# Net biome production of managed forests in Japan

Alexandrov Georgii & Yamagata Yoshiki

National Institute for Environmental Studies, Tsukuba, Ibaraki 305-8506, Japan
Correspondence should be addressed to Alexandrov Georgii (email: g.alexandrov@nies.go.jp)

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**Abstract** Net biome production (NBP) is considered as the most appropriate concept for analyzing long-term and large-scale changes of the carbon cycle induced by land use. We have estimated NBP potential of Japanese managed forests, based on their age structure, to be 16 Mt C/a. Fifty-nine percent of this sink is located in the warm-temperate broadleaf forest zone and the remaining 39% is located in the cool-temperate broadleaf forest zone. This potential of NBP could be achieved under a long rotation period (70 a) and may serve as a target for sink enhancement efforts with the potential to uptake up to 4% of current fossil fuel emissions.

**Keywords: aboveground biomass, carbon sinks, land use.**

Net biome production denotes the amount of carbon that remains at the site annually after subtracting respiratory (e.g., heterotrophic respiration) and non-respiratory losses (e.g., fires or harvest), or after subtracting non-respiratory loses from the net ecosystem productivity (NEP). At the ecosystem scale emissions associated with disturbances are infrequent events and therefore are difficult to count as processes in the annual carbon budget. In order to include non-respiratory carbon released into the annual budget we need to consider larger areas, for example, whole biomes. At this scale fire or forest harvest can be considered as a process since it occurs every year at one or another part of the biome and NBP can be defined as the difference between net ecosystem production (NEP) and emission associated with disturbances ($E_d$), i.e., NBP = NEP – $E_d$. Since the meeting of IGBP Terrestrial Carbon Working Group[1] held in 1998, NBP is considered as the most appropriate concept for analyzing long-term and large scale changes to the carbon cycle induced by land use.

The predominant land cover type in Japan is forest, where closed-canopy forests cover about 67% of the territory. The major part (59%) of Japanese forest is intended for environment protection, for nature conservation and for recreational use. The remaining 41%, the so-called managed forest, is used for timber production and harvested on regular basis.

NBP of the managed forests is determined mainly by changes in age at which forest is usually harvested (the length of rotation). NBP is positive when the length of rotation is increasing, and negative otherwise. The shifts in the harvest pattern manifest itself in the age structure of the forest. It becomes unstable over a period of time that may lead to the abrupt variations of NBP.

In this paper, we estimate NBP of Japanese managed forest from the data on its age structure. First, we formulate a forest management model that links harvest pattern to the age distribution among the forest stands. Second, we describe the model of carbon cycle for estimating carbon stocks in stands of given age and location. Finally, we predict net biome production as that resulted from changing age structure of Japanese forest.

## 1 Method

### 1.1 Land-use model

Managed forests in Japan are used in a sustainable way such that the area of reforested sites is roughly equal to the area of cleared sites. This type of forest management may be described in general by the following system of difference equations:

$$s(t+w) = U(s(t) - v(t)) + g(t),$$
$$s(t_0) = s_0, \quad g_1(t) = \sum_{k=1}^{m} v_k(t), \tag{1}$$
$$s = \begin{pmatrix} s_1 \\ s_2 \\ \vdots \\ s_m \end{pmatrix}, \quad v = \begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_m \end{pmatrix}, \quad g = \begin{pmatrix} g_1 \\ 0 \\ \vdots \\ 0 \end{pmatrix}, \quad U = \begin{pmatrix} 0 & 0 & \cdots & 0 \\ 1 & 0 & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 1 & 0 & \cdots & 1 \end{pmatrix},$$

where $s_i$ is the area under the forest stands of the $i$-th age class, $v_i$ the area of cleared stands of $i$-th age class, $g_1$ the area of reforested land, $m$ the number of age classes, and $w$ the width of each age class.

This model assumes that forest area is kept constant, but it does not assume that forest age structure is fixed. The latter may change dramatically depending on its initial state ($s_0$) and cause either increase or decrease in the carbon stock of the forest.

The carbon stock of the forest managed as defined by eq. (1) is given by the formula

$$C_\Omega = \sum_{k=1}^{m} s_k C_k, \tag{2}$$

where $C_k$ is the carbon stock at the stands of $k$-th age class. Then NBP, defined as the difference between $C_\Omega(t+w)$ and $C_\Omega(t)$:

$$P_b(t+w) = \frac{C_\Omega(t+w) - C_\Omega(t)}{w} = \frac{1}{w}\left(\sum_{k=1}^{m} s_k(t+w)C_k - \sum_{k=1}^{m} s_k(t)C_k\right)$$

is given by the formula

$$P_b(t+w) = \frac{1}{w}\sum_{k=1}^{m}(s_k(t+w) - s_k(t)C_k). \tag{3}$$

### 1.2 Carbon cycle model

For calculating $C_k$ we employ a model whose general form is similar to that of the Osnabrück Biosphere Model[2]:

$$B(a) = b_l P_n \bullet a, \tag{4}$$

$$\begin{cases} \dfrac{\mathrm{d}L_i}{\mathrm{d}a} = m_i(a)B - r_i L_i \quad (i = 1, 2, 3), \\ L_i(1) = \dfrac{L_{f,i}(a_{\max}) + B_{f,i}}{(1 - \mathrm{e}^{-r_i(a_{\max} - l)})}, \end{cases} \tag{5}$$

where

$$B_{f,i} = f_i h_i B(a_{\max}), \tag{6}$$

$a$ is stand age, $a_{\max}$ is maximum stand age (the length of rotation), $B$ is carbon stock in living biomass, $b_1$ and $b_2$ are allometric coefficients, $B_{f,i}$ is the amount of living biomass entering the $i$-th litter pool in the end of rotation period, $f_i$ is the part of the felled tree biomass fraction (corresponding to those of litter) remaining at the site, $\{h_1, h_2, h_3\}$ is the composition of the felled tree organic matter that provides for the composition of litter adopted, $L_i$ is the stock of carbon in the $i$-th fraction of non-living organic matter, $L_{f,i}$ is the stock of carbon in the $i$-th fraction of fresh (accumulated within the current rotation period) non-living organic matter, $m_i$ is the rate of biomass transition into the $i$-th litter pool (e.g. due to the shedding of leaves), $P_n$ is net primary production, and $\{r_1, r_2, r_3\}$ are decay rates of respective litter pools.

The carbon stock in living organic matter is modeled by an allometric formula, eq. (4), describing age dependence of stand biomass. Non-living material is subdivided into three fractions ($L_1$, $L_2$, $L_3$) of different resistances to decay, associated with herbaceous litter, woody litter and soil organic matter.

Initial conditions for eq. (5) depend on the previous history of site. We assume that forest was continuously regenerating at the site and set initial conditions at the values corresponding to the infinite number of the previous rotation by using of the formula derived by Alexandrov et al.[3]. The entries of this formula are calculated by the following equation:

$$\begin{cases} \dfrac{\mathrm{d}L_{f,i}}{\mathrm{d}a} = m_i(a)B - r_i L_{f,i} \quad (i = 1, 2, 3), \\ L_{f,i}(1) = 0. \end{cases} \tag{7}$$

The coefficients related to biomass growth, composition of organic matter and climate dependence of decay rate are set at the values proposed by Esser[2]. The detailed explanation of the model was presented in the paper of Alexandrov et al.[3].

Net primary production ($P_n$) is estimated by means of TsuBiMo, a process-based model of NPP as a function of climate, that is scaled up[4] from canopy to globe by using the Osnabrück collection of NPP data[5] after some filtering[6] of this collection.

The model gives us the amount of carbon stocks at each year of rotation period (fig. 1) and allows us to calculate the values of $C_k$ as

$$C_k = \frac{1}{w} \sum_{a=k}^{k+w-1} \left[ B(a) + \sum_{i=1}^{3} L_i(a) \right]. \tag{8}$$

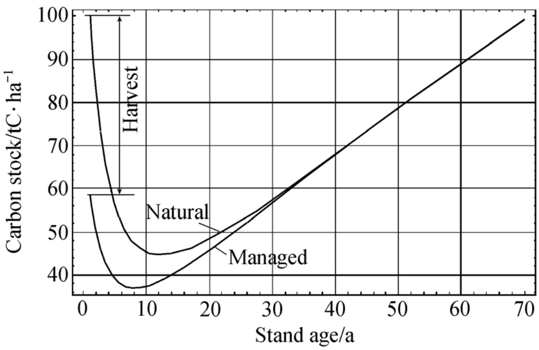


Fig. 1. The changes in carbon stock in course of rotation period as simulated by the model for environmental conditions of the site studied by Kawaguchi et al.[7].

Substituting them into eq. (3), we obtain NBP.

### 1.3 Input data

We apply this model over the geographical grid of 1 km×1 km (exactly, 30″×45″) resolution and use for this purpose the girded data set GFD-J[3] that contains information on the area of managed forest (subdivided into 15 age classes of 5-year width) needed for land-use model and monthly climate data (temperature, precipitation and solar radiation) in carbon cycle model.

The data on the age structure of Japanese forest are in vector format. The forest age structure is known at the level of the smallest administrative units (so called “shi-chyo-son”) which is as large as 50 km$^2$, especially in rural regions. The polygons representing shi-chyo-son units were transformed into the zones of grid cells overlaying the polygon areas. The forest age structure at the cells was defined by using some additional information. In most cases, the accuracy of cell data is higher than that it might be assumed.

## 2 Results

With only a few exceptions, NBP simulated for a regionally uniform scenario of forest management ($w$ = 5, $m$ = 15, $a_{\max}$ = 75, $v_1 = \cdots = v_{m-1}$ = 0, $f_1$ = 0, $f_2 = f_3$ = 0.5) is positive (Plate I) in every node of the grid. Its total amount comprises to 16 Mt C/a in 2000 and declines to 10 Mt C/a in 2015, suggesting that managed forests of Japan may provide a sink compensating about 4% of country emissions.

The decline in the sink magnitude results from the instability of the age-class distribution of the managed forest. Under the constant climate and fixed length of rotation, the age-class distribution is cyclically changing that alter sink to source and vice versa. At the moment Japanese managed forests are in the phase of sink, the length of which depends on forest management.

Our scenario implies that this phase of sink can be as long as 25 a, but it could be much longer if selective cutting would replace eventually clear cuts. In the case of selective cutting, an even-aged stand ready for harvest becomes eventually to an uneven-aged stand of the same average age. Therefore, transforming from the forest of even-age stands to the forest of uneven-aged stands would stabilize the age-class distribution of the managed forest and thus prevent the phase of source.

The major part of NBP (73% in 2000 and 87% in 2015) is stored in the pool of standing biomass. NBP decline shifts the partition of accumulating carbon between the pools: the more observable part of sink (standing biomass) declines slower than the less observable part (soil organic matter).

It is also worth mentioning that the major part of the sink is located in the warm-temperate broadleaf forest zone. This zone is the largest one covering 53% of the land. Therefore, it is not surprising that 59% of sink is located there. The most of remaining part is located in the cool-temperate broadleaf forest zone. It covers 41% of land and host 39% of sink.

## 3 Discussion

In most developed countries, forest management policies are changing to address the need to increase carbon sinks as a way to contribute to the stabilization of atmospheric carbon dioxide. This is resulting in relevant shifts in forest management. We formalize the anticipated result of the changes in the form of the forest management scenario that assumes no harvest in biologically premature stands and assess the carbon flux implied by this scenario.

Building a plausible scenario of forest management is a major challenge. It has been widely recognized that Japanese forests have a variety of functions, but forestry has been normally developed as an industry for producing wood. The Forest and Forestry Basic Law adopted in 2001 changes the priorities and treats forest not just as an industrial sector, but as an integral part of human activity and national culture. The shift to longer rotation period started, in fact, earlier, somewhere in 1990s, when domestic wood lost in the price competition with imported wood. Therefore, our scenario (70 a rotation period) may be considered as a potential "business-as-usual" scenario, if we shut our eyes to simplifications arising from the lack of quantitative information about the shifts in the harvest pattern.

The next question is whether the model of carbon cycle is producing a representation of the real forest ecosystem. To answer this question we compare the simulated carbon stock to the carbon stock estimates derived from forest inventory data[8].

Forest inventory data provide information about the wood volume that is converted into biomass carbon values by means of conversion factors. There is no consensus, however, about the true values of the conversion factors: the estimates vary from 0.354 to 0.6 t $C/m^3$. Summarizing studies of Russian forest, Krankina et al.[9] came to the conclusion that a cubic meter of wood volume corresponds, on the average, to 0.516 t of biomass carbon, and following Birdsey's work, Sampson[10] set the conversion factor at 0.53 t $C/m^3$ for USA forest.

Our results fit the estimates derived from the forest inventory data[8] if the conversion factor is 0.25 t $C/m^3$ for managed forest and 0.52 t $C/m^3$ for natural forest. The latter value is in rough agreement with what was used by Krankina et al.[9] or Sampson[10], but the former is beyond the range of values reported in carbon budget studies. Nevertheless, the data reported by Tadaki et al.[11], which can be also found in Cannell[12], indicate that 0.25 t $C/m^3$ is a plausible value of the conversion factor for managed forest. In general, the larger the fraction of branches and roots in the total tree biomass, the larger the conversion coefficient. Thinking of a natural forest as a beech (*Fagus crenata*) forest and managed forest as a Cryptomeria (*Cryptomeria japonica*) plantation, one would gain an impression about the cause of the above variations in the conversion factor.

Due to the lack of information on the stocks of litter and soil carbon in forest inventory data, we compare simulation results to some carbon budget models. Our results show the ratio (100∶202) between living and non-living organic matter similar to the ratio (100∶238) suggested by Alexeev et al.[13] for the forests of the European part of Russia and to the ratio (100∶212) suggested by Birdsey[14] for USA forests. The larger amount (≈100∶500) of non-living organic matter reported by Kurz et al.[15] for Canadian forests and by Alexeev et al.[13] for the forests of the Asian part of Russia (100∶352) may reflect a climate dependence in the litter decay processes.

The data on carbon stocks changing with the stand age are also limited. We found only one work where the carbon stocks in stands of different ages were studied in detail[7]. Simulated pattern conforms in general with the observed one. Both show that carbon stock passes a minimum after the age of ten years, that is, not immediately after the break-up or cut. They differ only in the figures: observations show that carbon stock may reach its minimum later and that the range of carbon stock changes may be wider than that suggested by simulations.

## 4 Conclusion

Proceeding from the age structure of Japanese managed forest, we estimate its NBP potential at 16 Mt C/a. This magnitude of NBP could be achieved under a long rotation period (70 a) and may serve as an expedient target for the shifts in forest management that are anticipated in connection with the emerging demand for creating and enhancing carbon sinks in the forest sector.

**Supplemental material** The models used in calculations are available in the form of package that can be run under Mathematica 4 (an integrated environment for technical computing developed by Wolfram Research Inc.).

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