How much birch (*Betula papyrifera*) is too much for maximizing spruce (*Picea glauca*) growth: a case study in boreal spruce plantation forests

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ABSTRACT: Interest in conifer-broadleaf mixedwood forests has greatly increased due to continuous demand for hardwood products and a shift towards more biological or ecosystem-based management. In British Columbia, more than 30% of the productive forest land is a conifer–broadleaf mixture and current forest regulations are more conifer biased rather than maintaining a mixed-species condition. The aim of this study was to examine the impact of paper birch on white spruce growth. Spruce growth data from 10 to 18 years old complex stands indicate that radial, height, and stem volume was not impacted by retaining up to 3,000 stems·ha^{-1} of birch. Similarly, growth and yield model projections suggest spruce-birch stands would be more productive up to a threshold birch density (3,000 stems·ha^{-1}) than pure spruce stands. At a 4% real interest rate, the removal of birch from these stands does not appear to be warranted as an investment. The results suggest that instead of encouraging uniform broadleaf removal across conifer plantations, mixed species management strategies could enhance the forest productivity, stand diversity and resilience.

Keywords: competition; future value; growth and yield model; forest management; productivity

Boreal mixedwood forests are ecologically and economically important ecosystems in northern Canada as they demonstrate greater resource heterogeneity, complexity and higher biodiversity than most pure species stands (Taylor et al. 2000; Martin, Gower 2006). Mixed species management has been historically associated with lower stand yields. In part, this is due to a legacy of ambiguous reports (Mard 1996). As a result, intensive vegetation control has been justified to enhance conifer productivity (Lavender et al. 1990; Wagner et al. 2006). However, ecosystem management of mixedwood stands is favoured as it focuses on the conservation of all seral stages (Bergeron et al. 1999). Such a coarse filter approach conserves forest structure at the landscape level to help maintain diversity. In addition to maintaining biodiversity, mixedwood stands yield a greater wood volume than a single-species stand (Man, Lieffers 1999) and may enhance stand resistance to wind damage, disease (Baleshta et al. 2005), insect outbreaks (Taylor et al. 1996; Simard et al. 2004), and site nutrient imbalance (Richards et al. 2010). Moreover, a mixed forest condition (complex forest) is better able to deal with the uncertainty of future stand development and environmental (Gayer 1886, page 5) risk as well as having potential economic advantages and managerial flexibility (Knoke 2008; Newsome et al. 2010).

Generally in British Columbia (BC) forest managers are forced by regulation to measure a regenerating plantation's performance against pure conifer stands where all deciduous vegetation is treated as a competitor (Forest and Range Practices Act of BC 1996; Simard, Vyse 2006). Therefore in early stand development most broadleaved species [e.g.

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paper birch (*Betula papyrifera* Marsh.), trembling aspen (*Populus tremuloides* Michx.), black cottonwood (*Populus balsamifera* L. ssp. *trichocarpa* T. and G.)] are routinely removed from plantations to ensure the successful regeneration of conifers (Comeau et al. 2000). Generally this practice has been consistently applied across Canada regardless of stand age or species composition.

Forest managers are always facing challenges when managing the forests as the decision-making process needs to address environmental, social and economic issues using adequate decision support tools to model and test sustainable management of forest resources. Intensive forest management activities require the forest industry to spend large amounts of money for future economic gain. Therefore it is important for managers to be able to predict with relative accuracy the effect of management practices on tree and stand productivity. Several tree and stand growth models have been developed as decision support tools to help forest managers in this quest. Among the numerous growth and yield models that have been developed, the Lakes States version of TWIGS (The Woodsman's Ideal Growth Projection System; Miner et al. 1988) and TIPSY (Table Interpolation Program for Stand Yields; Mitchell et al. 1992) were used in this investigation to predict future yield and economic return.

Furthermore to develop effective management strategies for mixed species stands where softwood timber production is the primary objective, silviculturists require information about levels of broadleaves that can be retained without critically affecting conifer performance. They also require practical ways of using this information to develop cost-effective treatment prescriptions. The goal of this research was to increase our level of understanding about the (i) interactions between conifers (spruce) and associated broadleaf competition (paper birch) and (ii) to project the effect of different birch densities on spruce growth and long-term productivity by using the different growth and yield models.

MATERIAL AND METHODS

Sites

The study sites are located in north-eastern BC within the Fort Nelson forest district. The area lies in the moist, warm sub-zone of the Boreal White and Black Spruce (BWBSmw2) biogeoclimatic zone (DeLong et al. 1990). Snow can occur throughout the year, but the wettest period is the summer between May and September. Mean annual precipitation is 330–570 mm and about 35–55% falls as snow. The mean annual temperature is –1.4°C with 106 frost-free days and the ground freezes deeply for a large part of the year. Soils are well to poorly drained with a wide range of soil types Cumulic Regosols, Organic Cryosols and Luvic Gleysols. The investigated stands have a significant birch component and white spruce (*Picea glauca* (Moench) Voss) was the target crop tree.

Sampling

In total, eight mixed forest stands were randomly selected and they had to have at least five hectares

Table 1. Site history of the sampled stands

Site	Latitude (N)	Longitude (W)	Year of plot establishment	*Stand age at plot establishment	Total plots	Mean DBH (cm)	Stand grouping
Klua 91	58°47'	122°21'	2005	8	60	2.79	1
B51-271	59°13'	123°40'	2005	10	60	4.57	2
B56-272	59°09'	123°44'	2005	10	37	4.69	
B56-408	59°10'	123°42'	2005	10	7	4.82	
Profit	59°09'	122°38'	2005	13	12	5.64	3
Beaver	59°00'	123°22'	2004	15	54	8.27	4
J84-012	58°44'	123°34'	2004	17	13	9.38	5
J84-011	58°52'	123°22'	2004	17	63	10.92	

*Stand age at establishment – between October of the year indicated and the following March

Table 2. Regression equation and r^2 for the relationship between plot density (stems·ha^{-1}: birch) and spruce basal area for the population and each stand group

Spruce variable	r^2	Equation	
BA per plot	0.3269	0.0015440 + 0.0005610 × stems per plot	
BA class	0.4135	0.0004355 + 0.0011470 × density class	
BA class	0.4512	–0.0000820 + 0.0011910 × density class	group 1
BA class	0.3063	0.0000634 + 0.0009168 × density class	group 2
BA class	0.4151	0.0001860 + 0.0009969 × density class	group 3
BA class	0.5900	0.0004533 + 0.0015130 × density class	group 4
BA class	0.4870	0.0007082 + 0.0015120 × density class	group 5

planted to spruce (Table 1). Given the difficulty of establishing spruce plantations in the Fort Nelson area, all stands were subject to an aerial application of the herbicide glyphosate at a rate of 6 l·ha^{-1} (Vision = contains about 35.6% glyphosate) approximately two years post planting, as a means of vegetation control.

Single tree temporary sample plots (TSP) were established based on the nearest individual method (Kent, Coker 1992). A systematic grid point was established on every stand at a 100 meter interval and the closest undamaged spruce tree was selected as a target tree for each grid-point (by BC regulation 1,000 stems·ha^{-1} are recommended density for target species). Sample trees were free of defects and taller than 1.37 m. Defects may have been induced by pathogens or insects and reduced growth would not be due to competition (stand density). Based on the target tree a temporary sample plot (TSP) with 1.78 m radius (10 m^2) was established. Several birch specific density classes 1,000, 2,000, 3,000, 5,000, and 6,000 stems·ha^{-1} including control (no birch) were selected by plots to investigate the impact on spruce growth. All spruces and birches within the plot taller than 1.30 m were measured. Height and diameter at breast height (DBH) for birch and total height, height to live crown, crown width, DBH, and age (using tree cores at DBH) for spruce were measured.

Height to diameter ratio (HDR) is an alternative competition index used to determine the competition between birch and spruce. This competition index was widely used in northern British Columbia to determine the vigour and 'free growing' status of crop trees, especially young lodgepole pine (*Pinus contorta* Dougl.) and spruce (Opio et al. 2000). The HDR was calculated individually for each target tree by dividing the height of the tree by its DBH. Depending on the stand, 10–15 sample plots per specific density classes were established in each stand. In total 622 sample plots were established across the eight sites. From each sample plot, the target tree (spruce) and birch stems were sampled. The stems were cut into cookies (cross-sectional discs) at 0 m, 0.5 m, 1.0 m, 1.3 m, 1.5, 2.0 m etc. in the field. In the laboratory, the annual rings of each cookie were counted to determine tree age at each height. The cookies were scanned to file for future reference.

Statistical analysis

All statistical analyses were based on the pooled data and visual tests for normality of data distribution were done using histograms with normal smoothing curves. Initially data were analysed using linear regression modules to predict the impact of birch on spruce growth. However regression analysis showed that birch stems per plot were a poor predictor of spruce basal area per plot when all data were pooled or individual single stand was considered (Table 2 and Fig. 1). The relationships were better when pooled class data were used instead of raw data and class data showed variation among the different stand groups and in no instance did the regression account for 60% of the variation (Table 2). Therefore GLM analysis was done for each stand group where birch stem density and basal area classes were used as independent variables and different spruce variables as dependent variables. Spruce DBH (cm), stem volume (m^3) and HDR were used as the primary indicators of birch competition on crop tree performance. Total broadleaf basal area per plot was assigned from 0 to ≥ 9.0 (m^2·ha^{-1}) with 0.5 m^2 interval classes. Comparisons were made among sites and within sites. In this investigation 8 stands were converted

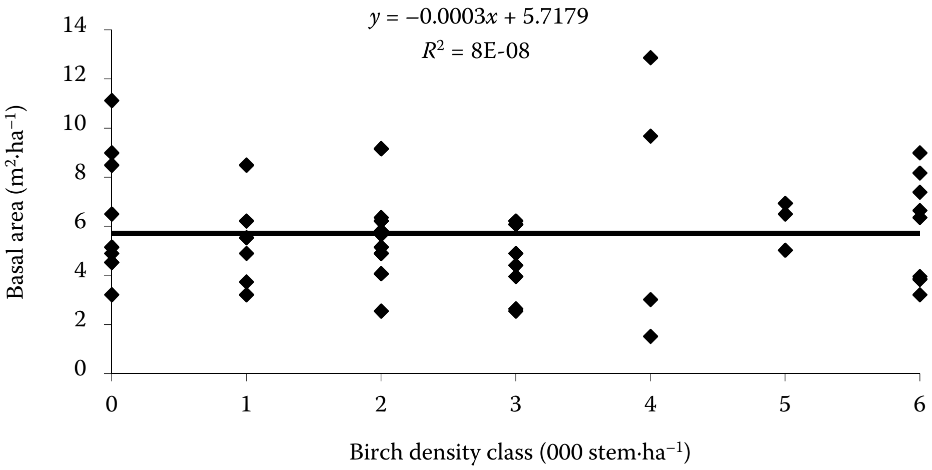

Fig. 1. The relationship between spruce basal area and birch density classes based on temporary sample plots (TSP) at a single stand Beaver site (Group 4)

to five different forest groups based on stand age (Table 1).

After the overall GLM analysis, a sequential analysis for each of the density or basal area classes was carried out to determine the density threshold that no longer significantly affected DBH, HDR or stem volume. Threshold levels were identified using a ceiling function which described the upper boundary of the data and enveloped at least 95% of the observations (Burton 1993). All statistical analyses were carried out using SYSTAT® v. 12.

Growth and Yield Models

TWIGS is a spatial growth and yield simulation program developed by the US Forest Service (Miner et al. 1988). It is useful for forest managers in making silviculture and forest planning decisions because its output is based on actual tree lists developed from permanent sample plot data. This program represents the complex stand growth on the basis of its projections of tree lists, annual diameter increment and stand site index. Although we did not use long-term re-measurement data to evaluate the performance of this model, TWIGS was extensively validated by Lacerte et al. (2004) at higher latitudes in Ontario and the performance was consistent with other studies where long-term re-measurement data were not used (Payandeh, Huynh 1991; Payandeh, Papadopo 1994). This model projection also provided confident prediction in boreal-northern forest transition of the Lakes States: MN, WI, MI Upper Peninsula (Miner et al. 1988). All those findings made us optimistic to apply this model in our ongoing study and validation of TWIGS can be done when long-term re-measurement data will be available in the near future. The TWIGS Lakes State version growth routines are based on permanent sample plot (PSP) data. Two different sites (i) poor site [SI_{50} = 15 m (site index or SI_{50} = is defined as top height at a reference age of 50 years at breast height in BC)] and (ii) better or good site (SI_{50} = 21.4 m) were selected to project the spruce yield. The characteristics of the poor site are poorly drained soil and nutritionally poor. For the poor site (SI_{50} = 15 m) four tree lists with nominal birch densities of 450, 1,200, 1,650 and 5,800 stems·ha^{-1} each with 1,000 stems·ha^{-1} of spruce [BC's legislative recommended density (BC Ministry of Forests 2000)] were used based on TSP result. The characteristics of the better site are well drained and nutritionally rich. Similarly five tree lists with nominal birch densities of 500, 2,000, 3,000, 5,000 and 8,600 stems·ha^{-1} each with 1,000 stems·ha^{-1} of spruce were projected for the better site (SI_{50} = 21.4 m).

TIPSY (Table Interpolation Program for Stand Yields) is a spatial growth and yield model which enables timber supply analysts to predict future volumes for a variety of harvesting patterns and silvicultural regimes ranging from clear-cutting to variable retention (Mitchell et al. 1992). This model projection can be easily calibrated with the BC online database system which contains more than 15,000 permanent sample plots or 548 managed stand yield tables across BC (Lucca 1999, http://www.for.gov.bc.ca/hre/gymodels/TIPSY/index.htm). In our study, the yield information in TIPSY was calibrated with the BC online database system for more accurate prediction.

Growth from zero to 120 years in a managed stand can be predicted by this model if the stand is growing in a relatively pest-free environment (Mitchell et al. 1992). TIPSY is the standard single species stand (monoculture) growth and yield

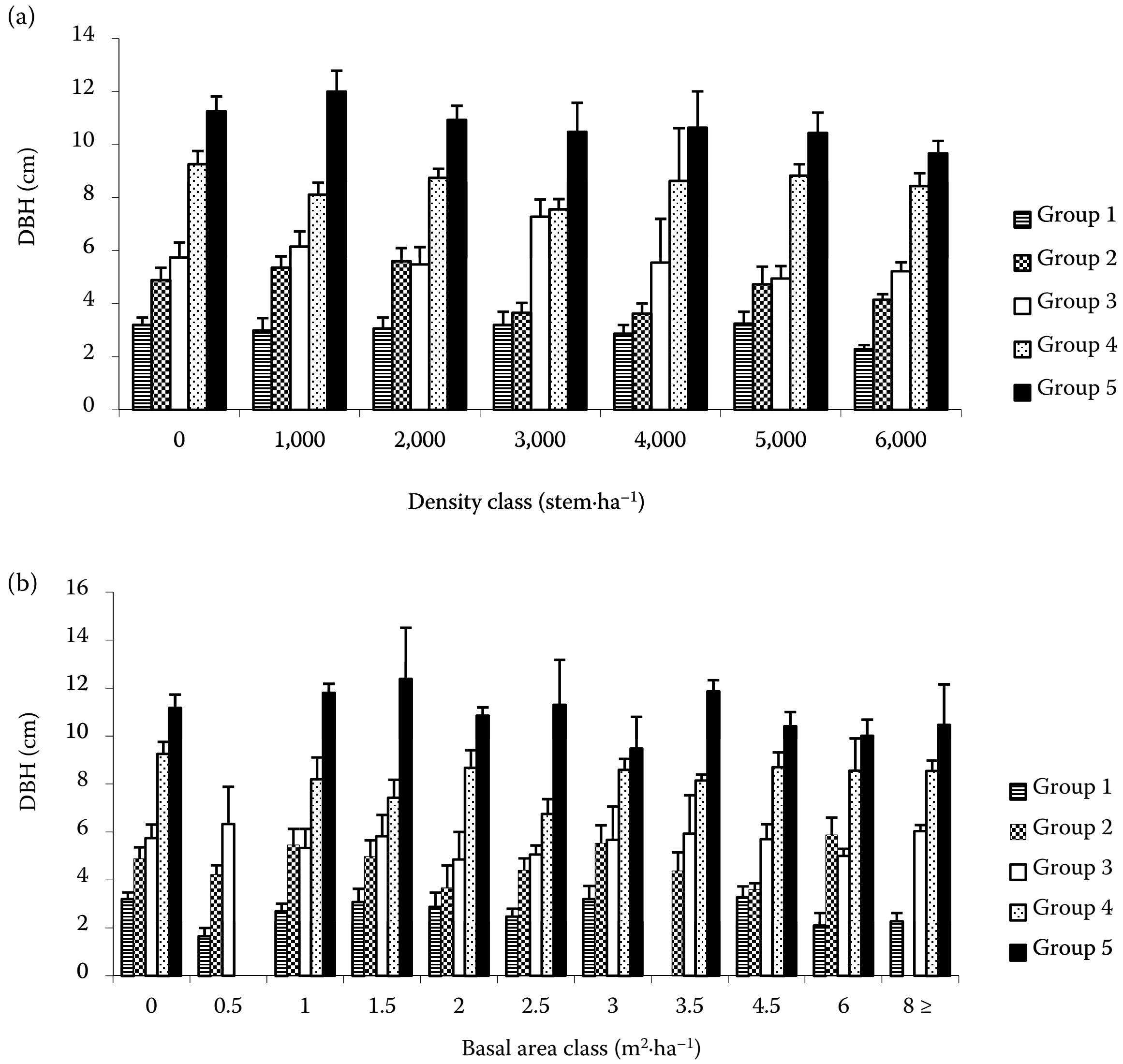

Fig. 2. Mean (± SEM) DBH by (a) density and (b) basal area class for each stand group

model for BC and was used to do projections on both sites [SI_{50} = 15 m (poor site) and SI_{50} = 21.4 m (better site)] in this study. For the TIPSY projection, a stand was treated as a pure spruce stand with all birch trees removed. All projections were done 100 years into the future at 10 year intervals and short-term annual projections were also done for the better site. The TIPSY model projections were also based on annual diameter increments of the crop trees.

Future values of several growth and yield scenarios were determined using an aerial herbicide application at a cost of 500 USD·ha^{-1}, real interest rates of 2, 4 or 6%, and spruce revenues of 40, 60 or 80 USD·m^{-3}. Potential revenue from birch was ignored due to the poor market value in BC. The scenarios were as follows:

(a) TWIGS all broadleaves removed (base case),
(b) TWIGS 80% broadleaves removed,
(c) Mean of the TWIGS runs with birch present on the better site (SI_{50} = 21.4 m),
(d) TIPSY spruce projection for the better (SI_{50} = 21.4 m) and poor sites (SI_{50} = 15 m).

RESULTS

DBH, stem volume and height to diameter (HDR) responses

Based on the density and basal area, DBH showed different responses among the groups (Fig. 2). Neither density class nor basal area class was significant in explaining the DBH response for all groups (Table 3). Based on the GLM analysis a non-significant threshold density was determined for each

Table 3. GLM results based on overall spruce DBH and density threshold for DBH in each stand group by birch density (stems·ha^{-1}) and basal area class

Group	Source	Based on all DBH data				Based on threshold density				Threshold density
		mean square	F ratio	*P* (F)	r^2	mean square	F ratio	*P* (F)	r^2	
1	density class	1.74033	2.1614	0.0656	0.391	0.39600	0.4126	0.7978	0.384	< 6,000
	BA class	1.40182	1.7410	0.1088		1.67368	1.7436	0.1415		
	error	0.80519				0.95977				
2	density class	3.44097	2.1412	0.0702	0.403	2.25710	1.1688	0.3345	0.279	< 3,000
	BA class	1.99863	1.2437	0.2978		1.78073	0.9221	0.5035		
	error	1.60700				1.93111				
3	density class	5.39883	1.9731	0.1056	0.269	0.71933	0.2228	0.9484	0.312	< 6,000
	BA class	1.67054	0.6105	0.8078		1.78179	0.5518	0.8195		
	error	2.73618				3.22906				
4	density class	1.59455	0.4934	0.7796	0.178	0.77900	0.2771	0.7601	0.189	< 3,000
	BA class	1.66923	0.5166	0.8702		1.65441	0.5884	0.7601		
	error	3.23147				2.81183				
5	density class	5.79904	1.8067	0.3845	0.223	0.55473	0.0897	0.7671	0.101	< 3,000
	BA class	3.73131	0.6992	0.7201		1.51020	0.2441	0.9780		
	error	5.33648				6.18544				

Density only shown where the GLM changes from significant to non-significant ($P = 0.05$). The threshold level was identified using a ceiling function which described the upper boundary of the data and enveloped at least 95% of the observations (Burton 1993)

stand group. The threshold density for groups 2, 4, and 5 was < 3,000 stems·ha^{-1} while it was < 6,000 stems·ha^{-1} for groups 1 and 3 (Table 3). A similar result was found for stem volume in relation to density and basal area for all groups (Table 4). The threshold response for stem volume by groups was similar to the DBH response (Tables 3 and 4).

The result showed that the HDR was generally greater in stand groups 1, 2 and 3 with the exception of group 4 at < 3,000 stems·ha^{-1} class

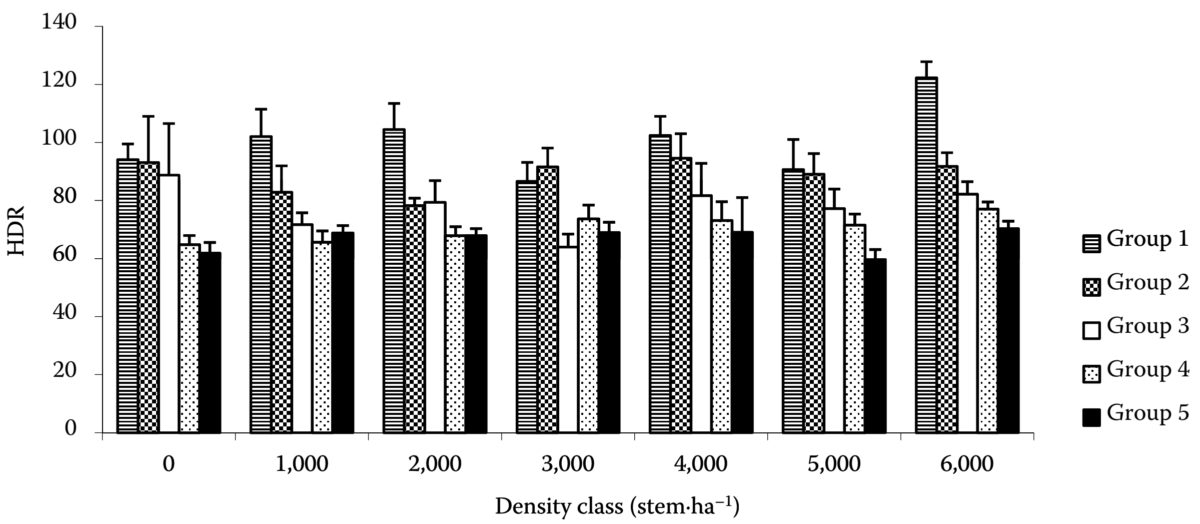

Fig. 3. Mean (± SEM) height to diameter ratio (HDR) by density class for each stand group

Table 4. GLM results based on overall spruce stem volume and density threshold for volume in each stand group by birch density (stems·ha^{-1}) and basal area class

Group	Source	Based on all stem volume data				Based on threshold density				Threshold density
		mean square	F ratio	*P* (F)	r^2	mean square	F ratio	*P* (F)	r^2	
1	density class	0.0000007	2.1675	0.0649	0.382	0.0000001	0.2681	0.9286	0.389	< 6,000
	BA class	0.0000006	1.8512	0.0863		0.0000008	1.9928	0.1003		
	error	0.0000003				0.0000004				
2	density class	0.0000066	2.0675	0.0795	0.422	0.0000058	1.8661	0.1851	0.432	< 3,000
	BA class	0.0000047	1.4880	0.1867		0.0000059	0.8918	0.1409		
	error	0.0000032				0.0000031				
3	density class	0.0000098	1.4857	0.2100	0.281	0.0000006	0.0781	0.9881	0.137	< 6,000
	BA class	0.0000043	0.6532	0.7588		0.0000053	0.6899	0.7223		
	error	0.0000066				0.0000077				
4	density class	0.0000152	0.3516	0.9056	0.151	0.0000033	0.0770	0.9261	0.169	< 3,000
	BA class	0.0000193	0.4467	0.9024		0.0000245	0.5705	0.7737		
	error	0.0000432				0.0000429				
5	density class	0.0001838	1.3473	0.2561	0.224	0.0000170	0.1206	0.8869	0.132	< 3,000
	BA class	0.0001138	0.8338	0.5989		0.0000435	0.3081	0.9437		
	error	0.0001364				0.0001413				

Density only shown where the GLM changes from significant to non-significant ($P = 0.05$). The threshold level was identified using a ceiling function which described the upper boundary of the data and enveloped at least 95% of the observations (Burton 1993)

Table 5. GLM results based on overall HDR and density threshold for HDR in each stand group by birch density (stems·ha^{-1}) and basal area class

Group	Source	Based on overall HDR				Based on threshold density		Threshold density
		mean square	F ratio	*P* (F)	r^2	*P* (F)	r^2	
1	density class	1753.89	2.9680	0.0163	0.365	0.6540	0.321	< 6,000
	BA class	595.859	1.0083	0.4484		0.3521		
	error	590.930						
2	density class	196.241	0.2409	0.9601	0.132	0.9519	0.093	< 5,000
	BA class	373.717	0.4587	0.8931		0.9838		
	error	814.716						
3	density class	658.011	0.7817	0.5693	0.134	0.9837	0.1254	< 6,000
	BA class	209.171	0.2485	0.9914		0.9986		
	error	841.723						
4	density class	58.0057	0.4201	0.8325	0.215	0.8055	0.192	< 6,000
	BA class	111.831	0.8098	0.6203		0.7726		
	error	138.090						
5	density class	26.4563	0.6362	0.7006	0.273	0.9122	0.189	< 5,000
	BA class	120.851	0.8348	0.5981		0.9056		
	error	139.523						

Density only shown where the GLM changes from significant to non-significant ($P = 0.05$). The thresholds level was identified using a ceiling function which described the upper boundary of the data and enveloped at least 95% of the observations (Burton 1993)

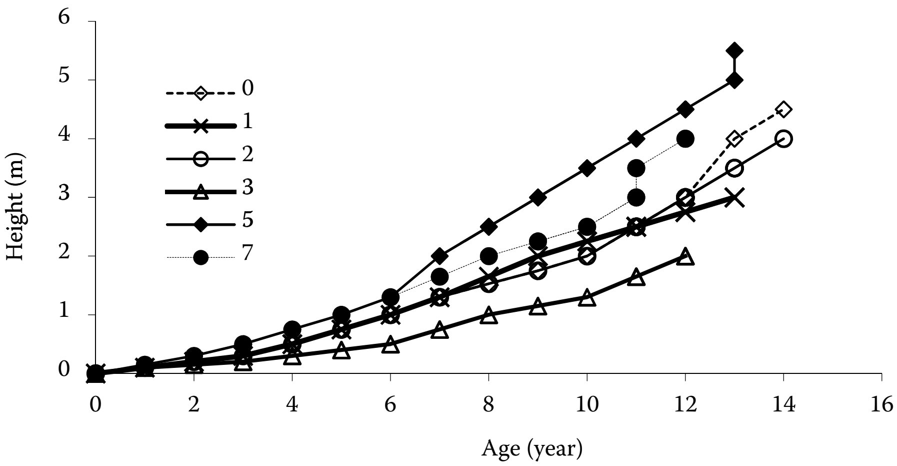

Fig. 4. Plantation height over age curves for spruce grown at different birch density

(Fig. 3). HDR response to birch density was inconsistent, for some groups it increased and for other groups it decreased with increasing birch density. Neither density class nor basal area class was significant in explaining the HDR response for all groups except in group 1 where density class was significant (Table 5). The threshold for group 5 was < 6,000 stems·ha^{-1}. Further density class reductions did not improve the result for this stand group. The density thresholds were larger for HDR than for DBH for groups 2, 4 and 5 (Tables 2 and 4).

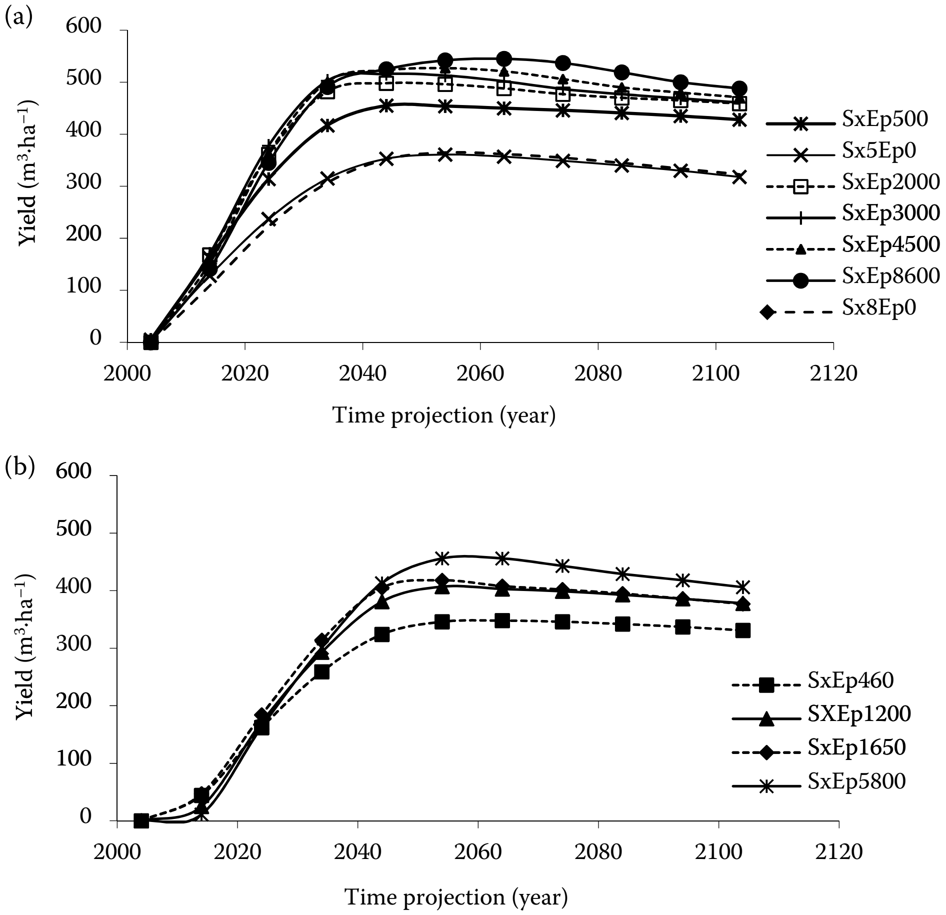

Fig. 5. TWIGS spruce yield (m^3) projection based on 1,000 spruce (Sx) stems·ha^{-1} for (a) better site (SI_{50}=21.4 m), birch (Ep) densities were 500 (SxEp 500), 2,000, 3,000, 4,500 and 8,600 stems·ha^{-1}, projections were also done at the two extreme densities classes (SxEp 500 and SxEp 8600) without birch: Sx5Ep0, Sx8Ep0, (b) poor site (SI_{50} = 15.0 m), birch densities were 460 (SxEp 460), 1,200, 1,650 and 5,800 stems·ha^{-1}

Table 6. Future values (USD·ha^{-1}) of different stand age for the five scenarios described in the text with three different wood revenues (40, 60, 80) and real interest rates. Brushing treatment cost was fixed·500 USD·ha^{-1}

Real interest rate (%)	Projected year	TWIGS (all broadleaves remove)			TWIGS (80% broadleaves removed)			TWIGS high (SI_{50} = 21.4 m)			TIPSY high (SI_{50} = 21.4 m)			TIPSY low (SI_{50} = 15 m)		
		40	60	80	40	60	80	40	60	80	40	60	80	40	60	80
2	2044	13,015	20,076	27,135	10,192	15,840	21,488	19,032	29,100	39,168	13,215	20,375	27,535	4,295	6,995	9.695
	2054	13,094	20,314	27,534	10,206	15,982	21,758	18,910	29,038	39,166	16,934	26,074	35,214	5,934	9.574	13,214
	2064	12,639	19,779	26,919	9,783	15,495	21,207	18,407	28,431	38,455	19,359	29,859	40,359	7,279	11,739	16,199
	2074	11,960	18,940	25,920	9,168	14,752	20,336	17,624	27,436	37,248	21,000	32,500	44,000	8,320	13,480	18,640
4	2044	11,719	18,779	25,839	8,895	14,543	20,191	17,735	27,803	37,871	11,919	19,079	26,239	2,999	5,699	8,399
	2054	10,886	18,106	25,326	7,998	13,774	19,550	16,702	26,830	36,958	14,726	23,866	29,006	3,726	7,366	11,006
	2064	9,020	16,160	23,300	6,164	11,876	17,588	14,788	24,812	34,836	15,740	26,240	30,740	3,660	8,120	12,580
	2074	6,174	13,154	20,134	3,382	8,966	14,550	11,838	21,650	32,462	15,214	26,714	31,214	2,534	7,694	12,854
6	2044	8,977	16,037	23,097	10,153	12,801	17,449	14,993	25,061	35,129	9,177	12,337	23,497	2,575	2,957	5,657
	2054	7,229	12,449	19,669	12,341	14,117	13,893	11,045	21,173	31,301	9,069	13,209	27,349	4,930	5,709	5,349
	2064	9,210	7,926	12,066	15,069	16,423	16,354	10,554	13,578	23,602	7,506	15,006	25,506	5,537	6,113	9,346
	2074	15,577	9,597	11,617	18,369	17,785	17,201	9,913	10,123	19,710	6,537	14,962	18,462	9,217	8,057	10,897

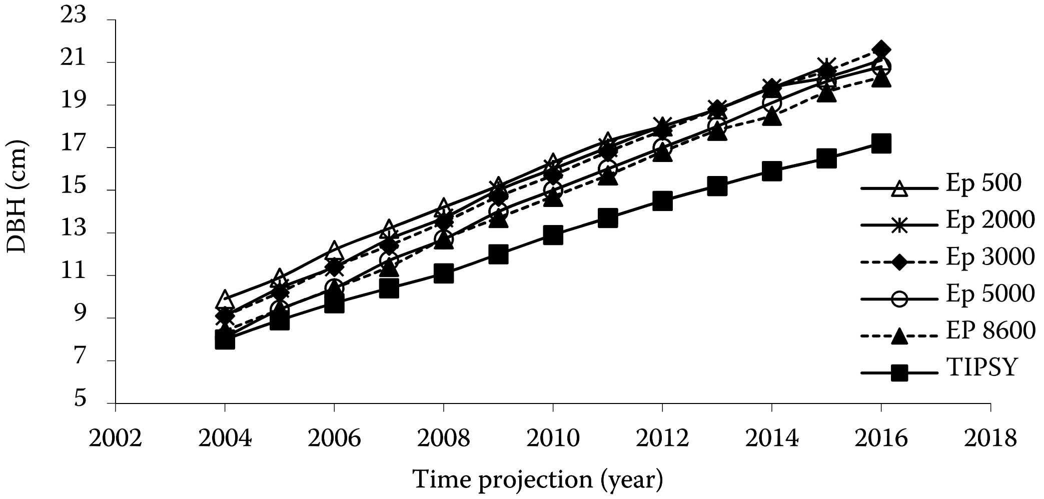

Fig. 6. Comparison of TWIGS and TIPSY (a pure stand of spruce) projection for DBH growth over 12 years at better site (SI_{50} = 1.4 m) for the various birch densities

Height over age curves

Spruce height over tree age curves were variable with respect to birch density (Fig. 4). Spruce height growth was generally greater than that of birch (not presented) and the tallest spruce was from a higher density while some of the shorter spruce trees were from both low and high density plots. Even though birch started height growth later, it often surpassed the height growth of the spruce crop tree by the time of initial TSP measurements.

Growth and yield models prediction

At both SI_{50} of 21.4 and 15.0, the TWIGS projection suggests spruce yields will increase with increased birch density (Fig. 5). When all the birches were removed at the highest and lowest densities for SI_{50} of 21.4, the projection indicated spruce yield would be significantly lower without birch (Fig. 5a). The spruce yield at economic rotation on the better site was about 500 m^3 for the higher birch densities. On the poorer site it was 420 m^3 for 500 birches per ha and about 320 m^3 when all the birches were removed (Fig. 5b). The TIPSY yield projection at a stand age of 65 to 70 years for a pure spruce stand was similar to the TWIGS projection of the pure spruce stand (data not presented).

TWIGS DBH projections over the next decade suggest DBH will converge among density regimes: there will be small density-induced changes in spruce mean DBH (Fig. 6). The TWIGS DBH projections are increasing at a greater rate and are diverging from the TIPSY DBH projection for a pure spruce stand at the better site (SI_{50} = 21.4).

TWIGS future value projections assume no vegetation removal at any point in future, as a result, there are no costs incurred, only revenues generated at harvest (Table 6). These do not change regardless of interest rate. In TIPSY, both better (SI_{50} = 21.4) and poor (SI_{50} =15 m) site projections assume the vegetation control. TIPSY future value decreased with increased interest rate and increased with increased revenue for the wood (Table 6). Economic rotation ages decreased with increased interest rates for the TIPSY projection. At 2% real interest, TIPSY better site had the best future value in the years 2064 and 2074 followed by TWIGS base (all broadleaves removed) and TWIGS-80% (80% broadleaves removed), respectively. Based on 4 and 6% real interest, TWIGS better site showed the best future value among the scenarios whereas TIPSY poor site represented the worst future value of all scenarios (Table 6).

DISCUSSION

Diameter at breast height is an excellent response variable for competition studies because interspecific competition affects diameter growth more than it affects height growth (Jobidon 2000; Valkonen, Ruuska 2003; Newsome et al. 2010). Radial development is an integrative index of tree physiological responses to environmental variation (Misson et al. 2003), and it is the first energy sink to be abandoned when growth is challenged (Oliver, Larson 1996). The TSP data suggest there is a density threshold above which DBH is negatively impacted. The density threshold varies according to the stand group (Table 3). If a non-conservative approach is taken, the threshold could be equal to or greater than 5,000 stems·ha^{-1} (Table 3). However, this must be tempered because of the relatively small sample size for the five stand groups, approximately 300 TSP. With a conservative approach, the density threshold is still far greater (~ 3,000 stems·ha^{-1}) than 1,000 stems·ha^{-1} of paper birch allowed in the current guidelines (BC Ministry of Forests 2000). The TWIGS projections also suggest there is a minimal impact on future yield throughout the projected time frame when birch densities are higher than current free to grow guidelines (1,000 stems·ha^{-1}). The data also suggest TWIGS has utility in north-eastern BC because an earlier TWIGS model projection has been validated for boreal-northern forest transition (Miner et al. 1988).

Not surprisingly, mean stem volume followed a similar trend to DBH with respect to density thresholds (Table 4). However, the density threshold affecting HDR was large compared to the other metrics (Table 5). This is of interest as HDR can be used in BC to determine a stand's candidacy for a free to grow declaration if it exceeds density (stems·ha^{-1}) guidelines (BC Ministry of Forests 2000). For the most part, even at 0 stem·ha^{-1} birch density, the HDR exceeds what is considered to be optimal for spruce in the central BC interior (Opio et al. 2000). These observations also support the hypothesis that birch at the observed densities does not appear to be deleterious for spruce growth.

There is a low relationship between spruce height growth over tree age and birch density (Fig. 4). The poorest height growth was seen at 3,000 stems per ha while the best was observed at 5,000 and 7,000 stems·ha^{-1} with the 0 stem·ha^{-1} or standard operational treatment being intermediate. Generally, the birch is taller than the spruce even though the block was treated with herbicide after the spruce was planted. However, spruce height appears to generally be 'keeping up' with birch height growth without any negative influence on DBH. Spruce DBH growth was greater than that of birch. This supports the observations of Frivold and Frank (2002) Simardand and Vyse (2006) that the competitive effects of birch likely diminish as the stand ages. Further, Legare et al. (2004) reported that black spruce DBH and height were greater when grown with aspen up to a threshold basal area of about 40% of the stand basal area. They also concluded that broadleaf stand components should not only be viewed as tolerable but also in some cases as beneficial. Whereas a negative relation with birch density was reported by Simard and Hannam (2000), according to them the birch density reduction from 2,500 to 50 stems·ha^{-1} significantly increased the conifer growth.

The TWIGS projection showed increased spruce yield with increasing birch density up to a certain density (Fig. 5). This might be due to the effect of interspecific competition between these two species. Simard (1990) reported that paper birch density up to 2,100 stems·ha^{-1} had a low effect on conifer growth. While in another study Simard et al. (2001) reported that a birch density up to 4,400 stems·ha^{-1} had a low impact on Douglas-fir growth in 10 to 15 years old stands. Looking at DBH projections, the results indicate DBH is also increasing at a greater rate than the projected pure spruce stand at SI_{50} = 21.4 (Fig. 6). These findings are also supported by observations in the central BC interior (Hawkins, Dhar 2011) and in the southern BC interior mixedwood forest (Simard et al. 2005; Simard, Vyse 2006). Some other investigations also reported that mixedwood stands showed greater productivity than single species stands (Man, Lieffers 1999; Legare et al. 2004; Kelty 2006). This also lends confidence to the TWIGS projection even though the version used was for the boreal-northern forest transition of the Lakes States (Miner et al. 1988) and higher latitude Ontario Canada (Payandeh, Papadopol 1994; Lacerte et al. 2004).

Short-term DBH projections for spruce in TWIGS suggest up to a certain density level, paper birch competition will have a low impact over the next decade. This will be verified by follow-up measurements as well as establishment of controlled experiments. The latter is an important step as species response gradients may be confounded with environmental gradients (Garber, Maguire 2005). On the other hand, the TIPSY projections for a pure spruce stand indicate lesser DBH growth throughout the projection period. However, further validation is required for accurate projection of the TWIGS model in this area. Moreover we also suggest that forest managers and practitioners need caution when use our results in the field due to potential limitations of the model projection. It is also mentionable that the main objective of our study was to anticipate the gross effects of treatments in birch spruce mixedwood stands.

Future value

The overall reasonable real interest rate used was 4.0%. The rate was based on a survey of a range of conservative Canadian Mutual Funds' (stocks, bonds, T-Bill, index, energy) performance over the past 20 years: after inflation was taken into account, the return was about 3.9%. However, only at a 2% real interest rate for brushing any of the stands proves to be a good investment (Table 6). At 4 and 6%, the best future values, regardless of wood re-venue (value), were found at the better site in the TWIGS projection. This suggests that the brushing of these stand types does not enhance stand commercial value and it may detract from biodiversity values. The money allocated to such brushing activities would be better used for other management activities.

CONCLUSIONS

From our study it appears that a single early broadcast brushing might be sufficient to ensure the survival and future growth of spruce-birch stands in the Fort Nelson forest district. Model projections, field data, and economic analysis also suggest a second brushing may not be warranted at paper birch densities at or below 3,000 stems·ha^{-1} for these stands. Considering potential savings with a targeted brushing program, a higher broadleaf component could be financially advantageous in addition to the noted biological benefits. In another study Hawkins et al. (2012) reported that broadcast brushing did not remove all birches and suggested a move away from broadcast vegetation control to spot control, where warranted, could result in better tree growth, improved forest health and structural diversity. Therefore the inclusion of other broadleaf species in these complex processes may have more beneficial effects on spruce growth. Conversely, spruce growth may be negatively impacted when all broadleaf species are removed from the stand. Therefore further steps should be made to investigate more at the site level to determine whether target trees of particular sites can accommodate higher densities of broadleaf species. This knowledge will provide the framework for more diverse provincial policies regarding the maintenance of mixedwood species composition.

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References

Baleshta K.E., Simard S.W., Guy R.D., Chanway C.P. (2005): Reducing paper birch density increases Douglas-fir growth rate and Armillaria root diseases incidence in southern interior British Columbia. Forest Ecology and Management, ***208***: 1–13.

Bergeron Y., Harvey B., Leduc A., Gauthier S. (1999): Forest management guidelines based on natural disturbance dynamics: stand-and forest-level considerations. The Forestry Chronicle, ***75***: 49–94.

British Columbia Ministry of Forests (2000): Establishment to Free Growing Guidebook, Prince George Forest Region. Victoria, British Columbia Ministry of Forests: 162. Available at http://www.for.gov.bc.ca/tasb/legsregs/fpc/fpcguide/free/EFG-PG-print.pdf (accessed December 20, 2011)

Burton P.J. (1993): Some limitations inherent to static indices of plant competition. Canadian Journal of Forest Research, ***23***: 2141–2152.

Comeau P.G., Biring B.S., Harper G.J. (2000): Conifer Response to Brushing Treatment: Summary of British Columbia Data. Extension Note 41. Victoria, British Columbia Ministry of Forests: 12. Available at http://www.for.gov.bc.ca/hfd/pubs/docs/en/en41.pdf (accessed December, 2011).

DeLong C., MacKinnon A., Jang L. (1990): A Field Guide for Identification and Interpretation of Ecosystems of the Northeast Portion of the Prince George Forest Region. Land Management Handbook 22. Victoria, British Columbia Ministry of Forests: 57. Available at http://www.for.gov.bc.ca/hfd/pubs/docs/Lmh/Lmh22.pdf (accessed May, 2012).

Forest Practices Code of British Columbia Act (1996): RSBC, Chapter 159. Victoria, British Columbia Ministry of Forests: 26. Available at http://www.bclaws.ca/EPLibraries/bclaws_new/document/ID/freeside/00_96159_01 (accessed May 4, 2012).

Frivold L.H., Frank J. (2002): Growth of mixed mirch-coniferous stands in relation to pure coniferous stands at similar sites in south-eastern Norway. Scandinavian Journal of Forest Research, ***17***: 139–149.

Garber S.M., Maguire D.A. (2005): The response of vertical foliage distribution to spacing and species composition in mixed conifer stands in central Oregon. Forest Ecology and Management, ***211***: 341–355.

Gayer K. (1886): Der gemischte Wald oseine Begründung und pflege insbesonder durch horst- und Gruppenwirtshaft. Berlin, Paul Parey Verlag: 168.

Hawkins C.D.B., Dhar A. (2011): Mixtures of broadleaves and conifers are ecologically and economically desired in an uncertain future changing climate. In: Muys B. (ed.): Proceedings of the Conservation and Management of Forests for Sustainable Development: Where Science Meets Policy. Leuven, 23.–24. November 2011. Belgium, Katholieke University Leuven: 20.

Hawkins C.D.B., Dhar A., Lange J. (2012): Vegetation management with Glyphosate has little impact on understory species diversity or tree growth in a sub boreal spruce plantation – a case study. Plant Biosystems (in press).

Jobidon R. (2000): Density-dependent effects of northern hardwood competition on selected environmental resources and young white spruce (*Picea glauca*) plantation growth, mineral nutrition, and stand structure development a 5-year study. Forest Ecology and Management, ***130***: 77–97.

Kelty M.J. (2006): The role of species mixtures in plantation forestry. Forest Ecology and Management, ***233***: 195–204.

Kent M., Coker P. (1992): Vegetation Description and Analysis: A Practical Approach. Exeter, Short Run Press: 354.

Knoke T., Ammer C., Stimm B., Mosandl R. (2008): Admixing broadleaved to coniferous tree species: a review on yield ecological stability and economics. European Journal of Forest Research, ***127***: 89–101.

Lacerte V., Larocque G.R., Woods M., Parton W.J., Penner M. (2004): Testing the Lake States variant of FVS (Forest Vegetation Simulator) for the main forest types of northern Ontario. The Forestry Chronicle, ***80***: 495–506.

Lavender D.P., Parish R., Johnson C.M., Montgomery G., Vyse A., Willis R.A., Winston D. (1990): Regenerating British Columbia's Forests. Vancouver, UBC Press: 385.

Legare S., Pare D., Bergeron Y. (2004): The response of black spruce growth to an increased portion of aspen in mixed stands. Canadian Journal of Forest Research, ***34***: 405–416.

Lucca D.C.M. (1999): TASS/SYLVER/TIPSY: systems for predicting the impact of silvicultural practices on yield, lumber value, economic return and other benefits. In: Bamsey C.R. (ed.): Proceedings of the Stand Density Management Conference: Using the Planning Tools. Edmonton, 23.–24. November 1998. Edmonton, Clear Lake Ltd.: 7–16.

Man R., Lieffers V.J. (1999): Are mixtures of aspen and white spruce more productive than single species stands? The Forestry Chronicle, ***75***: 505–513.

Mard H. (1996): The influence of a birch shelter (*Betula* spp.) on the growth of young stands of *Picea abies*. Scandinavian Journal of Forest Research, ***11***: 343–350.

Martin L.J., Gower T.S. (2006): Boreal mixedwood tree growth on contrasting soils and disturbance types. Canadian Journal of Forest Research, ***36***: 986–995

Miner C.L., Walters N.R., Belli M.L. (1988): A guide to the TWIGS Program for the North Central United States. St. Paul, USDA Forest Service: 111.

Misson L., Vincke C., Devillez F. (2003): Frequency responses of radial growth series after different thinning intensities in Norway spruce (*Picea abies* [L.] Karst.) stand. Forest Ecology and Management, ***177***: 51–63.

Mitchell K.J., Grout S.E., Macdonald R.N., Watmough C.A. (1992): User's Guide for TIPSY: A Table Interpolation for Stand Yields. Victoria, British Columbia Ministry of Forests: 78.

Newsome T., Heineman J.L., Nemec A. (2010): A comparison of lodgepole pine responses to varying levels of trembling aspen removal in two dry south-central British Columbia ecosystems. Forest Ecology and Management, ***259***:1170–1180.

Oliver C.D., Larson B.C. (1996): Forest Stand Dynamics. John Wiley and Sons, New York: 540.

Opio C., Jacob N., Coopersmith D. (2000): Height to diameter ratio as a competition index for young conifer plantations in northern British Columbia, Canada. Forest Ecology and Management, ***137***: 245–252.

Payandeh B., Huynh L.N. (1991): ONTWIGS: A Forest Growth and Yield Projection System Adapted for Ontario. Sault Ste. Marie, Ontario Great Lakes Forestry Centre: 19.

Payandeh B., Papadopol P. (1994): Partial calibration of ONTWIGS: a forest growth and yield projection system adapted for Ontario. Northern Journal of Applied Forestry, ***11***: 41–46.

Richards A.E., Forrester D.I., Bauhus J., Scherer-Lorenzen M. (2010): The influence of mixed species tree plantations on the nutrition of individual species: a review. Tree Physiology, ***30***: 1192–1208.

Simard S.W., Vyse A. (2006): Trade-offs between competition and facilitation: A case study of vegetation management in the interior cedar-hemlock forests of southern British Columbia. Canadian Journal of Forest Research, ***36***: 2486–2496.

Simard S.W., Hagerman S.M., Sachs D.L., Heineman J.L., Mather W.J. (2005): Conifer growth, *Armillaria ostoyae* root disease and plant diversity responses to broadleaf competition reduction in temperate mixed forests of southern interior British Columbia. Canadian Journal of Forest Research, ***35***: 843–859.

Simard S.W., Sachs D.L., Vyse A., Blevins L.L. (2004): Paper birch competitive effects vary with conifer tree species and stand age in interior British Columbia forests: implications for reforestation policy and practice. Forest Ecology Management, ***198***: 55–74.

Simard S.W., Heineman J.L., Mather W.J., Sachs D.L., Vyse A. (2001): Effects of Operational Brushing on Conifers and Plant Communities in the Southern Interior of British Columbia: Results from PROBE 1991–2000 Protocol for Operational Brushing Evaluations. Land Management Handbook No. 48. Victoria, British Columbia Ministry of Forests: 422.

Simard S.W., Hannam K.D. (2000): Effects of thinning overstory paper birch on survival and growth of interior spruce in British Columbia: implications for reforestation policy and biodiversity. Forest Ecology and Management, ***129***: 237–251.

Simard S.W. (1990): A Retrospective Study of Competition between Paper Birch and Planted Douglas-fir. FRDA Report 147. Victoria, Forestry Canada and British Columbia Ministry of Forests: 19.

Taylor S., Alfaro R.I., Delong C., Rankin L. (1996): The effects of overstory shading on white pine weevil damage to interior white spruce and its effects on growth rates. Canadian Journal of Forest Research, ***26***: 306–312.

Taylor K.C., Arnup, R.W., Merchant B.G., Parton W.J., Nieppola J. (2000): A Field Guide to Forest Ecosystems of North-Eastern Ontario. Field Guide FG-001. Timmins, Ontario Ministry of Natural Resources: 325.

Valkonen S., Ruuska J. (2003): Effect of *Betula pendula* admixture on tree growth and branch diameter in young Pinus sylvestris stands in Southern Finland. Scandinavian Journal of Forest Research, ***18***: 416–426.

Wagner R.G., Little K.M., Richardson B., McNabb K. (2006): The role of vegetation management for enhancing productivity of the world's forests. Forestry, ***79***: 57–79.

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