

A Multi-layered Integrated Numerical Model of Surface Physics—Growing Plants Interaction, MINoSGI

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INTRODUCTION

It has long been recognized that the geographical distribution of functional types of terrestrial ecosystems is determined by climatic conditions such as temperature, precipitation, radiation (e.g., Holdridge, 1947). This can be viewed as the result of competition among plants with different strategies in each climatic regions. On the other hand, climate is influenced by terrestrial ecosystems through its control of exchanges of energy, moisture, momentum, and carbon dioxide (CO₂) at the ground surface. That is, the processes between climate and terrestrial ecosystems construct a closed feedback loop, or interaction, which should be elucidated for an extensive understanding of the past, present and future development of both climate and terrestrial ecosystems. Until recently, however, little has been studied regarding this interaction, partially due to a lack of long-term observations and also a lack of theoretical and numerical modeling framework. In particular, this interaction is totally missed in most of the future climate change projection studies (IPCC, 1996).

Among climate modelers, the significance of vegetation processes as a lower boundary condition of the atmosphere has been recognized because the land-surface schemes for climate models including vegetation canopy, e.g., SiB (Sellers *et al.*, 1986) and BATS (Dickinson *et al.*, 1986), were developed and their effectiveness was shown. In those schemes, the vertical structure of vegetation canopy is integrated into one or two layers, and the stomatal control of transpiration is treated as if the canopy were composed of one “big leaf”. Multi-layered schemes, which represent the vertical structure of the canopy and canopy air explicitly, have also been developed mainly for application to studies of boundary-layer meteorology (e.g., Kondo and Watanabe, 1992). Recently, some of the land-surface schemes began to include more sophisticated ecosystem feedbacks. Some ecosystem models originally developed for more biogeochemical purposes, e.g.,

CENTURY (Parton *et al.*, 1988), also began to be coupled with climate models (Lu *et al.*, 2001).

The feedback of terrestrial ecosystems on climate change can be put into three categories: physiological, structural, and biogeochemical feedbacks. The physiological feedback includes a change in stomatal control of transpiration, which is coupled with the photosynthesis of plants. Sellers *et al.* (1996) developed "SiB2" by adopting the biochemical photosynthesis model proposed by Farquhar *et al.* (1980) combined with the stomatal model by Ball (1988). This model allows more realistic responses of stomata to changes in temperature, humidity, radiation and CO₂ concentration than the previous models with more empirical treatment of stomata. The structural feedback includes changes in the radiative and aerodynamic properties of the canopy due to the growth of plants or transition of ecosystems as a result of competition among plants. Betts *et al.* (1997) used a climate model iteratively coupled with an equilibrium vegetation model and contrasted the physiological and structural ecosystem feedbacks in future climate change projections. Their model represents a structural feedback mainly in terms of a change in the density of vegetation (leaf area index) not allowing for ecosystem transition. Some dynamic vegetation models can represent competition between different plant functional types, but in a simple or empirical manner (e.g., Foley *et al.*, 1996). The biogeochemical feedback includes change in the carbon balance of ecosystems, which results in a source or sink of atmospheric CO₂, followed by the radiative effect of anomalous CO₂. This feedback can be fully represented only if atmospheric CO₂ concentration is a prognostic variable of a climate model. An integrated climate-carbon cycle model including terrestrial and marine ecosystems is desirable for this purpose, but such models are still emerging just recently (Cox *et al.*, 2000).

Many models have been proposed for the study of growth dynamics in plant populations. These models are divided into two categories, spatial and non-spatial models (e.g., the review by Hara, 1988). Most of these models consider interactions between individual plants based on the growth of each individual in a plant population. Spatial models take into account the spatial distributions of individuals, whilst non-spatial models do not, assuming that the spatial distribution of individuals is homogeneous. These spatial (or individual-based) models (e.g., Firbank and Watkinson, 1985; Prentice and Leemans, 1990; Clark, 1990; DeAngelis and Gross, 1992; Pacala *et al.*, 1996), however, assume a priori growth equations and/or competition functions between individuals.

Yokozawa and Hara (1992, 1995) proposed a non-spatial canopy photosynthesis model for the growth of individual plants in a stand based on the diffusion model (Hara, 1984). Assuming no a priori growth or competition functions but an allometric relationship between plant height and weight (i.e., an allocation-growth pattern), this model reproduced realistic size-dependent growth of individuals as affected by competition between them. In this paper, we employ Yokozawa and Hara's (1992) canopy photosynthesis model to describe the dynamics of stand structure based on the continuity equation (a simple version of

the diffusion model; e.g., Hara, 1984). It is almost impossible to couple spatial plant growth models and land-surface physical processes. This is because spatial plant growth models consider the growth of each of horizontally distributed individual plants while land-surface physical processes are usually considered in the vertical layer in a plant stand (or it is almost impossible to measure land-surface physical processes for each individual plant).

In the present study, a new modeling framework for the study of climate-ecosystem interaction, the Multi-layered Integrated Numerical model of Surface physics-Growing plants Interaction (MINoSGI), is proposed. In the MINoSGI, a multi-layered canopy micro-meteorology model and a size-structured vegetation dynamics model are coupled to realistically represent the physiological and structural feedbacks of ecosystems to climate. The biogeochemical feedback is out of the scope of this study for the time being. The micro-meteorology model is based on that of Kondo and Watanabe (1992), which has been used for studying the boundary layer over a vegetated surface. The size structure model is based on that of Yokozawa and Hara (1992) which has been used for studying plant growth and competition between plants. The advantage of the size-structured model for studying the structural feedback is that it can explicitly represent the transition of ecosystems as a result of competition among plants with different size and species, which has been assumed implicitly or empirically in previous dynamic vegetation models. The use of the multi-layered canopy model enhances this advantage, providing vertical distributions of radiation flux, temperature, humidity, wind speed, and CO₂ concentration in the canopy space. For representing the physiological feedback, the same photosynthesis and stomatal models as in SiB2 (Sellers *et al.*, 1996) were incorporated. We have implemented a one-dimensional version of the MINoSGI and validated it against observational data. At this stage, the MINoSGI can be a novel research tool for studying plant growth and competition because it incorporates climatic conditions for plants far more realistically than previous models. However, our final goal is to couple the MINoSGI and a climate model to elucidate the interaction mechanisms between ecosystems and climate and to reduce the uncertainty in future climate change projections.

MODEL

The model is composed of two sub-models describing (1) dynamics of plant size distribution and (2) microclimate within the plant canopy. The first sub-model describes a change in the size distribution of a plant stand as a result of growth and mortality of the individuals. This sub-model produces the canopy architecture of a stand as an input to the second sub-model. The second sub-model then predicts vertical profiles of the photosynthetic and respiration rates of individual plants for given atmospheric boundary conditions and canopy architecture. The outputs are returned to the first sub-model, resulting in a new size distribution at the next time step. These processes represent a full interaction between vegetation dynamics and climate.

Dynamics of plant size distribution

The sub-model for the dynamics of plant size distribution is based on the model developed by Yokozawa and Hara (1992, 1995) and Yokozawa *et al.* (1996). The model describes the time development of size distribution density for a multi-species plant community. Let $f^i(t, x)$ denote the distribution density of i -th species' individuals ($i = 1, 2, \dots, n$) of size x (mass, plant height, trunk diameter, etc.) at time t in a community with n species. The governing equation for f^i is

$$\frac{\partial f^i(t, x)}{\partial t} = \frac{1}{2} \frac{\partial^2}{\partial x^2} [D^i(t, x)f^i(t, x)] - \frac{\partial}{\partial x} [G^i(t, x)f^i(t, x)] - M^i(t, x), \quad (1)$$

where G^i and D^i are the mean absolute growth rate and its variance, respectively, and M^i is the mortality rate. The diffusion term (the 1st term on the right side in Eq. (1)) may be important for a long-term simulation in which the variability in the growth rate among individuals may affect the size distribution considerably, but will be neglected in the present short-term simulation. The mean growth rate of individuals of size x is expressed as:

$$\begin{aligned} G^i(t, x) &= P_n^i(t, x) \frac{dw^i(x)}{dx}, & P_n^i > 0; \\ &= 0, & P_n^i \leq 0, \end{aligned} \quad (2)$$

where P_n^i is the net production rate of an individual, and dw^i/dx is the growth in weight w^i relative to the growth in x . The value of dw^i/dx is derived from the allometric relationships that will be shown later. The value of P_n^i is given as

$$P_n^i(t, x) = \int_0^h [a^i(x, z)A_n^i(i, z) - R_w^i(t, z)w_{\text{non}}^i(x, z)] dz - R_r^i(t)w_{\text{root}}^i(x), \quad (3)$$

where h is the plant height of an individual of size x , z is the height above the ground, a^i is the leaf area density, A_n^i is the net assimilation rate per unit leaf area, R_w^i and R_r^i are the respiration rates of non-photosynthetic organs above and under the ground, respectively, and w_{non}^i and w_{root}^i are the mass of the non-photosynthetic organs above and under the ground, respectively. Because the values of A_n^i , R_w^i and R_r^i depend on the environmental conditions, these are calculated in the microclimate sub-model. The mortality rate is much more difficult to be modeled correctly, because it depends not only on the plant activity but also on external factors such as natural disasters. Some statistical treatments may be relevant. In the present study, however, the mortality rate is assumed to be dependent only on the productivity of individuals for simplicity. The functional form is given by

$$\begin{aligned} M^i(t, x) &= -P_n^i(t, x)/w^i(x), & P_n^i < 0; \\ &= 0, & P_n^i \geq 0, \end{aligned} \quad (4)$$

so that the carbon budget of a plant stand is to be closed. This assumption may be adequate for a short-term simulation, in which the mortal process does not have a large effect on size distribution dynamics. The allometric relationships incorporated in the model are

$$d_0(h) = [\exp(\gamma h) - 1] / \beta \gamma, \quad (5)$$

$$d(z, h) = d_0 \left[1 - \left(\frac{z}{h} \right)^\eta \right], \quad (6)$$

$$w_{\text{non}}(h) = \alpha d_0^2 h, \quad (7)$$

$$L(h) = \theta d_0^2, \quad (8)$$

$$a(z, h) = 2L\eta \left[1 - \left(\frac{z}{h} \right)^\eta \right] \frac{z^{\eta-1}}{h^\eta}, \quad (9)$$

where d_0 is the trunk diameter at ground level, d is the trunk diameter at height z above ground, and L is the total leaf area of an individual. α , β , γ , η and θ are parameters. The total mass of an individual is thus given by

$$w^i(x) = w_{\text{non}}^i(x) + L^i(x) / s^i, \quad (10)$$

where s^i is the specific leaf area.

Once the plant height h is given, all other size variables are determined through Eqs. (5)–(10), and we use h as the independent variable x in Eqs. (1)–(4) and (10).

Microclimate within the canopy

The framework of the microclimate sub-model is a one-dimensional multi-layer model presented by Watanabe and Mizutani (1996), and its revised version is incorporated in the present model. The model describes vertical profiles of climate conditions depending on the canopy architecture and physiological activities. Physical processes considered in the model include 1) transfer of photosynthetically active radiation (PAR), near-infrared radiation and long-wave radiation, 2) turbulent transport of momentum, heat, water vapor and CO_2 , 3) energy budget of a leaf and the ground surface, and 4) heat and moisture conduction into the soil. This sub-model also includes physiological processes such as 5) photosynthesis and respiration of a leaf, 6) stomatal regulation on transpiration and CO_2 uptake, and 7) respiration of non-photosynthetic organs.

The processes of 5) and 6) are expressed based on the C_3 photosynthesis model presented by Farquhar *et al.* (1980) and Collatz *et al.* (1991), the C_4 model of Collatz *et al.* (1992), and the stomatal model of Ball (1988). These biochemical components are programmed following Sellers *et al.* (1996), while their canopy integration technique is not adopted in the present multi-layer sub-model. The dependency of the respiratory processes on temperature is described by the Q_{10} -type functions as follows:

$$R_w^i(t, z) = R_{w25}^i Q_{10_w}^i \frac{T(t, z) - 25}{10}, \quad (11)$$

$$R_r^i(t) = R_{r25}^i Q_{10_r}^i \frac{T_s(t, z) - 25}{10}, \quad (12)$$

where R_{w25}^i and R_{r25}^i are the values of R_w^i and R_r^i at 25°C, respectively, T is the air temperature within the canopy layer, T_s is the soil temperature at the root depth, and $Q_{10_w}^i$ and $Q_{10_r}^i$ are parameters.

This sub-model produces vertical profiles of the net assimilation rate of a leaf and the respiration rate by non-photosynthetic organs, which are referred to by the sub-model for dynamics of plant size distribution.

DATA

Study site and field measurements

The field data used in the present study were taken in a plantation of an evergreen conifer species, sugi (*Cryptomeria japonica* D. Don, Japanese cedar), in the Nagoya University Experimental Forest at Inabu, Aichi Prefecture, central Japan. In the forest, a series of research studies on various aspects concerning gross productivity of *C. japonica* population was conducted (Katsuno, 1990). Items of the measurements include photosynthetic productivities at the leaf to stand levels, tree-heights, trunk-diameters and biomass for component trees for each year, and internal and external physical conditions such as light and temperature. All-inclusive measurements of this kind are suitable for validating the present model that includes parameters from the leaf to stand levels. Part of the published and unpublished data (Katsuno and Hozumi, 1987, 1988, 1990; Katsuno, 1990) during 1983 and 1988 was employed to validate the results of the present simulation model.

The altitude, annual mean temperature and annual precipitation in the *C. japonica* stand was 960 m, 8.8°C and 1900 mm year⁻¹, respectively (Katsuno and Hozumi, 1990). The measurements were conducted in the study plot with an area of 400 m² (20 m by 20 m). The stand age was 21 years in 1983, when 141 trees of *C. japonica* (density: 3525 ha⁻¹) were alive there. No artificial thinning of trees was done during the study period, so that the trees were allowed to self-thin; thereby, the number of trees decreased to 131 (density: 3275 ha⁻¹) in 1988.

Average tree-height increased from 13.0 m in 1983 to 15.0 m in 1988. Average DBH (trunk diameter at 1.3-m height) was 13.6 cm in 1983, which increased to 15.0 cm in 1988. The stand biomass increased from 124.5 ton ha⁻¹ to 156.5 ton ha⁻¹ during the 5 years (Katsuno, 1990).

Hourly surface air temperature, precipitation, wind speed, pressure, specific humidity, downward short-wave radiation, and downward long-wave radiation at Inabu experimental forest site are required as an input to the MINoSGI. Surface air temperature, precipitation, and wind speed were specified by using the AMeDAS (Automated Meteorological Data Acquisition System) data at Inabu (35°12.6' N, 137°30.6' E, 505 m). AMeDAS is an online telemeter system for meteorological observation developed by Japan Meteorological Agency, in which more than 1300 stations are managed over Japan, and hourly data on temperature, precipitation, wind vector, and sunshine duration are collected. A correction for altitude was applied to temperature because the Inabu experimental forest site is located at 960 m above sea level. Pressure was specified from three-hourly weather station data at Iida (35°31' N, 137°50' E, 482.3 m) with a correction for altitude. Specific humidity was estimated by assuming that the relative humidity is the same as that at the Iida weather station and using the pressure and surface air temperature at the Inabu forest site estimated above. Downward short-wave and long-wave radiations were estimated using the daily sunshine duration and daily mean temperature at the Inabu AMeDAS station and the relative humidity at the Iida weather station using the empirical equations by Kondo *et al.* (1991)

NUMERICAL SCHEME AND SETUP FOR THE TEST SIMULATIONS

The discretization and integration of Eq. (1) must be carried out by an accurate scheme; otherwise, the solutions to Eq. (1) would be unacceptably distorted by the numerical diffusion and dispersion. We therefore adopted the second-order Runge-Kutta method for the time increment and the fifth-order upwind scheme for the nonlinear growth term. An adequate limit was also imposed on the number flux between discrete grids in order to ensure positive values for the distribution density. The diffusion term (the first term on the right side in Eq. (1)) was neglected and $n = 1$ in the present simulation.

The distribution density measured in 1983 was used as the initial condition, and the integration was performed for 5 years. The final result of the size distribution was compared with the measurements made in 1988. The time step was 1 day for the size dynamics and 1 hour for the microclimate. The grid of x (or h in the present study) was positioned at 1-m intervals from 0 m up to 30 m. The boundary conditions at both boundaries were specified by inflow and outflow fluxes. In the present simulation, both fluxes were set at zero, which means that no seedlings were newly developed and no individuals exceeded 30 m in height during the simulation period. The same grids were also used for the vertical grids in the microclimate sub-model. Parameters in Eqs. (5)–(8) and in the photosynthetic model were determined to obtain the best fit to the observed allometric relationships

and photosynthetic rate (Katsuno, 1990). Concerning the parameters for the respiration rate of non-photosynthetic organs, the value of R_{r25}^i was adopted from the literature, but R_{w25}^i (no data were available) was treated as a tuning parameter, the value of which was determined so that the bulk growth rate of the stand should agree with the observations.

RESULTS AND DISCUSSION

Our model predicted diurnal variations in the microclimate and the plant physiological activities as well as seasonal and interannual developments in the size distribution. Examples of diurnal variations are shown for the energy budget of the forest (Fig. 1), the CO_2 flux above the canopy (Fig. 2) and the vertical profile of CO_2 concentration (Fig. 3) produced under clear weather conditions (10 May 1984). Each of these figures captures typical features of the microclimate of a forest stand. In the energy budget (Fig. 1), the sensible and latent heats were in the same order of magnitude in the morning, but the latent heat dominated in the afternoon. The heat storage was only about one sixth of the net radiation in the daytime but was a major component in the nocturnal energy budget. CO_2 flux above the canopy showed a clear diurnal cycle (Fig. 2): a negative flux (absorption by the forest) in the daytime and a positive flux (release from the forest) in the nighttime. The negative peak of the CO_2 flux appeared in the morning, because the respiration rate increased in the afternoon as the temperature increased. These diurnal variations in the plant activities were clearly reflected in the profile of CO_2 concentration (Fig. 3), which indicates that the leaves act as a strong sink for CO_2 in the daytime (especially in the morning) and as a source in the nighttime. Because of this, the range of daily variation in CO_2 concentration exceeded 40 ppm within the canopy layer.

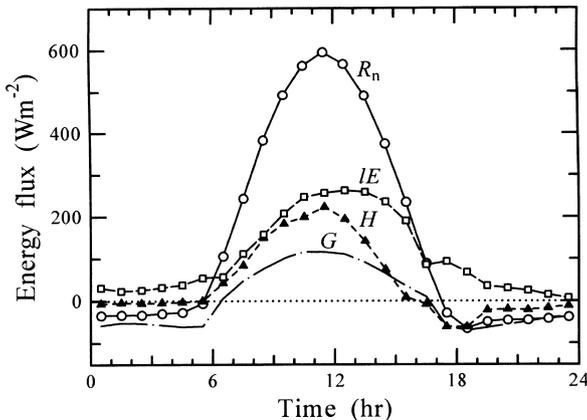


Fig. 1. Diurnal variations in the energy budget components (R_n : net radiation; H : sensible heat; LE : latent heat; G : heat storage) calculated for 10 May 1984.

These hourly values were integrated into the daily values, which were referred to by the sub-model for the dynamics of plant size distribution. The model then predicted a day-by-day development in the size distribution and the allometric canopy architecture. Figure 4 shows the simulated 5-year course of the daily summed net production rate and the leaf area index of the forest. The net

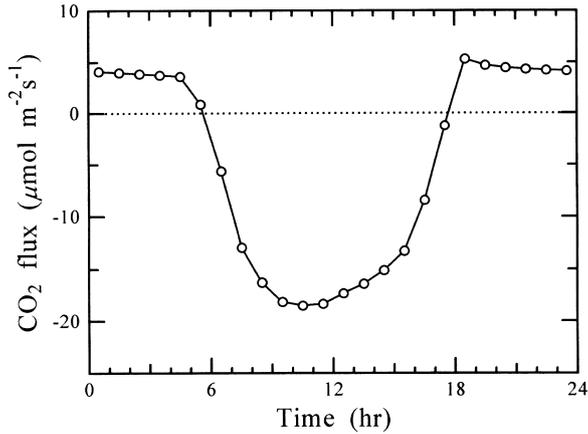


Fig. 2. Diurnal variation in CO_2 flux above the plant canopy calculated for 10 May 1984.

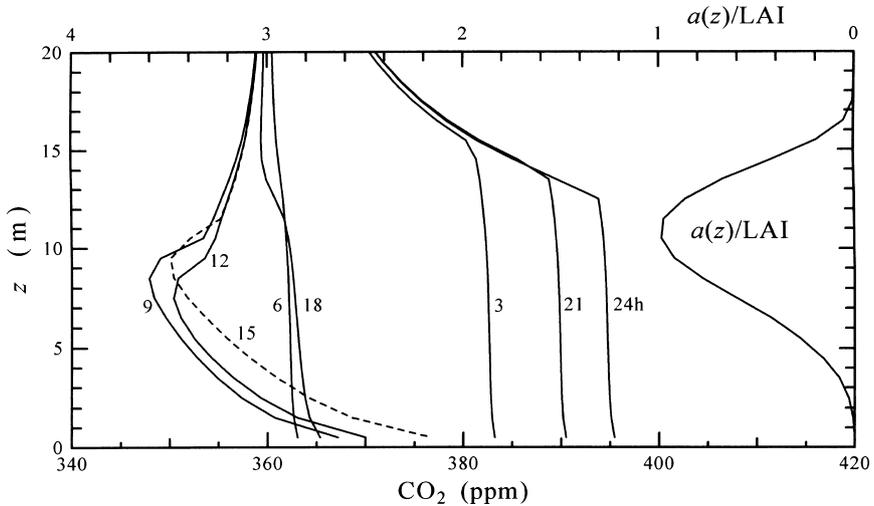


Fig. 3. Diurnal variation in the vertical profile of CO_2 concentration within the canopy layer, along with the vertical profile of the normalized leaf area density. The numbers near the curves denote the time of day on 10 May 1984.

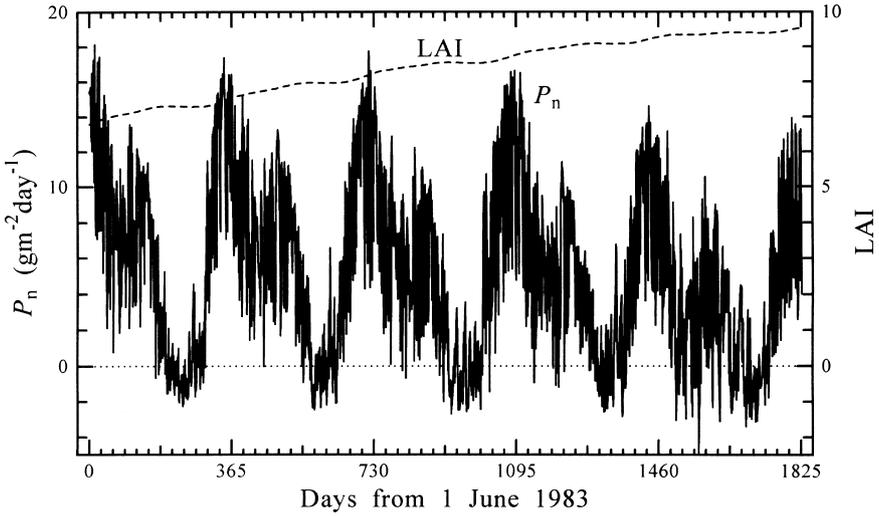


Fig. 4. Seasonal and interannual variations in the daily net production and the leaf area index of the forest. The net production is shown in units of dry matter weight.

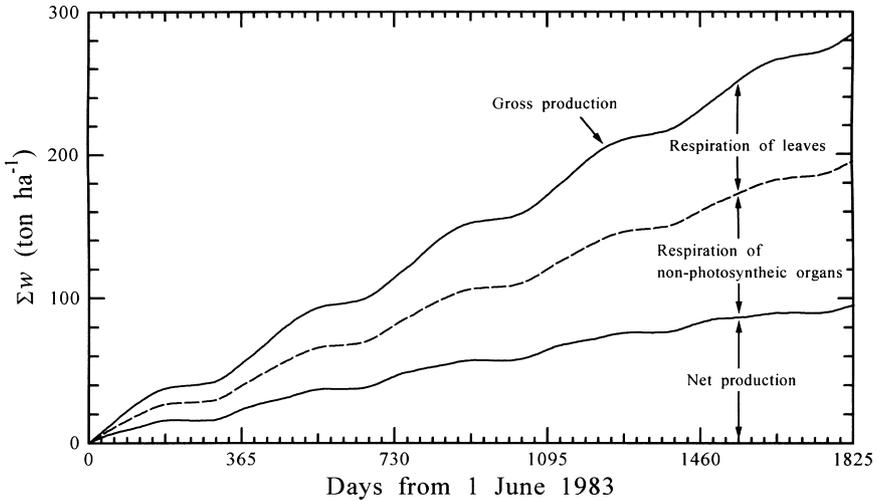


Fig. 5. Time integrations of the gross production, respiration and net production of the forest.

production of the forest was obtained through the integration of $\int P_n^i$ with respect to x . The value of daily net production was small and mostly negative in winter but drastically increased in spring toward its maximum in June. The net production then decreased in mid-summer mainly because of high temperature, and it

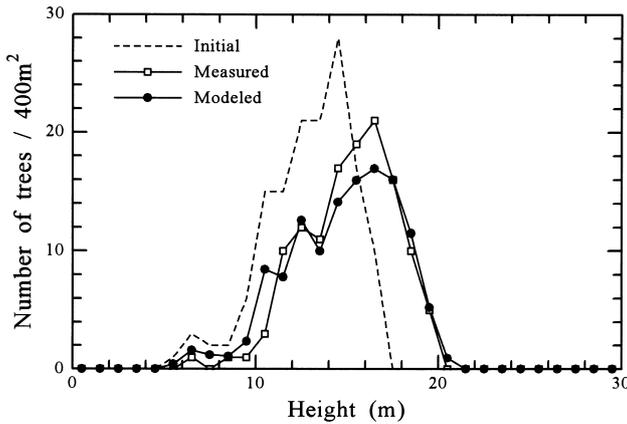


Fig. 6. The 5-year simulated result of the size distribution density compared with the actual measurement.

increased again in autumn, producing a bimodal seasonal pattern. The leaf area index gently increased during the 5-year simulation, showing weak seasonal variations corresponding to the seasonal patterns in the net production.

Figure 5 shows the time-integrated values of gross production, respiration and net production. The figure portrays that more than two thirds of the photosynthates were expended in the respiratory processes. The ratio of the net production to the gross production decreased with time because the growth in plant size led to a larger increase in the respiration of non-photosynthetic organs than the increase in leaf assimilation. In this figure, the gross production and leaf respiration were estimated with reasonable confidence, because parameters for the models of photosynthesis and leaf respiration processes were given based on the actual measurements. However, the respiration of non-photosynthetic organs depended totally on the result of a trial-and-error adjustment of R_{w25}^i conducted so that the final result of the simulated distribution density agrees on the average with the actual measurement. To confirm the partitioning ratios in Fig. 5, much more field data are required on the respiration rate of branches, trunks and roots.

The final result in the size distribution density obtained after the 5-year simulation was compared with the actual measurement in Fig. 6. As a matter of course, the ensemble of modeled histogram overlapped well with the measured one because of the parameter tuning. The model obviously showed good performance for predicting variations in the distribution density. The model successfully predicted the location of the maximum peak, the presence of a secondary peak at a lower height, and a negatively skewed distribution pattern, all of which are important characteristics of the measured size distribution. We see some problems, however, in the exact value of distribution density at the dominant middle height classes and lower classes. These problems may be due to difficulties in modeling the growth rate of smaller-sized plants. In the modeled

environment, smaller-sized plants seem to be overshadowed by taller plants much more extensively than in reality. The overestimation of the leaf amount of taller plants by the allometric relations may be one of the reasons. The other reason may be that the patchy structure of the canopy, in which light can penetrate freely through open sections, was not sufficiently taken into account in the light transmission modelling. Some revisions of these processes will improve the model performance.

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