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Individual Tree Growth Models for Natural Mixed Forests in Changbai Mountains, Northeast China

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Abstract : The data used to develop distance-independent individual models for natural mixed forests were collected from 712 remeasured permanent sample plots (25,526 trees) of 10-year periodic from 1990 to 2000 in Baihe Forest Bureau of Changbai Mountains, northeast China. Based on analyzing relationship between diameter increment of individual trees with tree size, competitive status, and site condition, the diameter growth models for individual trees of 15 species growing in mixed-species uneven-aged forest stands, that have simple form, good predicting precision, and easily applicable, were developed using stepwise regression method. The main variables influencing on diameter increment of individual trees were tree size and competition, however, the site conditions were not significantly related with diameter increment. The tree size variables (ln*DBH* and DBH^2) were the most significant and important predictors of diameter growth existing in all 15 growth models. The diameter increment was directly proportional to tree diameter for each species. For the competitive factors in growth model, the relative diameter (*RD*), canopy closure (*P*), and the ratio of diameter of subject tree with maximum diameter (*DDM*) were contributed to the diameter increment at a certain extent. Other measures of stand density, such as basal area of stand (*G*) and stand density index (*SDI*), were not significantly influenced on diameter increment. Site factors, such as site index, slope and aspect were not important to diameter increment and excluded in the final models. The total variance explained by the final models of squared diameter increment (R^2) for all 15 species ranged from 35% to 72% and these results compared quit closely with those of Wykoff (1990) for mixed conifer stands. Using independent data set, validation measures were evaluated for predicting models of diameter increment developed in this study. The result indicated that the estimated precision was all greater than 94% and the models were suitable to describe diameter increment.

Keywords **:** *mixed-species stand, individual tree model, diameter increment, mortality model, stepwise regression*

Introduction

Decision making and planning in forest management has traditionally relied on yield tables to estimate yields. In past several decades, techniques for forecasting stand yields or dynamics have been referred to use growth and yield models. Growth models are the most important components in long-term forest planning systems, together with algorithms for stand establishment and models for harvest regimes. Munro (1974) classified growth models as whole stand models and individual tree model. The individual tree model was grouped into two classes by how competition among trees was handled: 1) Distance-dependent models, and 2) Distance-independent model (Munro, 1974).

For several decades, foresters and forest researchers in many countries have dedicated to the growth models study. But, the yield tables and growth models used in planning and prognosis have been developed mainly from even-aged forest (Li, 1988; 1995), where mean values and the mean tree of a stand are the basic components of the forecast. Because of complexity in the mixed species and development patterns and structures of stand, growth and yield models for natural mixed-species and uneven-aged stands have become a desirable but have been seldom studied over the last 30 years in China.

One way to forecast yields for uneven-aged mixed-species stands is to develop stand growth models that operate at the individual tree level. Some scholars developed distance-dependent single tree growth simulators

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for uneven-aged mixed-species stands (Munro, 1974; Arney, 1974; Ek and Monserud's, 1974). These models are useful in studying various thinning regimes for well documented samples of mapped stands. But, it is hard to apply in a wide range of forest condition and management actions (Wykoff, 1990). The distance-independent model does not require the co-ordinates of subject tree and its competitors (Belcher *et al*, 1982; Wykoff, 1986; Monserud and Sterba, 1996).

One of the few forest growth models that does not need site index, age, or mapped tree coordinates is the widely used Stand Prognosis Model developed by Stage (1973) and Wykoff *et al.* (1982). Originally designed for the Northern Rocky Mountains, the model can simulate the growth and development of stands with any composition, from pure even-aged to mixed-species uneven-aged. The basic modeling unit is the individual tree. An approach similar to that of the Prognosis Model has been used in Austria (Monserud and Sterba, 1996) and is considered more applicable.

According to the report from National Forestry Administration of China, the total area and growing stock for natural mixed forest are 34.48 million ha and 3000.3 million m^3, respectively, that are accounting for 92.5% of total forest area and for 95.1% of the total growing stock in northeast China. So, it is necessary to develop stand growth models that operate at the individual tree level for yields projection that can support sustainable forest management decisions. Li *et al* (2001) developed growth and yield models at the stand level for natural mixed forests. Unfortunately, there are a few single-tree growth models developed for uneven-aged mixed stands in northeast China.

In this study, the relationship between diameter increment of individual trees with tree size, competitive status, and site condition was analyzed and the growth models of individual trees for 15 main species were developed for the natural mixed forests in the Changbai Mountains, northeast China. The model developed here should be applied to simulate tree and stand growth and forecast forest dynamics in and do decision-making for management of natural uneven-aged forest stands. Also, this will present a challenge for future research on tree level model for uneven-aged stands in northeast China.

Materials and Methods

1. Study area

The data were collected from Baihe forest bureau in Jilin Province, P. R. China, which locates at the foot of Changbai Mountains, ranging across 127° 53'~128° 34'E, and 42° 01'-42° 48'N. The area belongs to temperate zone with continental monsoon climate. The annual mean temperature is 2.2°C and the mean temperature ranges from -26.6°C in January to 27.9°C in July. The annual precipitation is about 700 mm and about 60% concentrates in June, July and August. The elevation of the highest peak is1,537 m and mean elevation is 800m.

Table 1. Forest types by area and volume in Baihe Forest Bureau.

Forest Types	Area(ha)	%	Volume(m^3)	%	m^3/ha
Pinus koraiensis forest	1,000.0	0.58	291,546	1.15	291.5
Picea spp. Forest	294.0	0.17	89,327	0.35	303.8
Pinus densiflora var. forest	115.0	0.07	20,592	0.08	179.1
Larix olgensis forest	32,188.3	18.78	4,425,139	17.52	137.5
Abies nephrolepis forest	41.5	0.02	5,766	0.02	138.9
Junglus mandshurica forest	87.0	0.05	10,122	0.04	116.3
Tilia spp. Forest	1,167.0	0.68	235,259	0.93	201.6
Quercus mongolica forest	7,913.7	4.62	1,121,902	4.44	141.8
Ulmus spp. Forest	99.0	0.06	12,323	0.05	124.5
Acer mono forest	78.0	0.05	8,478	0.03	108.7
Betula costata forest	153.0	0.09	42,869	0.17	280.2
Batula platyphlla forest	14,956.9	8.73	1,824,498	7.22	122.0
Populus spp. Forest	2,503.3	1.46	356,836	1.41	142.5
Coniferous mixed forest	4,535.0	2.65	936,543	3.71	206.5
Coniferous-hardwood mixed forest	19,568.1	11.42	4,522,684	17.90	231.1
Hardwood mixed forest	73,498.80	42.9	10,920,847	43.24	148.6
Larch plantation	11,795.2	6.88	394,119	1.56	33.4
Poplar plantation	811.7	0.47	37,724	0.15	46.5
Korean pine plantation	548.5	0.32	5,775	0.02	10.5
Total	171,354.0		25,262,349		147.4

Brown coniferous forest soil and dark brown soil is the zonal soil in this area.

Baihe forest area is a part of Changbai vegetable flora which has abundant plant resources. Overstory tree species are *Pinus koraiensis*, *Picea koraiensis*, *Picea jezoensis*, *Abies nephrolepis*, *Larix olgensis*, *Fraxinus mandshurica*, *Junglus mandshurica*, *Phellodendron amurense*, *Tilia amurensis*, *T. mandshurica*, *Acer mono*, *Ulmus propinqua*, *Ulmus laciniata*, *Quercus mongolica*, *Betula costata*, *Betula platyphlla*, *Populus davidiana*, *Populus ussuriensis* etc.. Forest resource inventory in 2000 indicated that the total area was 190,470 ha, of which forest stands are about 171,354h, and forest coverage is up to 90%. The zonal climax community is the coniferous-hardwood mixed forest. However, in the natural forest, coniferous forest only account for 22.3% in area and 22.8% in volume.

With the disturbances such as cutting or plant diseases and insect pests etc., Changbai Mountains forest region succeeded into a status of secondary forest community gradually, therefore, there are few plantations distribute in the region, larch for instance, moreover, there are large proportion of mixed species forest types. Although a certain kind of species occupied majority area or volume in the stand, the stand can not be called a real pure forest as normal. The areas and volumes of different forest types are shown in Table 1.

2. Data collection

The data used to estimate the parameters of the individual tree growth model were provided by forest resources inventory of the Baihe forest bureau in 1990 and 2000. This inventory is a systematic permanent sample over the whole bureau, with a 10 year remeasurement interval. The permanent sample plots were measured in 1990 and consisted of about 1,030 plots systematically distributed in a 2 km by 1 km grid, every plot's area is 0.06 ha. In 2000, all permanent sample plots were remeasured and 810 valid plots were obtained. Eliminated all exceptional plots, included excessive cut, planting site, and origin from plantation, 712 sample plots were collected to establish the individual tree growth models for natural mixed forest. There are 15 main species (groups) in the sample plots which can typically represent the mixed forest growth status in Changbai Mountains. As the forest principle of Jilin Province, one dominant species occupy more than 50 percent of the consist in volume can be called a pure stand, also, the conifer species more than 70 percent can be called coniferous forest, conifer and broadleaf trees consist both no more than 50 percent can be called coniferous hardwood mixed forest, however, there are other species mixed with these dominant species. All statistical results of 15 species (groups) used in the individual tree diameter growth models are shown in Table 2.

This large sample provided an excellent data for developing individual tree growth model. The sample size is large (25,526 remeasured trees in total including 2,796 mortality trees) and representative of forest conditions throughout the Changbai Mountains. Because the systematic sampling grid extends across the study area, the result should yield an excellent cross-section of forest management practices in northeast China.

3. The diameter growth model

Forest growing conditions in the Changbai Mountains of China are quite variable. So, many variables were chosen to establish the individual tree growth model. Through compare with other growth models, a logarithmic model for diameter increment as a function of tree size, competition, and site variables (Wykoff, 1990) was selected eventually.

$$\ln(DGI) = a + \mathrm{b} \times SIZE + c \times COMP + \mathrm{d} \times SITE \quad (1)$$

Where *DGI* is square of the 10 year diameter increment (outside bark), *a* is the intercept, *b* is the vector of coefficients for the tree size variables, *c* is the vector of coefficients for the competition variables, and *d* is the vector of coefficients for the site variables.

Diameter and its transformation were selected as a measure of bole size and the following linear model was determined the proper relationship between diameter increment and size (Wykoff, 1990):

$$b \times SIZE = b_1 \ln(DBH) + b_2 \times DBH^2 \quad (2)$$

Where *DBH* is the diameter of breast height, b_1 and b_2 are coefficients. The diameter-squared term effectively serves to prevent unlimited growth for large diameter trees. Although *DBH* was chose as size variables, it also reflected the effects of past competition.

Competition measures are restricted to those that do not require a tree's spatial coordinates. Thus, stand density measures and variables were restricted to describe the rank of an individual tree within the diameter distribution of the stand. As a measure of the social ranking of the tree within the population, basal area in larger and trees (*BAL*) rather than the percentile in the basal area distribution (Wykoff, 1990) was used in the model. In this study, basal area (*G*) and Reineke's (1933) stand density index (*SDI*) were considered as measures of average stand density because they were found to be well behaved in growth and yield models at the stand level for natural mixed forests in china (Li *et al.*, 2001). Another density measure used in the model is crown closure (*P*).

Table 2. Stand attributes summary of 15 species in Changbai Mountains.

Species	N	Variables	Mean	Std error	Minimum	Maximum
Betula platyphylla	2,843	DBH	15.77021	0.14010	5.1	56.3
		SDI	1037.41	6.74515	96.4687	2129.259
		G	19.70526	0.14167	2.66	59.58
		P	0.82781	0.00338	0.14	1
		V	0.18925	0.00421	0.007999	2.442948
Abies nephrolepis	954	DBH	12.013312	0.19299	5.1	46.2
		SDI	902.49846	8.66991	225.6286	1885.252
		G	30.28932	0.29950	7.87	53
		P	0.80020	0.00573	0.2	1
		V	0.09619	0.00461	0.006604	1.822004
Tilia spp.	2,420	DBH	15.90264	0.23314	5	99.9
		SDI	988.85480	6.29433	225.62865	2028.981
		G	26.39714	0.19767	3.58	59.58
		P	0.87937	0.00263	0.2	1
		V	0.25748	0.01073	0.0075802	7.9589965
Betula costata	227	DBH	26.05318	1.13015	5.2	88.3
		SDI	946.1446	20.83655	303.11233	2028.981
		G	29.50760	0.66967	5.12	65.97
		P	0.856404	0.01032	0.38	1
		V	0.74932	0.06255	0.00842	6.20691
Pinus koraiensis	457	DBH	26.74221	0.74167	5.1	95
		SDI	911.82670	12.72764	129.7147	2028.981
		G	32.31608	0.47464	5.03	65.97
		P	0.80961	0.00708	0.14	1
		V	0.87329	0.05558	0.0066041	9.46797
Juglans mandshrica	362	DBH	20.90455	0.47147	1.70655	5.1
		SDI	800.8499	10.52167	0.790203	256.3428
		G	21.03285	0.34233	0.35644	4.18
		P	0.84944	0.00630	0.491901	0.4
		V	0.36773	0.02039	9.162848	0.007999
Phellodendron amurense	209	DBH	16.22957	0.50601	5.3	51.8
		SDI	913.8011	19.15744	180.1581	2129.259
		G	22.43922	0.49470	3.16	50.66
		P	0.86147	0.00919	0.24	1
		V	0.20793	0.01794	0.008865	2.04827
Larix olgensis	2,917	DBH	14.72542	0.18216	1.4	74.3
		SDI	803.5568	5.81476	167.1581	1885.253
		G	17.65706	0.13971	3.16	49.34
		P	0.74065	0.00339	0.16	1
		V	0.23006	0.00798	0.000241	5.469354

A number of studies have compared various distance-dependent or distance-independent competition indices as point-density measure (Arney, 1974; Alder, 1979; Lowell and Mitchell, 1987; Biging and Dobbertin, 1992; Wykoff, 1990). In order to develop distance-independent tree growth models in this study, relative diameter (*RD* and *DDM*) and summation of square diameter larger than subject trees in the stand (*DL*) were selected as competition indices.

Thus, the competition effects were expressed as:

$$c\times COMP = c_1\times BAL + c_2\times SDI + c_3\times G + c_4\times RD + c_5\times DL$$
$$c_6 + P + c_7\times DDM \qquad (3)$$

Where *BAL* is the summation basal area ($m^2\ ha^{-1}$) of trees larger in diameter than the subject tree, *SDI* is

Table 2. Stand attributes summary of 15 species in Changbai Mountains.

Species	N	Variables	Mean	Std.error	Minimum	Maximum
Acer mono	1,672	DBH	15.09081	0.22868	5.1	72.5
		SDI	961.816	7.00484	93.07366	2129.259
		G	26.68894	0.20080	5.19	65.97
		P	0.87883	0.00295	0.2	1
		V	0.17316	0.00636	0.006477	3.109986
Fraxinus mandshurica	404	DBH	17.71175	0.49121	5.1	78
		SDI	923.1672	14.80894	168.1581	2129.259
		G	21.47025	0.32138	3.16	57.87
		P	0.84551	0.00636	0.2	1
		V	0.29453	0.02176	0.007999	4.814823
Populus spp.	1,133	DBH	16.57058	0.27983	5.1	114
		SDI	1017.847	10.61162	96.4687	2028.982
		G	19.13369	0.23332	2.66	65.97
		P	0.815113	0.00455	0.32	1
		V	0.257043	0.01514	0.007999	10.40791
Ulmus spp.	1,273	DBH	14.31737	0.25766	5	92.8
		SDI	921.1973	8.29639	93.07366	2129.259
		G	21.6426	0.22134	2.45	57.87
		P	0.85314	0.00357	0.16	1
		V	0.199255	0.01075	0.007586	6.867958
Picea spp.	474	D	17.61936	0.66464	5.1	92.2
		SDI	954.0995	14.64069	218.6964	1885.253
		G	29.77377	0.49846	6.49	59.58
		P	0.830018	0.00694	0.2	1
		V	0.44912	0.04304	0.006604	8.862321
Quercus mongolica	2,254	DBH	17.53704	0.24506	5.1	103.9
		SDI	1003.073	6.12882	128.0269	2028.982
		G	23.83157	0.18432	2.45	59.58
		P	0.88486	0.00264	0.16	1
		V	0.25896	0.00978	0.007253	6.851702
Other broadleaf spp.	3,224	DBH	9.46617	0.06757	5.1	42.7
		SDI	955.1711	5.17444	93.07366	2129.259
		G	23.32141	0.15925	3.23	65.97
		P	0.843036	0.00259	0.14	1
		V	0.043299	0.00108	0.006477	1.035751

Where N is numbers of sample trees, SDI is stand density index, G is basal area, P is Crown closure, V is volume.

stand density index, *G* is stand basal area per hectare, *RD* is ratio of subject tree and stand average diameter, *DL* is summation of square diameter larger than subject trees in the stand, *DDM* is ratio of subject tree and maximum in diameter, and *P* is the crown closure.

Because the site description provided by the Chinese National Forest Inventory uses different approaches for different site properties, the last term in Eq. (1) is better written in parts as:

$$d\times SITE = d_1\times SCI+d_2\times SL+d_3\times SL^2+d_4\times SLS+d_5\times SLC \qquad (4)$$

Where d_i is the parameters, *SCI* is site class index, *SL* is tangent of slope, *SLP* is aspect, *SLS* and *SLC* are combinatorial term of slope and aspect, and, *SLS*=*SL* sin(SLP), *SLC*=*SL* cos(SLP).

4. Parameter estimation

The coefficients of the model were estimated using multiple regressions to test a specific series of hypotheses. Stepwise regression implemented in SAS 8.0 (SAS Institute Inc., 1999) was used to choose independent variables and estimate the parameters of logarithm linear regression model. The loss function was defined as the sum of squared residuals (observed minus predicted values). The goodness-of-fit was evaluated using the statistics of the residual sum of squares, RSS, the standard error of estimate, Sy.x {$Sy.x=[RSS/(n-p)]^{0.5}$, p is number of parameters}, and the multiple coefficient of determination (R^2). With the more variables added to the model, the coefficient of determination (R^2) increased gradually, but it would keep at a certain level eventually. A curve between R^2 and the number of variables (n) (see Figure 1) was used to determine final number of variables in the model.

5. Validation

The independent validation procedure for the diameter increment models and mortality model was used the independent data sets from 140 permanent sample plots with 5,018 remeasured trees, that are representing different species and forest types. The validation procedures are performed using the following statistical measures (Li *et al*, 2001): 1) Mean Error (ME); 2) Absolute Mean Error (AME); 3) Relative Mean Error (RME); 4) Absolute Relative Mean Error (ARME); 5) Precision Estimation (P%).

Results and Discussion

1. Diameter increment models

After data processing, toward every dominant tree species or groups, the study used stepwise regression in SAS 8.0 to establish the diameter growth models respectively. Coefficients for the effects of tree size (Eq. (2)), competition (Eq. (4)) and site (Eq. (3)) in the final models were fitted in similar method by different species.

Here, we take birch (*Batula platyphlla*) for an example to explain the whole procedure for developing the models. The models for the other species and groups differed only by the intercept or several coefficients.

The procedure of selecting variables in the diameter increment model for birch, crown closure of stand, slope and aspect with their combinations, *DDM*, and other variables were eliminated in the final model when the numbers of independent variables were 13. It indicated that the competition effects of *DDM* and *DL* on the diameter growth in the stand could be replaced by functions of diameter size. Furthermore, the effect of slope and aspect with their combinations on the diameter increment was not significant that could be ignored in the model. The fitting result of the diameter increment models for birch was presented in Table 3. The t-test at α=0.05 showed each parameter of 7 variables in the model was significant (Table 4).

Table 3. Fitting result of the diameter increment models for birch. n=2842.

Variable Numbers	Variables in Stepwise Regression	
1	*RD*	0.35938
2	*RD*, ln*DBH*	0.38284
3	*RD*, ln*DBH*, DBH^2	0.40521
4	*RD*, ln*DBH*, DBH^2, *SDI*	0.42780
5	*RD*, ln*DBH*, DBH^2, *SDI*, *G*	0.45727
6	*RD*, ln*DBH*, DBH^2, *SDI*, *G*, *P*	0.45960
7	*RD*, ln*DBH*, DBH^2, *SDI*, *G*, *P*, *SLS*	0.46072

Table 4. The parameter estimates and t-test result of the diameter increment models for birch.

Variables	Parameters	Standard Errors	t(2834)	p-level
Intercept	0.705751	0.135354	5.2141	0.000000
RD	2.191477	0.088544	24.7500	0.000000
ln*DBH*	0.605492	0.063826	9.4866	0.000000
DBH^2	-0.001657	0.000106	-15.6312	0.000000
SDI	-0.001232	0.000090	-13.6877	0.000000
G	0.057912	0.004527	12.7937	0.000000
P	-0.527144	0.144951	-3.6367	0.000281
SLS	-4.833E-10	0.000000	-2.4193	0.015615

The result of t-test showed that there is a linear association between all 7 variables entered in the model and the diameter growth. However, considering the practice of forest inventory and model application, more variables in the model would increase the intensity of the inventory with more problems to be resolved. In theoretically speaking, too many parameters will not always enhance the precision of the model. So, it is need to more refine the model.

The relationship between R^2 and the number of variables (p) in the model for birch (Table 3) showed in Figure 1. From Table 3, the multiple coefficient of determination (R^2) tends to linearly increase when the number of independent variables increase from 1 to 5 (eg. RD, lnDBH, DBH^2, SDI, and G) and then it tends to grow very slower when p>5. Obviously, the R^2 approached to a

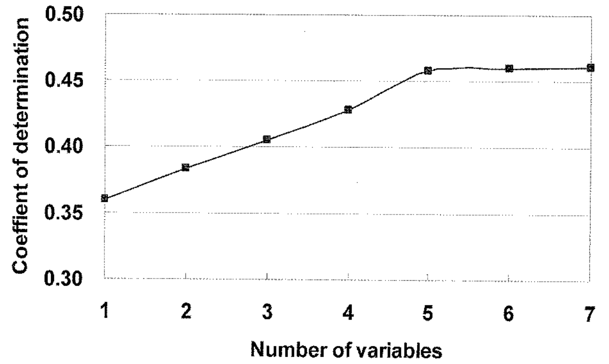

Figure 1. Relationship between R^2 and the number of variables (p) in the model for birch.

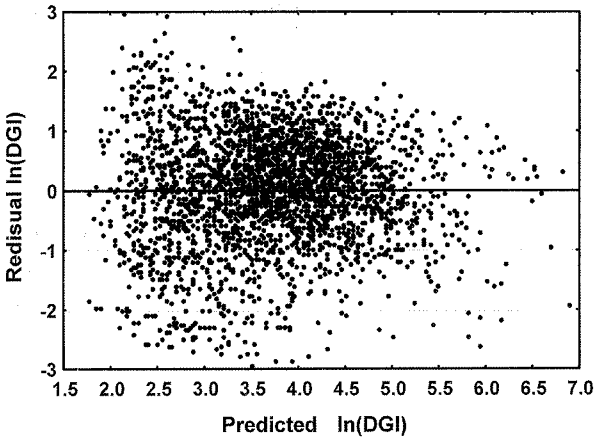

Figure 2. Residuals for the diameter increment model (7) of birch.

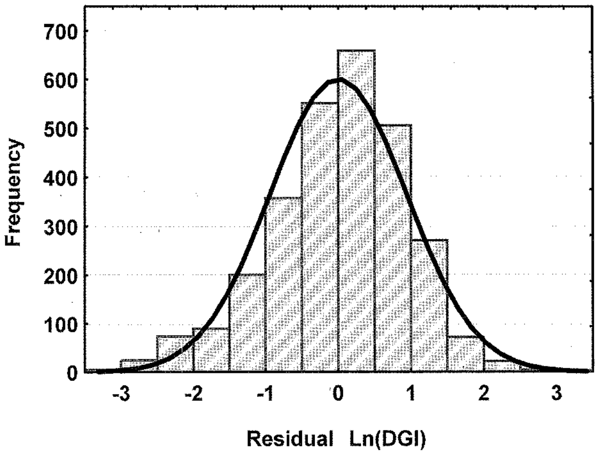

Figure 3. Histogram of residual distribution for model (7).

constant when variable numbers in the model were lager then 5. It indicated that crown closure of stand (P) as the degree of crown coverage stand could be behaved by basal area of the stand (G). The coefficient of the variable *SLS* in the model was too small and its contribution to the model was ignored. Therefore, the final model of squared diameter increment for birch was expressed by 5 variables:

$$\ln(DGI) = 0.7057571 + 2.191477RD + 0.605492\ln DBH - 0.001657DBH^2 - 0.001232SDI + 0.057912G \qquad (7)$$

The residuals of the model (7) displayed, in general, a good fit for the predicted value and residuals, the scatter plots of the residuals behaved as uniform distribution, without radiation and abnormal value, which showed a good estimate result (Figure 2). The frequency distribution of residual ln(*DGI*) also indicated that the residuals near to normal distribution (Figure 3).

Similar fitting method applied to other species and a series of diameter increment models developed for main 15 species in the Chaingbai Mountains. In the final models, the parameters of some independent variable were very small, even just one of ten thousand or hundred in the order of magnitude, such as *SLS*, *SL* and SL^2, for example, the model for birch in Table 3. The contributions to the model of these variables were ignored. Therefore, the final models were composed by 3~5 variables except *Ulmus* spp.. The fit statistics and parameter estimates for the effects of size and competition in the final models ware presented in Table 5 and Table 6.

The total variance explained by the final modes of squared diameter increment (R^2) for all 15 species ranged from 35% to 72% (Table 5). The models did good job in explaining the variation in squared diameter growth for 12 of the 15 species, all with R^2 over 45%. These results compared quit closely with those of

Table 5. Fitting statistics for squared diameter increment models of all species.

Species (groups)	*p*	Variables entered in stepwise regression	No. of trees (n)	R^2
Betula platyphylla	5	RD, lnDBH, DBH^2, SDI, G	2,843	0.45727
Abies nephrolepis	3	lnDBH, P, DBH^2	954	0.49203
Tilia spp.	4	lnDBH, DBH^2, P, RD	2,420	0.53002
Betula costata.	3	lnDBH, DBH^2, P	227	0.63258
Pinus koraiensis	3	lnDBH, DBH^2, RD	457	0.72353
Juglans mandshurica	4	lnDBH, DBH^2, RD, SDI	362	0.37799
Phellodendron amurense	3	lnDBH, DBH^2, DDM	209	0.48346
Larix olgensis	5	DBH^2, lnDBH, DDM, DL, RD	2,917	0.49000
Acer mono	3	lnDBH, DBH^2, DDM	1,672	0.47459
Fraxinus mandshurica	3	DDM, lnDBH, DBH^2	404	0.48723
Populus spp.	5	lnDBH, P, RD, DL, DBH^2	1,133	0.39409
Ulmus spp.	7	lnDBH, SDI, DDM, DBH^2, P, G, RD	1,273	0.54170
Picea spp.	3	lnDBH, DBH^2, RD	474	0.70448
Quercus mongolica	4	lnDBH, DBH^2, P, RD	2,254	0.54610
Other broadleaf spp.	5	lnDBH, P, DL, D^2, G	3,224	0.35284

Table 6. The final squared diameter increment model for 15 species in northeast China.

Species	p	Growth model
Betula platyphylla	5	$\ln(DGI)=0.705751+2.191477RD+0.605492\ \ln DBH-0.001657DBH^2-0.001232SDI+0.057912G$
Abies nephrolepis	3	$\ln(DGI)=0.650022+1.911184\ln DBH-0.961746P-0.001858DBH^2$
Tilia spp.	4	$\ln(DGI)=0.282283+1.662354\ln DBH-0.00064DBH^2-0.901787P+0.394921RD$
Betula costata	3	$\ln(DGI)=-0.03314+2.1304\ln DBH-0.00073DBH^2-0.00073DBH^2-1.35294P$
Pinus koraiensis	3	$\ln(DGI)=-0.21227+1.772991\ln DBH-0.000628DBH^2+0.520778RD-0.666483P$
Juglans mandshurica	4	$\ln(DGI)=1.553811+1.227795\ln DBH-0.000745DBH^2+0.47659RD-0.00075SDI$
Phellodendron amurense amurense	3	$\ln(DGI)=-0.031803+1.172702\ln DBH-0.000884\mathrm{DBH2}+2.245723DDM$
Larix olgensis	5	$\ln(DGI)=0.124+0.000951DBH^2+1.897\ln DBH+2.308DDM-0.0000753DL+0.784RD$
Acer mono	3	$\ln(DGI)=1.04164+0.89754\ln DBH-0.00139DBH^2+1.75959DDM$
Fraxinus mandshurica	3	$\ln(DGI)=1.379139+2.025252DDM+0.849694\ln DBH-0.000361DBH^2$
Populus spp.	5	$\ln(DGI)=3.25955+0.21065\ln DBH-1.55193P+1.59132RD-0.00003DL-0.00054DBH^2$
Ulmus spp.	7	$\ln(DGI)=2.02046+0.7807\ln DBH-0.00114SDI+0.79732DDM-0.00104DBH^2-1.52677P+0.06375G+1.12706RD$
Picea spp.	3	$\ln(DGI)=-0.047491+1.499033\ln DBH-0.000795DBH^2+0.811134RD$
Quercus mongolica	4	$\ln(DGI)=1.33394+1.10219\ln DBH-0.00072DBH^2-1.52157\mathrm{P}+0.6692RD$
Other broadleaf spp.	5	$\ln(DGI)=0.769+1.297\ln DBH-0.904P-0.00003558DL-0.002284DBH^2+0.03659G$

Table 7. Frequency of the variables including in the final models.

Variable	Size		Competition							Site				
	LnDBH	DBH^2	RD	G	DDM	BAL	P	SDI	DL	SCI	SL	SL^2	SLS	SLC
Times	15	15	9	3	5	0	7	3	3	0	0	0	0	0

Wykoff (1990) for mixed conifer stands in the Northern Rocky Mountains, where R^2 ranges from 44 to 69% for 11 species, and much better with those of Monserud and Sterba (1996) for even- and uneven-aged forest stands in Austria, where R^2 ranges from 20 to 63% for all nine species.

The frequency of the variables including in the diameter increment models was calculated and given in Table 7:

From the Table 6 and Table 7, it was conclusion that the main factors effecting squared diameter increment were tree size and competition, however, the site predictors of the stand was no significant. In all variables, $\ln DBH$, DBH^2, RD, P, and DDM contributed to the models significantly. The tree size variables given in Eq.(2) are the most significant and important predictors of diameter growth. In all cases, the coefficient of ln(DBH) is positive and is the most significant independent variables. The DBH^2 term effectively limits growth as size

Table 8. Validation results for squared diameter increment growth models.

Species(groups)	n	ME	MAE	RME%	ARME%	P%	F-test
Betula platyphylla	672	-0.1038	0.2803	-6.97	11.18	98.98	2.0138
Abies nephrolepis	242	-0.0958	0.3520	-4.16	9.59	98.34	1.3968
Tilia spp.	533	-0.0153	0.6095	-7.65	20.52	98.26	1.6607
Betula costata	40	-0.1336	0.5357	-6.52	14.67	94.24	0.6806
Pinus koraiensis	140	0.0786	0.4741	0.41	10.76	97.85	2.5142
Juglans mandshurica	122	0.0831	0.4072	0.42	8.82	97.76	1.4502
Phellodendron amurense	48	-0.0435	0.0906	-1.84	2.96	98.41	1.1728
Larix olgensis	604	-0.9857	1.1220	-18.45	21.49	96.70	426.26
Acer mono	472	-0.0761	0.5874	-0.79	12.53	97.93	2.3142
Fraxinus mandshurica	115	-0.0399	0.4518	-4.07	11.61	97.34	0.6615
Populus spp.	322	0.0939	0.3206	0.97	8.40	98.49	1.9719
Ulmus spp.	253	-0.1443	0.7793	-35.35	49.79	96.74	1.4112
Picea spp.	89	0.1477	0.4122	1.50	10.15	96.60	2.4679
Quercus mongolica	330	0.6319	0.9491	-6.36	39.66	96.92	80.4200
Other broadleaf spp.	676	0.1846	0.7170	-6.74	28.93	97.85	15.0080

increases, and is significant in all species. Some of competition terms in Eq.(3) are also the significant predictors in diameter growth model. Relative diameter *RD* and *DDM* in stand were significant for 9 species and 5 species, respectively, and all significant coefficients were positive, resulting in a decrease in diameter growth as tree competition increase. Crown closure (P) was significant for 7 species and its coefficients were negative, resulting in a decrease in diameter growth as crown competition increase. Surprisingly, effects of site condition (*SCI*), slope and aspect were not significant for all species.

2. Validation

For the validation procedure, the performance evaluation criteria were computed with the growth models developed in above for the validation data sets. The result of statistical validation test for squared diameter increment models of individual trees is summarized in Table 8.

The results indicated that difference measures were all fairly low, with relative mean error (RME%) in predicted logarithm diameter increment for all species less than ±8% except larch and elm. The estimated precisions of the 10 years diameter increment for the validation data sets were all greater than 94% for all species. F-test at 5% level between the predicted ln(*DGI*) vs. observed ln(*DGI*) showed all species accepted hypothesis except *Larix olgensis*, *Quercus mongolica* and other broadleaf species.

Conclusion

Traditional studies on individual tree growth model almost aim at plantation forest, seldom on natural forest. In this study, a diameter increment model of distance-independent for individual trees is developed for all 15 main species growing in mixed-species uneven-aged forest stands in Changbai Mountais. The models analyzed species-specific interrelationships between diameter increment and the various tree size, competition and site variables found in the Changbai Mountains, northeast China. Data come from 25,526 remeasured trees growing on 712 forested permanent plots. This large sample is representative of different forest conditions and therefore provided an excellent data base for the development an individual growth model.

The main factors effecting squared diameter increment were tree size and competition, however, the site predictors of the stand was no significant. The final growth models indicated that tree size variables (ln*DBH*, DBH^2) are the most significant and important predictor of diameter increment existing in all 15 growth models. In competition factors, relative diameter (*RD*), crown closure (*P*) and ratio of subject tree and maximum in diameter (*DDM*) which reflected tree's competitive status were contributed to the diameter increment at a certain extent. Diameter increment was inversely proportional to crown closure (P) for 7 species, *Pinus koraiensis*, *Abies nephrolepis*, *Tilia* spp, *Betula spp.*, *Ulmus* spp., *Quercus mongolica* and other broad-leaf speices, resulting in a decrease in diameter growth as crown competition increase. Other measures of stand density, such as basal area of stand (*G*), stand density index (*SDI*) and the summation basal area of trees larger in diameter than the subject tree (*BAL*) effected the diameter increment not significantly. Site factors, such as site class index (*SCI*), slope and aspect were not important to diameter increment and excluded in the final models. The total variance explained by the final models of squared diameter increment (R^2) for all 15 species ranged from 35% to 72% and these results compared quit closely with those of Wykoff (1990) for mixed conifer stands in the Northern Rocky Mountains.

Five kinds of validation measures and *F*-test for predicted diameter increment were evaluated using independent data sets. The results of validation test indicated that relative mean error values in predicted diameter increment for 15 species were less than ±8% except larch and elm, and the estimated precision values of the diameter growth for all species were all greater than 94%.

The growth model for individual trees developed in this paper can actually reflect the tree's diameter increment of 15 species and be generally well suited for simulating tree and stand growth for natural mixed forest stands in the Changbai Mountains. Furthermore, it will provide detail information of tree increment to intensive forest management and decision-making for natural mixed forest in Northeast China.

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