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The Development of Growth and Yield Models for the Natural Broadleaved-Korean Pine Forests in Northeast China[1]

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ABSTRACT

The growth and yield models for five different kinds of natural forest types were systemically developed in the natural Broadleaved-Korean pine Forests in Northeast China. The data were collected from 359 temporary plots and 58 permanent plots with area ranged from 0.06 ha to 1.0 ha, ranging in stand age from 43 to 364 years. The Site Class Index (SCI) was introduced to evaluate site quality and the Crown Competition Factor (CCF) was selected as a measure of stand density for the mixed natural forest. The Chapman-Richards function was adopted to develop SCI equation and height-diameter curve. The Schumacher growth function was selected as base model to develop the DBH, basal area, and stand volume growth models by using re-parameterized method. In modeling mean DBH and basal area growth, it was found that the asymptotic parameter A of Schumacher function was exponentially related to site quality (SCI) and stand density (CCF). The rate parameter k was related to stand density and it was independent of SCI. Several validation measures for predicted stand variables were evaluated in the growth and yield models using independent data sets. The results indicated that relative mean errors (RME) in predicted stand attributes were less than ±5% and the estimated precision values of the stand variables were all greater than 95%.

Key words : Pinus koraiensis, *natural mixed forests, Schumacher growth function, Chapman-Richards function, whole stand models, Site Class Index (SCI), Crown Competition Factor (CCF).*

要 約

이 연구는 중국 동북부 활엽수-잣나무 천연림의 다섯 가지 임형에 대하여 임분의 생장 모델과 수확 모델을 개발하기 위하여 수행되었다. 연구 자료는 43년생부터 364년생 범위에 이르는 임분에서 0.06ha에서 1.0ha 크기의 359개 임시 표본구와 58개의 영구 표본구에서 수집되었다. 입지조건을 평가하기 위하여 지위급지수(Site Class Index; SCI)를 도입하였고, 천연혼효림의 임분밀도를 측정하기 위하여 수관경쟁지수(Crown Competition Factor; CCF)를 채택하였다. SCI 공식과 수고-직경 곡선 모델은 Chapman-Richards 함수를 이용하였고, 흉고직경, 흉고단면적, 및 임분재적 모델의 개발

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은 Schumacher의 생장함수를 기본 모델로 선정하였다. 평균 흉고직경과 흉고단면적 생장 모델에서 Schumacher 함수의 점근매개변수 A는 입지조건(SCI)과 임분밀도(CCF)와 상관관계가 있는 것으로 나타났으며, 비율매개변수 k는 임분밀도와 관계가 있었고 입지조건과는 무관한 것으로 나타났다. 개발된 생장 모델과 수확 모델로써 예측된 임분 제원들을 평가하기 위하여 별개의 임분 자료를 이용하여 유효성 검정을 실시하였다. 검정 결과, 예측치의 상대평균오차(RME)는 ±5% 미만으로 산출되었고 임분 변수들의 정확도는 모두 95% 이상인 것으로 나타났다.

INTRODUCTION

Natural distribution of the broadleaved-Korean pine (*Pinus koraiensis*) forest is limited to east mountain area (the Lesser Xingan Moutains and the Changbai Mountains) in Northeast China (Wang, 1995). Due to extensive clearcutting and unbalanced growing stock between harvesting and annual increment, large amount of the broadleaved-Korean pine forest has been replaced by various tree species, with secondary forests. Now, the virgin forest of broadleaved-Korean pine can be found only in natural reserves, Fenglin and Linagshui Natural Reserve in the Lesser Xingan Moutains, Heilongjiang Province and Natural Reserve in the Changbai Mountains, Jilin Province in China.

The "re-parameterized method" was often used to develop for the whole stand model under different stand conditions for even-aged stands (Pienaar, 1979; Pienaar and Shiver, 1984; Li, 1995). For example, Pienaar and Rheney (1990) developed yield prediction models for slash pine plantation by using Chapman-Richards function as basic model. However, because of complexity in the component species and stand development patterns and structures, growth and yield models for natural mixed stands have been seldom studied over the last 30 years (Davis and Johnson, 1987). Li (1983) developed density-free yield tables for the broadleaved-Korean pine forest based on graphic method of construction.

In order to predict the growth and yield of the uneven-aged mixed forest and the attributes of sub-compartment in the Lesser Xingan Moutains, growth and yield models for the broadleaved-Korean pine forest were systemically developed by employing "re-parameterized method" in the present study. The models had been used to predict forest resources of Fenglin Natural Reserve in the UNDP Project of "Forest Sustainable Managing Capacity Construction, Research and Extension in Northeastern China".

MATERIALS AND METHODS

1. Study Area

Data were collected from Fenglin Natural Reserve, which is in Yichun City, Heilongjiang province, China, situated in the south of Lesser Xingan Mountains, ranging across 128°59′~129°15′ E and 48°01′~48°09′ N.

Most of this study area is composed of low- and medium-sized mountains, of which over 65% of total area is gentle slope within the elevation from 300 to 450m. The highest peak is 688m and relative elevation is from 100 to 300m. Over 90% of the area is flat and the average slope is 6°. The annual mean temperature is −0.5℃ and the mean temperature ranges from −24.2℃ in January to 20.3℃ in July. The annual precipitation is 680~750mm with the evaporation of 930mm. Dark brown soil is the zonal soil in this area and it accounts for about 80% of the forestry land.

The Fenglin Natural Reserve is the largest and well-protected natural distributive region of the broadleaved-Korean pine ecosystem. Large numbers of plant species inhabit in the area. Overstory tree species are *Pinus koraiensis*, *Picea koraiensis*, *Abies nephrolepis*, *Larix gmelini*, *Tilia amurensis*, *T. mandshurica*, *Acer mono*, *Phellodendron amurense*, *Fraxinus mandshurica*, *Juglans mandshurica*, *Ulmus propinqua*, *U. laciniata*, *Betula costata*, *B.*

platyphylla, *Quercus mongolica*, *Populus davidiana*, *P. ussuriensis*, etc.

Forest resource inventory in 1997 indicated that the total area was 18,165 ha. Forest coverage is up to 95.8%. The zonal climax community is the broadleaved-Korean pine forest, which was classified into 4 types : Oak-Korean pine Forest, Basswood-Korean pine Forest, Costata Birch (*Betula costata*)-Korean pine Forest and Spruce-Fir-Korean pine forest. In the valley area the boreal coniferous forest has been formed, in which spruce and fir are dominant species. It is the intra-zonal community and major types are fir forest and Spruce-Fir mixed forest. In addition, there are some successive community types such as the poplar forest, the birch forest and hardwood forests. The Areas and volumes of eight different forest types are shown in Table 1.

Table 1. Forest types in Fenglin Natural Reserve, China*.

Forest types	Area (ha)	%	Volume (m^3)	%	m^3/ha
Basswood-Korean pine Forest	513	2.95	177,560	3.85	346.1
Costata Birch-Korean pine Forest	3,591	20.64	1,164,690	25.25	324.3
Spruce-Fir-Korean pine Forest	5,104	29.34	1,650,510	35.79	323.4
Spruce-Fir Forest	2,045	11.75	429,130	9.31	392.0
Coniferous Mixed Forest	3,482	20.01	831,860	18.03	428.9
Conifer-Hardwood Mixed Forest	1,345	7.73	220,470	4.78	163.9
Hardwood Forest	1,313	7.55	136,780	3.98	718.5
Scots pine Plantation	5	0.03	600	0.01	120.0
Total	17,398	100	4,611,560	100	265.1

* Note : The Oak-Korean pine forest is not included for sporadic distribution

From Table 1, zonal climax forest type (Oak-Korean pine Forest, Basswood-Korean pine Forest, Costata Birch-Korean pine Forest and Spruce-Fir-Korean pine Forest), intrazonal climax forest type (Spruce- Fir Forest), and original Conifer-Hardwood Mixed Forest or Coniferous Mixed Forest added up accounting for 92.0% of the total forest area and for 96.6% of the total growing stock. Successive forests (oak forest, birch forest, poplar forest and other hardwood forests) are accounting for 8.0% and 3.4% of the total forest area and the total growing stock, respectively.

2. Data Collection

The available data to develop growth models for natural mixed forests were collected in Fenglin Natural Reserve from 1953 to 1997. All of the research plots were grouped into the following three categories :

a) 183 temporary sample plots with area ranged from 0.3 ha to 1.0 ha were collected in 1953;

b) 43 permanent and 60 temporary sample plots with area 0.2 ha to 0.5 ha were collected from 1973 to 1987;

c) 176 temporary sample plots with area 0.06 ha, which were set up systematically by 1km ×1km covering total area, were collected in 1997.

514 sample plots in total were used to develop growth models for natural mixed forests after deleting 8 plots by data analysis. The plots distributed by forest types are shown in Table 2.

Table 2. The number of sample plots established by forest types for natural mixed forests.

Forest type		Number of plots
Broadleaved-Korean pine Forest	Oak-Korean pine Forest	9
	Basswood-Korean pine Forest	57
	Costata Birch-Korean pine Forest	62
Spruce-Fir-Korean pine Forest		183
Spruce-Fir Forest		60
Coniferous Mixed Forest		87
Conifer-Hardwood Forest	Conifer-Hardwood Forest	39
	Hardwood Forest	17
Total		514

Table 3. Summary of stand attributes for the each forest type.

Forest type	Stand Variables	Number of Plots	Min	Max	Mean	SD	CV(%)
Broadleaved-Korean pine Forest	Stand age (years)	128	75.0	358.0	198.8	49.77	25.04
	D.B.H (cm)	128	18.1	80.9	42.7	10.56	24.74
	Mean Height (m)	128	13.8	35.1	25.1	3.72	14.82
	SCI (m)	128	12.4	26.3	18.9	2.48	13.13
	Number of trees per ha	128	184.0	1,067.0	478.2	162.60	34.00
	CCF	128	283.3	1,270.3	672.3	209.46	31.15
	Basal area (m^2/ha)	128	13.9	60.8	37.7	10.07	26.75
	Volume (m^3/ha)	128	127.0	735.0	426.2	126.05	29.58
	Mortality (m^3/ha)	128	0.0	233.0	37.6	46.25	123.11
Spruce-Fir-Korean pine Forest	Stand age (years)	183	72.0	409.0	195.3	45.62	23.35
	D.B.H (cm)	183	24.0	92.0	44.4	10.52	23.70
	Mean Height (m)	183	17.0	34.1	25.7	3.27	12.72
	SCI (m)	183	14.7	23.3	19.4	1.69	8.71
	Number of trees per ha	183	184.0	1,046.0	436.4	163.76	37.53
	CCF	183	303.3	1,127.5	579.9	161.96	27.93
	Basal area (m^2/ha)	183	15.2	66.3	34.3	9.58	27.89
	Volume (m^3/ha)	183	168.0	832.0	401.1	125.22	31.22
	Mortality (m^3/ha)	183	0.0	193.0	31.4	37.47	119.28
Spruce-Fir Forest	Stand age (years)	60	44.0	207.0	85.1	32.22	37.89
	D.B.H (cm)	60	10.2	60.9	24.2	7.43	30.70
	Mean Height (m)	60	11.5	35.9	19.7	4.66	23.63
	SCI (m)	60	10.5	27.9	18.7	3.81	20.37
	Number of trees per ha	60	217.0	2,234.0	640.4	323.03	50.45
	CCF	60	274.4	843.5	497.5	130.60	26.25
	Basal area (m^2/ha)	60	13.5	43.9	23.8	6.26	26.35
	Volume (m^3/ha)	60	110.0	526.0	268.1	84.78	31.62
	Mortality (m^3/ha)	60	0.0	174.0	31.7	43.26	136.67
Coniferous Mixed Forest	Stand age (years)	87	44.0	364.0	119.8	66.87	55.84
	D.B.H (cm)	87	10.2	61.9	28.2	10.17	36.07
	Mean Height (m)	87	11.5	35.9	21.5	5.15	23.92
	SCI (m)	87	10.5	27.9	19.2	3.54	18.45
	Number of trees per ha	87	217.0	2,234.0	634.3	290.91	45.87
	CCF	87	220.4	877.1	478.8	141.34	29.52
	Basal area (m^2/ha)	87	12.1	43.9	23.4	6.11	26.07
	Volume (m^3/ha)	87	110.0	526.0	262.2	81.04	30.91
	Mortality (m^3/ha)	87	0.0	174.0	30.1	41.10	136.69
Conifer-Hardwood Forest	Stand age (years)	56	43.0	250.0	99.3	41.03	41.33
	D.B.H (cm)	56	8.8	70.3	30.5	13.40	43.97
	Mean Height (m)	56	8.8	33.9	21.5	5.38	25.05
	SCI (m)	56	9.3	22.2	15.7	3.26	20.85
	Number of trees per ha	56	117.0	2,017.0	612.7	389.92	63.64
	CCF	56	201.6	1,617.1	582.7	320.93	55.08
	Basal area (m^2/ha)	56	6.8	41.9	20.3	6.97	34.35
	Volume (m^3/ha)	56	52.0	427.0	212.0	75.55	35.63
	Mortality (m^3/ha)	56	0.0	108.0	19.1	26.02	136.43

Considering the plot distribution (Table 2) and actual area distribution (Table 1) of forest types in Fenglin Natural Reserve, five different forest types were divided to develop the growth models of natural mixed forests in this paper : 1) Broadleaved-Korean pine Forests : including Oak-Korean pine Forest, Basswood-Korean pine Forest, and Costata Birch-Korean pine Forest; 2) Spruce-Fir-Korean pine Forest; 3) Spruce-Fir Forest : including Spruce Forest, Fir Forest and Spruce-Fir Forest; 4) Coniferous Mixed Forest; 5) Conifer-Hardwood Mixed Forest: including Conifer-Hardwood Mixed Forest and Hardwood Forest. Summary of the characteristics used in the growth and yield model selection and parameter estimation procedures for the five forest types are presented in Tables 3.

Otherwise, for each of 183 plots investigated in 1953, mean age and mean height of dominant or non-dominant species in stands were measured. These data were used to construct Site Class Index (SCI) curves, of which detailed discussion will be given in the chapter of Results and Discussion. The characteristics of species attributes were listed in Table 4.

Table 4. Statistics of mean age and mean height for each species.

No.	Species	Number of Stems	Mean age			Mean Height (m)		
			Range	mean	SD	range	mean	SD
1	*Pinus koraiensis*	255	20~405	162	66.5	10.3~34.2	22.1	5.09
2	*Picea koraiensis*	160	28~214	108	35.9	12.3~30.6	20.8	4.47
3	*Abies nephrolepis*	125	24~ 94	58	14.7	9.5~26.0	16.4	3.40
4	*Larix gmelinii*	38	70~419	191	72.0	18.0~31.8	25.6	3.21
5	*F. P. J.* *	93	8~150	51	25.8	5.0~28.0	12.6	4.36
6	*Ulmus* spp.	46	35~125	88	20.9	10.0~22.8	17.1	2.79
7	*Betula costata*	85	40~197	102	31.9	12.0~29.4	21.1	3.67
8	*Quercus mogonica*	31	8~114	66	26.5	5.0~25.6	16.2	3.84
9	*Acer mono*	45	45~140	81	20.1	8.0~20.0	13.6	2.96
10	*Tilia* spp.	130	34~198	94	30.4	11.0~30.0	19.5	3.41
11	*Betula platyphylla*	33	20~120	74	24.5	11.0~26.5	19.0	3.71
12	*Populus* spp.	40	25~135	75	21.5	12.0~26.0	20.5	3.22

*Note : Fraxinus mandshurica, Phellodendron amurense, and Juglans mandshurica

3. Growth and yield models

By comparing six growth equations discussed by Zeide (1993), the Chapman-Richards function (Richards, 1959), Schumacher growth equation (Schumacher, 1939), and Schumacher yield model (Clutter, et al., 1983) were selected as basic candidate functions to develop growth and yield models for the natural forest.

The Chapman-Richards function has been widely utilized in modeling biological phenomena (Ratkowsky, 1983; Amaro et al., 1998) :

$$H = A(1-\exp(-kt))^c \quad (1)$$

where : H is the mean height(m); t is the mean age of the stand (yrs), A is the asymptote of height, k is the parameter related to growth rate, c is a shape parameter.

The Schumacher equation was applied to base model for developing the mean DBH, basal area growth models, and yield models for the natural forest

$$y = A\exp(-k/t) \quad (2)$$

where : A is asymptotic parameter, k is param-eter related to growth rate, y is stand attributes (DBH, basal area or stand volume); t – stand age.

The re-parameterized method (Pienaar and Shiver, 1984; Tang 1991; Li, 1995) was introduced to construct the growth prediction models. The procedure involves the following steps : a) selecting a nonlinear growth model as base model eq.(1) or eq.(2) and fitting to the data; b) for each fitted curves, determining the value of stand conditions (site, stand density and so on); c) relating the parameters of fitted curves to stand condition through linear or nonlinear regression procedure; d) refitting the final model to estimate parameters of the model.

The parameter estimates of nonlinear growth model were performed using DUD method implemented in SAS 6.12 software (SAS Institute Inc., 1990). 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 coefficient of determination, R^2.

4. Validation

The independent validation procedure was used the data sets of 15 permanent plots, which are representing different forest types, with 3 replications from 1982 to 1998. The characteristics for the validation data set are summarized in Table 5.

Table 5. Characteristics for the validation data set.

Stand Variables	Number of Plots	Min	Max	Mean	S.D	CV (%)
Stand age (years)	45	46.0	293.0	186.6	59.10	31.67
D.B.H (cm)	45	11.2	71.8	42.0	12.51	29.79
Mean Height (m)	45	11.9	30.8	24.2	4.12	17.00
SCI (m)	45	10.5	23.4	18.4	2.88	15.66
Number of trees per ha	45	141.0	1,291.0	456.5	231.30	50.67
CCF	45	271.5	826.7	504.3	140.55	27.87
Basal area (m^2/ha)	45	12.1	58.5	30.9	11.70	37.89
Volume (m^3/ha)	45	144.0	735.0	373.1	152.10	40.77

The validation procedures are performed using the following statistical measures.

1) Mean Error : $ME = \sum_{i=1}^{n}\left(\frac{y_i - \hat{y}_i}{n}\right)$

2) Absolute Mean Error : $AME = \sum_{i=1}^{n}\left|\frac{y_i - \hat{y}_i}{n}\right|$

3) Relative Mean Error :

$$RME = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{y_i - \hat{y}_i}{y_i}\right)\times 100\%$$

4) Absolute Relative Mean Error :

$$ARME = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{y_i - \hat{y}_i}{y_i}\right|\times 100\%$$

5) Precision Estimation : $P = (1 - \frac{t_{0.05}S_{\bar{y}}}{\hat{\bar{y}}})\times 100\%$;

$$\text{where } S_{\bar{y}} = \sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{n(n-p)}}$$

Where : y_i is observed value, $\hat{y}_i$ is predicted value, p is number of parameters

RESULTS AND DISSCUSION

1. Site Class Index (SCI)

Over the last decades, many countries have used the site index, which had replaced the earlier site class concept to evaluate site quality. The site index could be usually defined as the mean height of the dominants and co-dominants at a reference age. The inventory procedure to collect plot data in 1953 didn't measure the mean height of the dominants and co-dominants, but the data set contained the mean height for each species. Therefore, the concept of site class index was introduced in this study to evaluate site condition for the natural mixed forest. The site class index (SCI) is defined as the mean height of the dominant species at a reference age.

The Chapman-Richards function (1) was used to develop SCI equation. Parameter estimates and fit statistics of equation (1) for data of each species (Table 4) are shown in Table 6. The fitting results of SCI curves for the Broadleaved- Korean pine Forest are shown in Figure 1.

The SCI is defined as :

$$SCI = H\frac{(1-\exp(-kt_I))^c}{(1-\exp(-kt)^c} \quad (3)$$

where t_I is index age, which is determined for each species : Korean pine, spruce, and larch are 100 years ; birch and poplar are 30 years; other species are 50 years.

Table 6. Parameter estimates and fit statistics of Site Class Index equation (3) for each species.

No.	Species	Parameters			*n*	RSS	Sy.x	R^2
		A	*k*	*c*				
1	*Pinus koraiensis*	34.0113	0.00461	0.6117	255	2404.8	3.08	0.7968
2	*Picea koraiensis*	45.7329	0.00179	0.4439	160	1802.9	3.39	0.6581
3	*Abies nephrolepis*	44.0807	0.00485	0.6966	125	647.5	5.26	0.7406
4	*Larix gmelinii*	34.1254	0.00402	0.4256	38	132.1	1.94	0.8084
5	*F. P. J*	48.1821	0.00361	0.7376	93	388.1	2.08	0.8984
6	*Ulmus spp.*	26.1693	0.00903	0.6884	46	157.7	1.92	0.7417
7	*Betula costata*	30.0026	0.00804	0.5684	85	587.9	2.68	0.6925
8	*Quercus mogonica*	35.8088	0.00294	0.4420	31	123.9	2.10	0.8487
9	*Acer mono*	46.0479	0.00304	0.7950	45	144.4	1.85	0.7900
10	*Tilia spp.*	26.3807	0.00986	0.5558	130	863.0	2.61	0.6516
11	*Betula platyphilla*	28.0963	0.01102	0.6295	33	166.6	2.36	0.7891
12	*Populus spp.*	23.7513	0.03419	1.4105	40	187.6	2.25	0.7329

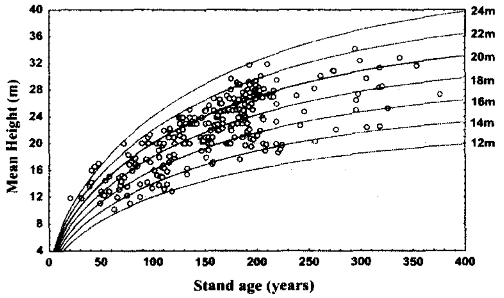

Figure 1. SCI curves for the Broadleaved-Korean pine Forest.

2. Crown Competition Index (CCF)

Krajicek et al. (1961) proposed a measure of stand density is appropriate for both even-aged and all-aged stands (Clutter et al., 1983). The relationship between crown width (CW) and diameter (D) for open-grown tree is assumed to be of the form :

$$CW = \alpha_1 + \alpha_2(1-\exp(-\alpha_3 D)) \quad (4)$$

where : α_1, α_2 and α_3 are parameters to be estimated; $CW_{max} = \alpha_1 + \alpha_2$.

Table 7. Parameter estimates and fit statistics of equation (4) for each species.

No.	Species	Parameters			n	MSE*	R^2
		α_1	α_2	α_3			
1	*Pinus koraiensis*	0.9694	20.1989	0.02963	142	3.6184	0.8126
2	*Picea koraiensis*	0.6563	15.1656	0.05579	34	1.1311	0.9109
3	*Abies nephrolepis*	0.5580	12.3247	0.07607	118	1.5296	0.8599
4	*Larix gmelinii*	0.8685	15.6040	0.01826	55	0.4910	0.7630
5	*F. P. J*	1.2863	29.1042	0.04289	64	3.3211	0.8120
6	*Ulmus spp.*	1.3355	23.7265	0.04801	44	2.3383	0.8854
7	*Betula costata*	0.4303	18.9154	0.03618	61	1.3574	0.8719
8	*Quercus mogonica*	1.2863	29.1042	0.04289	64	3.3211	0.8120
9	*Acer mono*	0.6494	23.5985	0.06182	36	4.2570	0.7052
10	*Tilia spp.*	1.1053	21.7229	0.05110	59	3.0123	0.8560
11	*Betula platyphilla*	1.1880	24.7109	0.00988	90	2.6632	0.8804
12	*Populus spp.*	1.2863	29.1042	0.04289	64	3.3211	0.8120

* Note : MSE=RSS/(n-p)

Parameter estimates and fit statistics of equation (4) for each species are shown in Table 7.

The maximum crown area (MCA_i) for each tree in a stand is given by

$$MCA_i = \frac{\pi}{40000} CW_i^2 = \frac{\pi}{40000} \{\alpha_1 + \alpha_2 [1 - \exp(-\alpha_3 D_i)]\}^2 \quad (5)$$

$$CCF = 100 \times \sum_{i=1}^{n} MCA_i / S \quad (6)$$

where : S is stand level basis (1 ha), n is number of trees per ha

3. Stand Growth and Yield Models

1) Mean DBH growth model

Using the Schumacher equation (2) as base model, it was found that the asymptotic parameter A was positively related to site condition (SCI) and negatively related to stand density (CCF).

The parameter k in equation (2) was independent of SCI and negatively related to stand density (CCF). As a result, the mean DBH growth model was constructed as :

$$DBH = a_0 SCI^{a_1} (CCF/100)^{-a_2} \exp(-a_3 (CCF/100)^{-a_4} / t) \quad (7)$$

where : $a_0 \sim a_4$ are parameter to be estimated.

Parameter estimates and fit statistics of mean DBH growth model (7) for each forest type by using SAS 6.12 software are listed in Table 8. The predicted mean DBH of different SCI for the Broad-leaved Korean pine Forest is shown in Figure 2.

Table 8. Parameter estimates and fit statistics of mean DBH growth model (7) for each forest type.

Forest type	Parameters					Number of plots	RSS	Sy.x	R^2
	a_0	a_1	a_2	a_3	a_4				
Broadleaved-Korean pine	40.9230	0.69523	0.65905	550.7779	0.71259	128	2991.14	4.93	0.7906
Spruce-Fir-Korean pine	191.0151	0.28940	0.80909	723.5305	0.82480	183	4018.40	4.75	0.8017
Spruce-Fir	7.4837	0.81954	0.59126	173.6626	1.30804	60	1281.60	4.83	0.6129
Coniferous Mixed	14.1237	0.55368	0.34157	85.2964	0.45841	87	3411.69	6.45	0.6209
Conifer-Hardwood	40.8397	0.38653	0.32958	119.7512	0.28812	56	3667.26	8.48	0.6351

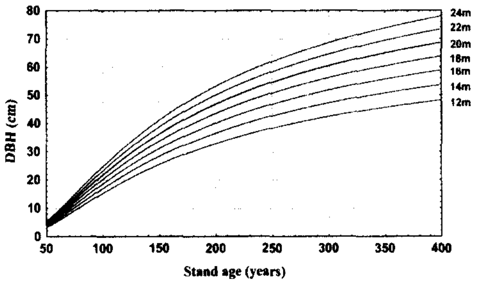

Figure 2. Mean DBH growth curves of different sites (SCI) for the Broadleaved-Korean pine Forest (CCF=600%).

2) Height-Diameter Curve

Because the stand height growth may not be affected significantly by stand density, the height-diameter model was developed as

$$H = 1.3 + b_0 SCI^{b_1} (1 - \exp(-b_2 DBH))^{b_3} \quad (8)$$

where : $b_0 \sim b_3$ are parameters to be estimated

Parameter estimates and fit statistics of height-diameter equation (8) for each forest type using SAS 6.12 software are listed in Table 9. The predicted height of different SCI for the Broadleaved-

Table 9. Parameter estimates and fit statistics of the model (8) for each forest type.

Forest type	Parameters				Number of plots	RSS	Sy.x	R^2
	b_0	b_1	b_2	b_3				
Broadleaved-Korean pine	6.6123	0.54496	0.02659	0.79075	128	252.42	1.43	0.8576
Spruce-Fir-Korean pine	2.4882	0.90252	0.01477	0.52312	183	190.93	1.03	0.9025
Spruce-Fir	6.8340	0.65490	0.00465	0.41149	60	225.51	2.01	0.8271
Coniferous Mixed	7.5612	0.63752	0.00630	0.49003	87	364.34	2.08	0.8420
Conifer-Hardwood	12.2713	0.32741	0.03548	0.85161	56	257.48	2.23	0.8414

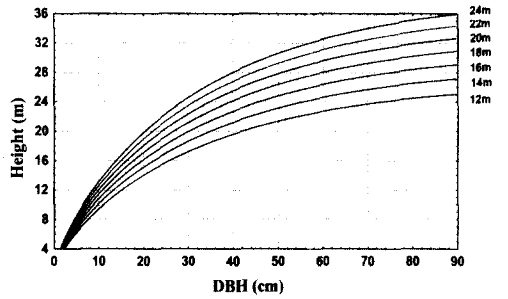

Figure 3. Height-diameter curves of different sites (SCI) for the Broadleaved-Korean pine Forest.

Korean pine Forest is plotted as a function of DBH as shown in Figure 3.

3) Basal area growth model

Analyzing the parameters of Schumacher equation (2) for different stand condition, it was found that the asymptotic parameter A was exponentially related to SCI and stand density (CCF). The shape of basal area growth curves was determined by stand density. Therefore, the parameter k in equation (2) was curvilinearly related to stand density (CCF) and unrelated to SCI. As a result, a model for predicting basal area growth was developed as :

$$BAS = c_0 SCI^{c_1} (CCF/100)^{c_2} \exp(-c_3 (CCF/100)^{c_4} / t) \quad (9)$$

where : $c_0 \sim c_4$ are parameter to be estimated.

Parameter estimates and fit statistics of basal area growth model (9) for each forest type using SAS 6.12 software are presented in Table 10. The predicted basal area of different SCI for the Broadleaved-Korean pine Forest is shown in Figure 4.

Table 10. Parameter estimates and fit statistics of basal area growth model (9) for each forest type.

Forest type	Parameters					Number of plots	RSS	Sy.x	R^2
	c_0	c_1	c_2	c_3	c_4				
Broadleaved-Korean pine	1.7822	0.46581	1.02529	2.5983	1.46258	128	5599.83	6.7474	0.75408
Spruce-Fir-Korean pine	1.2143	0.59635	1.12664	14.6179	0.88669	183	7018.68	6.2793	0.76284
Spruce-Fir	2.2071	0.36091	0.90724	0.2998	2.02807	60	1220.96	4.7116	0.69366
Coniferous Mixed	4.2631	0.25007	0.66812	1.3667	0.91765	87	1813.90	4.7011	0.66380
Conifer-Hardwood	4.8925	0.16111	0.64223	1.1945	1.12167	56	1361.86	5.1672	0.70654

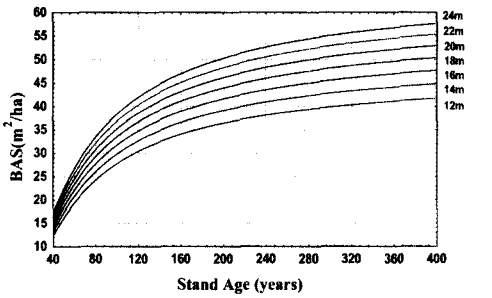

Figure 4. Basal area growth curves of different sites (SCI) for the Broadleaved-Korean pine Forest(CCF=800%).

4) Yield predicton model

Using multiple regression method, the stand yield models for the natural mixed forest were developed by selecting stand age (t), site condition (SCI), and basal area (BAS) as independent variables.

$$VOL = d_0 SCI^{d_1} BAS^{d_2} \exp(-d_3 / t) \quad (10)$$

where : VOL is stand volume, SCI is site class index, BAS is stand basal area, $d_0 \sim d_3$ are parameters to be estimated.

Parameter estimates and fit statistics of stand yield model (10) for each forest type by using SAS 6.12 software are listed in Table 11. The predicted stand volume of different SCI for the Broadleaved-Korean pine Forest is shown in Figure 5.

Table 11. Parameter estimates and fit statistics of yield model (10) for each forest type.

Forest type	Parameters				Number of plots	RSS	Sy.x	R2
	d_0	d_1	d_2	d_3				
Broadleaved-Korean pine	2.3153	0.52396	1.0508	25.3601	128	142659.6	33.92	0.9299
Spruce-Fir-Korean pine	3.3048	0.43889	1.0493	40.2246	183	110640.8	24.86	0.9614
Spruce-Fir	3.1899	0.08143	1.1561	4.7962	60	44404.2	28.16	0.8970
Coniferous Mixed	6.1288	0.10432	1.1071	2.3964	87	69750.3	28.99	0.8779
Conifer-Hardwood	12.4095	0.08264	1.0185	0.0651	56	12251.3	15.35	0.9617

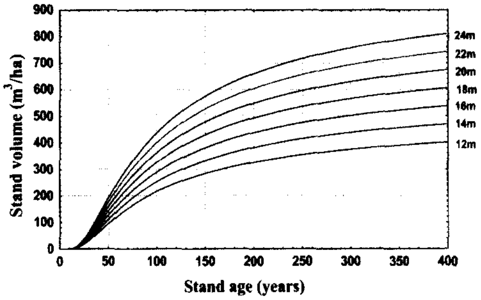

Figure 5. Stand volume growth curves of different sites (SCI) for the Broadleaved-Korean pine Forest (CCF=800%).

5) CCF Prediction model

The data from 43 permanent plots were used to develop the CCF prediction model. It was found the relative growth rate of CCF was a constant and not significantly affected by site condition and forest type. It can be expressed as :

$$\frac{dCCF(t)/dt}{CCF(t)} = -K \qquad (11)$$

Where : $CCF(t)$ is CCF value at time t, K is a constant.

The CCF prediction model can be derived by integrating the difference equation (11) with initial condition $CCF=CCF_1$ when $t=t_1$:

$$CCF_2 = CCF_1 e^{-K(t_2-t_1)} \qquad (12)$$

The fitting results of equation (12) for the natural mixed forest are :

$$CCF_2 = CCF_1 e^{-0.0054517(t_2-t_1)} \qquad (13)$$

n=62, RSS=45355.901, $S_{y.x}$=27.2679, R^2=0.95784

6) Prediction equation for the number of trees per hectare (N)

The analysis of each data set indicated that the number of trees per hectare (N) was correlated with stand site (SCI) and stand density (CCF). Using multiple regression method, the final selected model of N for the natural mixed forest is :

$$N = \beta_0 + \beta_1/t - \beta_2 SCI + \beta_3 CCF \qquad (14)$$

where : N is Number of tree per ha, t is stand age, $\beta_0 \sim \beta_3$ are parameters to be estimated.

Parameter estimates and fit statistics of model (14) for each forest type are listed in Table 12.

Table 12. Parameter estimates and fit statistics of equation (14) for each forest type.

Forest type	Parameters				Number of plots	RSS	Sy.x	r
	β_0	β_1	β_2	e_3				
Broadleaved-Korean pine	298.3088	11121.12	11.9975	0.50480	128	892381.9	84.83	0.8282
Spruce-Fir-Korean pine	437.3028	10701.98	21.6814	0.61750	183	2079849.5	107.79	0.7590
Spruce-Fir	47.3338	10183.24	5.05106	0.99794	60	918156.8	128.05	0.7941
Coniferous Mixed	453.0172	4448.948	17.2268	0.88917	87	2207645.2	163.09	0.7217
Conifer-Hardwood	231.3752	31174.16	25.8403	0.74186	56	1913079.5	191.81	0.8832

7) Mortality Rate

The analysis of mortality rate (MR%) based on the 43 permanent plots with 3 replications indicated that the MR% was independent with stand conditions (stand age, SCI, CCF). The coefficient of simple correlation between MR% and stand age, SCI, CCF are -0.1135, -0.0052, and -0.1527, respectively. In this paper, mean mortality rates ($\overline{MR}$ %) for each forest type was calculated based on 43 permanent plots (Table 13).

Table 13. Mean mortality rates ($\overline{MR}$ %) and mean cumulative mortality rate ($\overline{CMR}$ %) for each forest type.

Forest Type	$\overline{MR}$ %	Number of Plots	$\overline{CMR}$ %
Broadleaved-Korean pine	1.03	128	7.22
Spruce-Fir-Korean pine	1.61	183	6.55
Spruce-Fir	1.66	60	7.97
Coniferous Mixed	1.71	87	8.30
Conifer-Hardwood	0.73	56	6.17

4. Validation

For the validation procedure, the performance evaluation criteria was computed with the growth models developed in above for the validation data sets (Table 5). The result of statistical validation test is summarized in Table 14.

Table 14. Validation results for independent data sets.

Stand variables	ME	AME	RME (%)	ARME (%)	Precision (%)
Mean DBH(cm)	-0.06	3.26	-0.11	8.52	97.01
Mean Height(m)	0.41	1.20	1.43	4.95	97.00
Number of trees per ha	-19.26	38.70	-3.61	7.82	95.39
Basal area(m2/ha)	-0.91	1.50	-1.48	8.05	95.72
Volume (m3/ha)	-19.20	21.00	-4.85	9.86	95.31

The results indicated that deviance measures were all fairly low, with relative mean error (RME) in predicted stand attributes less than ±5%. All kinds of stand variables except for mean height were overestimated with RME(%), ranging from - 0.11% to - 4.85%. The models for predicting mean DBH, mean height, and basal area growth were generally better fit for all kinds of forest types with lesser values of ME and AME than predicting equations for number of trees per hectare and stand volume. The estimated precision values of the stand characteristics for the validation data sets were all greater than 95%.

5. Application of the Growth and Yield models

The system of growth and yield models for the natural mixed forest in northeast China is consisted of

(1) Site Class Index (SCI) curves, Equation (3);
(2) Crown Competition Factor (CCF), equation (6);
(3) Mean DBH growth model, equation (7);
(4) Mean height - diameter curves, equation (8);
(5) Basal area growth model, equation (9);
(6) Yield prediction model, equation (10);
(7) CCF Prediction model, equation (13);
(8) Predicting equation of the number of trees per hectare (N), equation (14); and
(9) Stand mortality rate (Table 13).

Based on the forest resources data of Fenglin natural reserve in 1997, stand attributes of characteristics of each sub-compartment and every forest type in 1997 and 2005 were predicted by using the growth and yield models for uneven-aged mixed forest developed in this paper (Table 15).

The total volume increment is 250,000 m^3 during 1997 - 2005 with annual volume increment 31,250 m^3 in total and annual increment per hectare is 1.8m^3. For each kind of forest types except conifer-hardwood mixed forest, the relative mean error (RME) in predicted stocking was less than 2%. The accumulative mortality is 859,700 and 894,900 m^3 in 1997 and 2005, respectively. Annual mortality rate is 1.2% and the attributes, which can reflect the structure of forest stand, increased gradually such as stand age, DBH, height, basal area, and stand volume. It indicates that the structure and function of the forest ecosystem are steady and sustainable without the human activity in Fenglin Nature Reserve.

Table 15. The prediction of the stand attributes in Fenglin natural reserve for each forest type.

Forest types	Area (ha)	1997 Volume of standing tree (×1000 m^3)	RME* (%)	Volume of mortality (×1000 m^3)	2005 Volume of standing tree (×1000 m^3)	Volume of mortality (×1000 m^3)
Basswood-Korean pine Forest	513	175.2	1.33	16.0	184	16.6
Costata Birch-Korean pine Forest	3,591	1,172.1	-0.64	316.8	1,232.4	335.1
Spruce-fir-Korean pine Forest	5,104	1,651.1	-0.04	227.0	1,758.3	241.3
Spruce-Fir Forest	2,045	436.2	-1.65	61.4	459.4	65.9
Coniferous Mixed Forest	3,482	834.3	-0.29	159.7	860.9	165
Conifer-Hardwood Mixed Forest	1,345	200.0	9.28	60.5	218.6	52.1
Hardwood Forest	1,313	137.7	-0.67	18.4	142.6	19.2
Scots pine Plantation	5	0.6	0	0	1.0	0
Total	17,398	4,607.2	0.10	859.7	4,857.2	894.9

* Note : RME = (Vobs-Vpre)/V_{obs} × 100, Where : V_{obs} is inventory value in 1997 (Table 1) ; V_{pre} is model predicted value in 1997.

CONCLUSION

Accordingly Forest Resources Inventory System of national forest in China, the height of dominant or co-dominant trees for dominant species are not measured. Therefore, the Site Class Index (SCI) can be considered as a useful index instead of site index (SI) to evaluate site quality for natural forests. Crown Competition Factor (CCF) is useful index to reflect stand density for mixed natural forests. The results indicated that the CCF was closely associated with DBH, basal area and stand volume growth and it was independent of stand age and site quality (SCI).

The growth and yield models for the uneven-aged mixed forest were systematically developed in this paper. The Chapman-Richards function was adopted to develop SCI equation and height-diameter curve. The Schumacher growth function was selected as base model to develop the mean DBH, basal area, and stand volume growth models by using re-parameterized method. It was found that the asymptotic parameter A of Schumacher function in modeling mean DBH and basal area (BAS) growth was exponentially related to site quality (SCI) and stand density (CCF). The shape of DBH and BAS growth curves was determined by stand density and the rate parameter k in Schumacher's growth function was related to stand density (CCF) and it was independent of site quality (SCI).

Five kinds of validation measures for predicted stand variables were evaluated using independent data sets. The results of test indicated that relative mean error values in predicted stand attributes were less than ±5% and the estimated precision values of the stand variable were all greater than 95%. The future characteristics of natural forests or sub-compartments in northeast China can be predicted by using the growth and yield models constructed in this paper. The results of the study will provide the basis for constructing the planning of sustainable forest management in Fenlin Natural Reserve.

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