BIOMASS ESTIMATION BY COUPLING LIDAR DATA WITH FOREST GROWTH MODEL IN CONIFER PLANTATION

Hitoshi Taguchi†, **Takahiro Endo**† **and Yoshifumi Yasuoka**†
Institute of Industrial Science, The University of Tokyo,
4-6-1 Komaba, Meguro-ku, Tokyo, 153-8505 Japan
Tel: +81-3-5452-6415, Fax: +81-3-5452-6410
E-mail:tagchan@iis.u-tokyo.ac.jp

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ABSTRACT: Recent studies have shown the potential of remote sensing data at optical wavelengths to provide spatially referenced input data for process-based ecosystem models. Airborne Light Detection and Ranging (LiDAR) data have great possibility to provide the stand development of forest and spatially referenced input data for the models. The aim of this study is to coupling airborne LiDAR data with a process-based forest growth model. In this study, 3-PG (Physiological Principles to Predict Growth) which is one of the simplest forest growth models is used. The model requires few parameter values and only readily available input data. Species specific parameters for the model are specified by field measured data and literatures. Stand forest parameters such as tree height, population and biomass are estimated by LiDAR data and a tree size distribution function. The fit between simulated and the stand parameters derived by LiDAR data is improved by calibrating parameter values. The coupling method is applied in Japanese cedar (Sugi) plantation. The estimations are corresponded with field measured data and yield table. It is concluded that coupling LiDAR data with the process-based forest growth model can estimate the forest growth and productivity. This coupling method focused in this study can play an important role in improving the estimating above-ground biomass and forest productivity.

1 INTRODUCTION

There is increasing demand for precise estimates of forest biomass, potential productivity and forest growth, with the aim of understanding of interactions between forests and the atmosphere. Process-based ecosystem models are applied to simulate forest productivity at local to global scales. Recent studies have shown the potential of remote sensing data at optical wavelengths, such as leaf area index (LAI) and land cover, to provide spatially referenced input data for the models. Coupling optical remote sensing data with the models provides estimates of forest productivity (Running et al. 2004). A specific challenge is to develop methods for applying other land surface characteristics derived by remote sensing data to process-based ecosystem models over large areas (Turner et al. 2004). Airborne Light Detection and Ranging (LiDAR) data can estimate useful information for stand forest development, such as tree height, stem populations and biomass. LiDAR data have great possibility to provide spatially referenced input data to process-based ecosystem models.

Landsberg and Waring (1997) developed a simple process-based forest growth model called 3-PG (Physiological Principles to Predict Growth) based on a number of established biophysical relationships and constrains. The model generates a number of growth parameters which are directly measurable. The 3-PG has demonstrated the potential to provide forest growth estimation, and has been applied to wide range of forest species (Landsberg et al. 2003). Using forest stand growth parameters derived by LiDAR data, the 3-PG has the great possibility to estimate the biomass and productivity precisely and spatially. The aim of this study is to coupling airborne LiDAR data with the process-based forest growth model in Japanese cedar Sugi(Cryptomeria japonica D. Don) plantation.

2 MATERIALS ANS METHODS

2.1 The 3-PG model

The 3-PG is a monthly time-step process-based forest growth model (Landsberg and Waring, 1997). The model requires as inputs initial stand data (stem populations and stem, foliage, and root biomasses), soil data and climate data for the sites. A number of the species-specific parameters needed are generic (e.g., stomatal response and vapor pressure deficit), readily estimated from general knowledge of the ecology of the under study (e.g temperature limits and optimum), or readily available literature. After each interval, the model provides a range of outputs which include stem, root, and foliage biomass; available soil water; stand transpiration; leaf area index (LAI); stem diameter at breast height (DBH). For this study we focus on stem biomass and stem populations, which can be estimated by LiDAR data. The model estimates gross primary production (GPP) based on the monthly absorbed photosynthetically active radiation (APAR) times a theoretical maximum canopy quantum efficiency reduced by physiological (age, vapor pressure deficit or soil water) or environment modifiers (temperature, soil fertility and frost). Soil fertility is expressed as simple rating factor (FR). APAR is calculated based on the Beer-Lambert law, and LAI is calculated from the foliage biomass and specific leaf area (SLA). Net primary production (NPP) is calculated as GPP times a NPP:GPP ratio to account for respiration. Allocation of NPP to below-ground biomass is inversely proportional to the harshness of the environment and soil fertility, within maximum and minimum allocation limits defined for the species. Allocation of NPP to above-ground biomass is based on allometric equations describing foliage and stem mass in terms of DBH. The ratio of foliage to stem allocation declines as DBH increases. The establishment of this ratio can be based on species- and site- specific foliage and stem biomass allometrics and is represented in 3-PG by two partitioning parameters. For this study, we coded the 3-PG model in C-language.

2.2 Study area

The study area ”Shichinohe” which is located in the northern part of Japan (E141°5’, N40°6’) is Japanese cedar plantation owned by a paper company. There are 40 plots. Most areas are planted in 1961, and two plots are planted in 1987. Altitude varies from 100 to 300 m. The study area is plateau topography and falling off into incised valley. Main soil texture is clay. Mean daily maximum and minimum temperature for August are 26.4 C° and 17.4 C°, and for January are -0.1 C° and -6.3 C°. Mean monthly rainfall is the range of 97.5 mm and 234.8 mm. Solar radiation of June and December is respectively 18.1 MJm^{-2} and 4.5 MJm^{-2}. These climate data are extracted from gridded climate data (Japan Meteorological Agency, 2002). These climate data are used for the simulation.

2.3 Field measurements

Field measurements were conducted in summer of 2004. The DGPS (GPS Pathfinder Pro/XR by Trimble Inc) was used for specifying a reference point. From the reference point, the laser range finder (LaserAce300 by MDL Inc) determined tree positions, DBH and tree height (H) in 4 plots. Using the field measurement, the allometric equation between DBH and stem biomass is derived (equation 1).

$$Stem\,biomass = 0.019 * DBH^{2.96} \quad (R^2 = 0.991) \tag{1}$$

The relation between field measured tree height (H) and DBH is estimated (equation 2). The equation is used for estimating DBH from tree height (H) estimated by LiDAR.

$$DBH = 6.55 * e^{0.065*H} \quad (R^2 = 0.909) \tag{2}$$

2.4 The estimation of stem biomass and populations by LiDAR data and the tree size distribution function

The tree height and stem populations are estimated using small-footprint LiDAR data. The data were acquired with the ALS50 by Leica Geosystem on 11 and 12 August 2004. The flight altitude was approximately 1829 m (average) and its speed was 110 kt (average). The overall pulse rate was 46 kHz. The digital elevation model (DEM) was generated by a semi-automatic filtering technique.

A method of detecting model-based individual conifer tree crown (Taguchi et al. in review) is used. The method uses the model-based conifer crown which has a solid geometry form, and the model-based crown can be expressed by a geometric equation which is the function of crown radius, crown height, crown curvature and 3-dimentional tree top position. To estimate crown parameters at each tree, LiDAR point clouds which represent the tree crown shape are extracted. Then, the tree crown parameters are estimated by hill-climbing method. Finally, tree crown parameters, tree height and stem populations are estimated. Previous studies show the underestimation of tree height because the tree crown top is not hit by LiDAR pulse. In this method, the hill-climbing method searches best fit crown parameters. Therefore the estimated tree top elevation is higher than pulse based tree top elevation. The underestimation is reduced with almost 1 m (Taguchi et al. in review).

In crown closed forest plot, detected stem populations and biomass are underestimated due to the existence of suppressed trees. However, it is possible to reduce the underestimation by a theoretical distribution function. In this study, the MNY method which uses beta-type distribution (Hozumi 1971) is applied to canopy-closed plot. Using the method, total stem populations and biomass are estimated.

2.5 The 3-PG calibration and simulation

Parameter values required for the 3-PG model are established (Table 1). Canopy quantum efficiency is assumed 0.05 molC/molPAR for conifer (Landsberg et al. 2003). Temperature modifier with T_{min} = -2 C°, T_{opt} = 20 C°, T_{max} = 40 C° is used (Landsberg et al. 2003). The default SLA value of 3.5 (Landsberg et al. 2003) is used as constant value. Litterfall rate in the 3-PG is assumed to be at a constant value through one year. Generally, the conifer leaf life is 3 years (Tadaki 1976). For this reason, the litterfall rate with 0.0275 per month is used. The conductance parameters with default values are used. We assumed that the stands did not reach effective canopy closure until 15 years. Average root turn over rate is used default value with 0.015 per month.

Before applying the model at each plot, parameters of allocation to stems and foliage, pFS2 and pFS20, are parameterized by an initial test with an assumption of a typical stand. The simulation assumes that the leaf biomass is from 15 to 20 t/ha just after canopy closed year (Tadaki 1976) and stem biomass is almost 150 t/ha at 40 years (Fukuda et al. 2000). The values of pFS2 and pFS20 are parameterized with 0.9 and 0.5 respectively.

Using parameterized values (Table 1), the 3-PG is calibrated by fitting to stem biomass and populations which are estimated by LiDAR data and the MNY method. In general, biomass production is constrained by the canopy quantum efficiency, FR, weather conditions and soil water content (Landsberg et al. 2003). Since the FR and soil water content are not known in the study, we assume that soil water does not constrain canopy quantum efficiency. As a result, the modifier of vapor pressure deficit and available soil water content is set as unity. The FR is allowed to vary from +/-0.1 to 1.0 within 0.1. Since initial stem populations are not known in the study area, we use initial populations that correspond to standard practice and adjust the constant in the mortality equation so that stand densities at the time are corresponded to populations estimated by LiDAR data and the MNY method.

Table 1 **Parameter values that are different from default value**

Parameters	Units	Values	Source
Foliage:stem partitioning ratio at D=2 cm	-	0.9	This study
Foliage:stem partitioning ratio at D=20 cm	-	0.5	This study
Minimum temperature for growth	C°	-2	
Optimum temperature for growth	C°	20	Landsberg et al (2003)
Maximum temperature for growth	C°	40	
Canopy quantum efficiency	molC/molPAR	0.05	Landsberg et al (2003)
Litterfall rate	1/month	0.0275	Tadaki (1973)
Age at canopy cover	Year	15	This study
Specific leaf area	m^2/kg	3.5	Landsberg et al (2003)
Fertility ratio	-	0.1-1.0	Tuning
Maximum stand age used in age modifier	Year	200	This study

3 RESULTS AND DISCUSSION

3.1 The comparison with LiDAR data and field measurements

Table 2 shows the comparison with field measured data and variables estimated by LiDAR data and the MNY method. Plot 6 which is not canopy-closed forest is not applied the MNY method. (2) LiDAR is underestimated with exception of plot 6. (3) LiDAR and the MNY method increase stem populations and biomass. In plot 39, stem biomass corresponds with field measurements, although stem population is approximately twice as field measurements.

3.2 Calibration results

Figure 1(left) is a plot of simulated stem biomass against data for the calibration. Most of the plot can simulate stem biomass accurately; however two young plots (plant year 1987) are overestimated. The overestimation may be influenced by the overestimation of population by the MNY method. Additionally simulated populations also correspond with the observed data (figure is omitted). Figure 1(right) is a plot of simulated tree height against estimation by LiDAR data. With the exception of two young plots, tree height is simulated accurately. Since simulated LAI values vary from 5 to 7 at all stands. the range of LAI is reasonable value for Sugi plantation (Tadaki 1976). If periodic measurements of stem biomass or LAI are available, the calibration can describe stand growth better than one time measurement (Landsberg et al. 2003). In case of coupling with remote sensing data, time series data are preferable. In Japan, aerial photographs, which can generate canopy height by Digital Surface Model (DSM), have been taken from 1960s periodically. Time-series tsree height can be estimated by aerial photographs.

Table 2 **The comparison with (1) field measured, (2) LiDAR data and (3) LiDAR data and the MNY method**

		(1) Field measured			(2) LiDAR			(3) LiDAR + MNY	
Plot	Plant Year	Mean H (m)	Population (stem/ha)	Stem Biomass (t/ha)	Mean H (m)	Population (stem/ha)	Stem Biomass (t/ha)	Population (stem/ha)	Stem Biomass (t/ha)
1	1956	22.33	1088	239.1	22.7	897	192.7	1229	232.1
6*	1961	25.72	530	187.7	24.88	528	175.3	528	175.3
12	1961	21.02	1146	206.2	19.97	963	131.1	1190	162
39	1987	6.84	1965	30.4	6.45	1162	13.6	3943	28.8

* Plot 6 is not applied the MNY method, because it was not canopy-closed forest.

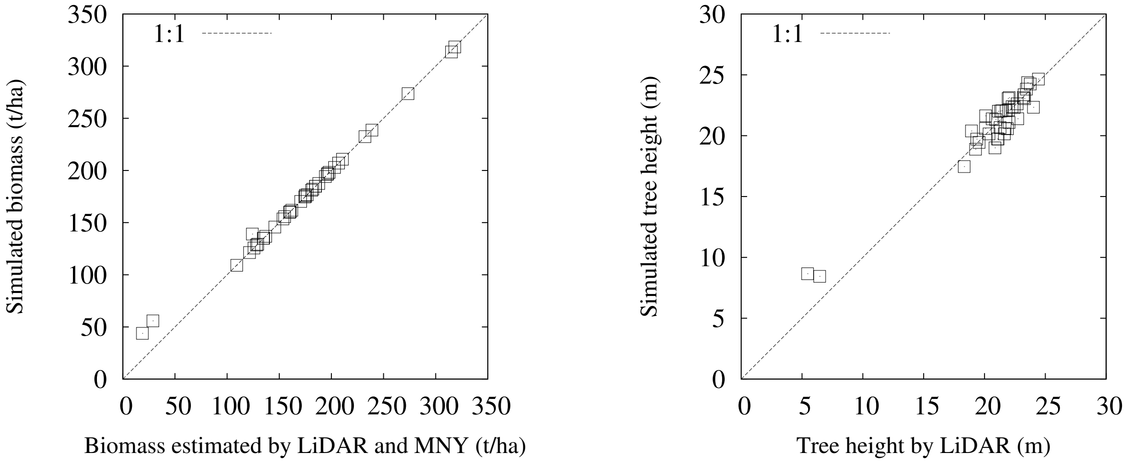

Figure 1 **The comparison of stem biomass between the calibration and the simulation by 3-PG model (left), and between simulated tree height and estimation by LiDAR data(right)**

The FR value can constrain the conversion factor (canopy quantum efficiency) and the production. Figure 2 shows the relation between FR and simulated stem biomass of 43 years (planted in 1961). Stem biomass have strong linear relationship with FR value. If stand age is known, tuned constrain factor in each plot are possible to estimate appropriately.

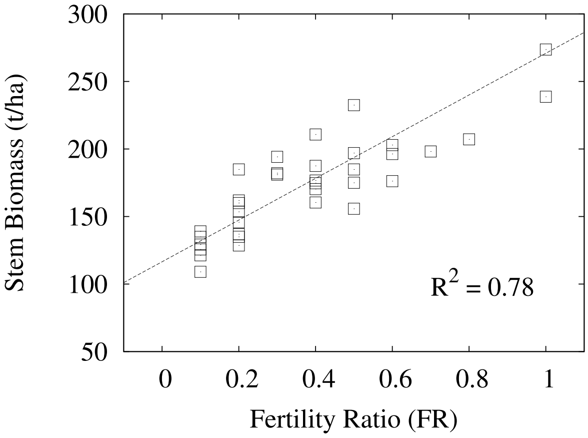

Figure 2 **The relation between stem biomass and FR values at 43 years**

In this study, the FR is assumed to be the only parameter for constraining the conversion factor. However, in case of scaling up over wide areas, constrain factors such as the FR and soil water holding capacity are necessary to be known previously, because stand age is unknown. Consequently, it is difficult to calibrate the FR or soil water value over wide areas. Many studies showed that micro topography influences a stand quality for forest growth and productivity. In particular, the growth of conifer tree is sensitive to soil water. The 3-PG assumes flat plate topography, although soil water is influenced by micro topography. Digital elevation model (DEM) has the possibility to estimate FR value and soil water holding capacity for wide areas.

3.3 Estimation of time-series stem biomass

To evaluate time-series estimation of stem biomass, the values at each plot are compared with yield table values (Aomori prefecture. 1997). Figure 3 shows the model values (dotted

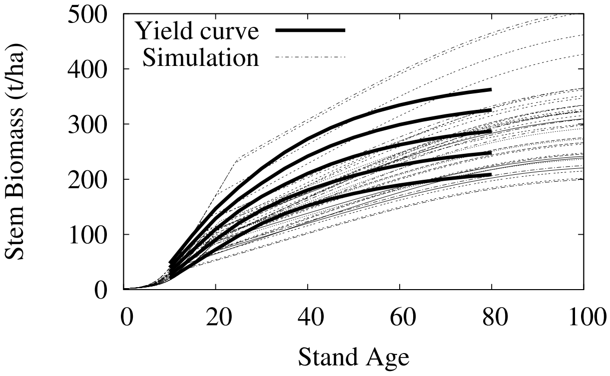

Figure 3 **Time series estimated stem biomass with yield table values**

line) and yield table values (thick line). Lowest thick line shows lowest site index, and top thick line shows highest site index. This figure shows that the 3-PG model estimated time series biomass appropriately.

4 CONCLUSION

In this study, LiDAR data is coupled with process-based forest growth model in Japanese cedar plantation. The 3-PG model can be calibrated using stem populations and biomass which are estimated by LiDAR data and the tree size distribution function. The calibration is worked well. Compared with yield table values, time-series biomass estimations are reasonable. The DEM data is the key for scaling up over wide areas. Tree height data derived by operational remote sensing would play an important role in improving estimating time-series forest biomass and productivity.

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