International Research Journal of Plant Science (ISSN: 2141-5447) Vol. 3(8) pp. 164-173, October 2012
Available online http://www.interesjournals.org/IRJPS

Full Length Research Paper

Development of tree growth prediction with gray model in an old – growth *Chamaecyparis obtusa* stand, in the Akazawa Forest Reserve

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Abstract

Akazawa Reserve Forest in kiso town is a precious forest for research of science and well protected all the time. Hinoki is the dominant tree species whose age about 300 years used to construct the palace in past mainly. In 1988 a plot of 4 hectares was established and the survey had been done periodically in the following 20 years. In this research, we used the collected data of the growth of tree individuals and the stand. Recently in Japan the long rotation management process of conifer plantation is being popular. The collected past and present dataset through this process plays a very important role for the future prediction of forest resource. With the gray theory of mathematics, this research developed a program of calculating tree growth by using the data of the stand surveyed in 1988, 1998, 2003 and 2008. By this program a prediction has been made for the growth of the tree stand in year 2018, 2028 and 2038 respectively. In the understory, the average forecast error of *Chamaecyparis obtusa* was 23.8% in 1998, 18.6% in 2003 and 11.9% in 2008. For *Thujopsis dolabrata*, it was 15.8% 13.6% and 9.7% respectively in the three years. And broad-leaved trees' error was 17.6%, 12.9% and 10.7% in 1998, 2003 and 2008. In middle layer, *Chamaecyparis obtusa*'s errors were 22.8%, 16.8% and 8.9% respectively, while they were 16.5%, 18.5% and 11.3% for *Thujopsis dolabrata*, and 14.9%, 11.9%, 8.7% for broad-leaved trees. In the dominant layer, they were 22.4%, 13.6%, 6.8% for *Chamaecyparis obtusa*, 9.8%, 13.5%, 17.9% for *Thujopsis dolabrata*, and 15.6%, 12.8%, 8.9% for broad-leaved trees in the specified years respectively.

Keywords: Akazawa Forest Reserve, gray theory, growth calculation, DBH.

INTRODUCTION

Forests offer many different kinds of services, for example: wood production, environment protection, provision of scenic beauty and recreation, and so on (Forest Agency, 2006). However, they are effected easily in short term by all kinds of human disturbances, including harvesting, over-harvesting and degradation, fire control, and also impacted evidently by many natural causes such as large-scale occurrence of wildfires, strong winds, pest and disease outbreaks, snow damage , and especially climate change of long term (Morisawa, 1999). Studies on the change of forest in the past are to understand its development in the future, then provide some commendation for forest management and improve its function. In recent years, how to predict growth of forest was paid more and more attention (FFPRI, 2012). But now it seems that traditional prediction methods cannot meet completely the need of modern forest with more emphasis on ecological protective function. Recently in Japan the long rotation management process of conifer plantation is being popular , and through predict growth of forest plays a very important role for the long rotation management process of conifer plantation.

Analysis on stand structure characteristics and reasonable forecast results were the important departments of forest management. The diameter at breast height (DBH) of tree describes the growth process of tree, and DBH has relationship with geographic factors and environmental factors (Minowa, 1995). So the

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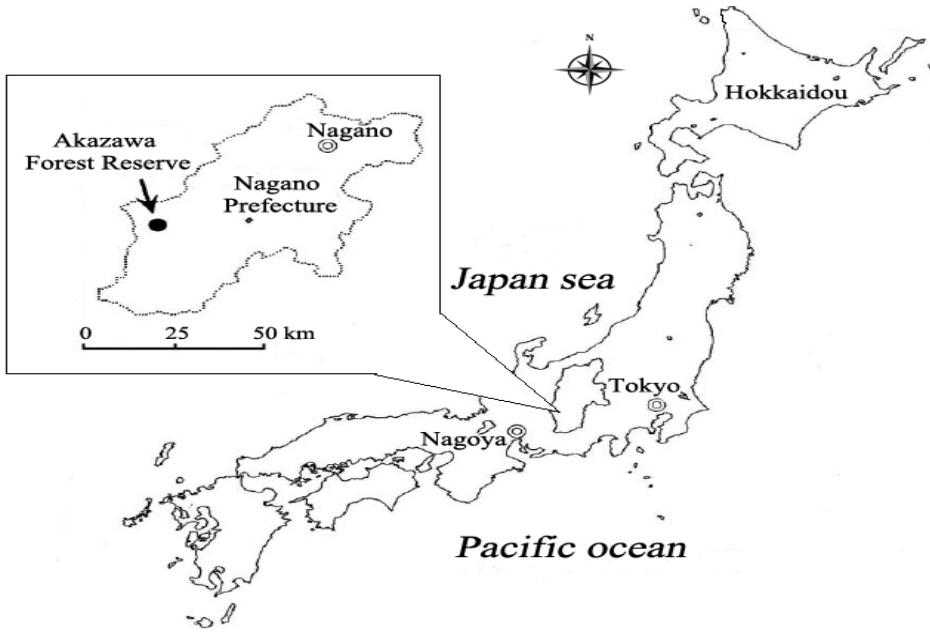

Figure.1 The location of Akazawa Forest Reserve

diameter at breast height (DBH) of tree, a basic and very important parameter in forest research, was essential for calculation of tree volume and describing forest structure. Even though a great of forest forecast systems had been developed (Ando, 1968; Kikukawa, 1981; Matumoto, 2005; Shiraishi, 2005), most of them couldn't predict DBH of tree individuals, and they needed environmental and geographical factors in forecasting growth of total stand. Grey theory, which defined grey derivative and differential equation with correlation analysis and smooth discrete function, needn't environment data and may resolve the above shortcomings in predicting forest growth (Deng, 1990).

Although collected data can be used to do some simple prediction by simple line regression, the objective of this study, based on the survey of tree DBH in the past 20 years, attempted to firstly develop a precise tool for forecasting DBH growth of tree individuals by mathematics. And then it was used to analyze the change law of forest structure and development process by every ten years. This paper might provide a new forecast theory and offer some recommendation for management of modern forest.

MATERIALS AND METHODS

Study Area and vegetation

Field survey was conducted in the Akasawa Forest Reserve with an area of about 1046 ha, Kiso town of Nagano Prefecture, central Japan (35°43'57"N, 137°37'50"E) (Figure 1), which was the birthplace of forest bathing and known as one of three most beautiful forests in Japan (NRFO, 1985). The altitude ranges from 1080 to 1558 m above sea level. Annual precipitation is about 2500 mm, and snow accumulation is 50~100 cm per year. The reserve is on an elevated peneplain with a gentle slope. The geology is dominated by acidic igneous rocks such as granitite, granitite porphyry, and rhyolite. Soils are mainly dry and wet podzolic soils, although brown forest soils appear on hillsides and along mountain streams (NRFO, 1985).

Chamaecyparis obtusa generally dominates the canopy layer within the reserve, with occasional associates of *Thujopsis dolabrata* and some hardwoods, while on lower slopes or along mountain streams, *Chamaecyparis pisifera* frequently occurs and dominates in some stands. Old-growth *Chamaecyparis obtusa* stands on this reserve, like other *Chamaecyparis obtusa* forests in the Kiso District, might have been established after the severe cutting during the years 1688-1703 (NRFO, 1985). Since that period most stands have been protected from clear-cutting, although selection cuttings have been made for purposes of forest management.

Plot measurements

In 1988, one permanent plot with size of 200 × 200 m was established in an old-growth *Chamaecyparis obtusa* stand with clear-cutting in 350 years ago and selective-cutting in 60 years ago. All of trees whose DBH was larger than 5 cm were surveyed, including species, DBH and height, crown size, clear bole height and coordinate in 1988, 1998, 2003 and 2008 (Hoshino et al.,2002; Hoshino et al., 2003; Yamamoto,1993). Additionally, trees of DBH≥ 5 cm had been confirmed as live or dead in 2009 and all of live trees were selected to predict tree growth in this study.

Analyses: Prediction theory

Grey theory developed by Julong Deng in 1982 is a subject of applied mathematics, which might be used to research the systems that include some known and also unknown information at same time (Deng, 1990). Both grey theory and regression analysis are major tools in the field of prediction. In this theory, the completely known information was defined as white system, and completely unknown information was defined as black system, while incomplete information was defined as grey system. And it defined grey derivative and differential equation with correlation analysis and smooth discrete function. A differential equation model called GM (Grey Model) would be established when the known data set met the principle convergence of relevance (Usuki and Kitaoka, 2001). For example, GM (1, N) is a 1-order differential equation based grew model, which had N variables and might be expressed by the formula as follows:

$$\frac{\mathbf{dX_1}}{\mathbf{dt}} + \mathbf{aX_1} = \mathbf{b_1X_2} + \mathbf{b_2X_3} + \ldots\ldots + \mathbf{b_{N\ 1}X_{\mathit{N}}} \qquad (1)$$

And when the number of known variable is one, the above model became GM (1, 1) and might be represented by the formula (2):

$$\frac{\mathbf{dX^{(1)}}}{\mathbf{dt}} + \mathbf{aX^{(1)}} = \mathbf{u} \qquad (2)$$

Calculation process

Tree growth was mainly decided by its gene and also influenced by a lot of factors such as site condition and climatic environment. However, it was difficult to express the information of tree's gene and effect of environment using numerical value directly. DBH, one of basic parameters of forest structure, might be measured accurately and used to reflect the interaction of all of impact factors. It is completely known information in forest system. Therefore, Grey Model can be used to predict growth of trees well without local environment information. In this study, DBH of trees in the stand surveyed in 1988, 1998, 2003 and 2008 was as the completely known information and GM (1, 1) was adopted to establish derivative equation to forecast the growth of every tree individual. For prediction, time series data with even-interval such as 5 or 10 years is necessary. Because of lacking the survey data in 1993, the average growth of every tree from 1988 to 2008 was used to assess its DBH in 1993. Then the time series data in 1988, 1993, 1998, 2003 and 2008 was used to establish one-order matrix by the formula as follows:

$$\mathrm{X}^{(m)}_{(n+5)} = \left\{\mathrm{X}^{(m)}_{(1988)}, \mathrm{X}^{(m)}_{(1993)}, \mathrm{X}^{(m)}_{(1998)}, \mathrm{X}^{(m)}_{(2003)}, \mathrm{X}^{(m)}_{(2008)}, \ldots\ldots \mathrm{X}^{(m)}_{(n)}\right\} \quad (3)$$

Where *X*(*m*)(*n*) is predictive value of tree DBH, *m* is tree No. marked in survey, and *n* is survey year. The differential equation of GM (1, 1) might be expresses as follows:

$$\hat{X}^{(m)}_{(k+1)} = (X^{(m)}_{(1)} \quad \frac{u}{a})e^{\quad ak} + \frac{u}{a} \qquad (4)$$

Where *a* is development parameter of the numerical sequence, *u* is the control parameter on *a*, and *e* is natural logarithm. The parameter *a* related with *u* as follows:

$$\hat{a} = [a, u] \qquad (5)$$

And $\hat{a}$ might be calculated by the formula

$$\hat{a} = (B^T B)^{\ 1} BY \qquad (6)$$

In the above equation, in order to explain the process of calculation easily, here Y was a code with no real meaning, and also for B. And BT is the transposed matrix of B. They might be expressed by the next matrixes as (7) to (9):

$$\mathbf{Y} = \begin{vmatrix} \mathbf{X^{(m)}_{(1993)}} \\ \mathbf{X^{(m)}_{(1998)}} \\ \mathbf{X^{(m)}_{(2003)}} \\ \mathbf{X^{(m)}_{(2008)}} \end{vmatrix} \qquad (7)$$

$$B = \begin{vmatrix} -\frac{(X^{(m)}_{(1988)} + X^{(m)}_{(1993)})}{2} & 1 \\ -\frac{(X^{(m)}_{(1993)} + X^{(m)}_{(1998)})}{2} & 1 \\ -\frac{X^{(m)}_{(1998)} + X^{(m)}_{(2003)}}{2} & 1 \\ -\frac{X^{(m)}_{(2003)} + X^{(m)}_{(2008)}}{2} & 1 \end{vmatrix} \qquad (8)$$

$$B^T = \begin{vmatrix} -\frac{(X^{(m)}_{(1988)} + X^{(m)}_{(1993)})}{2} & -\frac{(X^{(m)}_{(1993)} + X^{(m)}_{(1998)})}{2} & -\frac{(X^{(m)}_{(1998)} + X^{(m)}_{(2003)})}{2} & -\frac{(X^{(m)}_{(2003)} + X^{(m)}_{(2008)})}{2} \\ 1 & 1 & 1 & 1 \end{vmatrix} \qquad (9)$$

Finally, a program for the above calculation process was written by using the Visual Basic of Microsoft Corporation. By this program, the growths of tree individuals can be forecasted with every 5-year and we only have calculated the DBH of every tree in 2018, 2028 and 2038 in this study.

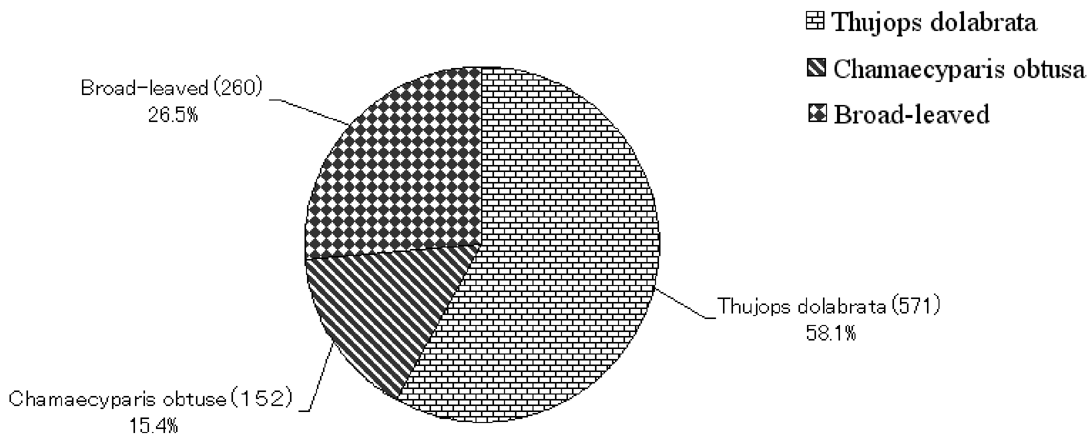

Figure 2. Stand Overview

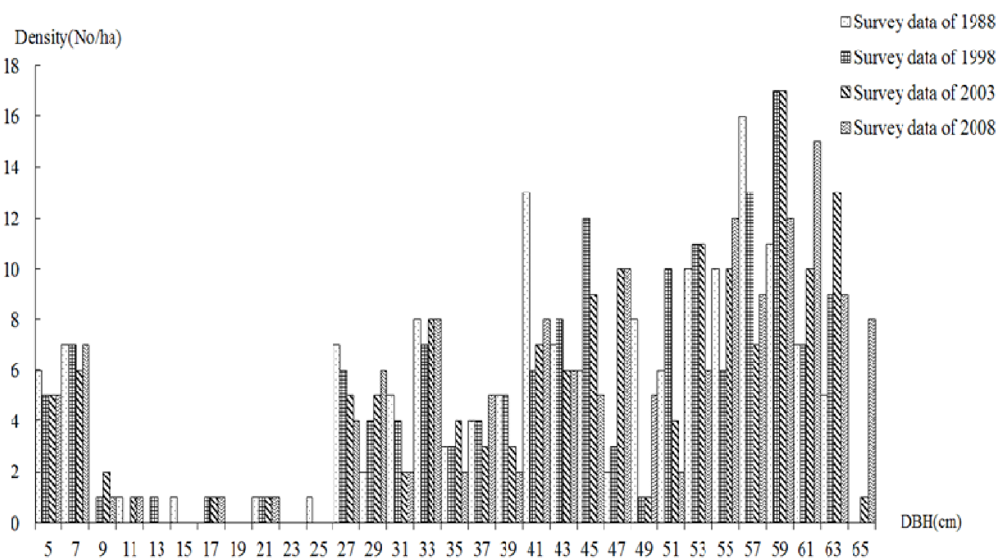

Figure 3. Survey data of changes in DBH distribution of *Chamaecyparis obtusa*

Prediction accuracy

Forecast error may be calculated by the formula:

$$\varphi = (X - M) / X \times 100 \quad (10)$$

φ is forecast error, X is survey data and M is calculated by grey program in same year.

RESULTS AND DISCUSSION

Basic characteristics of the forest

Total stem density of the stand in study area was 983 stems/ha in 2008. *Chamaecyparis obtusa* was 152 stems/ha, accounted for about 15.4%. *Thujopsis dolabrata* and broad-leaved trees were 571 stems/ha and 260 stems/ha respectively (Figure 2). From DBH structure, the stand was dominated by *Chamaecyparis obtusa* in DBH or basal area. But there were few regenerated trees of *Chamaecyparis obtusa* (Figure 3). On the other hand, *Thujopsis dolabrata* was absolutely dominant in density in the 20 years (Figure 4). And they were distributed in the under layer of forest together with broad-leaved trees (Figure 5). Additionally, in order to promote the recruitment of *Chamaecyparis obtusa*, most of *Thujopsis dolabrata* and broad-leaved tree individuals with large size were cut by clear-cutting in 350 years ago and by selective-cutting in 60 years ago.

Prediction for *Chamaecyparis obtusa*

The DBH distribution can be used to explain the change

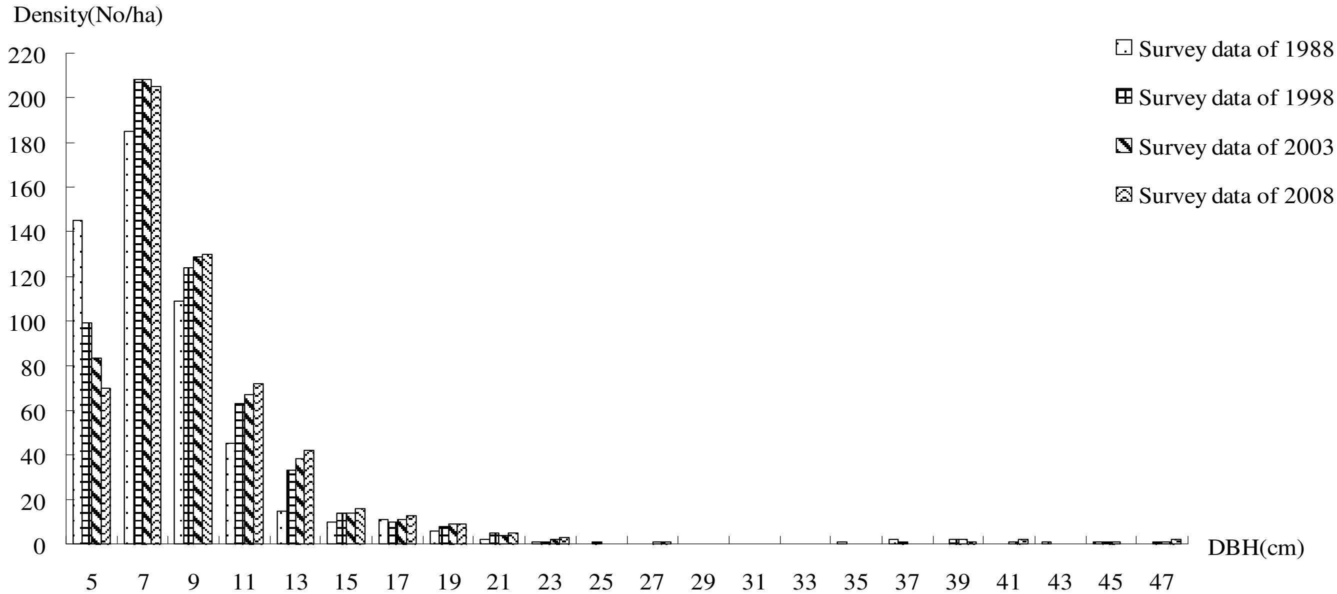

Figure 4. Survey data of changes in DBH distribution of *Thujopsis dolabrata*

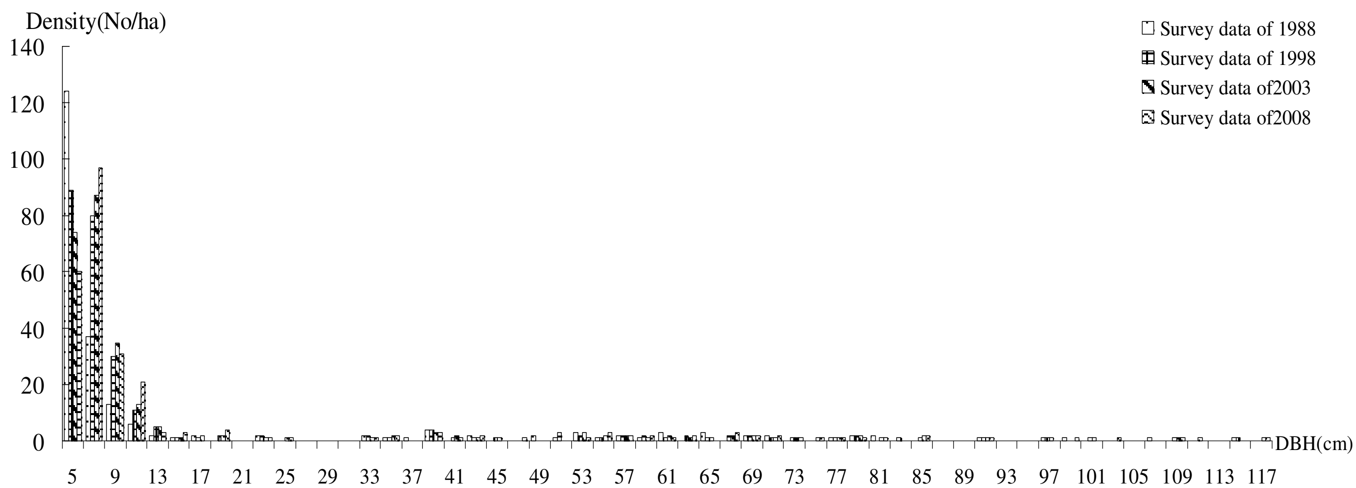

Figure 5. Survey data of changes in DBH distribution of *broad-leaved trees*

of forest dynamics. But finding the change of DBH distribution of old-growth forest needed much time and survey data. Using grey theory of mathematics, this research developed a program of calculating tree growth by using the data of the stand surveyed in year 1988, 1998, 2003, 2008 and the presumed data of 1993 by average growth method. By this program, the growth of every *Chamaecyparis obtusa* individual was predicted in 2018, 2028 and 2038 respectively (Figure 6). According to survey data, average DBH increment of *Chamaecyparis obtusa* was only 0.5-1.5 cm in every 5 years, the DBH distribution had no significant change. In order to improve forecast accuracy and grasp the changes of forest dynamics, the DBH of every tree was grouped by 2 cm intervals, and all of trees were classified as under layer, middle layer or dominant layer based on their DBH. In this study, the DBH range of understory layer was 5cm to 24cm, middle layer was 24cm to 58cm, and dominant layer was 58cm to 80cm.

Results of prediction indicated that the DBH distribution of *Chamaecyparis obtusa* ≤ 24cm had no obvious change except the classes from 5 cm to 10 cm in the next 30 years (Figure 6). This is because sufficient light is necessary for the growth of *Chamaecyparis obtusa*, but in understory of the stand, illuminance was no enough due to the closed canopy, which led to the slow growth of *Chamaecyparis obtusa* trees in understory. Another season is a frost disturbance in 1998 may be a large part

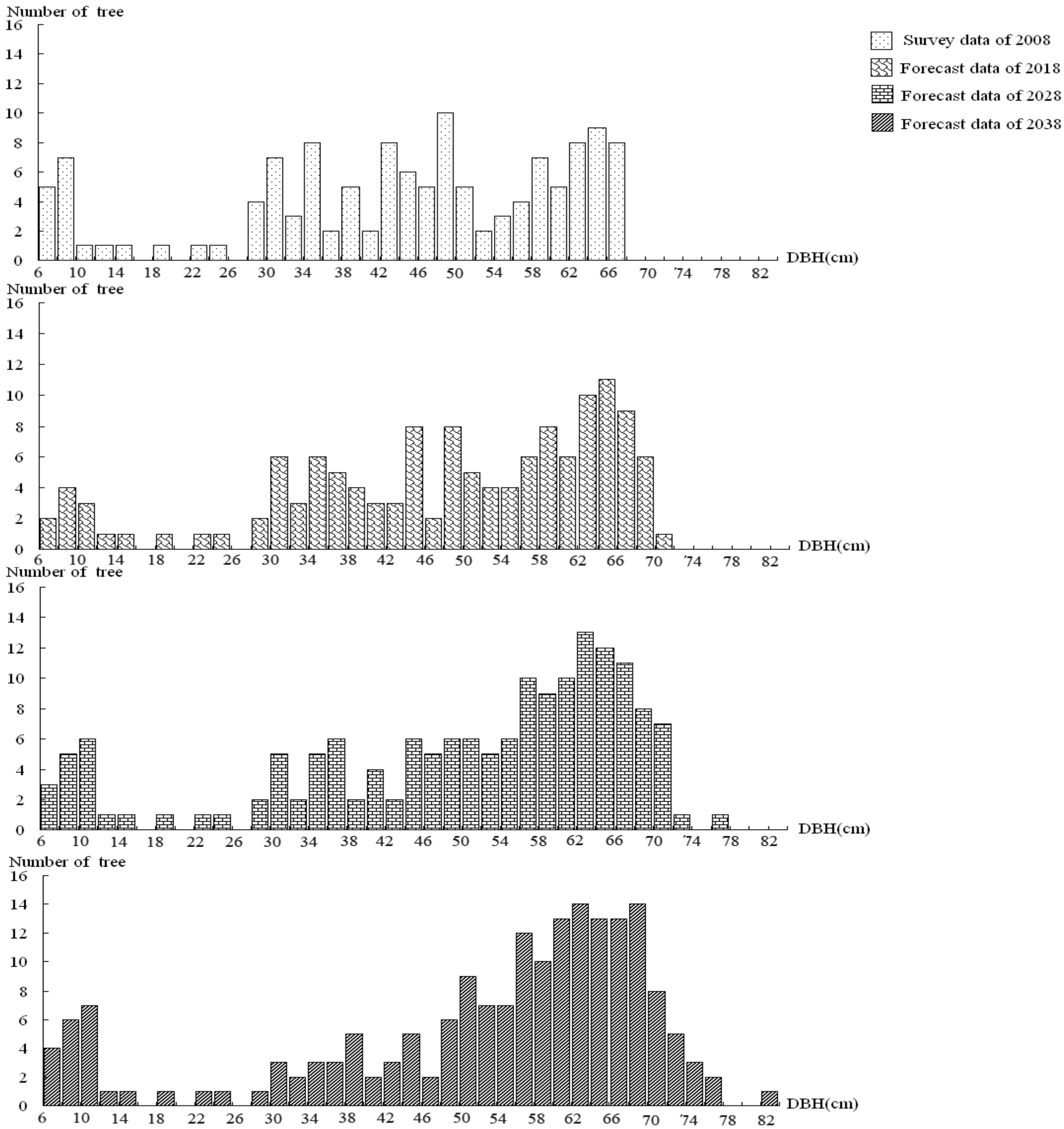

Figure 6. Forecast of changes in DBH distribution of *Chamaecyparis obtusa*

of a cause of mortality for stems in smaller size classes (Morisawa, 1999). In addition, a number of trees with DBH from 5 cm to 10 cm may increase markedly in the next 30 years, because these saplings mainly distributed in the canopy gaps between in big trees. The canopy gaps may provide good light environment for the growth of *Chamaecyparis obtusa*. Furthermore, the forest floor was cleaned up in the clear-cutting in 350 years ago and selective-cutting in 60 years ago, thence *Chamaecyparis obtusa* seed can germinate on the forest floor, and these saplings can regenerate well.

In middle layer of the forest, the number of *Chamaecyparis obtusa* trees from 36 cm to 42 cm may be decreases with time. However, the number of trees from 52 cm to 58 cm may be increases. This illustrated that the *Chamaecyparis obtusa* in middle layer would have good growth and be in advantage in the competition with other species, because most of big *Thujopsis dolabrata* and

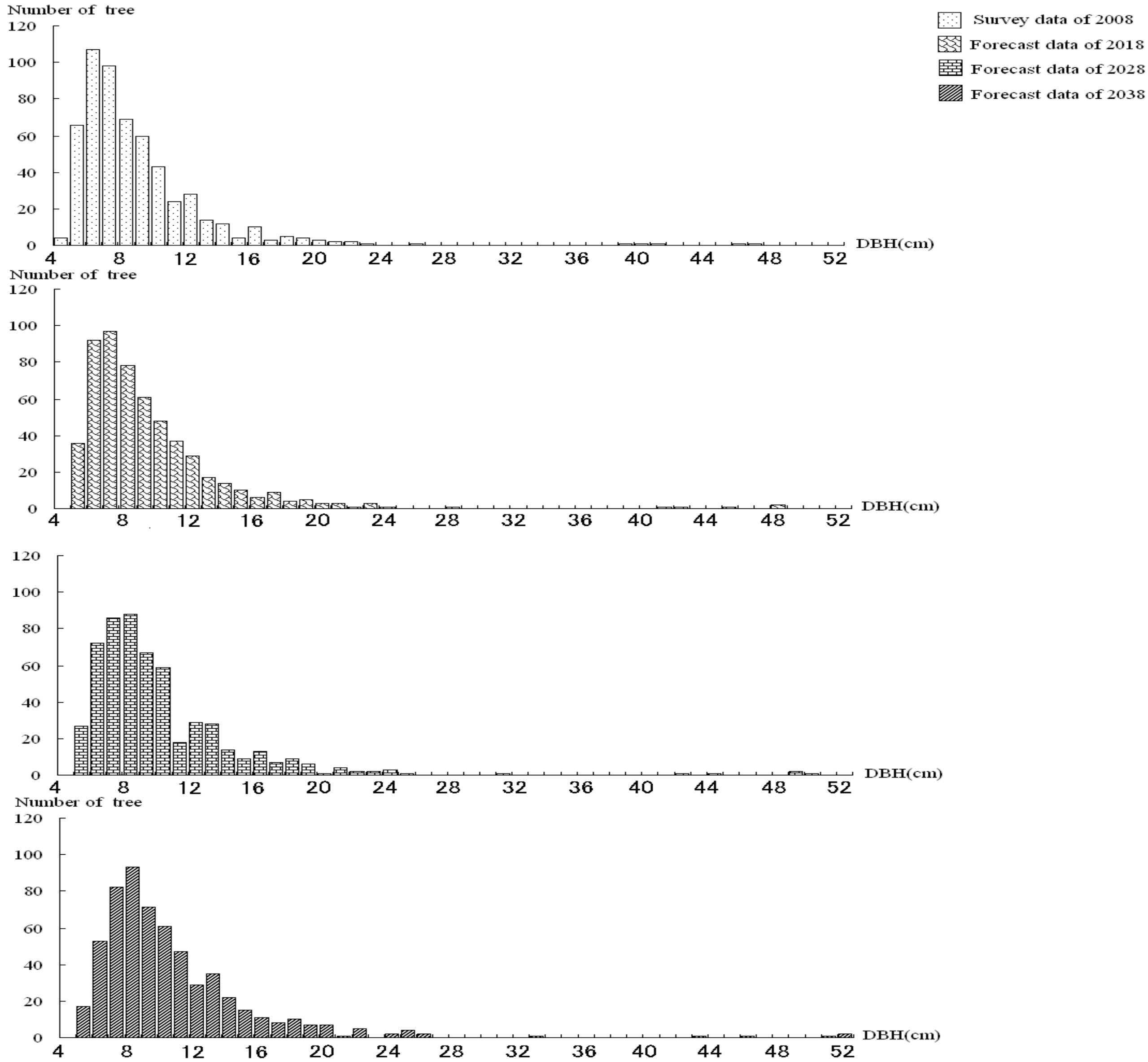

Figure 7. Forecast of changes in DBH distribution of *Thujopsis dolabrata*

Broad-leaved trees were cut in the selective-cutting of 60 years ago (Hoshino et al., 2002). In the dominant layer, the number of old-growth *Chamaecyparis obtusa* individuals would have no significant change. Even though some trees in middle layer will come into dominant layer, some old trees will die with natural succession and old-growth *Chamaecyparis obtusa* grow very slowly.

Prediction for *Thujopsis dolabrata*

In this study, the species of *Thujopsis dolabrata* with DBH from 5cm to 14cm was classified as under layer to middle layer from 14cm to 27cm, and middle layer to dominant layer from 27cm to 48cm. *Thujopsis dolabrata* was absent in the larger classes, but more trees occurred in the smaller classes. The DBH distribution of *Thujopsis dolabrata* was characterized by L-shape, the features of natural regeneration, which showed an inverse pattern with *Chamaecyparis obtusa* (Figure 7). Saplings of *Thujopsis dolabrata* predominated understory of the stand with a mixture of broad-leaved trees. Forecast result showed that in the future 30 years, the number of *Thujopsis dolabrata* individuals with DBH from 5cm to 8 cm would decrease with time, while the trees with DBH from 8cm to 14cm would be increased (Figure 8). Because of vigorous growth of understory plants, it indicated that intra-species competition between saplings

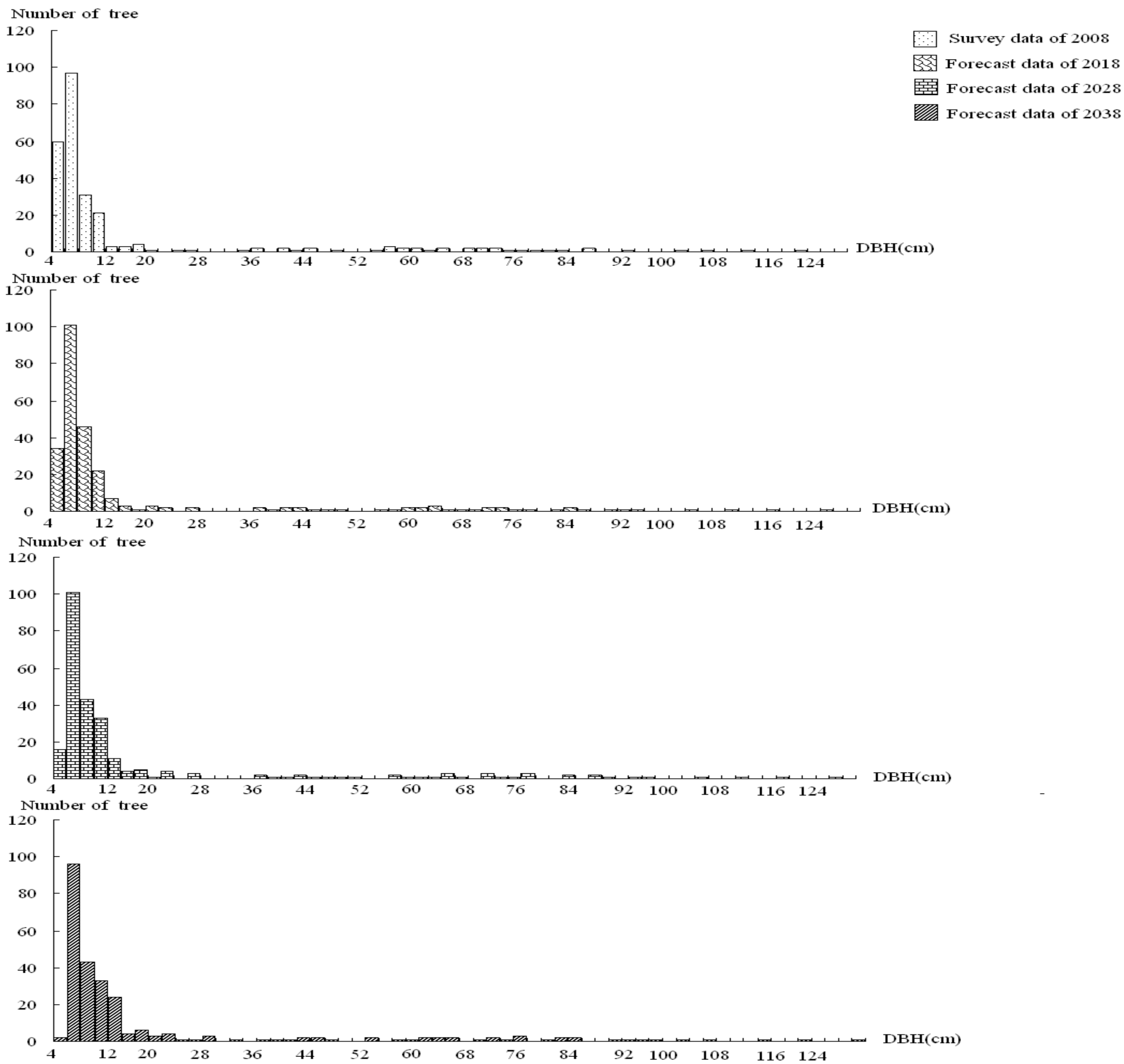

Figure 8. Forecast of changes in DBH distribution of broad-leaved trees

will become more and more severe and existing small trees will advance to higher-order DBH class with high-speed growth.

The trees in middle layer will be increased significantly with time, which mainly result from fast growth of the trees distributed in the understory now. Closed canopy formed by big *Chamaecyparis obtusa* and *Thujopsis dolabrata* provided a suitable environment for the growth of regenerated *Thujopsis dolabrata* trees. On the other hand, the total number of trees in the dominant layer will be not changed in the next 30 years, because of the lack of trees distributed in middle layer now.

Prediction for broad-leaved trees

All of broad-leaved trees were divided into three layers: under layer is the trees with DBH from 5cm to 14cm, middle layer is from 14cm to 34cm, and dominant layer is from 34cm to 82cm. most of broad-leaved trees are mainly in under layer with DBH≤12 cm (Figure 8). The DBH distribution is also characterized by L-shape,

Table 1. Prediction accuracy validation

Species	Year	Average prediction error (%)		
		Understory layer	Middle layer	Dominant layer
Chamaecyparis obtusa	1998	23.8	22.8	22.4
	2003	11.9	12.5	13.6
	2008	9.6	8.9	6.8
Thujops dolabrata	1998	25.8	23.5	23.5
	2003	13.6	14.9	13.8
	2008	9.7	11.3	10.9
broad-leaved	1998	26.7	25.6	23.9
	2003	12.9	13.2	15.6
	2008	10.7	8.7	8.9

showed the features of natural regeneration. Few broad-leaved trees with the DBH size over 54 cm survived in the plot because of the selective-cutting in 60 years ago According to the survey, the understory is characterized by a dense coverage of *Thujopsis dolabrata* and broad-leaved saplings, so the growth of small trees in understory was mainly effected by the competition between *Thujopsis dolabrata* and broad-leaved trees. In the understory layer, the number of broad-leaved trees with DBH ≤ 6 cm will be decreased evidently in the future 30 years. However, the trees with DBH from 6cm to 14cm will be increased. It indicated that inter-species competition between *Thujopsis dolabrata* and broad-leaved trees will become more and more severe and existing small broad-leaved trees will advance to higher-order DBH class with fast growth. In middle layer, the broad-leaved trees with DBH from 14 cm to 20 cm will be increased with time, which mainly derived from the increase of trees in the understory. Additionally, the total number of trees in the dominant layer will be not changed in the next 30 years, because there are few trees distributed in middle layer growing into big individuals now.

Prediction accuracy

In the understory, the average forecast error of *Chamaecyparis obtusa* was 23.8% in 1998, 18.6% in 2003 and 11.9% in 2008. For *Thujopsis dolabrata*, it was 15.8% 13.6% and 9.7% respectively in the three years. And broad-leaved trees' error was 17.6%, 12.9% and 10.7% in 1998, 2003 and 2008. In middle layer, *Chamaecyparis obtusa*'s errors were 22.8%, 16.8% and 8.9% respectively, while they were 16.5%, 18.5% and 11.3% for *Thujopsis dolabrata*, and 14.9%, 11.9%, 8.7% for broad-leaved trees. In the dominant layer, they were 22.4%, 13.6%, 6.8% for *Chamaecyparis obtusa*, 9.8%, 13.5%, 17.9% for *Thujopsis dolabrata*, and 15.6%, 12.8%, 8.9% for broad-leaved trees in the three years respectively (Table 1). From the total stand, forecast error was highest in 1998, because snow and ice damage occurred in that time. Additionally, results of forecast indicated that prediction accuracy increased with the increment of DBH, because anti-interference ability of dominant trees is higher than the trees in middle layer and saplings when natural disturbance occurred.

CONCLUSION

In the 20 years, *Chamaecyparis obtusa* dominated canopy layer and *Thujopsis dolabrata* generally dominated understory and middle layer in the plot of this old-growth forest. However, the demographic parameters showed that *Chamaecyparis obtusa* is the least species. *Chamaecyparis obtusa* dominant species in the canopy layer has resulted in the dark forest floor environment except some places of canopy gap. The low light environment of forest floor may lead to the regeneration barriers of *Chamaecyparis obtusa*. Therefore, this species will decrease in importance in the canopy layer and will decline in the proportion of tree number in the future, although its bimodal DBH indicates presence of relatively abundant small or young stems. *Chamaecyparis obtusa* Saplings did not grow in the place around *Thujopsis dolabrata*, but some saplings were found in canopy gaps together with small broad-leaved trees. On the other hand, we can found that abundant young stems of *Thujopsis dolabrata* in understory and middle layer of the plot, which had very few canopy stems, probably due to its high shade tolerance and vegetative reproduction. It also indicates that such environment is appropriate for *Thujopsis dolabrata*'s growth, and it will increase in the canopy layer. Furthermore, a lot of *Thujopsis dolabrata* saplings will appear around *Chamaecyparis obtusa* saplings in the future, suggesting *Thujopsis dolabrata* will interfere with the growth of young *Chamaecyparis obtusa* and its natural regeneration will become more and more difficult. However, the forest will be dominated by *Chamaecyparis obtusa* in the canopy layer at long term if no major disturbance. But, if no some measurement for promoting regeneration of *Chamaecyparis obtusa* saplings in the canopy layer of this forest, *Chamaecyparis obtusa* will become less important and the more shade-tolerant species, *Thujopsis dolabrata,* will become more important(Hoshino et al., 2003), and the forest will be dominated by *Thujopsis dolabrata* finally after senescence and wilt of old-growth *Chamaecyparis obtusa*. This prediction is maintained from the results of this study. Accidental factors cause a decline in forecast accuracy, such as disaster, plant diseases and insect pests. Because gray theory cannot take into accidental factors. But the disturbance of accidental factors decrease the long forecast period. Therefore, gray theory is suitable for Long-term forecasts of forest growth.

ACKNOWLEDGEMENTS

Firstly, we gratefully acknowledge some students of Nagoya University and all the staffs of Forest Measurement and Planning Laboratory for their support in the field and plot survey. We would like to thank Mr. S.Q. Deng and S.K. Wang for their advices on the research. We also thank Mr. M.ABDULLAH AL FARUQ for his revision on the paper. Finally we acknowledge helpful comments of anonymous reviewers and editor.

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