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論　説

Growth model of forests as a basis for climate change mitigation and nature-based solutions: Tentative estimation of a Japanese cider forest's growth model in Ehime

Noriko IRIE（Environmental Design）
Kumiko TAKESHIMA（Regional Resource Management）
Naoko KAWAHARA（Kindai University）

入　江　賀　子（環境デザイン学科）
竹　島　久美子（地域資源マネジメント学科）
川　原　尚　子（近畿大学経営学部）

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Abstract

Information on forest growth is important for the sustainable use of forests and maximising their value, such as by increasing carbon fixation. This study aims to tentatively estimate a growth model for forests using data on Japanese cedar forests in Ehime Prefecture by reviewing previous studies on how to estimate and use a growth model for forests.

要旨

森林の持続的な活用や炭素固定量を増やすなど、森林の価値を最大限発揮させるような利用のために重要となるのは、森林の成長量に関する情報である。本研究では、愛媛県のスギの林分データから、林分の成長モデルをいかに推定するのか、当該モデルをいかに利用するのかについて先行研究をレビューしつつ、林分の成長モデルを仮推定することを目的とする。

1. Importance of estimating forest growth models

In recent years, forest management plans have been developed to increase the overall value of forests. This value is not limited to only the wood supply for housing and wood products but also includes the use of forest biomass as an energy source and a sink for carbon dioxide (CO_2) to aid in decarbonisation. Moreover, the importance of forest ecosystem conservation measures as 'nature-based solutions' (IUCN, 2023) to so-called environmental and social challenges such as disaster resilience is also emphasised. For the sustainable and environmentally sound use of forests, it is necessary to know the exact rate of forest growth in terms age. This is because, for example, differences in thinning timing, thinning location, and thinning intensity may result in different growth rates, which are related to carbon fixation, degree of ecosystem conservation, and other factors. Therefore, a model that can predict forest growth is required to optimise forest use.

However, in numerous cases, the forest growth models have not yet been updated. This study aims to tentatively estimate a growth model for the forest based on Japanese cedar forest data in the Ehime Prefecture, referring to Yoshimoto et al. (2012), while reviewing the literature on how to update the growth model and use it for forest management.

2. Forest growth data and existing models

Data on forest growth have traditionally included forest registers, forest yield tables, and stand density management diagrams, which were prepared for each prefecture and other entities. A stand density management diagram is a model used to describe forest growth (Ando, 1966). This model is based on height (tree height), average volume (volume), and the decreasing curve of the number of trees that die because of natural decay over time (Ando, 1966; Yoshimoto et al., 2012).

This study estimates a forest growth model by adding the concept of time to the model (Yoshimoto et al., 2012). This study uses data from Toyota's (2013) real forest yield table for Japanese cedar previously measured and estimated in Ehime Prefecture forests (Table 1) and parameters from the stand density management diagram at Shikoku (Table 2). Because the parameters of the stand density management diagram were studied from 1978 to 1988, this study updated the information on these parameters.

The structure of the stand density management diagram is as follows (Yoshimoto et al., 2012). The coefficients are determined based on region and tree species; p_1–p_{12} are the parameters. Given the number of timber trees per hectare (number of standing trees) N and the height H, the average volume per tree $v\,(N,\,H)$ is given by Equation (1.1):

$$v\,(N,H) = \frac{1}{p_1\,N\,H^{p_2} + p_3\,H^{p_4}} \tag{1.1}$$

By multiplying (1.1) by N, the number of standing trees yields Equation (1.2) for the lumber volume per hectare.

$$V\,(N,H) = v\,(N,H)\,N \tag{1.2}$$

The number of standing trees and the height of the trees are used to calculate the value in Equation (1.3), which is the forest-shaped height.

$$HF(N,H) = p_5 - p_6\,H\,\frac{\sqrt{N}}{100} + p_7\,H \tag{1.3}$$

Assuming a cylinder with this forest-shaped height as its height and considering the lumber volume per hectare as the volume of the cylinder, the cross- sectional area per hectare can be calculated using Equation (1.4).

$$G(N,H) = \frac{v\,(N,H)}{HF\,(N,H)} \tag{1.4}$$

Furthermore, using Equation (1.4) and N, the average diameter of the cross-sectional area per tree can be obtained as in Equation (1.5).

$$Dg(N,H) = 200\sqrt{\frac{G\,(N,H)}{\pi\,N}} \tag{1.5}$$

The average diameter of the cross-sectional area is then adjusted by N and H to obtain the average breast height diameter per tree as in Equation (1.6).

$$DBH(N,H) = -p_8 - p_9\,H\,\frac{\sqrt{N}}{100} + p_{10}\,Dg(N,H) \tag{1.6}$$

Although not estimated in the present study, the relationship between N and the number of trees N_0 at the time of planting is calculated using the natural mortality line as in Equation (1.7).

$$\frac{1}{N} = \frac{1}{N_0} + \frac{v\,(N,H)}{p_{11}\,10^6\,N_0{}^{-p_{12}}} \tag{1.7}$$

3. Methodologies

The estimation methodology in this study followed that of Yoshimoto et al. (2012). The estimation flow is as follows: first, a height growth model was estimated; then, based on the estimated height and number of trees, the estimated values using the stand density management diagram were compared with the values in the forest yield table, and the parameters of the height growth model and stand density management diagram were re-estimated to best fit the measured data. The tree height growth model was estimated using the Chapman–Richards Equation (1.8) as a trial. All the parameters were exponentially transformed such that they were expected to be positive.

$$\mu\,(t;\,\Theta) = \exp\,(\alpha)\left(1 - e^{-\exp\,(\beta)t}\right)^{\exp\,(\gamma)} \tag{1.8}$$

First, the parameters (α, β, γ) of the height growth curve in Equation (1.8) were estimated by minimising the sum of residual squares. Using the estimated parameters and the parameters of the stand density management diagram as initial values, a tentative parameter $\tilde{\Theta}$ that minimises the sum of residual squares as shown in (1.9) was obtained. From this, the covariance matrix of the residuals was estimated using (1.10), and the generalised least square estimator (GLSE) $\hat{\boldsymbol{\Theta}}$ that minimises the weighted residual sum of squares was estimated as shown in (1.11).

$$\tilde{\boldsymbol{\Theta}} = \arg \min_{\Theta} \sum_{i=1}^{n} (\boldsymbol{y_i} - \mu_i(\boldsymbol{\Theta})' \ (\boldsymbol{y_i} - \mu_i(\boldsymbol{\Theta})) \quad (1.9)$$

$$\tilde{\boldsymbol{\Sigma}} = \frac{1}{n} \sum_{i=1}^{n} (\boldsymbol{y_i} - \mu_i\left(\tilde{\boldsymbol{\Theta}}\right)' \ (\boldsymbol{y_i} - \mu_i(\tilde{\boldsymbol{\Theta}})) \quad (1.10)$$

$$\hat{\boldsymbol{\Theta}} = \arg \min_{\Theta} \sum_{i=1}^{n} (\boldsymbol{y_i} - \mu_i(\boldsymbol{\Theta})' \ \tilde{\boldsymbol{\Sigma}}^{-1} (\boldsymbol{y_i} - \mu_i(\boldsymbol{\Theta})) \quad (1.11)$$

4. Estimation results and discussion

Figure 1 shows graphs of the fitted and original data (in the forest yield table) of the estimated growth model. The thin circles represent the original data, and the dotted lines represent the estimated values. The latter reflects the original data very well.

This study tentatively estimated the parameters of the growth model and the stand density management diagrams of the ‘Shikoku National Forest Cedar’ created in the years 1978–1988, based on the data of the forest yield table of ciders with the site as type ‘1/5’ in Ehime Prefecture by Toyota (2013). The parameters can be estimated with the data of ciders with the site as type ‘2/5’ to ‘5/5’ in the same way. Although the tentatively estimated parameter values must be confirmed in the future, this method enabled us to re-estimate the parameters of the growth model and stand density management diagrams.

The real forest yield table in Toyota (2013) was created based on 334 stand structures of Japanese cedar forests in Ehime Prefecture, rejecting outliers. Because the data in question are for Ehime Prefecture as a whole, if data in specific municipalities are collected in the same way and parameters are estimated, the tailor-made parameters in those specific areas can be estimated. For example, it is possible to use Bayesian statistics to re-estimate the posterior distribution of parameters by adding new data, using currently estimated parameters as prior information (Yoshimoto et al., 2012).

Such growth model updates could lead to uses that increase the overall forest value. For example, by updating the growth model for a given forest area in a given region, the amount of carbon that can be fixed from the forests in that area can be estimated more accurately. If the growth models of different forest areas can be compared, it will be possible to explore the factors that influence the growth of forest areas, such as thinning practices and other socio-environmental factors, which will be useful in formulating future management policies. Furthermore, dynamic planning models can be created based on growth models (Yoshimoto, 2003).

Although this study examined a useful model for forest unit management, future studies should examine optimal management methods for forest parcels or multiple forest units with additional constraints, such as conservation sites (Konoshima and Yoshimoto, 2013). Forest management for nature-based solutions is also an interesting topic. For example, it would be meaningful to study the optimisation of forest conditions (number of trees, height, breast height, diameter, etc.) as well as forest-level optimisation by considering spatial information such as adjacency and slope for disaster management (Yohimoto, personal communication, 1 July 2023).

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Tables and Figures

Table 1. Real forest yield: Japanese cedar site as type ‘1/5’

Adjustment in October 2009

Site index	forest age	Height of upper tier trees	Average tree height	Average diameter	Number of trees	Total cross-sectional area	Total trunk volume	Current annual increment	Average increment
24.60	5	12.1	10.2	12.1	2,863	34.27	215.6		43.1
24.60	10	14.3	12.5	15.5	1,946	38.09	267.0	10.3	26.7
24.60	15	16.3	14.5	18.8	1,437	41.39	315.8	9.8	21.1
24.60	20	18.2	16.5	21.9	1,124	44.27	361.9	9.2	18.1
24.60	25	20.0	18.3	25.0	916	46.82	405.3	8.7	16.2
24.60	30	21.6	19.9	27.9	770	49.10	446.2	8.2	14.9
24.60	35	23.2	21.5	30.7	663	51.14	484.7	7.7	13.8
24.60	40	24.6	23.0	33.3	582	52.99	520.8	7.2	13.0
24.60	45	25.9	24.3	35.9	520	54.67	554.7	6.8	12.3
24.60	50	27.2	25.6	38.2	470	56.20	586.5	6.4	11.7
24.60	55	28.4	26.8	40.5	430	57.59	616.3	6.0	11.2
24.60	60	29.5	27.9	42.6	397	58.87	644.2	5.6	10.7
24.60	65	30.5	29.0	44.6	369	60.04	670.4	5.2	10.3
24.60	70	31.4	29.9	46.5	346	61.11	694.9	4.9	9.9
24.60	75	32.3	30.8	48.2	326	62.10	717.8	4.6	9.6
24.60	80	33.1	31.7	49.9	309	63.01	739.2	4.3	9.2
24.60	85	33.9	32.5	51.4	295	63.85	759.3	4.0	8.9
24.60	90	34.6	33.2	52.9	282	64.62	778.0	3.8	8.6
24.60	95	35.3	33.9	54.3	271	65.34	795.6	3.5	8.4
24.60	100	35.9	34.5	55.6	261	66.00	812.0	3.3	8.1

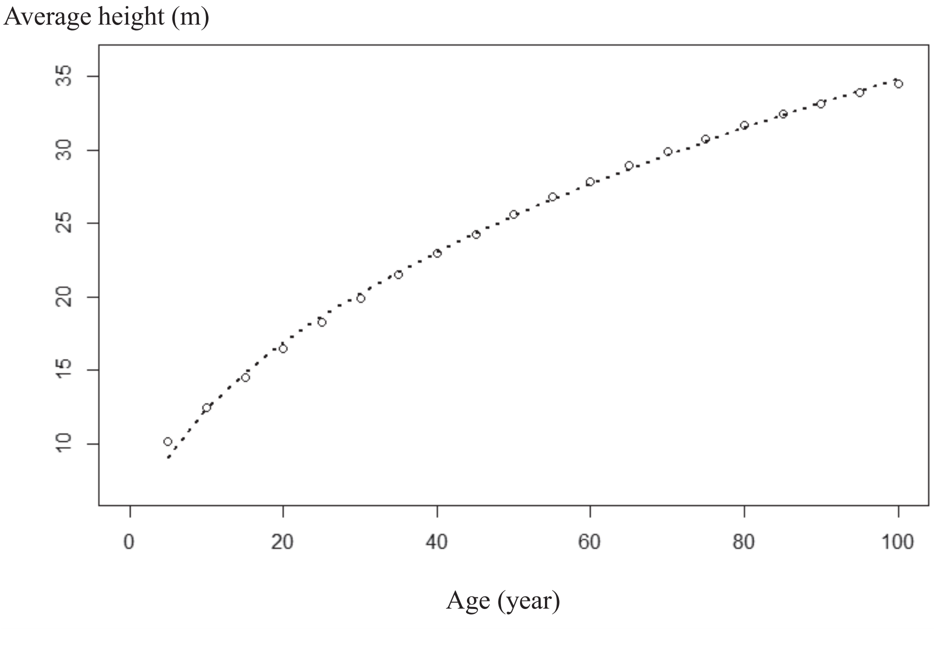
Reference Toyota (2013:31). Appendix 9. Yield table for a real forest area (Japanese cedar 1).

Table 2. Parameters of the stand density management diagram of ciders in national forests in Shikoku.

Formula	Parameter	Parameter Value	Formula	Parameter	Parameter Value
Trunk lumber volume per tree Formula (1.1)	1	0.0805	Average diameter of chest height Formula (1.6)	8	0.2529
	2	1.4295		9	0.0000
	3	5644.2		10	0.9813
	4	2.9858			
Shape height of a forest division Formula (1.3)	5	2.1726			
	6	0.1453			
	7	0.3004			

Forest Research and Management Organization (2023); Yoshimoto et al. (2012).

Note: Parameter values of the national cider forests in Shikoku from the Forest Research and Management Organization (2023) were used.



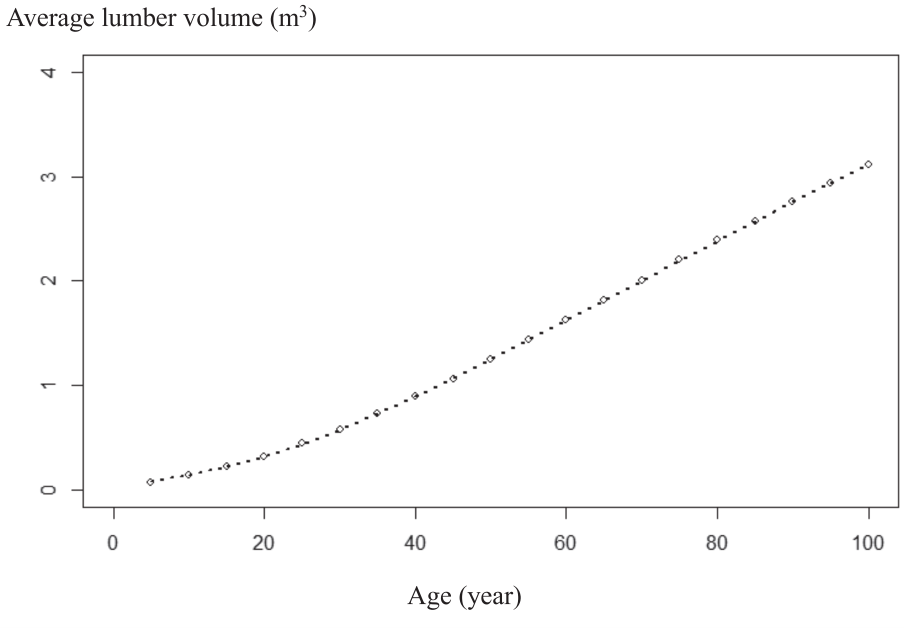


Figure 1. Graphs of fitted and original data (tree height, diameter at breast height, and lumber volume). Circles indicate original data and dotted lines indicate estimated values.