Model simulation of soil carbon dynamics with stand development in Japanese cedar (*Cryptomeria japonica*) plantations

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Abstract Soil carbon cycling in Japanese cedar plantations after clear-cutting, and in chronological order, was calculated with and without the consideration of forest management (pruning and thinning) by a mathematical model. The model employed a daily time step, used daily air temperature and observed precipitation near the plantations. The result of the calculations was compared with field observations. There were few differences in the changes of aboveground biomass, carbon flow and carbon accumulation with the forest regeneration between the calculations with or without consideration of management and field observation (p>0.05, by a one-way analysis of variance), as suggested by the small standard error between them. For example, the carbon accumulation and total soil respiration rate calculated with the consideration of management for a 60-year-old stand were 104 tC ha^{-1} and 4.8 tC $ha^{-1}y^{-1}$ with a field observation of 110 tC ha^{-1} and 4.5 tC $ha^{-1}y^{-1}$, respectively. The effect of forest management on the soil carbon cycling was also examined, suggesting that the soil respiration rates and carbon accumulations changed little by the management except for the clear-cutting. Consequently, it was suggested that the dynamics of carbon cycling following the clear-cutting of a Japanese cedar plantation could be simulated exactly by the model even if forest management was considered or not. That is, it indicates that the model can simulate the chronological change in carbon cycling at cedar plantations easily and correctly even if the history of management in the plantations is unknown.

Keywords Forest management ・ Japanese cedar plantation ・ Model simulation ・ Soil carbon dynamics ・ Validity of calculation

Introduction

As atmospheric CO_2 concentration rises, the concern about the risk to human beings increases (Arnell et al. 2002); therefore the forest ecosystems, which are affected by climate change, have been noticed recently (Cramer et al., 2001). Additionally, climate change with increasing atmospheric CO_2 concentration would change various forest ecosystems including forest soil, which have been considered as a major carbon sink.

Regarding the influence of increasing atmospheric CO_2, IPCC presented a scenario in these reports, which predicted that atmospheric CO_2 concentration, air temperature and the sea levels rose on the earth scale during the 21st century. Therefore, it is important to evaluate exactly what the absorbing ability of carbon by each forest is and to estimate the amount of carbon absorbed on a global scale.

To comprehend the global carbon cycle many attempts have been made, e.g. the simulation with a physiologically based model was performed in different environmental conditions (Grote & Erhard, 1999) and was also completed by using six dynamic global vegetation models (Cramer et al., 2001). The Carbon cycle has been simulated not only in terrestrial ecosystem (Huntingford et al., 2000) but also in the ocean (Lenton, 2000). On the other hand, a carbon flux was simulated by four different models to assess more general context (Wijik & Verstraten, 2002). Recently, there have been calculations, which simulated the carbon dynamics above and below ground (Rasse et al., 2001). Moreover, Mohren (2003) calculated the carbon dynamics in forests not only on a global scale but also on a stand scale of managed forests. To understand the carbon cycling in forests on a global scale, the simulation has to be performed within various types of forests over the world.

The Kyoto Protocol, adopted in 1997, showed the direction to cut down total CO_2 emission for developed countries considering a comprehensive balance of CO_2 in their forest area under rising interest about atmospheric CO_2. In fact, however, a reliable model has not been proposed for evaluating carbon cycling or carbon balance in and on forest soil, which may change significantly with stand age and by human disturbance. (based on field data except for Nakane et al. 1987, 1994). Consequently, it is very important to estimate exactly the change in balance and stock of soil carbon in forests with stand development and by human management.

In the forests of Japan, there are many Japanese cedar plantations (*Cryptomeria japonica* D. Don) which occupy about 45% of artificial forest areas or about 20% of total forest areas in Japan. The plantation is managed by pruning, thinning and clear-cutting generally. Therefore, the management has to be taken into consideration for analyzing the carbon cycling in Japanese cedar plantations. Although there is a study of carbon flux in cedar plantations by Chiba (1998) who calculated the biomass growth and CO_2 flux between the atmosphere and the cedar plantation associated with a thinning during the development, very few attempts have been made to simulate the soil carbon cycling in forest development (in chronological order), where management is conducted, and compare the calculation results to field observations.

In this study, the purpose is to calculate soil carbon cycling by a mathematical model in Japanese cedar plantations which are managed by pruning, thinning and clear-cutting. The results of the model simulation are compared to field observations reported by Shutou & Nakane (2004) for checking an agreement between them. The observation (Shutou & Nakane 2004) was conducted on 5-, 10-, 22-, 28-, 36-and 60-year-old Japanese cedar plantations on the same slope in Hiroshima Prefecture, west Japan, where there were adequate sites to study how the soil carbon cycling of the plantations changed following clear-cutting, due to the similar environmental conditions among these plantations.

Nakane et al. (1987, 1994) proposed the simulation model, which described the change in soil carbon cycling with the development of a forest stand following clear-cutting, based on the data observed before and just after it. However, they could not indicate the reliability of the calculation because of the lack of observations following clear-cutting except one before and just after it.

Thus, the attempt was made in the study to examine the compatibility of their model (Nakane et al. 1987, 1994) to the observation of soil carbon cycling with the development of the forest stand following clear-cutting. Furthermore, we have attempted to modify the model for the application to the forests managed by pruning and thinning.

This model simulation contributes strongly to assessing the better management in cedar plantations for the function of carbon stock or carbon sink, and at least to evaluate carbon balance in cedar plantations at the time of the ratified Kyoto Protocol.

Compartment model for model simulation

Figure 1 shows the compartment models proposed by Nakane et al. (1987) which represent the carbon dynamics before and just after clear-cutting, and the regenerating stage following clear-cutting.

In the model just after clear-cutting (Fig. 1-B), litterfall (L), root respiration (R_R) and fine root turnover ($\sigma \cdot Y_r$) cease, and fine and large roots killed by clear-cutting are transferred to the dead root compartments (M_{Rd}). In this compartment model, the regenerating stage (Fig. 1-C) and the litter (A_0 layer) includes two compartments. The accumulation on the forest floor before clear-cutting was ${}_dM_0$ and the litter during regenerating (flesh litter) was ${}_fM_0$.

Model structure

The compartment model for simulating the annual average of soil carbon cycling was already shown in Figure 1 (Nakane et al., 1987). This compartment model represents soil carbon cycling before clear-cutting (A), just after clear-cutting (B) and in the regenerating stage (C).

In the case of before clear-cutting (Fig. 1-A), pools of carbon in various parts of the soil system were classified into four pools: (i) A_0 layer (M_0); (ii) humus in mineral soil (M); (iii) dead roots (fresh fine root litter, M_r); and (iv) living fine roots (Y_r). Arrows in the diagram correspond to fluxes between pools, litterfall (L), supply of humus from A_0 layer to mineral soil (l_A: $\kappa_A M_0$) and from dead roots to mineral soil (l_R: $\kappa_R M_r$), root turnover (L_R: σB_r), total soil respiration (S_R), which includes A_0 layer respiration (S_{RA}: $\nu_A M_0$) and root respiration (R_R), mineralization of dead roots (S_{RD}: $\nu_R M_r$) and humus in mineral soil (S_{RH}: μM). The decomposition rates of A_0 layer, dead roots and humus in mineral soil are assumed to be equal to their respiration (CO_2-mineralization) rates. In the case of just after clear-cutting (Fig. 1-B), litterfall (L), fine root turnover (σY_r) and root respiration (R_R) stopped, but dead roots by the felling (M_{Rd}) was decomposed and transformed from humus to mineral soil. In the case of the regenerating stage (Fig.1-C), litterfall, fine root turnover, root respiration recover, residual litter ($_d M_0$), and residual dead roots (M_{Rd}) decreased.

Assumptions of the model

When the model calculated the soil carbon cycling, the following assumptions were used.

(i) The decomposition and transportation fluxes are assumed to be first order reactions (Fig. 1).

(ii) The ratio (δ_A) of the relative decomposition rate of A_0 layer (ν_A) to the transfer of carbon from the A_0 layer to humus (κ_A) is assumed to be constant. (Nakane 1980; Nakane et al. 1984) The same assumption applies to the corresponding ratio (δ_R) for dead roots.

(iii) The root respiration rate was 45% of the total soil respiration rate in forest stands with a closed canopy (Kawahara 1976; Nakane et al. 1984, 1997; Uchida et al. 1998; Ohashi et al. 2000).

(iv) Annual root turnover is a constant rate and it is 20% of fine root (diameter, ϕ<10 mm) biomass (Nakane 1978; Kira & Yabuki 1978; Nakane et al. 1997).

Model formulation

Prof. Kaneyuki Nakane at Hiroshima University confirmed the model used for this study. Please refer to Nakane et al. (1987) and Nakane (1994, 2001) for a detailed explanation about this model as described in this paper.

Soil carbon accumulation with time

The accumulation of soil carbon with time (t) is described by the following simultaneous differential equations based on the compartment model (Fig. 1-A), where σ and μ represent relative rates of fine root turnover and decomposition rates of humus in the mineral soil, respectively:

$$_{d}M_0/dt = L - (\nu_A + \kappa_A)M_0 = L - \nu_A(1 + 1/\delta_A)M_0$$
$$_{d}M_r/dt = \sigma Y_r - (\nu_R + \kappa_R)M_r = \sigma Y_r - \nu_R(1 + 1/\delta_R)M_r \qquad (1)$$
$$_{d}M/dt = \kappa_A M_0 + \kappa_R M_r - \mu M = (\nu_A/\delta_A)M_0 + (\nu_R/\delta_R)M_r - \mu M$$

Environmental factors influencing decomposition

The decomposition rate of litter and humus on or in mineral soil depends mainly on soil temperature (T_0) and moisture content of litter (V_0) or mineral soil (V_m). Ino and Monsi (1969), Nakane et al. (1984) reported that CO_2

evolution from the A_0 layer or mineral soil increased at various soil surface temperatures (T_0) and with an increase of water content of litter (V_0) or soil (V_m). These relations can be successfully approximated by:

$$\nu_A = \nu_{A0}^* \exp(\lambda T_0)(1- (1-V_0/V_0^*)^2) \quad (2)$$

$$\mu = \mu_0^* \exp(\omega T_0)(1- (1-V_m/V_m^*)^2) , \quad (3)$$

Where ν_{A0}^*, and μ_0^* are rates of ν_A and μ obtained when $T_0 = 0$ and $V_0 = V_0^*$, and when $T_0 = 0$ and $V_m = V_m^*$, respectively. Parameters V_0^* and V_m^* represent the optimal values of V_0 (on a dry weight basis) and V_m (ratio to maximum water-holding capacity) for decomposition, respectively. λ and ω are the temperature response coefficients of ν_A and μ, respectively.

On the other hand, the relative rate of decomposition of root litter (ν_R) may be expressed as a function of T_0, because of its relatively constant moisture content, as follows:

$$\nu_R = \nu_{R0}^* \exp(\omega' T_0), \quad (4)$$

where ν_{R0}^* is the rate of ν_R when $T_0 = 0$, and ω is the temperature response coefficient of ν_R. The values of coefficients in Eqs. 2, 3 and 4 were estimated from field data using a non-linear least squares method.

Soil temperature T_0 is correlated with air temperature (T_a^*) while V_0 and V_m are affected by precipitation and soil temperature (T_0). The empirical equations for these relationships as proposed by Nakane et al. (1987) are:

$$T_0 = k_1 T_a^* + k_2 \quad (5)$$

$$V_0 = k_3 + k_4 P_1 + k_5 P_2 + k_6 T_0 \quad (6)$$

$$V_m = k_7 + k_8 P_1 + k_9 P_2 + k_{10} T_0 \quad (7)$$

where P_1 is precipitation during the last 3 days and P_2 is precipitation during the last 2 weeks excluding P_1. The values of the coefficients (k_1 to k_{10}) were estimated from field data using a non-linear least squares method.

Influence of clear-cutting

Nakane et al. (1987) indicated that soil surface temperature in a *P. densiflora* forests in Japan increased significantly in summer, but decreased in winter after clear-cutting. Furthermore, Shutou and Nakane (2004) also indicated a similar tendency in Japanese cedar plantations. Nakane et al. (1987) suggested that the values of coefficients of the relationship between T_0 and T_a* (Eq. 5) and between V_0 or V_m and P and T_0 (Eqs. 6, 7) changed significantly after clear-cutting. Environmental conditions, which also changed abruptly after clear-cutting, gradually returned to the levels before clear-cutting with forest growth, as follows:

$$T_0 = ({}_fT_0 - {}_dT_0)(Y_L / Y_L^*) + {}_dT_0 \quad (8)$$

$$V_0 = ({}_fV_0 - {}_dV_0)(Y_L / Y_L^*) + {}_dV_0 \quad (9)$$

$$V_m = ({}_fV_m - {}_dV_m)(Y_L / Y_L^*) + {}_dV_0 \quad (10)$$

${}_fT_0$ and ${}_dT_0$ are values of T_0, ${}_fV_0$ and ${}_dV_0$ values of V_0, and ${}_fV_m$ and ${}_dV_m$ values of V_m before and during the first year after clear-cutting, respectively. Y_L and Y_L* represent the leaf biomass of regenerating vegetation and its asymptotic value at canopy closure prior to clear-cutting, respectively (Nakane et al. 1984, 1987).

Dynamics of compartments

The dynamics of soil carbon in a mature (closed canopy) cedar plantation can be calculated by Eqs. 1 ～ 7, using daily observations of air temperature, precipitation and the initial values of carbon accumulations and measurements of seasonal litterfall and root turnover rates.

After clear-cutting, the recovery of above-ground biomass, root respiration (R_R) and fine root turnover (σY_r) during the regenerating stage (Fig.1-C) is expressed by a simple logistic curve:

$$Y_T = Y_T^* / (1 + a_1 \exp(-b_1 t)) \quad (11)$$

$$Y_L = Y_L^* / (1 + a_2 \exp(-b_2 t)) \quad (12)$$

$$Y_B = Y_B^* / (1 + a_3 \exp(-b_3 t)) \quad (13)$$

$$L = L^* / (1 + a_4 \exp(-b_4 t)) \quad (14)$$

and

$$Y_r = c_1 Y_L \quad (15)$$

$$R_R = c_2 Y_r \quad (16)$$

where Y_T, Y_L, Y_B and L are aboveground, leaf, branch biomass and litterfall rate, respectively. Y_T*, Y_L*, Y_B* and L* represent their respective asymptotic values. Parameters a_1〜a_4, b_1〜b_4, c_1 and c_2 are species- and stand- specific coefficients, the values of which were obtained from field data using non-linear least squares estimation.

Symbols for variables and coefficients used in the model simulation described above are shown in Table 1. However, forest management, in particular thinning, may change these relations (Eqs.11-14). Thus, in this study, the modification of equations (11-14) was made for the calculation of Y_T〜L under the forest management.

Fundamental data applying to the model simulation in Japanese cedar plantation

To calculate the model, the VBA program (Microsoft Excel 97, a computer software, Microsoft 1997) of Muramoto (2000) was used. In this program, the weather data in Hiroshima City (air temperature, precipitation and the amount of snow) were applied, and these data were observed for the average year (1998) between 1971 to 2000. The annual mean values (air temperature, precipitation and snowfall) in 1998 in Hiroshima City that were applied to the calculation were 17.6^{o}C, 1508mm and 160mm, respectively. Coefficients used in this program are shown in Table 2. The calculation was carried out using a daily time step, daily air temperature, precipitation and the amount of snow cover.

Vegetation with forest development

Assumption for simulation with the consideration of forest management

The formulas (11)～(14) for aboveground biomass could not be applied to the forest stands of Japanese cedar plantation where thinning was carried out. Above ground biomass (Y_T and Y_L + Y_B, tC ha^{-1}; L, tC ha^{-1}y^{-1}) changed with the forest age (development) and in particular just after the management (thinning) in managed plantations. Consequently, the following assumptions were used for aboveground biomass:

(v) Forest thinning in a cedar plantation is carried out twice in 25- and 50-year-old stands, and the decreases of biomass by thinning, which are estimated based on a stand density control diagram, are 25% and 5% of the biomass in 25- and 50-year-old stands, respectively,

(vi) Pruning is carried out on 18-year-old stands, and the decrease of leaf and branch biomasses, which are estimated based on the data of plant biomass (Shutou & Nakane, 2004), are both 10% of each biomass at 18-year-old stands,

(vii) Based on a full density curve in the stand density control diagram, the future maximum stem biomass where the plantation grew sufficiently (e.g. a 150-year-old plantation) in the stands after both first and second thinning are estimated at 1,000 m^3 ha^{-1} and stem dry weight is 340 kg m^{-3}. Each part weight is derived from the stem dry weight using the allometric equation (Ando et al., 1968).

From the assumptions above, coefficients of formulas (11)～(14) for

0-year-old to 25-year-old stands before the first thinning are calculated from the biomass in 5-, 10-, 22- (the years of observation) and 150-year-old stands. The coefficients for 25- to 50-year-old stands after the first thinning are calculated from the biomasses of a 25-year-old stand that has decreased from thinning, 28-, 36- (the years of observation) and 150-year-old stands. More than 50-year-old stands after the second thinning was calculated from the biomass in 50-year-old stands just after the second thinning, 60- (the year of observation) and 150-year-old stands. Litterfall rate (L) was calculated as 30% of Y_L from the report of Shutou & Nakane (2004). The above coefficients obtained in this way are shown in Table 3.

Assumption for simulation without consideration of forest management

In the case without consideration of forest management, the developments of Y_T, $Y_L + Y_B$ and L are approximated by a simple logistic curve. The parameters of the simple logistic curve were determined by the least square method based on the data of field observation (Shutou & Nakane 2004), and given in Table 4.

Result-1 (with consideration of management)

Recovery of vegetation

Figure 2 shows the changes of above ground biomass (Y_T), leaf and branch biomass ($Y_L + Y_B$) and litterfall rate (L) with forest age. The change of litterfall rate (L) is shown in Fig 3. In the case of consideration of management, these are affected partially by the forest management. Closed circles in Figure 2 and 3 are the field data observation (Shutou & Nakane 2004). A solid line shows the calculated curve, which was taken the management into consideration. In Figures 2 and 3, a significant difference was not suggested between observations and calculations (p>0.05, by one-way analysis of variance).

Calculated Y_T increased exponentially with forest age until the first thinning. At the first and second thinning, Y_T decreased once (from 118 to 92 tC ha^{-1} at the first thinning and from 122 to 118 tC ha^{-1} at the second thinning), and after that, it recovered exponentially. After 60-year-old, it stabilized.

Calculated $Y_L + Y_B$ increased exponentially with forest age the change was the same as Y_T until pruning. When pruning was carried out on 18-year-old, $Y_L + Y_B$ decreased little once, and later it increased until the first thinning. At the first and second thinning, $Y_L + Y_B$ decreased again, and then recovered with forest development.

Calculated L also increased exponentially with forest age until pruning. When pruning was carried out on 18-year-olds, the L increased briefly from 2.4 to 4.6 tC ha^{-1}y^{-1} due to pruning leaves and branches. At the first and second thinning, the L decreased once, and then in the following stage it increased exponentially again.

Environmental condition

Soil temperature

Figure 4 shows the change in soil surface temperature (T_0). It shows T_0 observed in 5-, 10- and T_0 calculated in 10-year-old stands, which were plotted against that observed in 60-year-old stands, respectively. The T_0 calculated was lower than that observed in 5-year-old stand and higher than that observed in 60-year-old stand or similar to those observed in 10-year-old stands.

Moisture content

The mean moisture contents of A_0 layer (V_0) were calculated at 60, 67 and 98% in 5-, 10- and 60-year-old stands, respectively, while their contents observed were 66, 71 and 84 % in 5-, 10- and 60-year-old, respectively.

Mean moisture contents in mineral soil (V_m) were calculated at 67, 68 and 74% in 5-, 10- and 60-year-old stands, respectively, and the mean value of V_m observed were 63, 64 and 77% in 5-, 10- and 60-year-old stands, respectively.

In environmental conditions, the changes in both simulated and observed ones with forest development show similar values or tendencies.

Respiration rate (Carbon Flux)

Figure 5 shows the changes on A_0 layer (S_{RA}), mineral soil (S_{RM}) and total soil respiration rates (S_R) with a consideration of management, which was calculated by using formulas from (1) to (15). Closed circles, open circles and closed triangles were observed to be S_R, S_{RM} and S_{RA}, respectively. In these changes, a significant difference was not found between observations and calculations ($p>0.05$, by one-way analysis of variance).

Calculated S_{RA} decreased swiftly after clear-cutting from 1.41 to 0.53 tC $ha^{-1}y^{-1}$, and then increased in the following stage, due to the recovery of L (or $Y_L + Y_B$) after a 20-year-old stand. When the pruning was carried out on 18-year-olds, the calculated S_{RA} increased once. The first and second thinnings, calculated S_{RA} decreased once, and then it recovered exponentially with forest age and finally stabilized during the mature stage.

On the other hand, calculated S_{RM} increased sharply just after clear-cutting, and after that, it decreased gradually and stabilized around 3.4 tC $ha^{-1}y^{-1}$ after a 50-year-old. Calculated S_{RM} increased once at first and second thinnings, however, it changed little by pruning.

Calculated S_R which is the sum of S_{RA} and S_{RM} increased sharply just after clear-cutting, and after that, it decreased gradually and stabilized about 4.9 tC $ha^{-1}y^{-1}$ after 50-year-old stand. Whenever the forest management (pruning, first and second thinning) was carried out, calculated S_R increased temporarily.

Accumulation of carbon on or in soil (Carbon accumulation)

The changes in calculated carbon accumulation in A_0 layer (M_0), mineral soil (M) and dead roots (M_r) for the cases the consideration of management is shown in Figure 6. Closed circles, open circles and closed triangles are observed as M_0, M and M_r, respectively. In these changes, a significant difference was not found between observations and simulations (p>0.05, by one-way analysis of variance).

Calculated M_0 was decreasing for about 10 years following clear-cutting, but it later recovered. Calculated M_0 increased once at pruning, and it decreased slightly at first and second thinnings, later stabilizing conclusively around 11 tC ha^{-1} at the mature stage.

Calculated M decreased considerably following clear-cutting until ca. 20-year-old stands, and then, it increased gradually. Calculated M once increased slightly at first and second thinning, and it almost stabilized at ca. 120 tC ha^{-1} around the 120-year-old stage. The effect of pruning on calculated M was not indicated clearly.

Calculated M_r decreased rapidly by ca. 20-year-old after increasing by clear-cutting, and then, it increased slightly and stabilized later. Calculated M_r increased slightly at first and second thinnings, however, there was little effect of pruning on M_r.

Result-2 (without consideration of management)

The curves fitting approximately to the data of Y_T (above ground biomass),

$Y_L + Y_B$ (leaf and branch biomass) and L (litterfall rate) through the regeneration process, which do not take forest management into consideration, are shown in Figures 2 and 3 as broken lines, respectively. These curves are similar to those in the cases with consideration of management, but significant differences in Y_T and $Y_L + Y_B$ between observations and calculations were not found (p>0.05, by one-way analysis of variance).

In environmental conditions, calculated T_0 is also shown in Figure 4. Calculated T_0 with and without consideration of management were almost the same, so the difference between them is hardly displayed in Figure 4. Additionally, V_0 and V_m without consideration of management also show similar values to the ones with consideration of forest management.

Figures 5 and 6 show the changes in respiration rate (S_{RA}, S_{RM} and S_R) and carbon accumulation (M_0, M and M_r) without consideration of management using broken lines, respectively. These changes of simulated values also show similar changes to those with consideration of management. In these changes, a significant difference was not found between observation and calculation, and also between calculation with and without consideration of management (p>0.05, by one-way analysis of variance).

Discussion

Validity of calculated aboveground biomass and environmental condition under consideration of management

As shown in Figures 2 and 3, calculated aboveground biomass (Y_T, $Y_L + Y_B$) and calculated soil environmental conditions fit well to the observations during all regeneration stages. The fact suggests that the assumptions for stand development under forest managements are reasonable and the assumptions for change in soil environmental conditions after clear-cutting are also reasonable.

At 10-year-old stand, calculated Y_T was little influenced by pruning because the removal ratio of pruning was about only 10% of $Y_L + Y_B$ (Takeuchi & Hatiya, 1977). When thinning was taken into consideration, calculated Y_T decreased temporarily, but later it increased gradually to the asymptotic value, which could be estimated by 3/2 powers low (a theory of the dynamics of relation between stand density and mean individual weight after thinning: Ando et al., 1968).

Calculated and observed L increased exponentially at early stage and gradually to the asymptotic values at later stage, in relation to the change in Y_L, which are reasonably approximated by simple logistics or its modified curve. When thinning, calculated L decreased temporarily from 2.7 to 2.0 and 2.8 to 2.6 tC $ha^{-1}y^{-1}$ at first and second thinning, respectively, due to the decreasing of $Y_L + Y_B$.

The soil environmental conditions are assumed to recover with recovery of aboveground biomass, in particular, $Y_L + Y_B$ in the study as same as Nakane et al. (1987, 1994, 1997). The good fit between calculations to observations indicates that the canopy coverage is one of the most important factors controlling the forest floor conditions.

The change in carbon flux under consideration of management

In Figure 5, the reason why calculated S_{RA} increased a little just after clear-cutting might be that soil temperature after clear-cutting was higher than before, which caused the increase of decomposition rate of M_0. After that, however, calculated S_{RA} decreased swiftly because all standing trees in the plantation had been cut and so the litterfall was stopped until the recovery of vegetation. Calculated S_{RA} increased gradually with recovery of L (or vegetation) and stabilized at 1.42 tC $ha^{-1}y^{-1}$ (Figure 3). At pruning, simulated S_{RA} increased because litterfall increased temporarily by pruning. At the first and second thinnings, simulated S_{RA} decreased once due to significant decrease of L (or Y_L + Y_B) (Figures 2 and 3), and it recovered later with the recovery of L (or Y_L + Y_B). Thus, S_{RA} changes as similar as that of L (or Y_L + Y_B).

Calculated S_{RM} increased swiftly just after clear-cutting, and then, it decreased gradually and stabilized around 3.4 tC $ha^{-1}y^{-1}$. It suggests that S_{RM} increased swiftly due to many dead roots occurred by clear-cutting (Fig. 6) and decomposition rate of dead root became higher mainly by higher soil temperature after clear-cutting (Fig. 4). However, S_{RM} decreased gradually in the later stage because of decreasing the amount of dead roots brought on by clear-cutting (Fig. 6) and lower soil temperature with canopy closure (Fig. 4). At first and second thinnings, calculated S_{RM} increased swiftly temporarily, because of dead roots supplied by thinning (Fig. 6). The facts indicate that the change in S_{RM} is affected well by thinning.

The swift increasing of calculated S_R(=S_{RA}+S_{RM}) just after clear-cutting was derived mainly by the increasing of dead roots and larger decomposition rate of dead root and A_0 layer by higher soil temperature after clear-cutting.

Consequently, the model proposed in the study could simulate successfully the carbon fluxes in regeneration process following clear-cutting, taking forest management into consideration, which is proved by little differences between observation and calculation (p>0.05, by one-way analysis of variance).

The change in carbon accumulation under consideration of management

In Figure 6, calculated M_0 decreased swiftly just after clear-cutting because litterfall was stopped once by clear-cutting, and a 10-year-old stand, it increased gradually and stabilized conclusively around 11 tC ha^{-1} with the recovery of litterfall rate (Fig. 3). In a 18-year-old stand, calculated M_0 increased temporarily by pruning. At first and second thinnings, calculated M_0 decreased because of decrease of L (or Y_L + Y_B) due to thinning. After these thinning, M_0 increased with recovering of L (or Y_L + Y_B) with forest development. These changes in M_0 followed to the change in L (or Y_L + Y_B).

Calculated M_r increased swiftly just after clear-cutting due to large amount of dead roots killed, however, it decreased swiftly from 24 to 3 tC ha^{-1} due to decomposition by itself within few years and then gradually increased by recovery of root turnover, reaching to the asymptotic value (4.5 tC ha^{-1}) around 30-year-old. At first and second thinnings, calculated M_r increased slightly.

Calculated M increased temporarily by humus supply from large amounts of dead roots caused by clear-cutting and then decreased until 10-year-old because decreasing supply of humus from M_0 and higher decomposition rates of mineral soil due to higher soil temperature (Fig. 4). At first and second thinnings, calculated M increased slightly because dead root occurred again by thinning, however, the M seemed to be influenced little by the decrease of litterfall by thinning.

From the above, the results of simulation reflects the effects of forest management (pruning and thinning) on soil carbon accumulation well, suggesting that the model could calculate exactly the soil carbon accumulation even in managed plantation because there is little difference between observation and calculation (p>0.05, by one-way analysis of variance). Based on the model calculation, we could assess how to manage plantations to function more as CO_2 sink.

Comparing between the simulation with and without consideration of management

From the results of approximated simulation (without consideration of forest management), there is little difference between the results of calculation with and without consideration of management. In fact, the amount of carbon accumulation above (Y_T, Y_L+Y_B and L) and below ground (M_0, M and M_r) at 100-year-old with and without consideration of management was closely coincided with each other. Calculated M_0, M and M_r (carbon accumulation below ground) with and without consideration of management at

100-year-old were exactly the same values (M_0, M and M_r were 12.0, 113 and 5.9 tC ha^{-1}, respectively). Calculated Y_T, Y_L+Y_B and L with and without consideration of management at 100-year-old were also the same values (Y_T, Y_L+Y_B and L were 115, 12.9 and 3.23 tC ha^{-1}, respectively). On the other hand, calculated carbon flux rates at 100-year-old with and without consideration of management were 1.69 and 1.47 for S_{RA}, 3.60 and 3.85 for S_{RM}, 5.29 and 5.32 tC $ha^{-1}y^{-1}$ for S_R, respectively, which suggesting slight differences in carbon flux rates between them (p<0.05, by one-way analysis of variance).

Standard error (S.E.) between observed and calculated values with consideration of management was slightly smaller than that without consideration. However, both S.E. are very small, so both models are valid for the calculation of carbon cycling following clear-cutting in Japanese cedar plantations, suggesting that the calculation of carbon cycling could be carried out in the plantation even if its history of management is unknown.

However, for the model application to other cedar plantations, the field data of vegetation dynamics following clear-cutting and environmental conditions (soil temperature and moisture content) before and just after clear-cutting at least should be collected or estimated.

Using the model proposed in the study, we could assess how to manage plantations to function more as CO_2 sink, based on the calculation of change in carbon stock or carbon balance with forest growth or by forest management (e.g., clear-cutting interval), and at least evaluate the soil carbon balance in plantations in a given age or site.

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Figure legends

Fig. 1 Compartment models of soil carbon cycling before (A), just after (B) and regenerating stage (C) following a clear cutting of forest. Boxes: the accumulations, arrows: the flows.

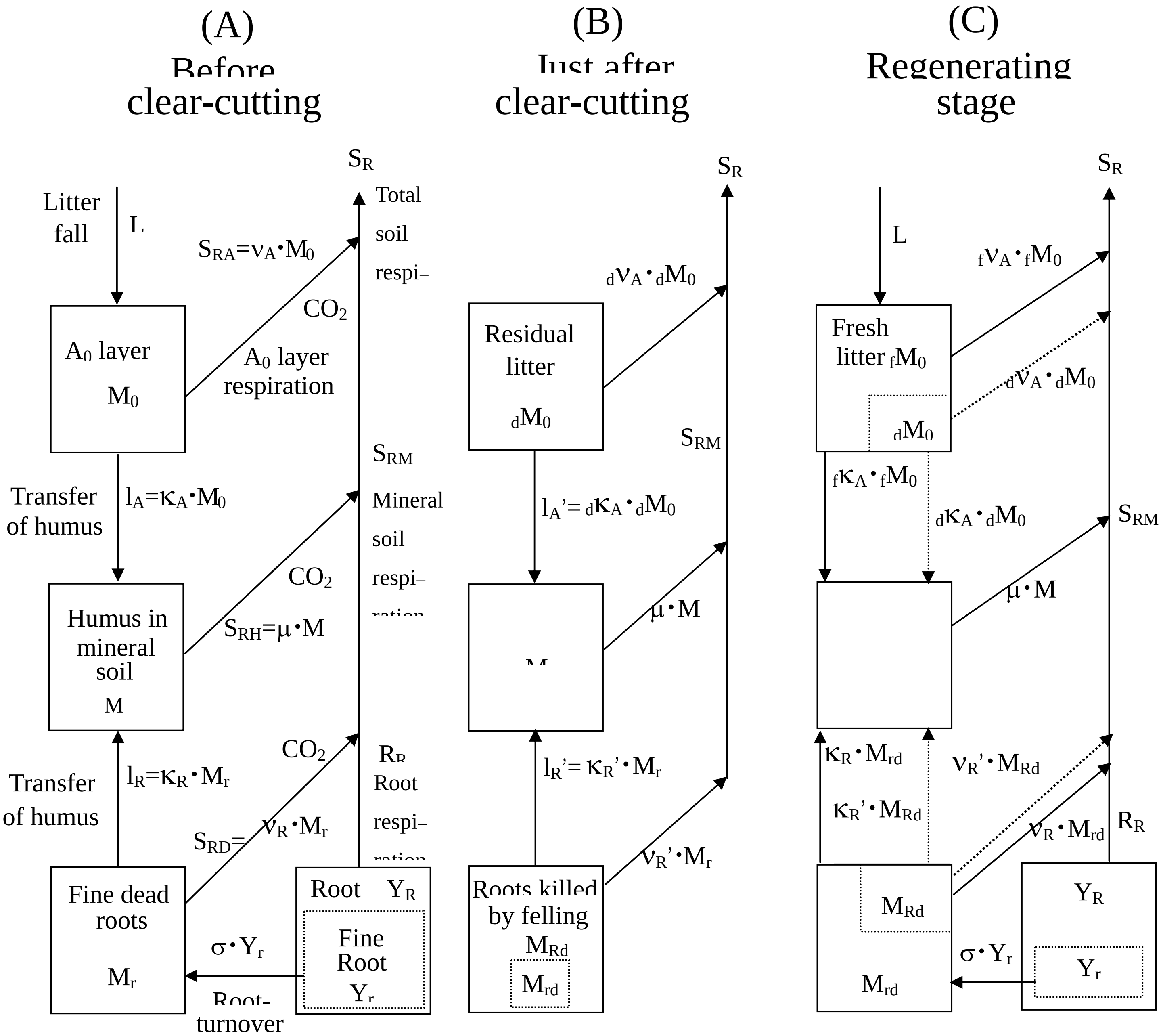
Fig. 2 Above-ground biomass (Y_T, tC ha^{-1}), and branch and leaf biomass ($Y_{L+}Y_B$, tC ha^{-1}) with forest age which were considered the effects of pruning in 21-year-old stand and the thinning in 25- and 50-year-old stands, and not considered the management. The slopes of exponential curves with consideration of management after these pruning and thinning were expected from field observation and stand density control diagram.
━━━ : Y_T (tC ha^{-1}) with consideration of management,——— : Y_L+Y_B (tC ha^{-1}) with consideration of management. ▬ ▬ ▬ : Y_T (tC ha^{-1}) without consideration of management, ------ : Y_L+Y_B (tC ha^{-1}) without consideration of management. ● and ○ are the results of observation in Y_T and Y_L+Y_B, respectively.

Fig. 3 Litterfall rate (L, tC ha^{-1}y^{-1}) with forest age (y) which was considered the effets of pruning in 21-year-old stand and the thinning in 25- and 50-year-old stands in forest age, and not considered the management. The slope of exponential curves after these thinning was expected by Y_T and stand density control diagram. Solid line: L (tC ha^{-1}y^{-1}) with consideration of management, Broken line : L (tC ha^{-1}y^{-1}) without consideration of management. ●: the result of observation.

Fig. 4 Observed soil temperature in 5-, 10- and 10- (calculated one) year-old stands, which are shown against observed that in 60-year-old stand plantation, respectively. • and ○ indicate observed soil temperatures in 5- and 10-year-old stands, respectively.
━━━ and ▬ ▬ ▬ indicate regression lines in 5- and 10-year-old stands plantation, respectively. ——— indicates calculated soil temperature with and without consideration of management in 10-year-old stand.
▒▒▒ represents the inclination of 45^{o}.

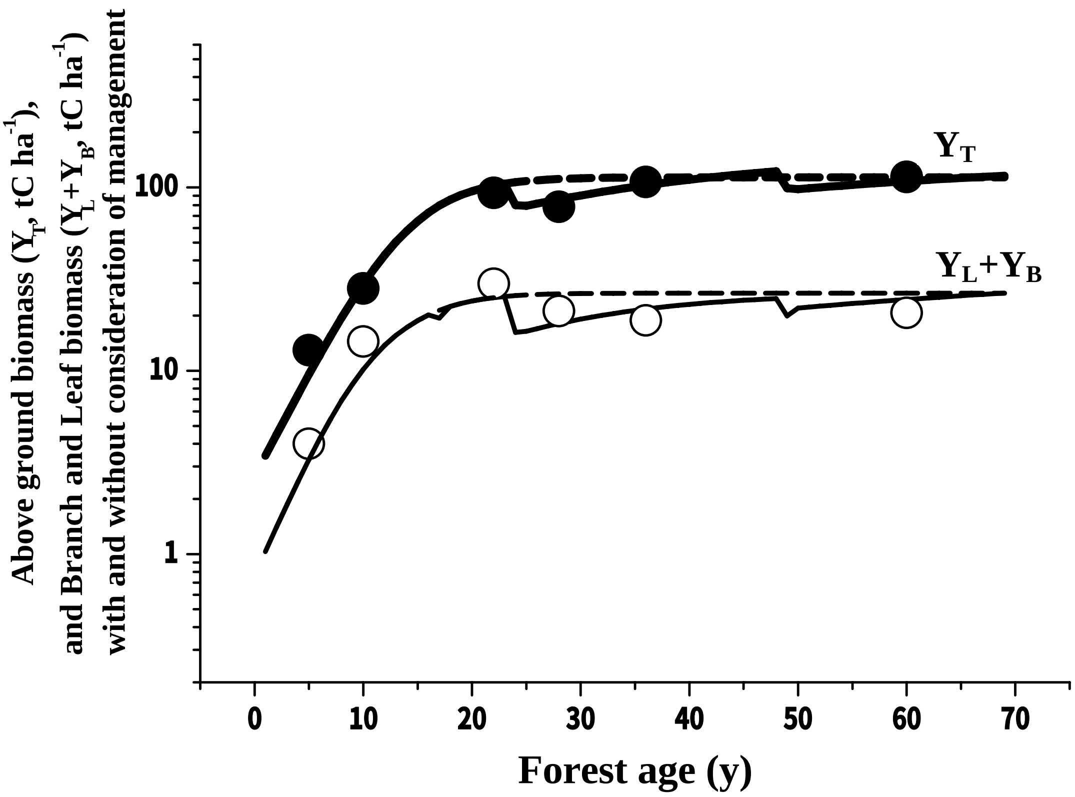
Fig. 5 Respiration rate of A_0 layer (S_{RA}), mineral soil (S_{RM}) and total soil respiration rate (S_R, tC ha^{-1}y^{-1}) with forest age (y) which was considered the effects of pruning in 21-year-old stand and the thinning in 25- and 50-year-old stands, and not considered the management. ━━━ : calculated S_R (tC ha^{-1}y^{-1}) with consideration of management, ▬ ▬ ▬ ▪ : calculated S_R (tC ha^{-1}y^{-1}) without consideration of management ●: observed S_R (tC ha^{-1}y^{-1}), ———— : calculated S_{RM} (tC ha^{-1}y^{-1}) with consideration of management, – – – – – : calculated S_{RM} (tC ha^{-1}y^{-1}) without consideration of management, ○: observed S_{RM} (tC ha^{-1}y^{-1}), ———— : calculated S_{RA} (tC ha^{-1}y^{-1}) with consideration of management, - - - - - - - : calculated S_{RA} (tC ha^{-1}y^{-1}) without consideration of management, ▲: observed S_{RA} (tC ha^{-1}y^{-1}).

Fig. 6 calculated carbon accumulation in A_0 layer (M_0), mineral soil (M) and dead roots (M_R, tC ha^{-1}) with forest age (y) which were considered the effects of pruning in 21-year-old stand and the thinning in 25- and 50-year-old stands, and not considered the management. ————: calculated M_0 with consideration of management, – – – - : calculated M_0 without consideration of management, ●: observed M_0, ———— : calculated M with consideration of management, – – – -: calculated M without consideration of management, ○: observed M, ————: calculated M_R with consideration of management, - - - - - - - -: calculated M_R without consideration of management, ▲: observed M_R.



(A)
Before
clear-cutting
(B)
Just after
clear-cutting
(C)
Regenerating
stage
S_R
Litter fall
I.
Total soil respi–
S_RA=ν_A•M_0
CO_2
A_0 layer
M_0
A_0 layer respiration
S_RM
Transfer of humus
l_A=κ_A•M_0
Mineral soil respi–
CO_2
S_RH=μ•M
Humus in mineral soil
M
CO_2
R_R
Root respi–
Transfer of humus
l_R=κ_R•M_r
S_RD=
ν_R•M_r
Fine dead roots
M_r
σ•Y_r
Root-
turnover
Root Y_R
Fine Root
Y_r
dν_A•dM_0
Residual litter
dM_0
S_RM
l_A'=dκ_A•dM_0
μ•M
l_R'=κ_R'•M_r
ν_R'•M_r
Roots killed by felling
M_Rd
M_rd
L
fν_A•fM_0
Fresh litter fM_0
dν_A•dM_0
dM_0
fκ_A•fM_0
dκ_A•dM_0
S_RM
μ•M
κ_R•M_rd
ν_R'•M_Rd
κ_R'•M_Rd
ν_R•M_rd
R_R
M_Rd
M_rd
σ•Y_r
Y_R
Y_r

Fig. 1



Above ground biomass (Y_T, tC ha^{-1}),
and Branch and Leaf biomass (Y_L+Y_B, tC ha^{-1})
with and without consideration of management
Y_T
Y_L+Y_B
100
10
1
0
10
20
30
40
50
60
70
Forest age (y)

Fig. 2

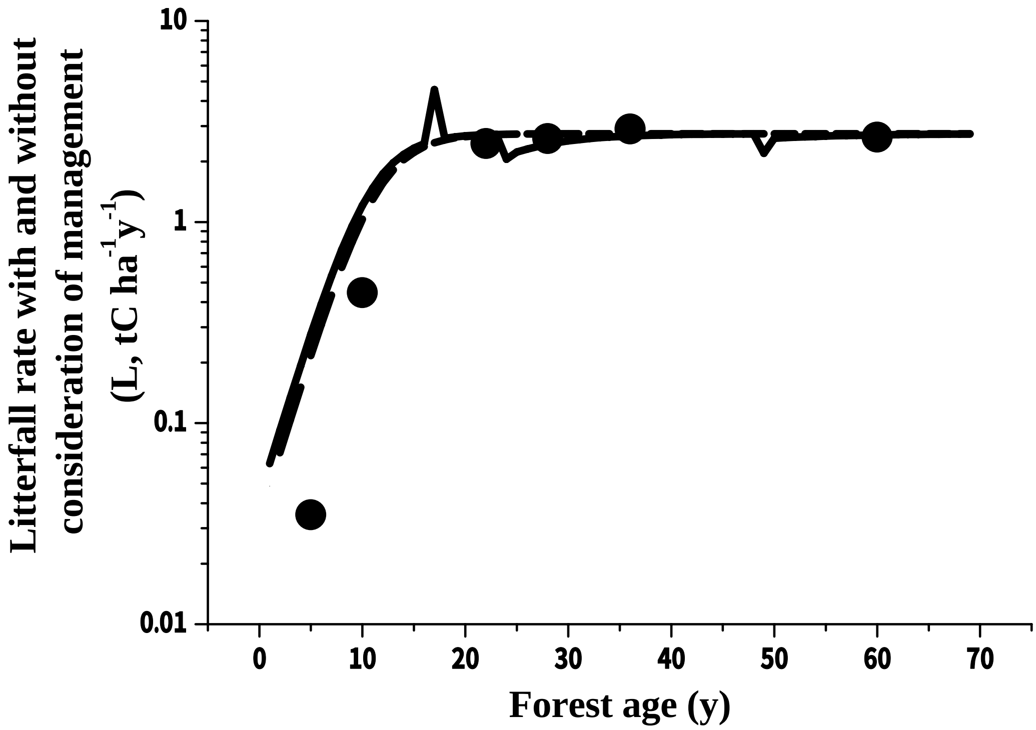

Litterfall rate with and without consideration of management (L, tC ha-1 y-1)
10
1
0.1
0.01
0
10
20
30
40
50
60
70
Forest age (y)

Fig. 3

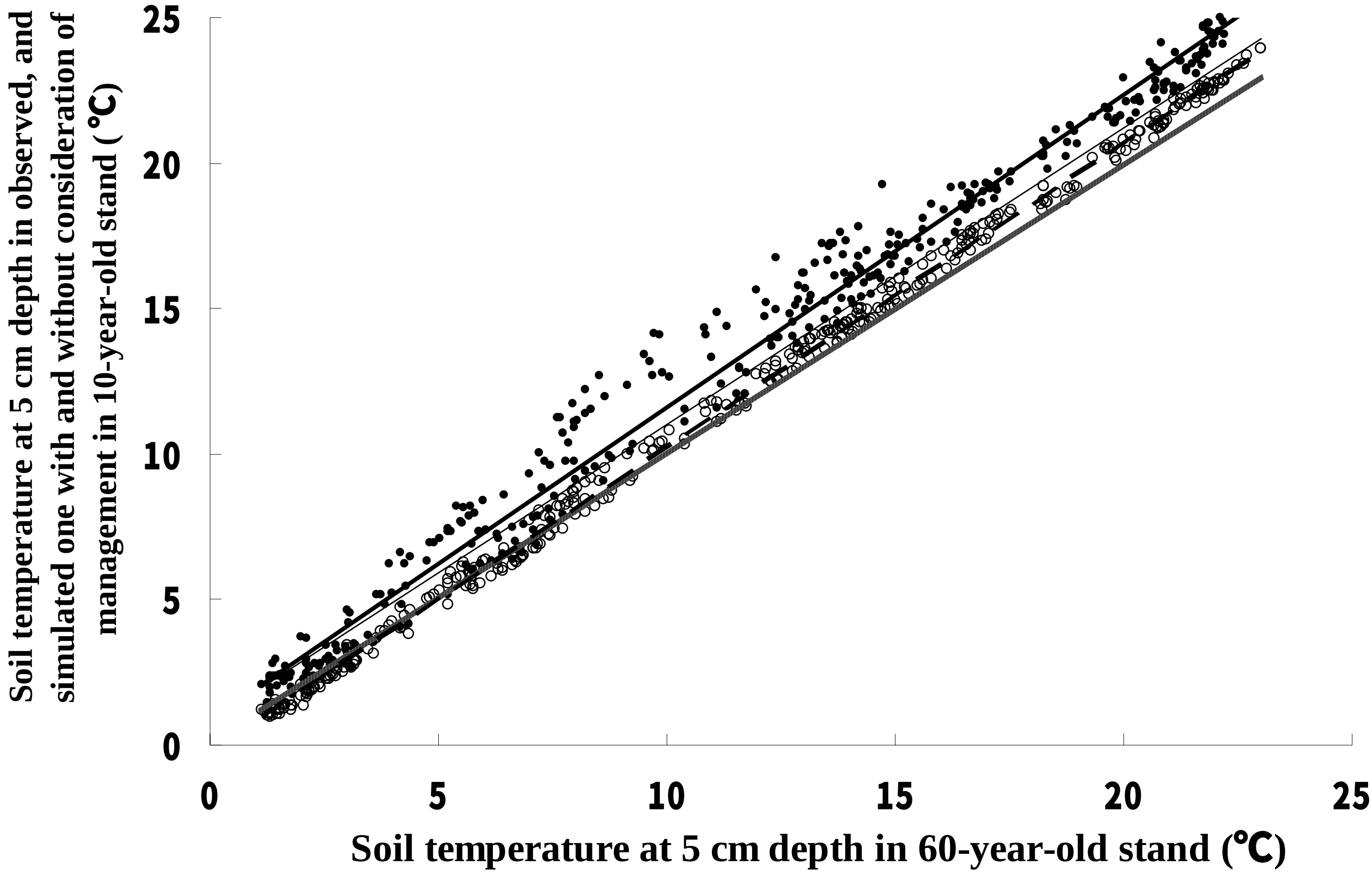
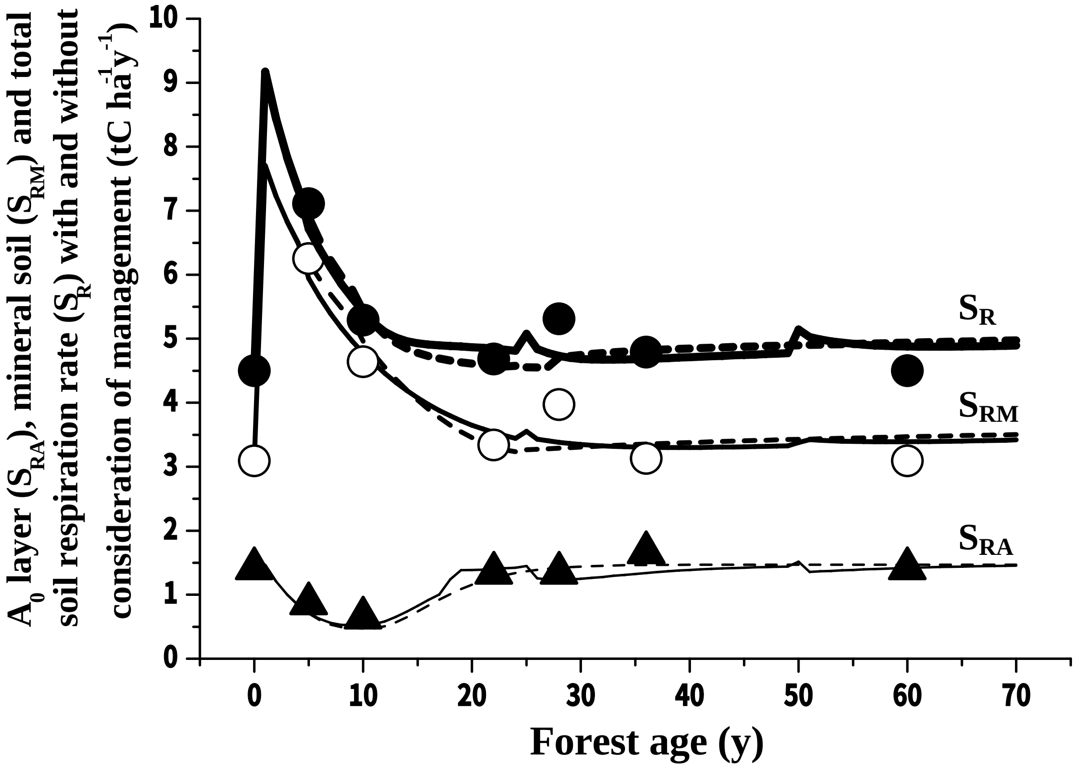
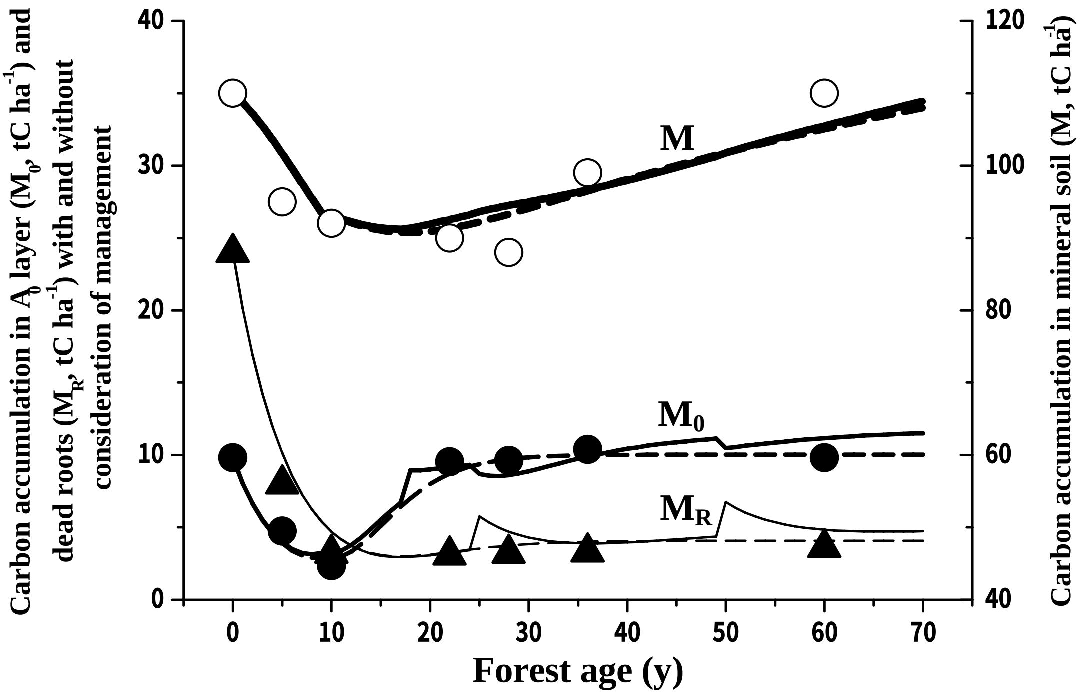

Soil temperature at 5 cm depth in observed, and simulated one with and without consideration of management in 10-year-old stand (℃)
25
20
15
10
5
0
0
5
10
15
20
25
Soil temperature at 5 cm depth in 60-year-old stand (℃)

Fig. 4



A0 layer (SRA), mineral soil (SRM) and total soil respiration rate (SR) with and without consideration of management (tC ha-1 y-1)
Forest age (y)
SR
SRM
SRA
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70

Fig. 5



Carbon accumulation in A0 layer (M0, tC ha-1) and dead roots (MR, tC ha-1) with and without consideration of management
Carbon accumulation in mineral soil (M, tC ha-1)
Forest age (y)
M
M0
MR
0
10
20
30
40
50
60
70
120
100
80
60
40

Fig. 6

Table 1-1. Nomenclature of coefficients and variables used for the simulation of soil carbon cycling with explanations and units

Y_T	Above ground biomass [1]	$g\ m^{-2}$
Y_T*	Asymptotic value of Y_T	$g\ m^{-2}$
a_1	Coefficient related to the initial value of Y_T	
b_1	Relative growth rate constant of Y_T	y^{-1}
Y_L	Leaf biomass [1]	$g\ m^{-2}$
Y_L*	Asymptotic value of Y_L	$g\ m^{-2}$
a_2	Coefficient related to the initial value of Y_L	
b_2	Relative growth rate constant of Y_L	y^{-1}
Y_B	Branch biomass [1]	$g\ m^{-2}$
Y_B*	Asymptotic value of Y_B	$g\ m^{-2}$
a_3	Coefficient related to the initial value of Y_B	
b_3	Relative growth rate constant of Y_B	y^{-1}
Y_r	Fine root biomass	$g\ C\ m^{-2}$
Y_R	Below ground biomass	$g\ C\ m^{-2}$
L	Litterfall rate [1]	$g\ m^{-2}y^{-1}$ or day^{-1}
L*	Asymptotic value of litterfall rate	$g\ m^{-2}y^{-1}$
a_4	Coefficient related to the initial value of L	
b_4	Relative increasing rate constant of L	y^{-1}
c_1	Ratio of fine (ϕ < 1cm) root biomass to leaf biomass	
c_2	Relative rate of root respiration per unit fine root biomass	day^{-1}
ν_A	Relative decomposition rate of A_0 layer	day^{-1}
${}_f\nu_{A0}$*	ν_A at 0 ℃, 300% moisture content before cutting	day^{-1}
λ	Coefficient of temperature response of ${}_f\nu_A$	$°C^{-1}$
μ	Relative decomposition rate of humus in mineral soil	day^{-1}
μ_0*	μ at 0°C, 80% soil moisture content	day^{-1}
ω	Coefficient of temperature response of μ	$°C^{-1}$
V_0*	Optimum water content of A_0 layer for decomposition [2]	%
V_m*	Optimum water content in mineral soil for decomposition [3]	%
ν_R	Relative decomposition rate of dead roots	day^{-1}
ν_{R0}	ν_R of dead fine roots at 0°C	day^{-1}
ν_{R0}'	ν_R of coarse dead roots at 0°C	
ω	Coefficient of temperature response of ν_R	$°C^{-1}$
δ_A	Ratio of ν_A to κ_A (transportation factor of humus from A_0 layer to mineral soil)	
δ_R	Ratio of ν_R to κ_R (transportation factor of humus from dead root to mineral soil)	
σ	Relative turnover rate of fine roots	day^{-1}
M_0	Accumulation of A_0 layer	$g\ C\ m^{-2}$
M	Accumulation of humus in mineral soil	$g\ C\ m^{-2}$
M_r	Accumulation of fine dead roots	$g\ C\ m^{-2}$
M_R	Accumulation of carse dead roots	$g\ C\ m^{-2}$
S_R	Total soil respiration rate	$g\ C\ m^{-2}\ day^{-1}$
S_{RA}	Respiration of A_0 layer (decomposition rate of A_0 layer)	$g\ C\ m^{-2}\ day^{-1}$
S_{RH}	Decomposition rate of humus in mineral soil	$g\ C\ m^{-2}\ day^{-1}$
S_{RD}	Decomposition rate of fine dead roots	$g\ C\ m^{-2}\ day^{-1}$
S_{RM}	Respiration of mineral soil (S_{RH}, S_{RD} and respiration of living roots)	$g\ C\ m^{-2}\ day^{-1}$

(1)$Y = Y^* / (1+a e^{-bt})$, (2)Dry weight basis, (3)Ratio to maximum water holding capacity

Table 1-2. Symbols used only in the carbon cycling compartment model

$\nu_R \cdot M_{rd}$	Decomposition rate of fine dead roots originated from root turnover	$t\ C\ ha^{-1}\ y^{-1}$
$\nu_R' \cdot M_{Rd}$	That of roots killed by felling	$t\ C\ ha^{-1}\ y^{-1}$
$\kappa_R \cdot M_{rd}$	Transportation rate of humus from fine dead roots to mineral soil	$t\ C\ ha^{-1}\ y^{-1}$
$\kappa_R' \cdot M_{Rd}$	That from roots killed by felling to mineral soil	$t\ C\ ha^{-1}\ y^{-1}$
M_{rd}	Accumulation of dead roots originated from fine root turnover	$t\ C\ ha^{-1}$
M_{Rd}	Accumulation of root killed by felling	$t\ C\ ha^{-1}$
$\kappa_A \cdot M_0$	Transportation rate of humus from A_0 layer to mineral soil	$t\ C\ ha^{-1}\ y^{-1}$
${}_f\kappa_A \cdot {}_fM_0$	That from fresh litters supplied by regenerated vegetation to mineral soil	$t\ C\ ha^{-1}\ y^{-1}$
${}_d\kappa_A \cdot {}_dM_0$	That from residual litters accumulated before the felling to mineral soil	$t\ C\ ha^{-1}\ y^{-1}$
${}_f\nu_A$	That of fresh litters	y^{-1}
${}_d\nu_A$	That of residual litters	y^{-1}
κ_A	Transportation factor of humus from A_0 layer to mineral soil	y^{-1}
${}_f\kappa_A$	That from fresh litters to mineral soil	y^{-1}
${}_d\kappa_A$	That from residual litters to mineral soil	y^{-1}
ν_R'	That of roots killed by felling	y^{-1}
κ_R	Transportation factor of humus from fine dead roots to mineral soil	y^{-1}
κ_R'	That from roots killed by felling to mineral soil	y^{-1}
${}_fM_0$	That of fresh litters	$t\ C\ ha^{-1}$
${}_dM_0$	That of residual litters	$t\ C\ ha^{-1}$
${}_f\nu_A \cdot {}_fM_0$	That of fresh litters	$t\ C\ ha^{-1}\ y^{-1}$
${}_d\nu_A \cdot {}_dM_0$	That of residual litters	$t\ C\ ha^{-1}\ y^{-1}$

Table 2. Values of coefficients of the equations for environmental conditions (Eqs 5-7)

	k_1	k_2 (°C)	k_3 (%)	k_4 (% mm^{-1})	k_5 (% mm^{-1})	k_6	k_7 (%)	k_8 (% mm^{-1})	k_9 (% mm^{-1})	k_{10}
Before cutting	0.48	0.2	90	3.2	0.5	0	33	0.37	0.14	0
Just after cutting	1.01	-3.63	56	1.9	0.3	-1.5	33	0.66	0.11	-0.44

Table 3. Values of coefficients and initial conditions with the consideration of forest management used for the simulation of soil carbon cycling after clear-cutting of Japanese cedar

Symbols	Unit	Values				
Vegetation				Forest age (y)		
		default	All stages	0<y≦25 years old	25<y≦50 years old	y>50 years old
Y_T*	t ha^{-1}			227	300	300
a_1				42	4	3
b_1	y^{-1}			0.27	0.06	0.04
Y_L^*	t ha^{-1}		35			
a_2				25	5	5
b_2	y^{-1}			0.32	0.09	0.09
Y_B^*	t ha^{-1}		18			
a_3				100	10	10
b_3	y^{-1}			0.3	0.1	0.1
Y_r	t C ha^{-1}	3.75				
Y_R	t C ha^{-1}	24				
L*	t ha^{-1}		5.5			
a_4				63	35	35
b_4	y^{-1}			0.39	0.2	0.13
c_1			0.0235			
c_2			0.122			

Symbols	Unit	Values			
Soil carbon				Forest age (y)	
		default	All stages	0<y≦10 years old	y>10 years old
$f\nu_{A0}^*$	day^{-1}		1.07×10^{-4}		
λ	°C^{-1}		0.14		
μ_0^*	day^{-1}			5.6×10^{-5}	2.1×10^{-5}
ω	°C^{-1}		0.053		
V_0^*	%		300		
V_m^*	%		80		
δ_A				5	1.3
δ_R			1.8		
σ	day^{-1}		8.22×10^{-4}		
ν_{R0}	day^{-1}		1.9×10^{-4}		
ν_{R0}'			2.8×10^{-4}		
ω'	°C^{-1}		0.033		
M_0	t C ha^{-1}	9.8			
M	t C ha^{-1}	110			
M_r	t C ha^{-1}	3.6			

Table 4. Values of coefficients and initial conditions without consideration of forest management used for the simulation of soil carbon cycling after clear-cutting of Japanese cedar

Symbols	Unit	Values
Vegetation		
Y_T*	t ha^{-1}	227
a_1		42
b_1	y^{-1}	0.27
Y_L^*	t ha^{-1}	35
a_2		25
b_2	y^{-1}	0.32
Y_B^*	t ha^{-1}	18
a_3		100
b_3	y^{-1}	0.3
Y_r	t C ha^{-1}	3.75
Y_R	t C ha^{-1}	24
L*	t ha^{-1}	5.5
a_4		82
b_4	y^{-1}	0.39
c_1		0.0235
c_2		0.122

Soil carbon				Forest age (y)	
		default	All stages	0<y≦10 years old	y>10 years old
${}_f\nu_{A0}^*$	day^{-1}		1.07×10^{-4}		
λ	°C^{-1}		0.14		
μ_0^*	day^{-1}			6.5×10^{-5}	3.1×10^{-5}
ω	°C^{-1}		0.053		
V_0^*	%		300		
V_m^*	%		80		
δ_A				5	1.15
δ_R			1.8		
σ	day^{-1}		8.22×10^{-4}		
ν_{R0}	day^{-1}		1.9×10^{-4}		
ν_{R0}'			2.8×10^{-4}		
ω'	°C^{-1}		0.033		
M_0	t C ha^{-1}	9.8			
M	t C ha^{-1}	110			
M_r	t C ha^{-1}	3.6			