Comparison of height growth and growth intercept models of jack pine plantations and natural stands in northern Ontario

Jin-ping Guo and Jian R. Wang

Abstract: Accurate estimates of forest productivity are required for sustainable forest management. Sixty-five jack pine (*Pinus banksiana* Lamb.) plantations (<50 years of age) were sampled to develop height growth and variable growth intercept (GI) models for jack pine plantations in northern Ontario, Canada. Based on the residual plots and model-fitting statistics, these models can be recommended for estimating site index (SI) of young (<40 years) jack pine plantations. To compare SI of plantations with that of natural stands, we used stem-analysis data from 383 plots of natural jack pine stands (aged 50–157 years) from the same geographic region to develop the GI models for natural stands. Also, polymorphic SI curves were developed for young (<40 years) plantations in northern Ontario. These SI curves were different from those for natural stands. Jack pine plantations had a higher site quality (SI) than did the original natural stands on the similar sites. The SI curves developed from natural stands should not be used to predict growth and yield of jack pine plantations before they are calibrated for jack pine plantations. These GI models will be used to estimate SI for silviculture and forest-management planning.

Résumé : L'aménagement forestier durable exige une estimation précise de la productivité des forêts. Soixante-cinq plantations de pin gris (*Pinus banksiana* Lamb.) de moins de 50 ans ont été échantillonnées dans le nord de l'Ontario (Canada) pour développer des modèles de croissance en hauteur et de croissance internodale variable. Selon les résultats de leur application aux placettes de validation et selon les statistiques d'ajustement, ces modèles peuvent être recommandés pour estimer l'indice de qualité de station des plantations de pin gris de moins de 40 ans. Pour comparer les indices de qualité de station des plantations à ceux des peuplements naturels, les résultats d'analyses de tiges provenant de 383 placettes établies dans des peuplements naturels âgés de 50 à 157 ans et situés dans la même région géographique ont été utilisés pour développer les modèles de croissance internodale variable des peuplements naturels. Des courbes d'indice de qualité de station polymorphiques ont également été développées pour les plantations de moins de 40 ans dans le nord de l'Ontario. Ces courbes d'indice de qualité de station étaient différentes de celles des peuplements naturels. Les plantations de pin gris ont des indices de qualité de station supérieurs à ceux des peuplements naturels qui occupaient les mêmes stations. Les courbes d'indice de qualité de station développées pour les peuplements naturels ne devraient pas être utilisées pour prédire la croissance et le rendement des plantations de pin gris sans avoir été préalablement calibrées pour les plantations de pin gris. Ces modèles de croissance internodale variable seront utilisés pour estimer l'indice de qualité de station dans le cadre de la production de plans d'aménagement et de stratégies sylvicoles pour les plantations de pin gris.

[Traduit par la Rédaction]

Introduction

Site index (SI) is an important tool in forest management and planning, since it is strongly related to, among other variables, the potential of a site to produce timber (Vanclay 1992). Obtaining an accurate SI for a young stand is often difficult. If an SI curve developed for mature natural stands was used in a young plantation, it may underestimate or overestimate the site productivity simply because the SI curve is not calibrated for young plantations. Therefore, basing a silviculture prescription on an estimate of site quality obtained from an SI curve may result in inaccurate stand prescriptions for plantations.

Growth intercept (GI) models are very useful management and decision-making tools. They are particularly useful in obtaining an accurate SI for juvenile stands (Economou 1990). GI models estimate SI from the mean annual height growth immediately above breast height. Typically, height growth is identified from annual branch whorls and is averaged over a 5 year period. The determination of GI period is relatively straightforward and most feasible for conifer species having obvious annual branch whorls such as red pine (*Pinus resinosa* Ait.) (Alban 1972, 1979). Advantages of this method outlined by Alban (1972) include (*i*) use in stands

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too young to be evaluated with SI curves, (*ii*) no need to measure total tree height or tree age, (*iii*) quick and easy to measure, and (*iv*) measurement above breast height eliminates many of the establishment period variability. However, in other species, such as jack pine, annual branch whorls are less obvious. This makes both the development and use of traditional GI models error prone. The variable GI model predicts SI from the average height growth above breast height using the total above breast height, not just 5 year height interval (Nigh 1996*a*).

Growth intercept models had been developed for predicting SI for red pine plantations in the Allegheny Plateau of Ohio (Brown and Duncan 1990), and in the northern Lake States (Bottenfield and Reed 1988; Alban 1972, 1976, 1979) and white spruce (*Picea glauca* (Moench) Voss) plantations in northern Ontario (Thrower 1987) and for young eastern white pine (*Pinus strobus* L.) (Brown and Stires 1981). GI was also used as an indicator of site quality of planted and natural stands of Crimean pine (*Pinus nigra* Arnold var. *pallasiana* (Lambert) Asch. & Graebn.) in Greece (Economou 1990). In British Columbia, GI is extensively used for young plantations of major conifer species such as interior lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia*) (Nigh 1995*a*); white spruce, Engelmann spruce (*Picea engelmannii* Parry), and their hybirds (Nigh 1995*b*; Nigh and Love 2000); Sitka spruce (*Picea sitchensis* (Bong.) Carr.) (Nigh 1996*b*, 1999); coastal and interior Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Nigh 1997*a*, 1997*b*); western larch (*Larix occidentalis* Nutt.) (Nigh et al. 1999); black spruce (*Picea mariana* (Mill.) BSP) (Nigh and Klinka 2001); ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) (Nigh 2002); and, especially, for some species without distinct annual branch whorls such as western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) (Nigh 1996*a*, 1999). Relationship between jack pine (*Pinus banksiana* Lamb.) growth and site variables was reported for jack pine plantations in New Brunswick using the GI approach (Hamilton and Krause 1985). Recently, GI models were developed for black spruce, jack pine, and balsam fir (*Abies balsamea* (L.) Mill) natural stands in Quebec (Mailly and Gaudreault 2005).

Jack pine is one of the most extensively planted and economically important species in northern Ontario. The gross volume of managed jack pine forest in Ontario is close to 600×10^6 m^3. Annual harvesting of jack pine nearly reached about 6×10^6 m^3 in 1998–1999 (OMNR 2002). Jack pine has also been planted extensively in northern Ontario. Information on growth of these young jack pine plantations in relation to changing site conditions is limited. Thus, it is difficult to compare growth and yield of local jack pine plantations with naturally regenerated jack pine stands. Although there are good SI curves (Carmean and Lenthall 1989; Carmean et al. 2001; Schmidt and Carmean 1988) for natural jack pine stands in northern Ontario, we do not know if these SI curves are applicable to young jack pine plantations. We cannot assume that the height growth pattern of plantations is the same as that of natural jack pine stands. Intensive forest management requires more information to assess site productivity of a planted area to make investment decisions. Therefore, variable GI models for jack pine plantations are needed for growth and yield predictions and management planning in this region.

Forest industries and the scientific community in Canada want to know if plantations grow faster that the original natural stands we harvested from the same site. The answer is important for calculating annual allowable cut and sustainable forest management. The objectives of this study are (*i*) to develop variable GI models for jack pine natural stands and plantations in northern Ontario, (*ii*) to develop polymorphic SI curves to be used in northern Ontario in young jack pine plantations, (*iii*) to compare GI models between natural stands and plantations. It is believed that this comparison could provide more information for the site-specific silviculture of jack pine natural stands and plantations.

Methods

Data collection

Two sets of data were used in this study. The first set was for the natural jack pine stands obtained from Ontario Ministry of Natural Resources. The data set was comprised of stem-analysis data collected from 383 plots throughout northern Ontario. The site index at age 50 years (SI_{50}) ranged from 7.6 m to 22.4 m, and breast-height ages (BHAs; total age minus years to reach breast height, 1.3 m) were 50–157 years (Carmean et al. 2001). The second set was collected in the fall of 2003 from 65 jack pine plantations located across northern Ontario with SI_{50}, (estimated from Carmean et al. 2001) ranging from 15.1 m to 21.4 m, and BHAs were 9–48 years. The sampled plantations were located around Thunder Bay (34 plots), Kenora and Dryden (12 plots), and Timmins (18 plots). Geographic location ranged from 81°26′W to 94°04′W and from 47°58′N to 49°51′N. All plots were established in plantations with jack pine over 75% stocked. Soil and microtopography in plots appeared to be similar. In most cases, two well-formed, undamaged free-growing dominant and codominant jack pine trees were selected and felled for stem analysis in each stand. The total tree height was measured accurately from felled trees in the field and recorded. All sampled trees were sectioned at the stump; at 0.3 m, 1.0 m, 1.3 m, and 2.0 m; then at 0.5 m intervals to the top of the tree. All discs were marked in the field with plot and tree identification, disc height, and compass direction.

Before stem analysis, all discs were sanded in the laboratory to make a clean working surface. Age at sectioning height was determined in the laboratory with Windendro software (Regent Instruments Inc., Quebec, Canada) by scanning the disc into a digital image. Stem analysis was done by the XLSTEM software using files created in Windendro. Individual sample trees on each plot were inspected by plotting height–age and diameter–height graphs for any abnormal tree height growth patterns that might have been caused by early suppression or by top damage. This inspection resulted in the deletion of seven trees from the data set. In addition, seven more trees were deleted because of age younger than 20 years at breast height. Height bias corrections were made using the Carmean method (Carmean 1972; Dyer and Bailey 1987). All height-growth data with the relevant ages were combined into an average curve for each plot for further analysis.

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Model fitting

Site index for natural jack pine stands was defined as the average height of dominant and codominant trees at 50 years after they reached breast height. For jack pine plantations younger than 40 years, the SI age was set at 20 years after reaching breast height. Therefore, SI of each stand was estimated using the corrected total tree height at 50 years BHA for natural stands and at 20 years BHA for plantations. Breast-height age was also used in many other studies as index age because SI curves based on BHA were more precise than curves based on total age (Carmen and Lenthall 1989; Carmean et al. 1989; Carmean 1996). In the existing data set from natural stands, we had total tree heights at 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 years BHA. There were limited jack pine plantations over 30 years or even 25 years BHA on different site conditions. We had only 10 plots over 40 years BHA. We determined that the height–age data over 40 years should be excluded from model fitting.

Determining years to breast height age

Years to breast height age (YTBH) for individual site trees was defined as the number of years that a site tree takes to reach breast height calculated using the following equation (Nigh 1996*a*):

$$[1]\qquad \mathrm{YTBH} = A_0 + \frac{1.3 - H_0}{H_1 - H_0}$$

where A_0 is total age (years) of the tree below breast height, H_0 is height (m) of the tree at $A0$ year; and H_1 is height (m) of the tree at BHA 1.

After we calculate YTBH, we need to link YTBH to SI to determine if there is a difference in YTBH on different site quality. Nigh (2002) suggested an equation to fit a model for the relationship between YTBH and SI:

$$[2]\qquad \mathrm{YTBH} = b_1 \times b_2^{\mathrm{SI}}$$

where b_1 and b_2 are parameters to be estimated.

Calculating GI

The height and BHA data, therefore, will be converted into GI for individual site trees using the following equation from Nigh (1996*a*):

$$[3]\qquad \mathrm{GI}_{\mathrm{BHA}} = \frac{(H_\mathrm{T} - 1.3) \times 100}{\mathrm{BHA}\,\dfrac{1.3 - H_0}{H_1 - H_0}}$$

where $\mathrm{GI}_{\mathrm{BHA}}$ is GI (cm/year) corresponding to BHA (total age (years) minus years to reach breast height, 1.3 m) and H_T is averaged total height of site trees (m).

Because the first year's height growth above breast height is only a part of that year's height growth, an adjustment for the BHA is needed to make sure the GI is more precise. In this study, the adjustments were calculated using eq. 3. The mean of the adjustments was 0.42 years.

Relating GI to SI

A power function modeling the relationship between GI and SI for BHAs 1–20 years for jack pine plantations and 5–50 years for natural jack pine stands is defined as follows (Nigh 1996*a*):

$$[4]\qquad \mathrm{SI} = 1.3 + b_1\,\mathrm{GI}_{\mathrm{BHA}}^{b_2} + \varepsilon$$

where SI may be defined as SI_{20} for plantations and SI_{20} or SI_{50} for natural stands in this study, b_i are model parameters (i = 1–4), and ε is random error.

Separate models were developed for BHAs 1–20 years for plantations and 5–50 years for natural stands. Models for BHAs over 20 years were not developed for plantations because SI can be estimated more accurately by SI models based on the height–age relationship. An analysis of residuals was done to confirm the regression assumptions of unbiasedness, normality, and homoscedasticity (Neter et al. 1996).

Comparing height-growth patterns of plantations and natural stands

Comparison between height-growth patterns must be made on the same site condition. Therefore, we developed two sets of models including GI models and SI curves. We redefined the SI age at 20 years for natural stands for comparison with plantations. Both Carmean's data set from natural stands (Carmean and Lenthall 1989) and our own plantation data set were used to develop the models with the same GI model form. Then, height growth curves for the same SI were compared between natural stands and plantations. GI models at the same ages were also compared between natural stands and plantations.

Modeling SI curves and SI prediction model

Growth intercept models are used to predict the SI of natural stands or plantations younger than the index age. For stands older than the index age (or a little younger), SI curves and SI prediction models are more convenient and precise to determine SI. Therefore, we developed a SI curve model and a SI estimation model for jack pine plantations using the same data set. To fit a SI curve, a model expressing polymorphic height growth pattern was needed. Many adaptations from Ek (1971) and Monserud (1984) models can be considered for developing the polymorphic SI curves, generally with excellent precision (Carmean et al. 2001). Newnham's (1988) model has been used frequently for fitting SI curves because of its flexibility and ability to constrain curves to pass exactly through the tree height specified at index age (Carmean et al. 1989, 2001). Accordingly, our SI curves were fitted using the Newnham (1988) constrained version of the Ek (1971) nonlinear regression model:

$$[5]\qquad \hat{H} = 1.3 + b_1(\mathrm{SI} - 1.3)^{b_2}\left(1 - K^{\frac{\mathrm{BHA}}{20}}\right)^{b_3(\mathrm{SI}-1.3)^{b_4}}$$

where

$$K = 1 - \left(\frac{\mathrm{SI} - 1.3}{b_1(\mathrm{SI} - 1.3)^{b_2}}\right)^{\frac{1}{b_3(\mathrm{SI}-1.3)^{b_4}}}$$

and $\hat{H}$ is the predicted height (m) of dominant and codominant tree, and b_i are the regression coefficients to be estimated (i = 1–4).

Based on the SI curve model, SI can be graphically estimated merely by locating measured tree height and BHA on

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the curves and then interpolating between the curves for an estimation of SI. However, this procedure is slow, inefficient and often subject to personal bias when interpolating between SI curves. More rapid and less subjective estimation of SI can be attained using a SI estimation model to directly calculate SI using total height and BHA. It is suggested that an SI prediction model be developed separately rather than solved backward from the SI (height growth) curve model (Carmean et al. 2001). As a result, the following equation was used in this study to estimate SI using measurements of total height and BHA as independent variables:

$$[6] \qquad \mathrm{SI} = b_0 + b_1(H_\mathrm{T} - 1.3) + b_2 \ln(H_\mathrm{T} - 1.3) + b_3 \ln(\mathrm{BHA}) + b_4 \ln(\mathrm{BHA})^2 + b_5\left(\frac{H_\mathrm{T} - 1.3}{\mathrm{BHA}}\right) + b_6(\mathrm{BHA})\ln(H_\mathrm{T} - 1.3)$$

where ln is natural logarithm and all other parameters were as previously defined.

All model parameters were estimated using maximum-likelihood direct numerical search Gauss–Newton algorithm (Neter et al. 1996) in a nonlinear procedure (NONLIN) in SYSTAT version 10 (SPSS Inc. 2000). Each model was evaluated by the root mean square error (RMSE) and mean corrected R^2 value of the model:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(\mathrm{SI}_i - \hat{\mathrm{SI}}_i)^2}{n - p}}$$

where SI_i is the observed SI and $\hat{\mathrm{SI}}_i$ is the predicted SI, n is the number of stands, and p is the number of parameters in the model. The SYSTAT software gives two types of R^2 value: the raw R^2 (R^2 = 1 – residual/total), the mean corrected R^2 (R^2 = 1 – residual/corrected). Some researchers object to the raw R^2 because the means are not removed (Neter et al. 1996). We used the mean corrected R^2 value.

Results

Years to reach breast height in jack pine plantations

The best model for fitting the relationship between YTBH and SI was eq. 2. Our results showed that the mean corrected R^2 was fairly low, the YTBHwere not closely related to SI:

$$[7] \qquad \mathrm{YTBH} = 5.2410 \times 0.9805^{\mathrm{SI}_{20}}, \quad \text{mean corrected } R^2 = 0.1898,\ \mathrm{RMSE} = 0.7336$$

YTBH was negatively related to site quality with small differences between different SIs. Analysis of the data showed that YTBH ranged from 3.5 years to 5.3 years. The weighted mean YTBH was 4.2 years (Table 1). This result is consistent with the overall mean of 5 or 6 YTBH commonly used in operational forestry in northern Ontario (Armson et al. 1980).

Table 1. Differences in years to breast height (YTBH) among different site indices (SIs) for plantations.

SI range (m)	Mean SI (m)	Mean YTBH	No. of trees
6.50–6.99	6.75	5.3	1
7.00–7.99	7.63	4.82	4
8.00–8.99	8.57	4.39	16
9.00–9.99	9.48	4.48	15
10.00–10.99	10.51	3.77	15
11.00–11.99	11.51	3.5	2
Overall		4.21	

Table 2. Result of the growth intercept model (eq. 4) at breast height ages (BHAs) 1–20 years for jack pine plantations (n = 54).

BHA	b_1	b_2	R^2	RMSE
1	8.6112	0.0316	0	1.5460
2	5.1523	0.1642	0.1285	1.3516
3	4.7102	0.1872	0.1270	1.3539
4	4.6387	0.1906	0.1108	1.3793
5	4.5995	0.1911	0.1143	1.3743
6	3.4993	0.2602	0.1627	1.2985
7	2.7773	0.3195	0.2301	1.1929
8	1.9425	0.4097	0.2589	1.1495
9	2.2149	0.3775	0.2305	1.1939
10	1.7814	0.4329	0.3022	1.0818
11	1.1999	0.5332	0.4001	0.9289
12	0.7927	0.6372	0.5078	0.7618
13	0.6546	0.6852	0.6021	0.6152
14	0.3782	0.8242	0.7291	0.4197
15	0.2947	0.8882	0.8146	0.2870
16	0.2508	0.9305	0.8556	0.2232
17	0.2056	0.9831	0.9015	0.1522
18	0.2051	0.9853	0.9422	0.0897
19	0.1883	1.0079	0.9772	0.0348
20	0.1884	1.0098	0.9971	0.0041

Growth intercept models for jack pine plantations and natural stands

The results of the nonlinear regression analysis of GI models eq. 4 for jack pine plantations were shown in Table 2. For brevity, the results of the GI models for BHAs 1, 5, 10, 15, and 20 years were plotted in Fig. 1. The results in Table 2 and Fig. 1 indicate that, as the BHA increases, the relationship between GI and SI becomes more linear and more precise. The model parameters in Table 2 could be used to estimate SI of jack pine plantations from 1 year to 20 years of stand age in northern Ontario. It can be seen by the values of the mean corrected R^2 and RMSE in Table 2 and plots of residuals versus GI in Fig. 2 that precision in estimating SI increased as the BHA increased.

The GI model parameter estimates for natural stands based on index ages at 20 years and 50 years are presented in Table 3. The models for index age of 20 years were used for comparison with plantations, and the models for index age of 50 years were available to estimate SI for jack pine natural stands younger than 50 years in northern Ontario.

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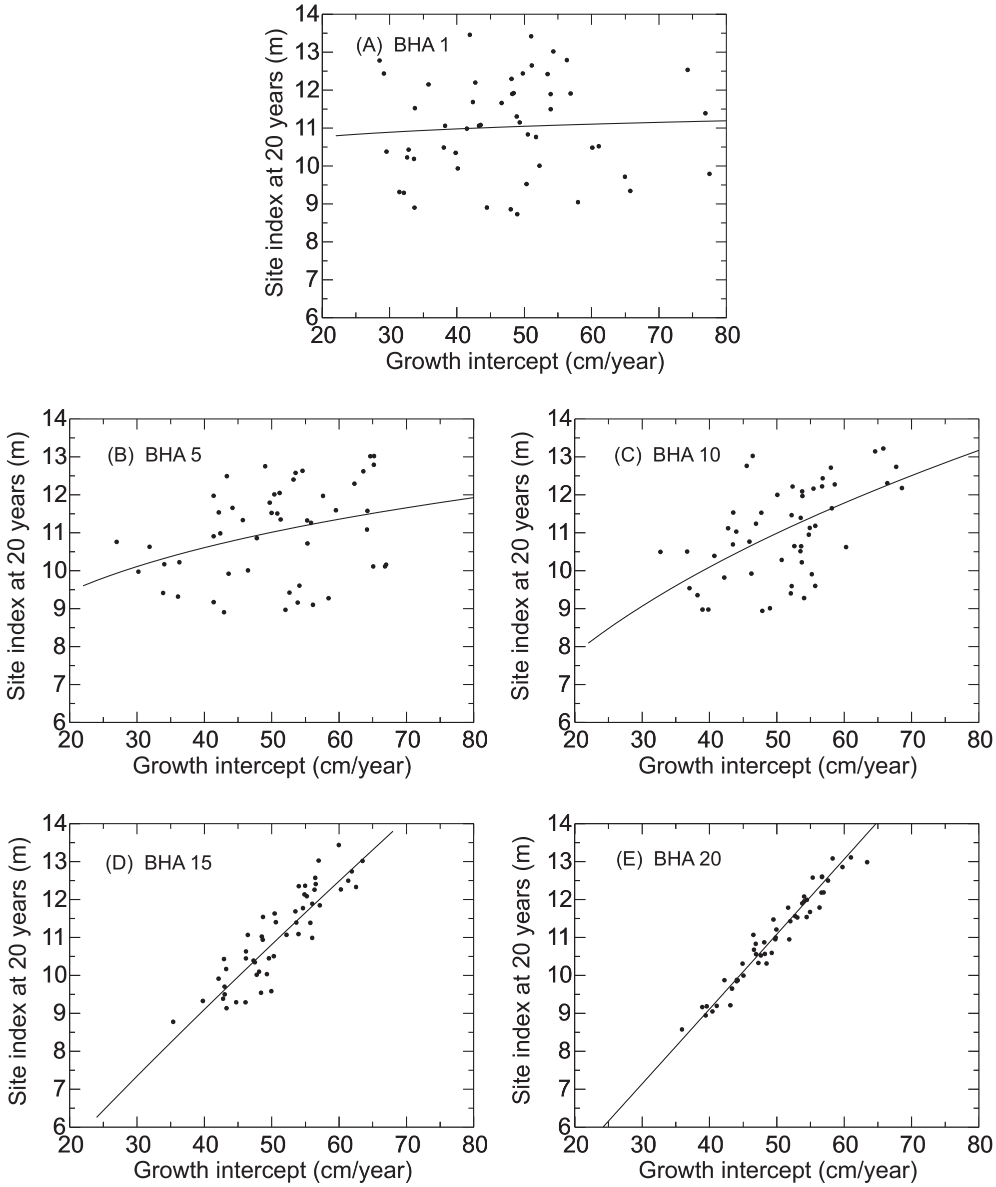
Fig. 1. The relationship between site index at age 20 years and growth intercept (data points and regression lines) for jack pine plantations at breast height ages (BHAs) of (A) 1 year, (B) 5 years, (C) 10 years, (D) 15 years, and (E) 20 years.



Models for jack pine plantations

A polymorphic height growth model (eq. 5) based onSI_{20} and BHA was developed as

$$[8] \qquad \hat{H} = 1.3 + 112.9445(SI_{20} - 1.3)^{(-0.6973)} \times \left(1 - K^{\frac{BHA}{20}}\right)^{0.2401(SI_{20}-1.3)^{0.7486}},$$

mean corrected R^2 = 0.9866, RMSE = 0.5265

where

$$K = 1 - \left(\frac{SI_{20} - 1.3}{112.9445(SI_{20} - 1.3)^{(-0.6973)}}\right)^{\frac{1}{0.240072(SI_{20}-1.3)^{0.7486}}}$$

All other variables were as defined in eq. 5.

Based on this polymorphic height growth model a set of SI curves (Fig. 3A) were developed for jack pine plantations in northern Ontario. Because our data were restricted to 40 years as the maximum stand age, we recommend that the model and curves should be used only for plantations younger than 40 years. It must be noted that, in Fig. 3A, the mean total height on poorer sites was higher than on richer sites at early ages immediately after reaching breast height. It was difficult to find jack pine plantations on poor sites, because most planting was carried out on rich or medium sites. SI range of the curves was limited to 6 m to 14 m at 20 years BHA.

For the convenience of estimating SI by measuring H_T and BHA, an SI prediction model following eq. 6 was developed based on the same data set for jack pine plantations in northern Ontario:

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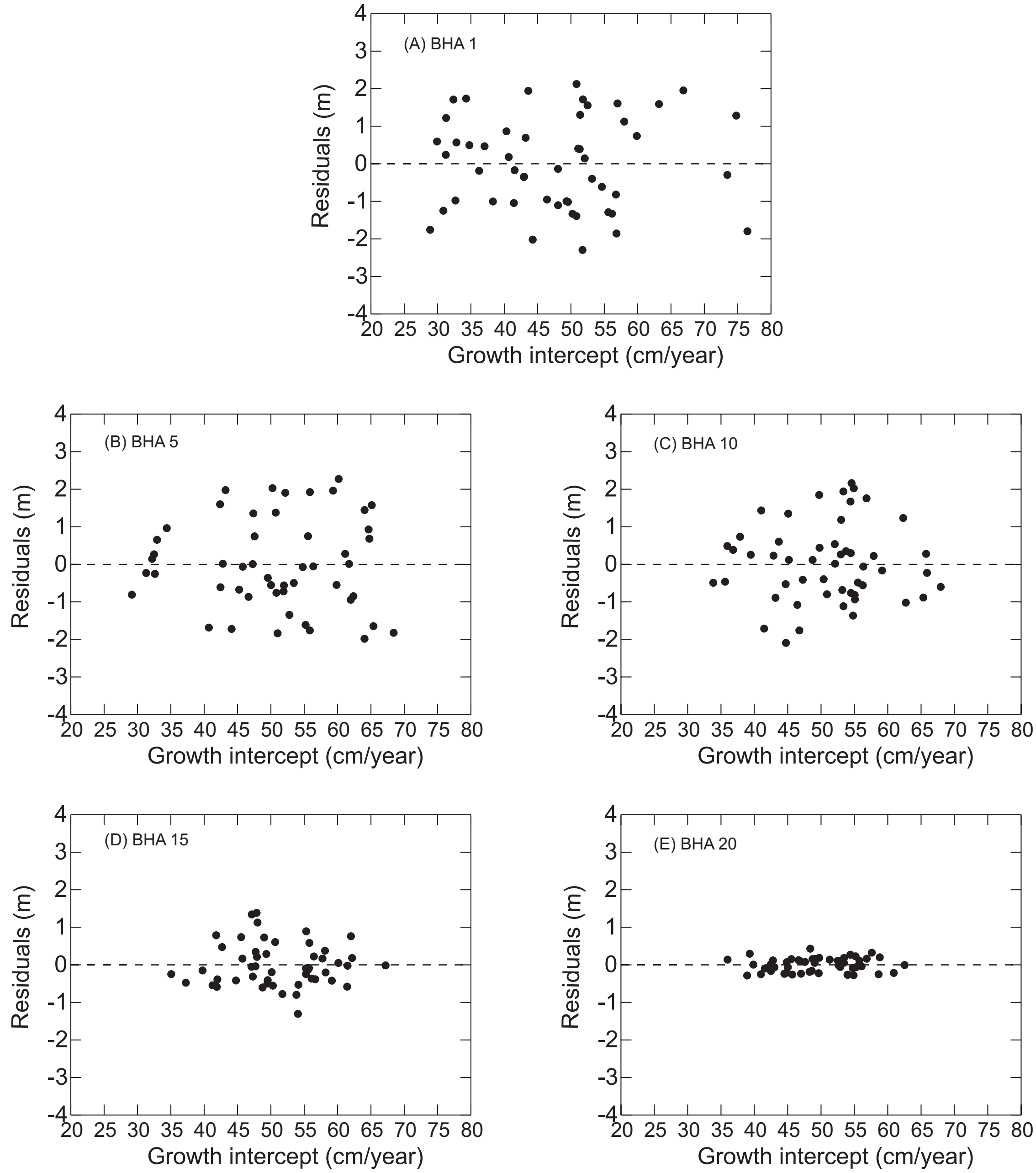
Fig. 2. Plot of residuals versus growth intercept for the regression lines for jack pine plantations in northern Ontario at breast height ages (BHAs) of (A) 1 year, (B) 5 years, (C) 10 years, (D) 15 years, and (E) 20 years.



$$[9] \qquad \hat{\mathrm{SI}}_{20} = 19.8631 + 0.3897(H_\mathrm{T} - 1.3) + 9.6989\ \ln(H_\mathrm{T} - 1.3) + 6.0632\ln(\mathrm{BHA}) - 8.0833\ \ln(\mathrm{BHA})^2 - 8.8027\left(\frac{H_\mathrm{T} - 1.3}{\mathrm{BHA}}\right) - 0.0226(\mathrm{BHA})\ln(H_\mathrm{T} - 1.3),$$

mean corrected R^2 = 0.5427, RMSE = 0.8463

All variables were as defined in eq. 6.

Models for jack pine natural stands

A polymorphic height growth model based on eq. 5 for natural stands was also developed. It was only used for comparison with that of plantations. Therefore, we redefined the SI as the average height of dominant and codominant trees at 20 years BHA. The SI model for natural stands in northern Ontario based on SI_{20} and BHA was expressed as

$$[10] \qquad \hat{H} = 1.3 + 28.7773(\mathrm{SI}_{20} - 1.3)^{(-0.0756)} \times \left(1 - K^{\frac{\mathrm{BHA}}{20}}\right)^{1.2181(\mathrm{SI}_{20} - 1.3)^{(-0.06661)}},$$

mean corrected R^2 = 0.9658, RMSE = 0.8594

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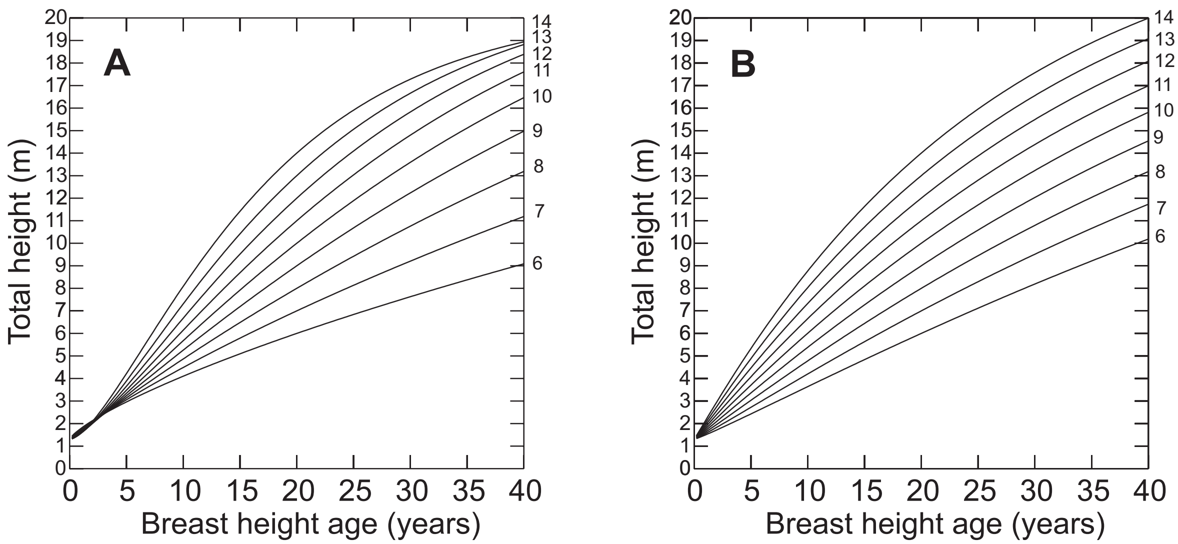
Table 3. Result of the growth intercept model (eq. 4) at 10 breast height ages (BHAs) for jack pine natural stands in northern Ontario (n = 383).

	Site index age 50 years				Site index age 20 years			
BHA	b_1	b_2	R^2	RMSE	b_1	b_2	R^2	RMSE
5	4.486	0.3353	0.3186	5.1199	1.2196	0.5082	0.5143	1.3527
10	2.555	0.4872	0.4901	3.8308	0.5798	0.7084	0.7094	0.8103
15	1.6952	0.6009	0.6272	2.8010	0.3506	0.8478	0.8422	0.4393
20	1.2903	0.6806	0.7122	2.1624	0.2658	0.9305	0.8995	0.2797
25	1.0521	0.7432	0.7873	1.5978	0.2700	0.9347	0.8593	0.3912
30	0.8127	0.8227	0.8612	1.0430	0.2506	0.9649	0.8290	0.4740
35	0.6722	0.8856	0.9178	0.6175	0.2534	0.9728	0.7880	0.5877
40	0.5820	0.9368	0.9606	0.2958	0.2635	0.9727	0.7467	0.7028
45	0.5448	0.9670	0.9864	0.1022	0.2845	0.9622	0.7123	0.7988
50	0.5225	0.9916	0.9975	0.0184	0.2948	0.9641	0.6895	0.8606

Fig. 3. Polymorphic site index at age 20 years (SI_{20}) curves for jack pine (A) plantations and (B) natural stands in northern Ontario. The numbers 6 to 14 on the right side of the figures are site indices.



where

$$K = 1 - \left(\frac{SI_{20} - 1.3}{28.7773(SI_{20} - 1.3)^{(-0.0756)}}\right)^{\frac{1}{1.2181(SI_{20}-1.3)^{(-0.06661)}}}$$

All variables are as defined in eq. 5. The SI curves based on the model were plotted in Fig. 3B.

Comparison of GI models between plantations and natural stands

Since the stem-analysis data from natural stands showed height data at 5 year rather than annual intervals, only the GI models for BHAs 5, 10, 15, and 20 years were compared (Figs. 4A–4D). Results indicated significant differences between GI models derived from jack pine plantations and natural stands if BHA <10 years. We believed the reason for these differences is the different height-growth patterns in plantations and natural stands. However, we could not assume that these illustrated differences are only due to site conditions influenced by climate, soil, and topography. To illustrate all the possible reasons, we need more plantation plots over 50 years of age.

Comparison of total height growth pattern

The SI curves for plantations based on eq. 8 were very different from those for natural stands based on eq. 10 (Fig. 5). On very poor sites (e.g., SI = 6 m; Fig. 5A), the top tree height growth of plantations was faster than that of natural stands in early ages (younger than 20 years old) owing to vegetation competition but slowed down quickly in later years. On medium to poor sites (e.g., SI = 8 m; Fig. 5B), total height growth patterns were similar. In contrast, on richer sites (e.g., SI = 10 m and 12 m; Figs. 5C and 5D), the total height growth of plantation was a little lower than that of natural stands in early ages but higher in later years.

Discussion

Years to breast height were not very closely related to SI for the range of jack pine plantations sampled in this study. Large variations also occurred in other species (Nigh 2002). Our results confirm why many researchers and foresters

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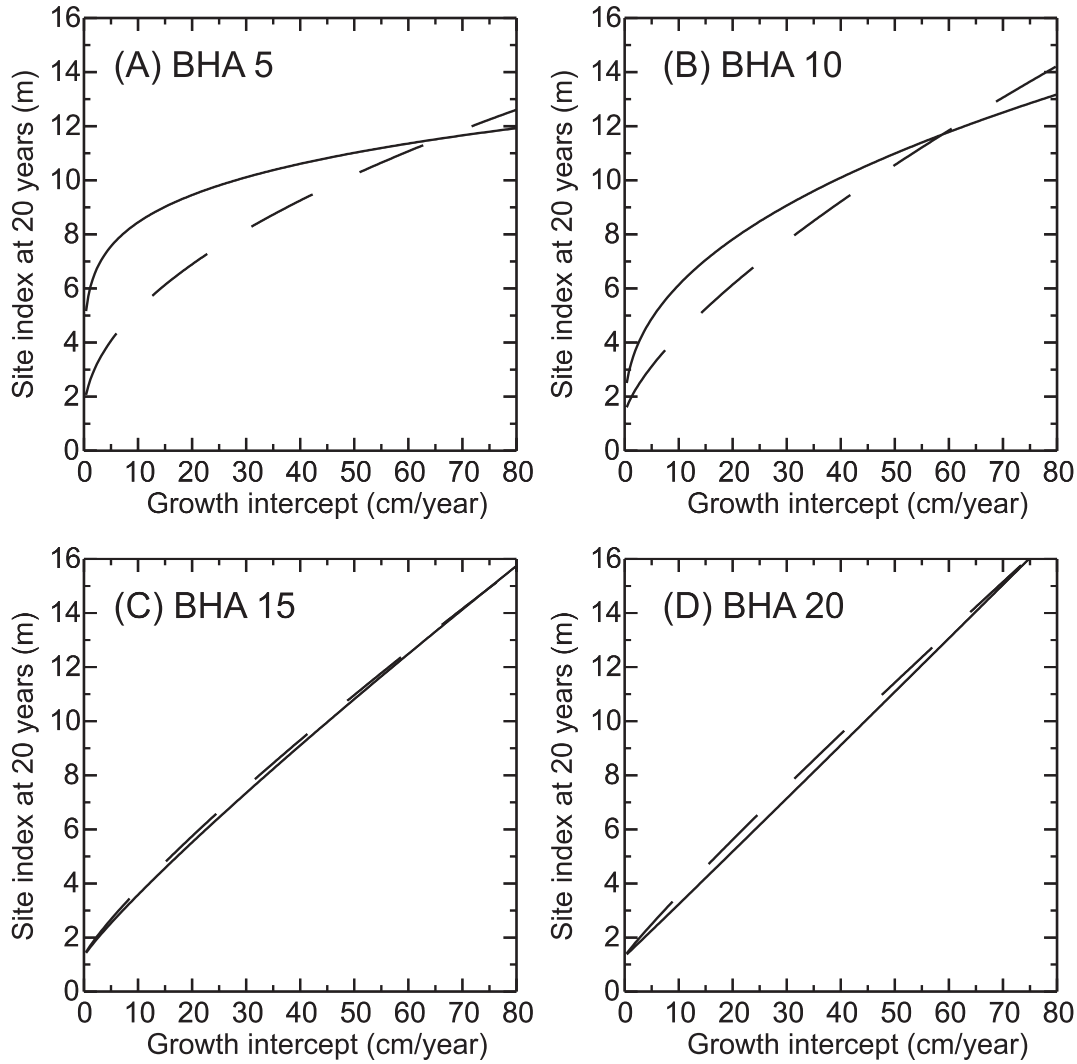
Fig. 4. Relationships between growth intercept and site index at age 20 years of jack pine plantations and natural stands at breast height ages (BHAs) of (A) 5 years, (B) 10 years, (C) 15 years, and (D) 20 years in northern Ontario. The broken lines show jack pine natural stands, and the solid lines show plantations.



used a BHA model instead of total age to avoid the early erratic height growth below breast height. Results indicated that trees on poor sites took more time to reach breast height with an average of about 4 years.

The RMSE in Table 2 indicated that variable GI models for jack pine plantation were unbiased and that the residuals were homoscedastic and normally distributed. It is typical for GI models that the accuracy of the model increased as tree age increased as shown in Fig. 1 (Nigh et al. 1999). A variable GI model in Table 2 was recommended for jack pine plantations for BHAs of 1–20 years. The polymorphic SI model (eq. 9) could be used to estimate SI mathematically for jack pine plantations older than age 20 years. Also, a variable GI model and SI estimation model were available for jack pine natural stands for BHAs of 5–50 years for both 20 years and 50 years as the index age (Table 3). Because traditional GI was defined as the average height growth of 5 years immediately above breast height, abnormal growing season impacted GI greatly and, hence, estimated SI. The smaller the GI period the larger of the effect on the estimated SI. Therefore, short-term climate fluctuations might cause inaccuracies in estimated SIs in the traditional GI model. For the same reason, the accuracy in the variable intercept model might be influenced by abnormal height growth in models for early ages.

Strong relationships between GI and SI were found in many species for younger BHAs. Other researchers found that early height growth was closely related with site productivity (Oliver 1972). However, in this study, considering the mean corrected R^2 and RMSE, there was still substantial error in SI prediction for very early ages, especially before age 5 years. The R^2 and RMSE in this study showed that a large percentage of variation in SI was accounted for. This means the variation of GI was large in practice and should be considered when scheduling a GI survey to reduce the influence of sampling error. In applying the variable intercept model, site trees must be carefully chosen to reflect the same characteristics used in developing the GI model. We recom-

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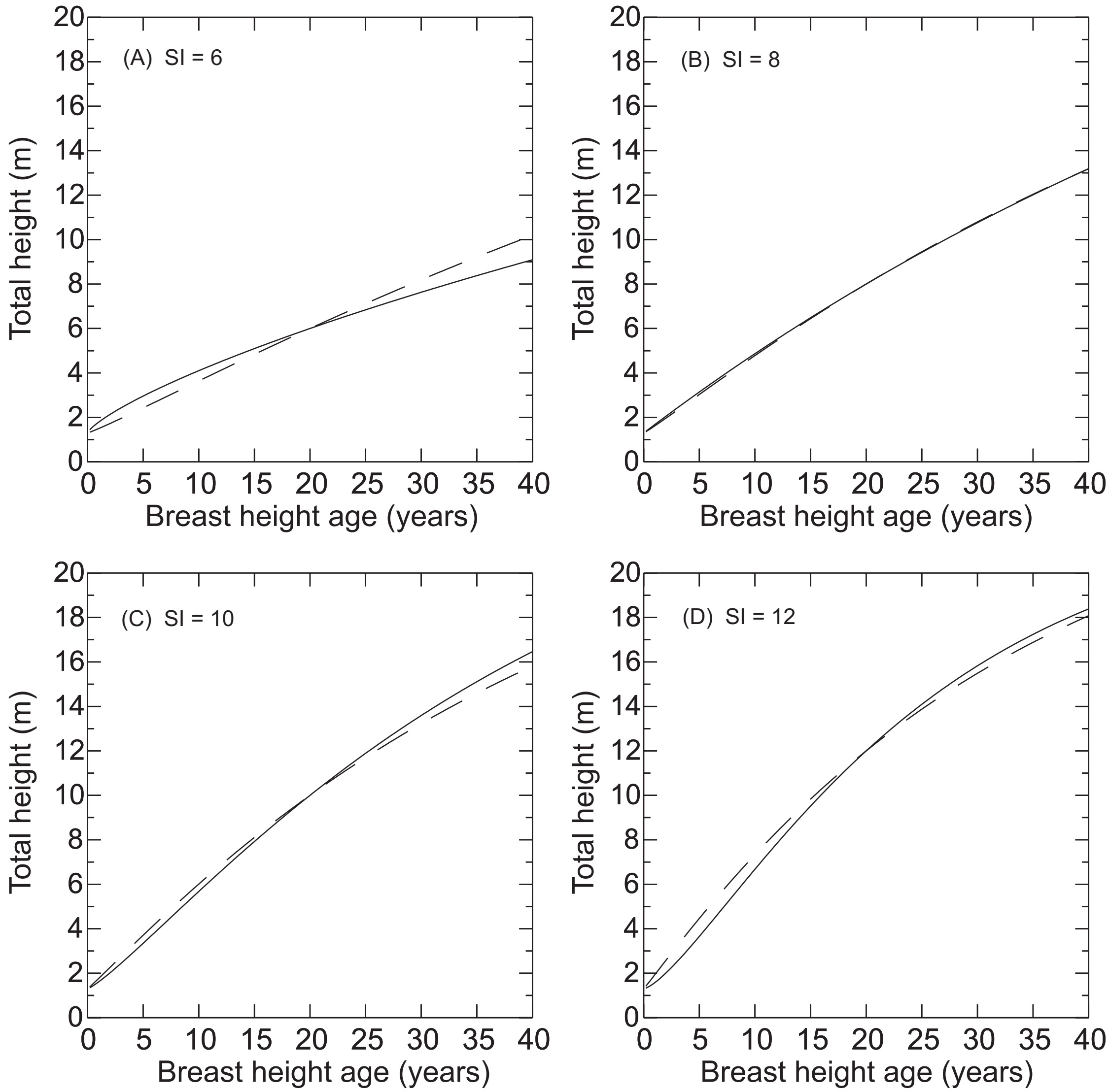
Fig. 5. Relationships between total height and breast height age of jack pine plantations (solid line) and natural stands (broken line) at 20 year site index (SI_{20}) classes of (A) 6 m, (B) 8 m, (C) 10 m, and (D) 12 m.



mend that three to five trees should be selected to provide accurate average estimates of BHA and total height used in the model.

According to the results, height growth pattern of jack pine plantations were different from that of natural stands. Based on published data and SI models (Carmean et al. 2001), total height in natural stands on richer sites was always higher than on poorer sites. This suggested that trees growing on rich sites reached a maximum rate of height growth earlier than trees growing on poor sites (Thrower 1987). In contrast, total height of a plantation on a richer site was a little lower than that on poorer sites at a very early age immediately after reaching breast height. This might be caused by early competition from more vigorously growing shrubs and grasses on richer sites. Compared with natural stands, mean total height of jack pine plantations on poor sites was higher in early ages and lower in later ages; in medium and richer sites, the opposite occurred The total height differences among different sites in plantations were smaller than in natural stands. The comparison of GI models between plantations and natural stands also identified that GI–SI curves in plantations at early ages were much flatter than those in natural stands. This might indicate that the total height of jack pine plantations was strongly affected by stand tending at early ages and might not accurately reflect site potential.

In summary, we first developed a model (eq. 7) from eq. 1 to predict YTBH for jack pine plantations in northern Ontario. The YTBH information is very important for vegetation management in plantations and indicates how long it takes the plantation to reach free-to-grow stage. Most importantly, we developed a model (eq. 4) to predict SI from GI for young jack pine plantations. At the same time, we developed polymorphic SI models (eq. 8) for jack pine plantations and eq. 10 for jack pine natural stands. Equation 9 can be use to develop SI curves. These models would be used in growth and yield prediction and better forest-management planning in northern Ontario.

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