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Biogeochemical forest model for evaluation of ecosystem services (BGC-ES) and its application in the Ise Bay basin

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Abstract

Forest ecosystem services (ES), including water resources, carbon sequestration, nitrogen absorption, timber production, and sediment production in the Ise Bay basin, were estimated using a process-based biogeochemical forest model (the BGC-ES model and the RUSLE). This model was proposed and studied in the Yahagi river basin by some of the authors. To evaluate the ES on a 5-km-mesh scale, simulations from 1960 to 2040 were carried out under the following scenarios: an artificial forest under standard management (FM) and under forest management abounded from 1990 (AFM). Forest management practices strongly affected carbon sequestration and timber volume compared to other ES related to forest area.

Keywords: Carbon sequestration rate; Ecosystem services; Process-based biogeochemical model of forest ecosystem (BGC-ES); Woody biomass

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1. Introduction

In Japan, the forest ecosystem covers approximately 68% of the total land surface. Goods and services from ecosystems are known as ecosystem services (ES; Millennium Ecosystem Assessment, 2005)0 and include carbon sequestration, timber production, water supply management, water quality control, disaster control, biodiversity conservation, cultural services, etc. However, Japanese artificial (plantation) forests are currently not well-managed by the Japanese forestry system, resulting in degradation of forest ES.

ES from a forest may change with management and conservation; however, ES were estimated by an oversimplified method in previous studies. In the calculations of the ecological footprint (Ewing et al, 2010)0, a forest absorbed carbon is calculated at a fixed rate. In the geographic information system (GIS) application for ES estimation from land use (InVEST; Tallis et al., 2011)0, the sequestration rate was estimated by a linear function regardless of the type of forest and management. Based on these simplified methods, the carbon sequestration rate depends primarily on forest area.

In practice, changes in ES should be evaluated under various conditions and scenarios. Consequently, reliable process-based ecosystem models are needed for a more detailed ES evaluation.

Recently, a new biogeochemical forest model—the BGC-ES model—was studied for the evaluation of forest ES in the Yahagi river basin, Japan (Ooba et al., 2010)0. This biogeochemical model was designed to simulate water, carbon, and nitrogen cycles in forest ecosystems. In the BGC-ES model, submodels of tree populations and an allometry that were validated by observations in Japanese forests have been incorporated, and mass cycles were considered as dynamic processes. Therefore, the feedback effects between forest management practice and ES can be clearly quantified using the model.

To evaluate ES, we collected forest data (inventories and maps) as well as environmental data in the Ise Bay basin in the Chubu region, Japan. More specifically, changes in the ES under different forest management scenarios were evaluated in the Ise Bay basin by the BGC-ES model on a 5-km-mesh scale. In addition, sediment production with respect to forest slope was also estimated.

2. Materials and methods

2.1. BGC-ES model

The BGC-ES model was developed according to the logic of the Biome-BGC model version 4.1.2 (Thornton et al., 2002)0. However, we modified many equations of the Biome-BGC model to incorporate more detailed processes (Ooba et al., 2010)0. The model consists of the following four submodels: biomass, water cycle, carbon-nitrogen (CN) cycle, and forest management.

A forest was assumed to consist of homogeneous tree species, and age and understory vegetation were ignored. Mixed forest stands (e.g., stands of broadleaf and needleleaf or mixed-age stands) were classified into homogeneous forest units based on their crown area. Forest biomass was estimated using a growth equation together with management charts. However, under insufficient light and nitrogen availability, biomass growth was controlled. The daily water cycle and yearly carbon and nitrogen cycles were simulated under forest management practices (thinning and forest updating).

The previous description (Ooba et al., 2010)0 had some minor problems. The minor revised BGC-ES (version 1.1) is explained in the following subsections.

2.2. Biomass submodel

An increase in the averaged tree height h depends primarily on the forest age t (y),

$$h = sc\, h_{\max}\, hf(t), \qquad (1)$$

where sc is the site coefficient (0.8 to 1.2), h_{max} is the maximum height (m), and $hf(t)$ is the growth function, which is an equation of Mitscherlich or Gompertz. These parameters were derived from the National Forest Resource Database (National Institute for Environmental Studies, 2007)0. This equation was corrected from Ooba et al. (2010)0, Eq. (1).

In a plant ecosystem consisting of one species, maximum population N_{max} (ha^{-1}) is related to maximum trunk volume V_{max} (m^3 ha^{-1}) (Yoda et al., 1963)0 by

$$V_{max} = \kappa N_{max}^{-\alpha}, \tag{2}$$

where κ and α are parameters. The current population N (ha^{-1}) and volume V (m^3 ha^{-1}) have the following relationship,

$$1 = V/(\kappa^* N_0^{-\alpha})+N/N_0, \tag{3}$$

where N_0 is N when $t = 0$, and κ^* is a parameter. In addition, N, V, and h have the following relationship,

$$V^{-1} = p_a h^{p_b} + p_c h^{p_d}/N, \tag{4}$$

where p_a, p_b, p_c, and p_d are parameters. The parameters in Eqs. (2)–(4) were given or derived from management charts of the domestic artificial forests (Japan Forest Technical Association, 1999; Ooba et al., 2010, Appendix A)00.

An individual tree has the following five components: leaf (**L**), branch (**B**), trunk (**T**), root (**R**), and fine root (**F**). Tauchi and Utsugi (2004)0 proposed the following allometry relationship. The above-ground biomass is related to the tree volumetric factor V_v by

$$b[\mathbf{x}] = b_a^{\mathbf{x}} V_v^{\,b_b^{\mathbf{x}}}, \tag{5}$$

where $b[\mathbf{x}]$ is the biomass in component **x** (kg-dw $tree^{-1}$), and $b_a^{\mathbf{x}}$ and $b_b^{\mathbf{x}}$ are parameters for **x** (Ooba et al., 2010; Table. 1)0. V_v is derived from $b[\mathbf{T}] = \rho_T V/N$, where ρ_T is the trunk density (kg-dw m^{-3}).

$b[\mathbf{R}]$ is proportional to the above-ground biomass at a rate of $b_a^{\mathbf{R}}$ (Tauchi and Utsugi, 2004)0,

$$b[\mathbf{R}] = b_a^{\mathbf{R}} \Sigma\, b[\mathbf{x}], (\mathbf{x} = \mathbf{L}, \mathbf{B}, \mathbf{T}). \tag{6}$$

An increase in the amount of fine root in dry and poor fertility soil, $b[\mathbf{F}]$, was assumed to be negatively related to sc according to Noguchi et al. (2007; Fig. 1)0,

$$b[\mathbf{F}] = b_a^{\mathbf{F}} \Sigma\, b[\mathbf{x}], (\mathbf{x} = \mathbf{L}, \mathbf{B}, \mathbf{T}, \mathbf{R}), \tag{7}$$

$$b_a^{\mathbf{F}} = (-2.5sc + 4) b_a^{\mathbf{F}\,\mathrm{base}}, \tag{8}$$

where $b_a^{\mathbf{F}\,\mathrm{base}}$ is a parameter.

The amounts of biomass and carbon in component **x** of the forest were estimated by $B[\mathbf{x}] = Nb[\mathbf{x}]$ and $C_C[\mathbf{x}] = c_C B[\mathbf{x}]$, respectively (the rate of carbon content, $c_C = 0.5$). The amount of nitrogen $C_N[\mathbf{x}]$ was calculated from the CN ratio for component **x** ($cn^{\mathbf{x}}$).

2.2.1. Water cycle submodel

The radiation balance and water balance were estimated from the following daily metrological data: air temperature, vapor pressure deficit, mean shortwave radiation during the daytime, precipitation, and day length. Energy and water-exchange surfaces were intercepted water surfaces, shade leaf, sun leaf, soil surface, and snow surface, of which the areas change under physical and biophysical processes.

Precipitation, P (mm), is snowfall if the air temperature is lower than a critical value (3 °C). For rainfall, part of the precipitation was intercepted, I_c (mm d^{-1}),

$$I_c = \min(pr_I L_a, P), \tag{9}$$

where L_a (m^2 m^{-2}) is the total leaf area, pr_I is the rate of interception (0.1 mm m^2 m^{-2}), and min() is the minimum function (corrected from Ooba et al., 2010; Eq. (B5))0.

The potential evapotranspiration rate was estimated by the Penman-Monteith equation (Monteith and Unsworth, 1990)0. Stomatal conductance was calculated from shortwave radiation, vapor pressure deficit, and leaf water potential. The actual evapotranspiration rate, $E_a[\mathbf{f}]$ (mm d^{-1}), was estimated from the amount of intercepted water, day length, leaf area index, and soil dryness (Ooba et al., 2010, Appendix B)0.

The amount of soil water W_t (mm) after daily effective precipitation P_n (mm d^{-1}) and evapotranspiration was calculated by

$$W_t = W[\mathbf{o}] + P_n - \Sigma E_a[\mathbf{f}], \tag{10}$$

where $W[\mathbf{o}]$ is the current soil moisture (mm).

To calculate runoff water (surface and subsurface layer flows), two critical values were used. $W[\mathbf{o}]^{sat}$ is the saturated soil water content (soil water potential: −0.05 MPa). $W[o]^{FC}$ is the field capacity (soil water potential: −0.015 MPa). A daily runoff R_d (mm d^{-1}) was estimated by

$$R_d = \begin{cases} W_t - W[\mathbf{o}]^{sat}, & (W_t > W[\mathbf{o}]^{sat}), \\ c_r(W_t - W[\mathbf{o}]^{FC}), & (W[\mathbf{o}]^{sat} > W_t > W[\mathbf{o}]^{FC}), \\ 0, & \text{(other)}, \end{cases} \tag{11}$$

where c_r is an empirical parameter. At the next day, $W[\mathbf{o}] = W_t - R_d$.

2.2.2. Carbon and nitrogen cycle submodel

In this submodel, yearly CN flux values were calculated. Leaf litter and dead trees were added to four litter pools (**L1** to **L4**) and coarse woody debris (**CWD**). Soil comprised the following four pools: fast, medium, and slow microbial pools and a recalcitrant soil organic matter pool (**S1** to **S4**), into which decomposed mass in the litter pools flowed. A pool of soil mineral nitrogen (**SMN**), which can be directly supplied to plants and soil microbes, played a key role in controlling plant growth and accumulating litter and soil (Ooba et al., 2010; Fig. 2)0.

In this study, the yearly rate of carbon absorption A_C (kg-C ha^{-1} y^{-1}) was defined as

$$A_C = \Sigma \Delta_a C_C[\mathbf{x}], \tag{12}$$

where $\Delta_a C_C[\mathbf{x}]$ is a change in the amount of carbon in the component or pool **x** (kg-C ha^{-1} y^{-1}). The definition of A_C was changed from that of Ooba et al. (2010; Eq. (C34)). In the calculation of A_C, timber removal from the forest was considered a release of carbon. A yearly carbon sequestration rate, S_C, was defined as

$$S_C = A_C + c_C \rho_T (U^{thin} + U^{update}), \tag{13}$$

where ρ_T is trunk density (kg m^{-3}), and U^{thin} and U^{update} are yearly rates of timber production due to thinning and forest updates, respectively (m^3 ha^{-1} y^{-1}).

For a plant component **x**, $\Delta_a C_C[\mathbf{x}]$ was estimated by

$$\Delta_a C_C[\mathbf{x}] = C_C[\mathbf{x}](t+1)^{est} - C_C[\mathbf{x}](t), \tag{14}$$

where $C_C[\mathbf{x}](t+1)^{est}$ and $C_C[\mathbf{x}](t)$ are carbon amounts in **x** at the current and the next year, respectively (kg-C ha^{-1}). Equation (14) was corrected from Ooba et al. (2010; Eq. (C20))0. Dead tree and tree biomass turnover were added to the pool of litter and **CWD** by the biomass submodel.

For a non-plant component, $\Delta_a C_C[\mathbf{x}]$ was represented by a balance of mass flux and decomposition of **x**,

$$\Delta_a C_C[\mathbf{x}] = \Sigma F_Q[\mathbf{y}, \mathbf{z}]^C - F_{ao}[\mathbf{x}]^C, \tag{15}$$

where $F_Q[\mathbf{y}, \mathbf{z}]$ is a mass flux by type Q (decomposing, dead, turnover, and forest management practice) from components **y** to **z** (kg-C ha^{-1} y^{-1}), and $F_{ao}[\mathbf{x}]^C$ is the actual decomposition rate of **x** (kg-C ha^{-1} y^{-1}). $F_{ao}[\mathbf{x}]^C$ depends on the decomposition rate and the nitrogen content in **SMN**, $C_N[\mathbf{SMN}]$. The decomposition rate depends on soil temperature and water potential (Ooba et al., 2010; section 2.5, Appendix C.2)0.

Nitrogen in the plant component moved into **CWD** and litter pools by turnover (Ooba et al., 2010, Appendix C)0. In soil pools, the contents of nitrogen were kept constant (Ooba et al., 2010; Table A1)0, and nitrogen exchange occurred between soil pools and **SMN**.

Nitrogen demand from the soil, D_I^N (kg-N ha^{-1} y^{-1}), and plants, D_P^N, are competitive. When the sum of potential demands was larger than $C_N[\mathbf{SMN}]$, the two processes were restricted. The actual rate of supply from **SMN**, pl_N, was defined by

$$pl_N = \begin{cases} C_N[\mathbf{SMN}]/(D_I^N+D_P^N), & (C_N[\mathbf{SMN}]<D_I^N+D_P^N), \\ 1. & \text{(other)}, \end{cases} \tag{16}$$

For a given component, **y**, the actual decomposition rate was estimated by

$$F_{ao}[\mathbf{y}]^Z = pl_N F_{po}[\mathbf{y}]^Z, \tag{17}$$

where $F_{po}[\mathbf{y}]^Z$ is the potential decomposition rate, and Z is an element (C or N). When $pl_N<1$, plant absorption from **SMN** was limited to $pl_N D_P^N$.

A change in $C_N[\mathbf{SMN}]$ was described as

$$\Delta C_N[\mathbf{SMN}] = \Sigma F_{as}[\mathbf{y}, \mathbf{z}]^N + F_{fix}^N + F_{dep}^N - F_{den}^N - F_{leach}^N, \tag{18}$$

where $F_{as}[\mathbf{y}, \mathbf{z}]^N$ is the nitrogen flux from **SMN** to **z** compensated by the nitrogen flux from **y** to **z**, and F_{fix}^N, F_{dep}^N, F_{den}^N, and F_{leach}^N are yearly nitrogen fixation rates, nitrogen decomposition, denitrification, and nitrogen leaching, respectively (kg-N ha^{-1} y^{-1}). F_{leach}^N depends on yearly integrated R_d and $C_N[\mathbf{SMN}]$ (Ooba et al., 2010; Eq. (C33))0.

2.2.3. Forest management submodel

Forest management practices were assumed to be thinning (population control) and clear cutting (forest update) (Ooba et al., 2010; section 2.6, Appendix E)0.

For thinning, the population decreased to N^{thin},

$$N^{thin} = (1 - \lambda_{thin})N, \tag{19}$$

where λ_{thin} is the rate of thinning. Thinning assumed that the initial population N_0 changes to a new value N_0^{thin}, which is obtained from Eqs. (3) and (4), with constant h. Part of the timber produced by thinning was removed from the forest as wood material, while the unremoved timber remained in the forest.

In an updating forest, it was assumed that the update process starts at the beginning of each year and requires one year for completion. During the process, turnover and natural mortality do not occur in the forest. The trunk is completely removed from the forest, and the other components are added to the litter pools.

2.2.4. Parameters and parameterization of BGC-ES

Plant ecophysiological parameters and soil parameters were determined based on the tree type and forest soil in Japan. The default values of the parameters indicated by Ooba et al. (2010)0 were used. Some parameters (stomatal conductance, runoff coefficient (c_r), and leaching coefficient) required adjustment using observation data and were also the parameterized value of Ooba et al. (2010)0 because the Ise basin contains the Yahagi river basin, which was the study area of Ooba et al. (2010)0.

2.3. Estimation of sediment production

Sediment production from the forest area, S_y (t ha^{-1} y^{-1}), by rainfall erosion was estimated by the revised universal soil loss equation (RUSLE; Renald et al., 1997)0,

$$S_y = R\,K\,L\,S\,C\,P_r. \tag{20}$$

R is the rainfall-runoff erosivity factor (mm MJ ha^{-1} h^{-1} y^{-1}). In the original equation, R was estimated from half-hourly rainfall data. We used a simplified calculation from hourly data proposed by Hosoyamada and Fujiwara (Kitahara et al., 2000)0.

K is the soil factor (Mg h mm^{-1} MJ^{-1}). Taniyama (2003)0 indicated values of K according to Japanese standard soil classification.

L and S are the slope length and steepness factor, respectively, calculated by the RUSLE.

C is the cover and management factor. Kitahara (2002; Table 1)0 summarized observed C in Japanese forests. Although the data vary, the following approximation was assumed. For a managed artificial forest aged t (y),

$$C = \begin{cases} 0.01257 - 1.114\times10^{-4}\,t, & (t < 40), \\ 0.008 - 6.667\times10^{-5}(t-40), & (40 \le t < 100), \\ 0.004, & (100 \le t). \end{cases} \tag{21}$$

For an unmanaged artificial forest and natural forest, C was assigned to be a constant value (0.01257 and 0.012, respectively).

P_r is the support practice factor and was assumed to be 1.

2.4. Study area and GIS database

In the upper stream area of the Ise basin, a large portion of the basin is covered by artificial forests (Japanese cedar, *Cryptomeria japonica*, and Japanese cypress, *Chamaecyparis obtusa*). In the middle stream, there are many secondary forests (species of *Quercus*, e.g., *Q. acutissima* and *Q. serrata*). There is insufficient management of these artificial and secondary forests. The flat lands in the bay basin is bordered by agricultural lands and urban areas (Nagoya city), which include industrial zones.

We collected datasets of both natural and social environments based on various resources (e.g., the Digital National Land Information by MLIT, Japan). Forest inventories, yield tables, and forest maps in 2007 were also collected from administrative agencies. Our GIS database (Fig. 1) includes the following attributions at stand-level (average area: ca. 52 ha): forest type, tree species, age, timber volume, site class, location, and shape. The dataset was assumed to be representative of 2000.

Past forest area and distribution were estimated from the 1960 census of agriculture and forestry in Japan (Ministry of Agriculture and Forestry Government of Japan, 1960). These statistics contained the area of the artificial and natural forests at a municipality level.

The forest polygons in 1960 and 2007 were converted to a 5-km mesh published by the Biodiversity center of Japan.

Parameters required in Eq. (21) were obtained by GIS (ArcGIS 9.2 and the spatial analyst tools).

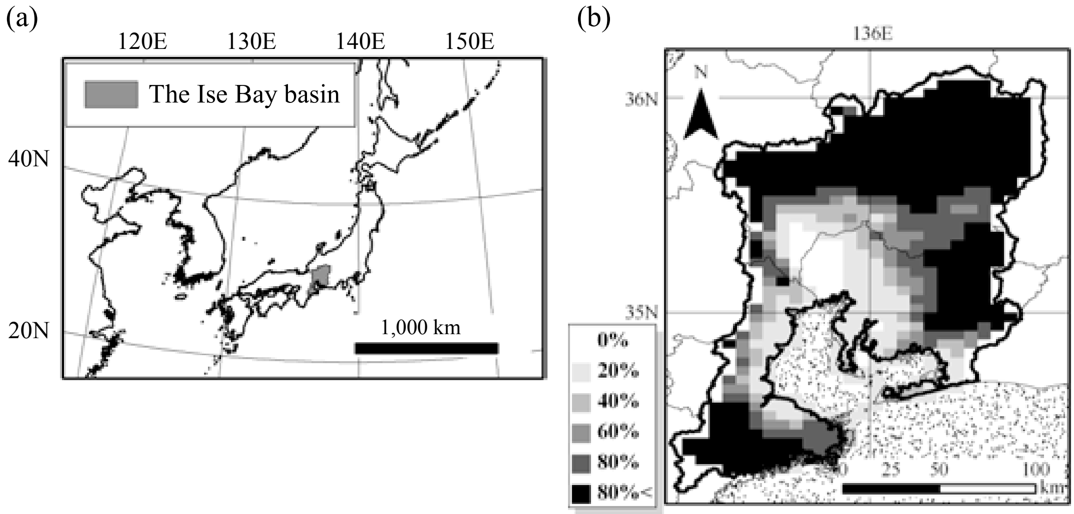


Fig. 1 The Ise bay basin. (a) Location, (b) Percentage of forest covers at the 5-km-mesh

2.5. Simulation conditions and forest scenarios

We introduced the following mesh-based simplification of the entire simulation over the Ise Bay basin.

The dominant tree types for artificial and natural forests were determined in each 5-km mesh, and simulations were carried out using ecophysiological parameter sets of dominant tree types. In each mesh, we assumed that the area of the artificial and natural forests changed linearly from 1960 to 2000, and after 2000, these areas did not change.

To estimate the effect of forest management practices in an artificial forest, two scenarios were applied: continuous management (FM) and management abounded from 1990 (AFM). Plantation density (N_0) was 3000 ha^{-1}, rotation length (harvest age) was 50 y, and thinning was carried out five times (λ_{thin} = 0.15 to 0.20). Forty percent of the trunks harvested during thinning were left and decomposed in the forest ecosystem. In the FM scenario, the practice area was not limited in order to evaluate the maximum effect of forest management on ES. In these scenarios, natural forests were not considered to be managed by either thinning or updating.

A metrological database for 46 observation stations in the basin was built from 1998 to 2007. For past and future simulations, the database was applied repeatedly. Each simulation in a mesh was assigned to a metrological data sequence of a neighborhood station by a Thiessen polygon. The site coefficient (*sc*), soil type, and nitrogen concentration of rain were fixed at 1.0, the medium-moist soil type, and 0.8 mg-N L^{-1}, respectively.

Based on the forest database, area-averaged forest ages of the artificial and natural forests in each mesh were calculated. Each forest was simulated from its year of plantation, referred to as the calculated forest age. Prior to the year of plantation, the tree type in the artificial forest was assumed to be that of the natural forest in the same mesh (spin-up simulation). In the spin-up simulation, the forest unit was updated by clear cutting and cyclic plantation (250 years), and the end of the spin-up simulation was indicated by the attainment of a steady state in the carbon and nitrogen balance of the ecosystem.

3. Results and discussion

3.1. Changes in the forests of the Ise Bay basin

In 1960, natural forests occupied a large area (ca. 613,000 ha), and timber volume was the same as that of artificial forests in the Ise Bay basin (4.77 and 4.16×10^7 m^3). After 47 years, the area of the natural forest decreased (393,000 ha) because almost all of the deceased forest was converted to an artificial forest (the extensive forest conversion in Japan). The area of artificial forests increased from 344,000 ha (1960) to 537,000 ha (2007). The timber volume of the artificial forest in 2007 was about two times larger than that in 1960 (10.3×10^7 m^3).

3.2. Changes in forest ES under different scenarios

To understand the effect of forest management, summations of 10-year-averaged ES for the entire forest in the basin were separated into that of the natural forest and the artificial forest. The area of both natural and artificial forests changed, and then the summation of ES were normalized by the total area of each forest type (Fig. 2).

3.2.1. Timber volume (V)

Area-averaged timber volume, V (m^3 ha^{-1}), in the natural forest increased at a constant rate up to 2040. V of AFM in 2040 was larger than that in 1960; however, the rate of increase approached 0. V of FM changed to around 120 m^3 ha^{-1} due to a large share of 40- to 60-aged forests in 2000 as a result of the extensive forest conversion around 1960, and these forests were updated simultaneously in 2000–2020. This can be avoided by limiting the practice area.

3.2.2. Yearly runoff rate (R_y)

The yearly area-averaged runoff rate (R_y) from forests to streams decreased in the natural forest. An integrated value of R_y inside the basin decreased more rapidly until 2000 due to an area decrease of the natural forest. R_y of the artificial forest increased from 1960 to 1970 due to forest growth, and R_y fluctuated after 1970. There was no clear difference between R_y under FM and AFM.

3.2.3. Carbon sequestration rate (S_C)

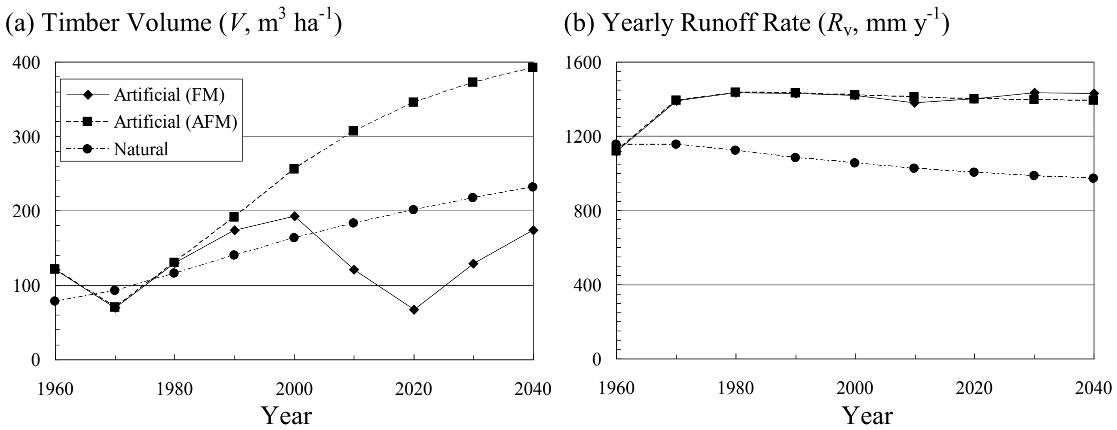
In both natural and artificial forests in 1960, area-averaged S_C values were negative because of the extensive forest conversion. S_C of the natural forest indicated a peak value of 880 kg-C ha^{-1} in 2000 and decreased gradually. S_C of FM showed a large change due to forest updating. An averaged S_c under FM from 2000 to 2040 was 1000 kg-C ha^{-1}. S_C of AFM decreased after 1990 and was lower than that of the natural forest in 2040.

Although the forest area changed until 2000, the integrated value of S_C inside the basin indicated nearly the same time series trend as the area-averaged S_C.

3.2.4. Nitrogen leaching (F_{leach}^N)

Area-averaged F_{leach}^N of the natural forest decreased until 2000. F_{leach}^N of the artificial forest increased until 1980, regardless of the management practice, and deceased gradually. F_{leach}^N of FM showed a large change with large-area forest updating due to harvesting.

3.2.5. Sediment production (S_y)



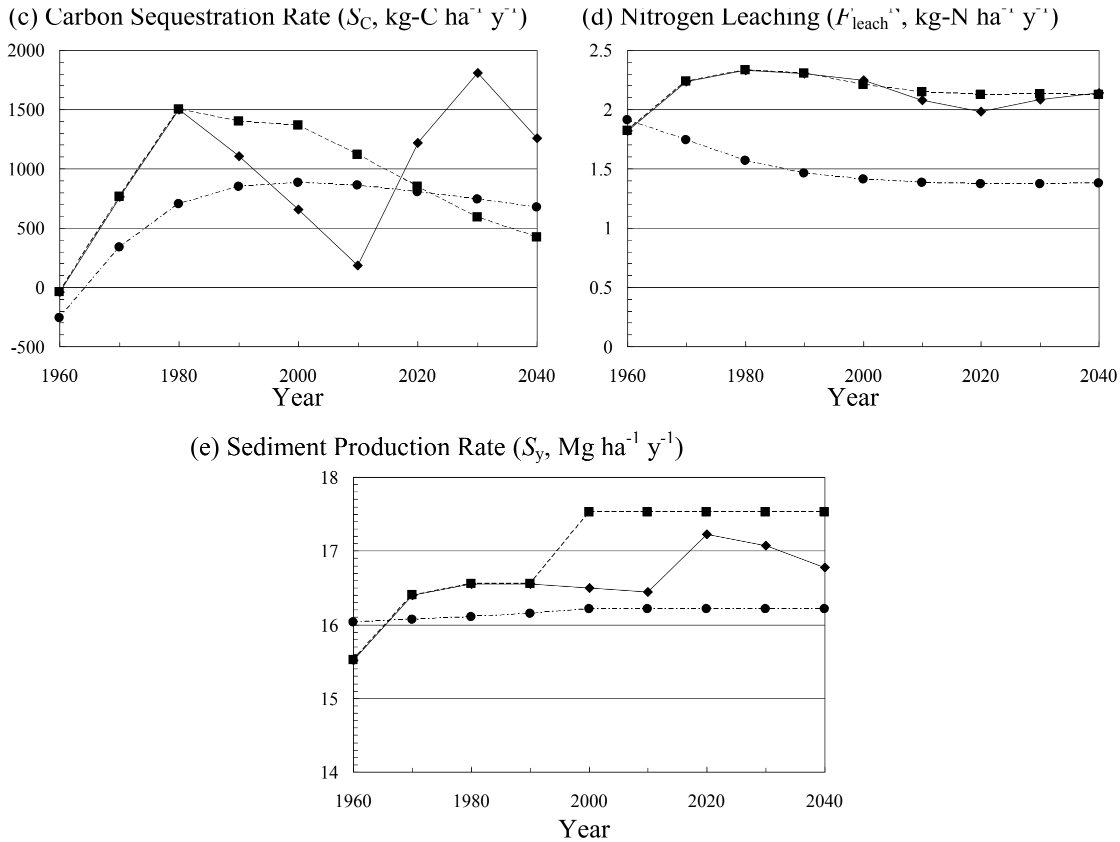


Fig. 2 Change of area-averaged 10-years-averaged ES from forests

S_y of the natural forests was almost constant. S_y increased from 1990 under the AFM scenario because the *C* factor in the RUSLE for an unmanaged forest was set to a larger value than that for a managed forest. S_y of the artificial forest under the FM scenario fluctuated with forest updates.

3.3. Relationship between ES and forest area

Clear linear relationships to the forest area were indicated by runoff and nitrogen leaching in a mesh (Figs. 3b and d). Thus, forest management has little effect on hydrological processes in the BGC-ES model (R_y and F_{leach}^N).

However, ES of timber volume and carbon sequestration were not linearly related to forest area. ES of *V* and S_C might depend on forest management (Figs. 3a and c). Under the FM scenario, *V* and S_C had a positive correlation in 2040, but under the AFM scenario, a correlation was not indicated (Fig. 4).

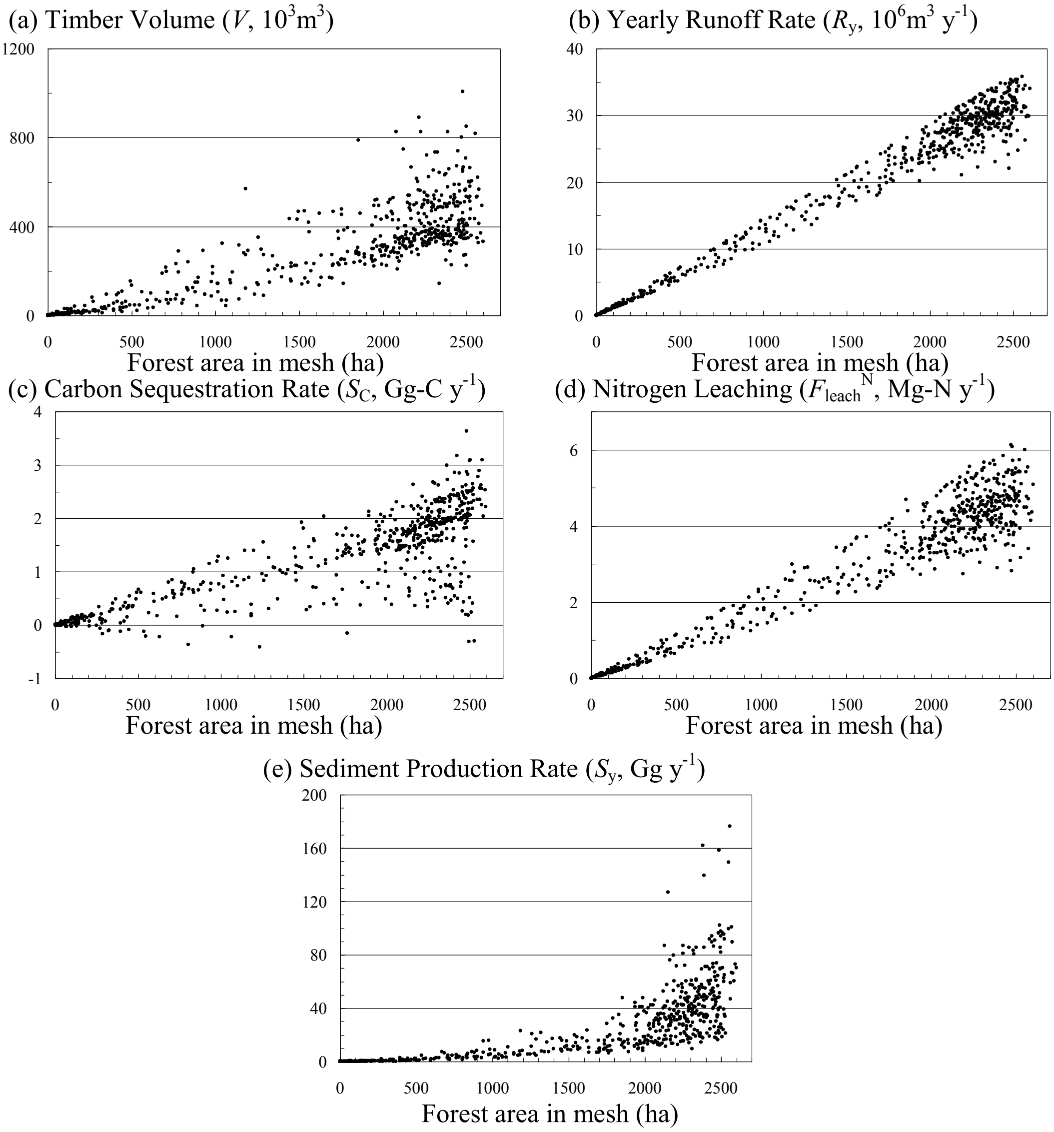


Fig. 3 Relationship between forest area and ES in 2000 under FM scenario in each mesh

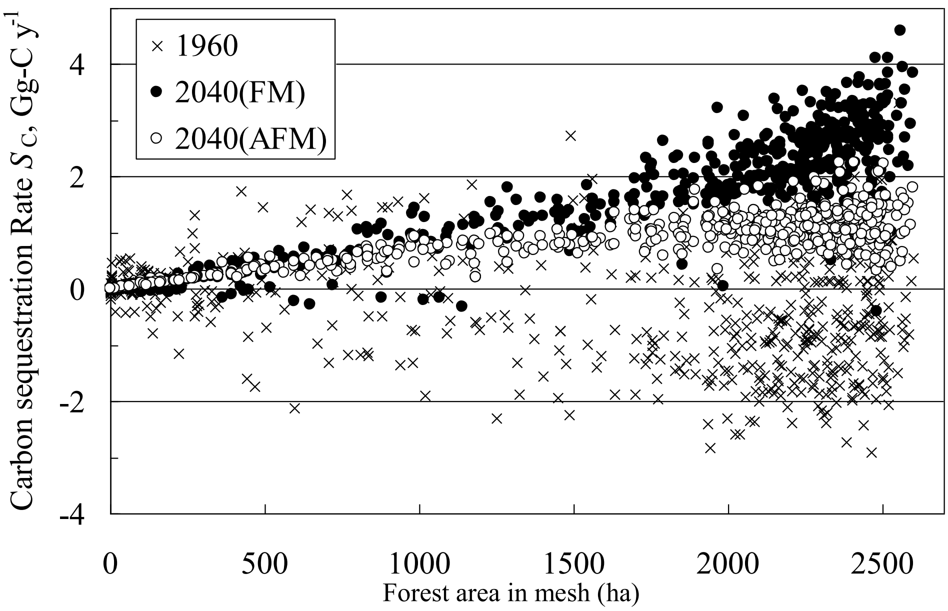


Fig. 4 Relationship between forest area and SC in 1960 and 2040 under FM and AFM scenarios in each mesh

ES of the sediment production was also not linearly related to forest area (Fig. 3e). Sy not only depends on forest management but also on geographical factors (Eq. (21)). Compared to Sc and V, dependency of Sy on forest management was small.

4. Conclusions

Forest ecosystem services in the Ise Bay basin were evaluated using a 5-km mesh. Simulation analysis was carried out by the forest biogeochemical model, BGC-ES, from 1960 to 2040 under different scenarios (FM: forest management, AFM: management abounded from 1990). Carbon sequestration rates under the FM scenario were larger than those under the AFM scenario. Carbon sequestration rate and timber volume accumulation did not exhibit a linear relationship with forest area. Thus, there is a need to evaluate ES with a dynamic-process forest model that accounts for forest management practices.

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