$Brand\ C.I. = \frac{\dfrac{\sum_{i=1}^{n} Hb_i * C_i}{n}}{Ht} * \left(\frac{Rb}{Rt} + 1\right)^{-1} * \sum_{i=1}^{n} C_i \qquad \text{... [4]}$$

Where:

Hb_i	=	Average height of competing $species_i$
C_i	=	Total percent cover of competing $species_i$
Ht	=	Height of target tree
Rb	=	Average distance from target tree stem to competitor tree stems (based on all individual competing trees in the plot) (ie. mean or average stem-to-stem distance of all trees)
Rt	=	Crown radius of target tree
n	=	number of competing tree species in plot

Note: -In this study, Rb is calculated based on stem-to-stem distances, whereas the published index used stem-to-inside crown of competitor.
-Average covers and heights are taken from species averages
-Heights and distances can be metres or centimetres since the units cancel out

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COMEAU: Comeau 1991

$$Comeau = \sum_{i=1}^{n} \frac{avg\ cover\ of\ competing\ species_i\ *\ avg\ height\ of\ competing\ species_i}{target\ tree\ height} \qquad \text{... [5]}$$

Where: n = number of competing tree species in a plot
Note: Average covers and heights are taken from species averages and only for tallest and closest trees

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DANIELS: Daniels(1976) pg 456, cited by Mugasha (1989)
This was originally proposed by Hegyi (1974), using plot radius of 3.05m.

$$Daniels = \sum_{i=1}^{n} \frac{\left(\dfrac{RCD\ of\ competitor_i}{RCD\ of\ target\ tree}\right)}{target\ tree\ stem\ to\ competitor_i\ stem\ distance} \qquad \text{... [6]}$$

Where: n = number of individual tallest and closest competing trees in the plot

DELONG: Delong 1991

$$Delong = \sum_{i=1}^{n} \frac{avg\ cover\ of\ competing\ species_i\ *\ avg\ height\ of\ competing\ species_i}{average\ stem\ to\ stem\ distance\ of\ competing\ species_i} \quad ...\ [7]$$

Where: n = number of competeing tree species in the plot
Note: -The published index uses proximity for the denominator, defined as average stem-to-stem
-Average covers and heights are taken from species averages
-Average stem-to-stem distances are calculated for each species
-Heights and distances can be metres or centimetres since the units cancel out

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LORIMER: Lorimer (1983) pg 358, cited by Mugasha (1989) Equation 18
In the published index, the plot radius is variable to make age-independent.

$$Lorimer = \sum_{i=1}^{n} \frac{RCD\ of\ competitor_i}{RCD\ of\ target\ tree} \quad ...\ [8]$$

Where: n = number of individual tallest and closest competing trees in the plot

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MACD1: MacDonald et al 1990 - BACD from pg 1062

$$MACD1 = \sum_{i=1}^{n} \frac{Basal\ Area\ of\ competitor_i}{target\ tree\ stem\ to\ competitor_i\ \ stem\ distance} \quad ...\ [9]$$

Where: n = number of individual tallest and closest competing trees in the plot
Note: RCD measurements must first be converted from mm to cm

MACD2: MacDonald et al (1990) - CVCD from pg 1062

$$MACD2 = \sum_{i=1}^{n} \frac{crown\ radius\ of\ competitor_i}{target\ tree\ stem\ to\ competitor_i\ stem\ distance} \quad ...\ [10]$$

Where: n = number of individual competing trees in the plot
crown radius = stem-to-stem minus stem-to-inside-crown of competitor
Note: Heights and distances can be metres or centimetres since the units cancel out

MACD3: MacDonald et al (1990) - ANG from pg 1062

$$MACD3 = \sum_{i=1}^{n} angle\ from\ target\ tree\ base\ to\ top\ of\ competitor_i \qquad \text{... [11]}$$

This angle is defined as: $TAN\left(\frac{height\ of\ competitor}{target\ tree\ stem\ to\ competitor\ stem\ distance}\right)$

Where: n = number of individual competing trees in the plot
Note: Heights and distances can be metres or centimetres since the units cancel out

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MACD4: MacDonald et al (1990) - derived from CVCD from pg 1062

$$MACD4 = \sum_{i=1}^{n} (angle\ from\ target\ tree\ base\ to\ top\ of\ competitor_i) * competitor_i\ location\ modifier \qquad \text{... [12]}$$

Where: n = number of individual competing trees in the plot
Note: Heights and distances can be metres or centimetres since the units cancel out
The competitor location factor weights the angle based on location of the competitor: N:1 E:2 S:4 W:3

MARTIN: Martin and Ek (1984) Equation 4

$$Martin = \sum_{1=1}^{n} \frac{\left(\frac{RCD\ of\ competitor_i}{target\ tree\ RCD}\right)}{target\ tree\ stem\ to\ competitor_i\ stem\ distance\ (m) + 1} \qquad \text{... [13]}$$

Where: n = number of individual tallest and closest competing trees in the plot
Note: The published index uses a linear expansion factor which is not used here.

RELVOL: MacDonald (1991) cited by MacDonald and Weetman (1993)
In the published index, the plot radius is 1.4 m.

$$RELVOL = \frac{\sum_{i=1}^{n} basal\ area\ of\ competitor_i \ * \ height\ of\ competitor_i}{basal\ area\ of\ target\ tree \ * \ height\ of\ target\ tree} \quad \text{... [14]}$$

Where: n = number of individual tallest and closest competing trees in the plot
BA= basal area
Note: Heights and distances can be metres or centimetres since the units cancel out

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STENECK: Stenecker and Jarvis (1963)

$$STENECK = \sum_{i=1}^{n} \frac{RCD\ of\ competitor_i}{target\ tree\ stem\ to\ competitor_i\ stem\ distance} \quad \text{... [15]}$$

Where: n = number of individual tallest and closest competing trees in the plot

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TOWILL: Towill and Archibald (1991) pg 16

$$Towill = \sum_{i=1}^{n} avg\ cov\ of\ competitor_i \ * \ avg\ ht\ of\ competitor_i \ * \ \left(\frac{avg\ competitor\ height_i}{target\ tree\ height}\right) \quad \text{.. [16]}$$

Where: n = number of competing tree species in the plot
Note: Average covers and heights taken from species averages

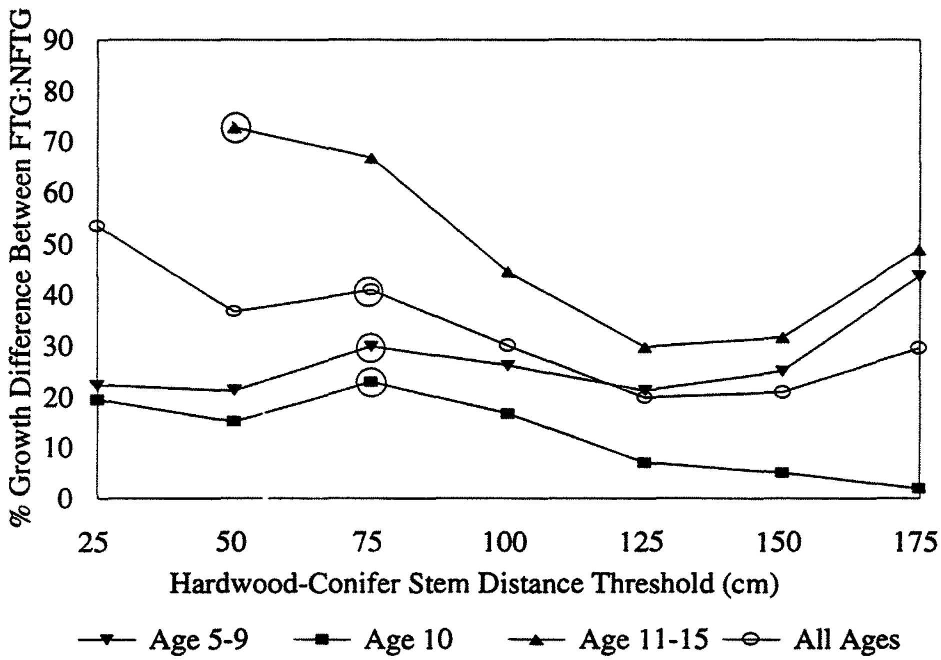
WAGNER: Wagner and Radosevich (1991)
This index is also referred to as EX11 in Wagner and Radosevich (1987)
The published index used a plot radius of 2.06 m.

$$Wagner = \sum_{i=1}^{n} average\ cover\ of\ competing\ species_i \quad \text{... [17]}$$

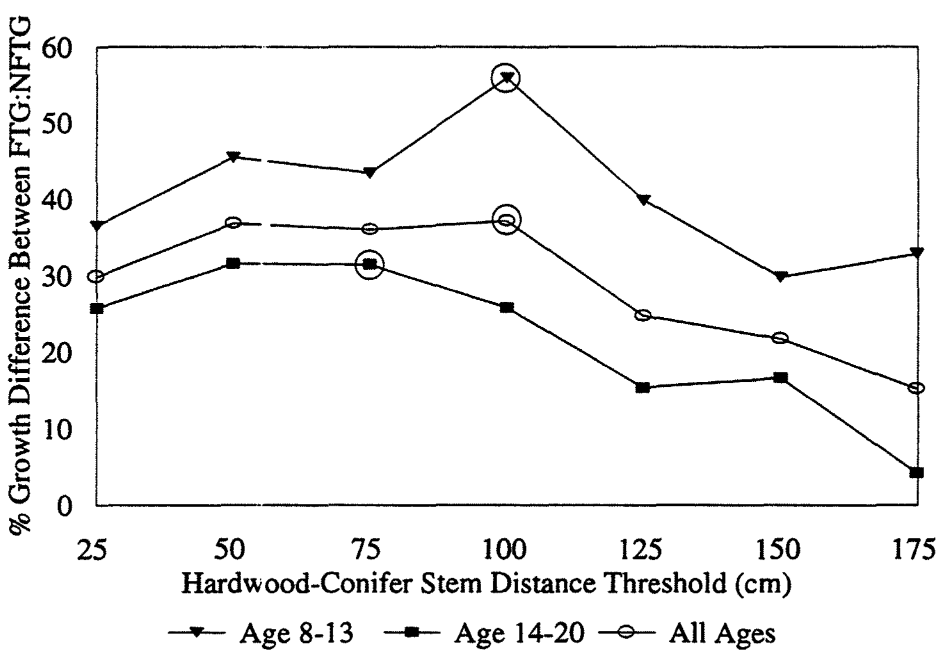
Where: n = number of competing tree species in the plot

Appendix 2

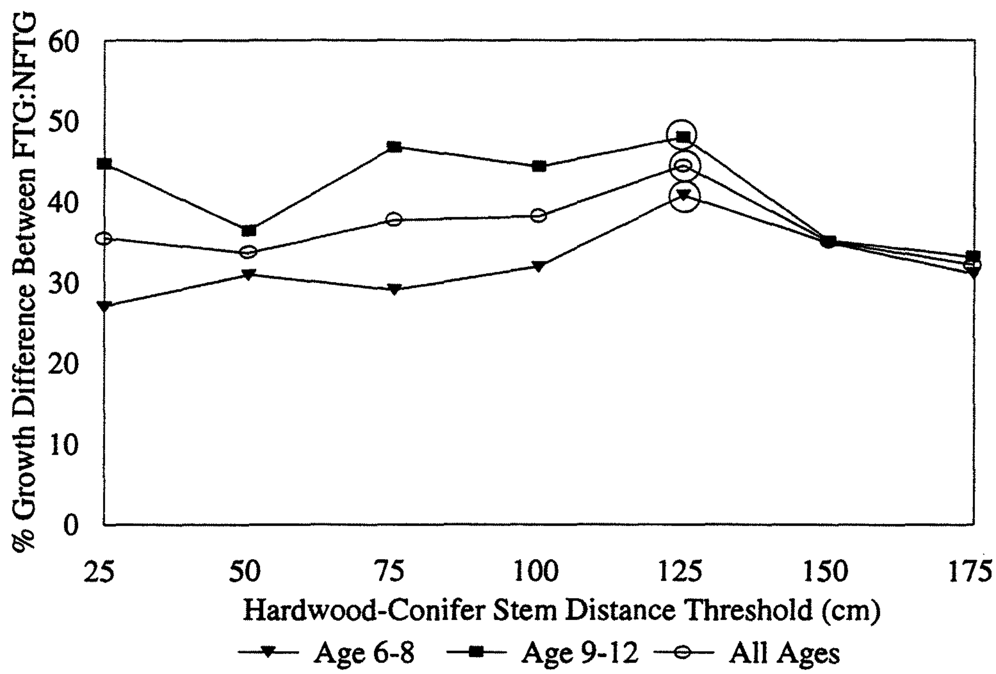
Effect of Hardwood-Conifer Stem Distance and Relative Height Ratio on Target Tree Radial Increment. Shown Separately for each Age Class for Each Conifer Species.



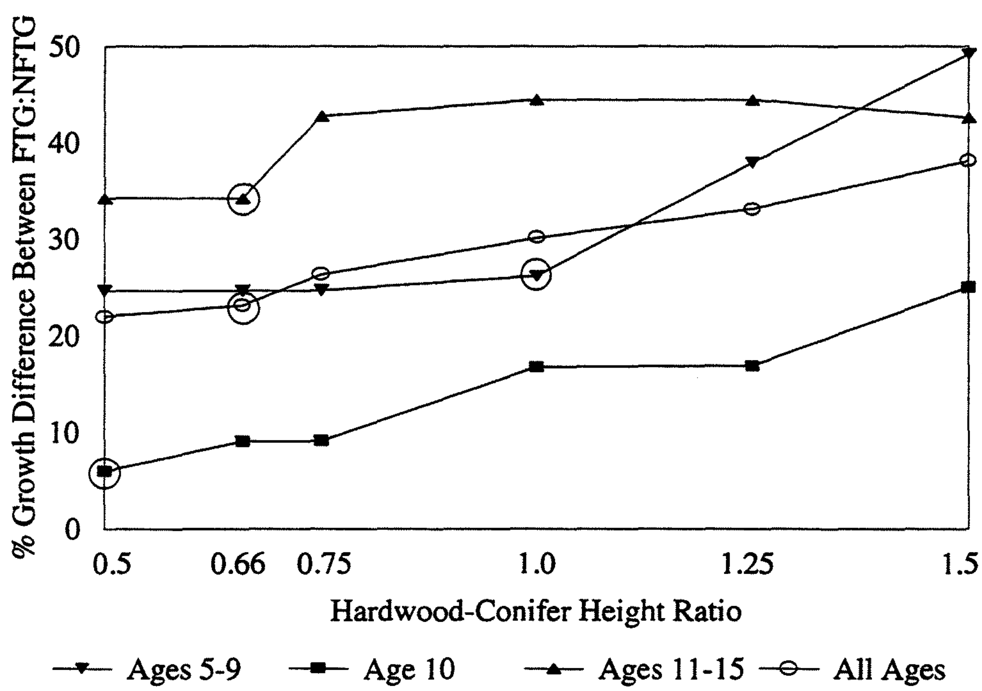
Effect of hardwood-conifer stem distance on radial increment growth response between free-to-grow and not-free-to-grow black spruce in Pine Falls, based on t-tests. The critical distance thresholds are circled on the lines. Tests based on hardwood-conifer height ratio of 0.66.



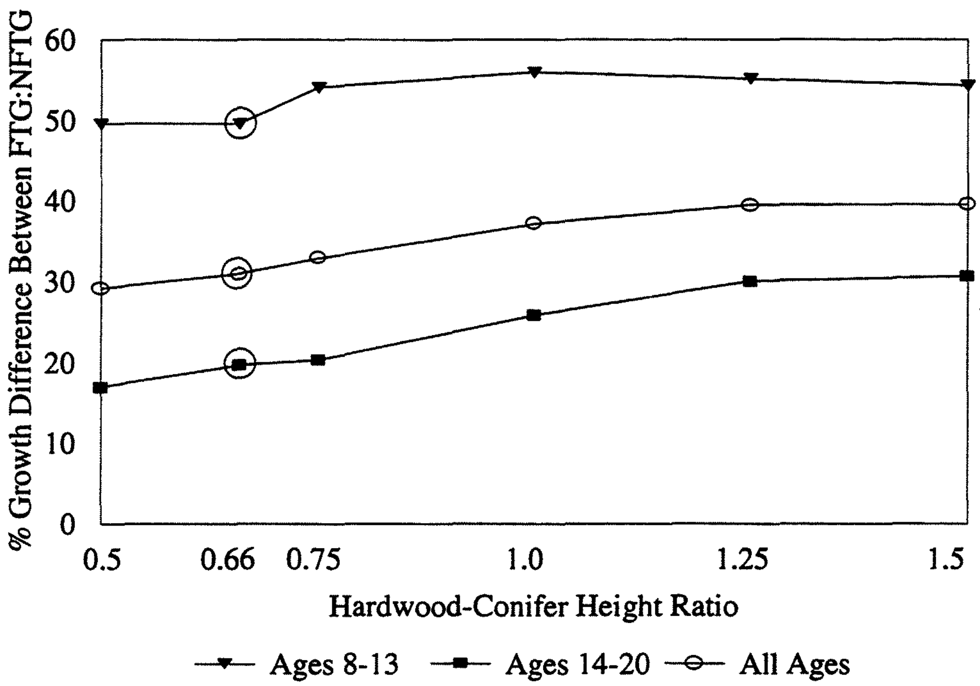
Effect of hardwood-conifer stem distance on radial increment growth response between free-to-grow and not-free-to-grow white spruce in Porcupine Hills, based on t-tests. The critical distance thresholds are circled on the lines. Tests based on hardwood-conifer height ratio of 0.66.



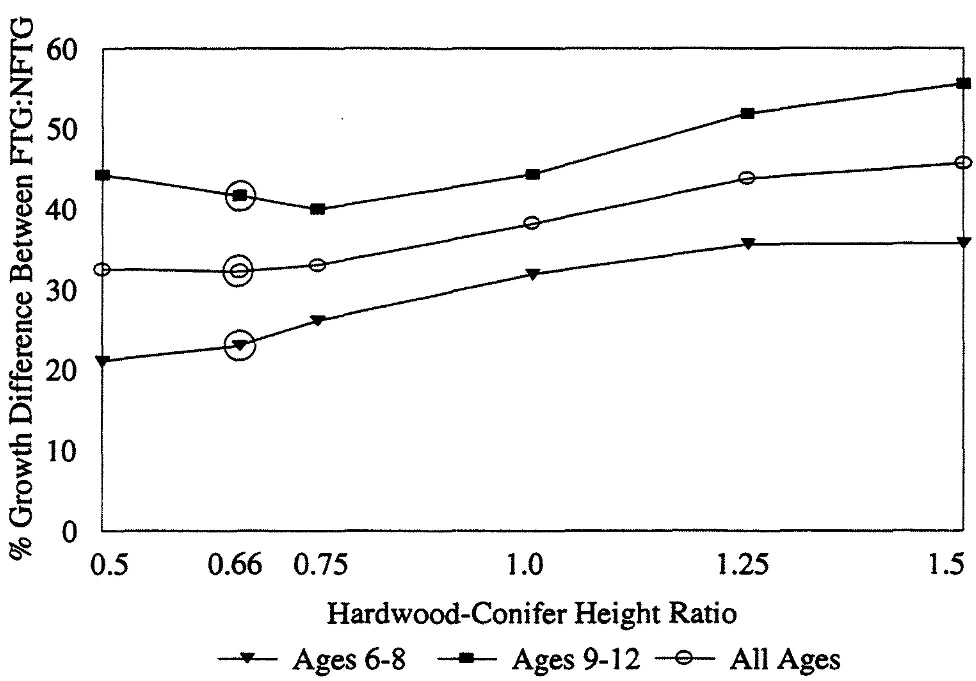
Effect of hardwood-conifer stem distance on radial increment growth response between free-to-grow and not-free-to-grow jack pine in The Pas, based on t-tests. The critical distances are circled on the lines. Tests based on hardwood-conifer height ratio of 0.66.



Effect of relative hardwood-conifer height ratio on radial increment growth response between free-to-grow and not-free-to-grow black spruce in Pine Falls, based on t-tests. The critical relative heights are circled on the lines. Tests based on hardwood-conifer stem distance of 1 m.



Effect of relative hardwood-conifer height ratio on radial increment growth response between free-to-grow and not-free-to-grow white spruce in Porcupine Hills, based on t-tests. The critical relative height thresholds are circled on the lines. Tests based on hardwood-conifer stem distance of 1 m.



Effect of relative hardwood-conifer height ratio on radial increment growth response between free-to-grow and not-free-to-grow jack pine in The Pas based on t-tests. The critical relative height thresholds are circled on the lines. Tests based on hardwood-conifer stem distance of 1 m.