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A long-term assessment of ecological-economic sustainability of woody biomass production in Japan

Makoto Ooba [a,*], Kiichiro Hayashi [a], Minoru Fujii [b], Tsuyoshi Fujita [b], Takashi Machimura [c], Takanori Matsui [c]

[a] *EcoTopia Science Institute, Nagoya University, Nagoya, Japan*
[b] *National Institute for Environmental Studies, Tsukuba, Japan*
[c] *Graduate School of Engineering, Osaka University, Suita, Japan*

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ABSTRACT

The forestry process in Japan, from plantation stage to wood biomass production, was assessed using a process-based ecological model, forestry cost calculation model, and an ecological footprint-like index. In order to estimate ecosystem dynamics under various forest management practices, the ecosystem model simulated material cycles. The cost calculation model estimated the economic cost for each stage of woody biomass (wood chip) production. An occupancy rate time index (ORT) was defined by a 200-year usage span for land, material, pollution and labor against the amount available for woody biomass production. The models and the index were combined and four forest management scenarios were evaluated on a community scale in Japan: business as usual (BAU), a forest management recommended by the local government to enhance and improve forest management to include woody biomass production; FM1, modified practices; FM2, extended practices; and CNV, converting part of a plantation into natural broadleaf forest under the FM2 scenario, considering the biodiversity of the forests. The results for long-term simulations revealed that the current forest management (BAU and FM1) was not efficient in the production of woody biomass in terms of economic cost and ORT. The FM2 scenario modified from the FM1 scenario would produce ecological and economical improvements, but integrated assessment by using ORT indicated an increase in carbon emissions and labor due to enhanced forest practices. Woody biomass production under the FM2 scenario needs to be supported by carbon offsetting, such as reduction of coal combustion in thermal power plants. Under the CNV scenario, ORT values were the same as those under BAU and FM1 if the carbon offset was considered. The CNV scenario was found to be the best, considering the impact on ecological and social systems.

1. Introduction

Forest ecosystems cover approximately 68% of the total land surface of Japan and they have accumulated rich wood resources (Ministry of Agriculture, Forestry and Fisheries, 2008). Such abundant wood resources were the result of a policy of forestation and conversion of natural forests to artificial forests during the 1960s. However, Japanese plantation forests are currently not managed well. Imported timber and wood materials, incurring significant disturbance to those regional forests, have an economical advantage over Japanese forestry products, which in turn eliminated the need for forest management, subsequently resulting in degradation of forest ecosystems.

After the major earthquake in the eastern region of Japan in March 2011, Japan suffered a serious energy crisis resulting from the accident at the Fukushima nuclear power plant. Before the accident, the Japanese government had planned a policy to shift energy production to renewable energy, thus addressing the global warming problem (Ministry of Economy, Trade and Industry, Japan, 2010). If the targets set within such a policy were to be achieved, the use of biomass as an energy resource needed to increase by up to 600% by 2030 compared to 2000. After the accident and the change in political administration in Japan in 2012, a new energy policy focusing on renewable energy has been planned.

Simultaneous combustion of biomass with coal in thermal power plants is an important option for climate change mitigation, improvements to the energy portfolio, and sustainable energy

* Corresponding author.
E-mail addresses: ooba.makoto@nies.go.jp, m3oba@nodai.ac.jp (M. Ooba).

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supplies (McIlveen-Wright et al., 2011; Zuwała, 2012). In Japan, almost all nuclear power plants have been suspended following the earthquake, whereas the operating rate of thermal power plants has increased (Reegle, 2012). In order to reduce carbon emissions, woody biomass combustion has been already introduced in some thermal plants in Japan. This biomass is imported from overseas rather than obtained from the rich biomass available in domestic forests. Part of the reason for this is the inhomogeneous quality of domestic woody biomass and problems in the supply chain (Ooba and Fujii, 2012, an interview related to the Hekinan thermal power plant of the Chubu Electric Power, Japan).

Japanese national and local governments are promoting the use of biomass energy; however, detailed and regional assessments of the effects of production and usage of biomass resources on ecosystems and social systems have not yet been undertaken. For example, productivity of woody biomass depends on management and harvesting methods. As already mentioned, plantation forests in Japan are not managed well, and the growth rate of trees is not at the maximum as estimated from the forest science theory. In addition, locations of many plantations are disadvantaged from view due to transportation cost for woody biomass. Geographical survey of the potential supply of woody biomass must be carried out bearing the current situation of plantation forests in Japan in mind. Governmental research (Ministry of the Environment, 2011) seems to have failed to consider these factors so far.

On the other hand, previous studies on woody biomass, apart from the Japan case studies, assessed the impact of woody biomass production from multiple aspects. Environmental and social impacts were assessed when the production of woody biomass was promoted in the context of sustainable carbon-neutral fuel (Mirata et al., 2005). González-García et al. (2013) have evaluated different types of forest management with low environmental impact based on six impact categories by using the life cycle assessment methodology. Forestry systems were also compared with the life cycle assessment approach (Valente et al., 2011) in terms of greenhouse gas emissions, cost, and employment. Jamali-Zghal et al. (2012) indicated that spatial limitation caused by the complexity of biomass transportation was also essential for its environmental impact. Sacchelli et al. (2014) analyzed the socio-economic and environmental effects on resources from financial, technological, geographical, and environmental aspects simultaneously, on a local scale.

A biogeochemical forest model (BGC-ES) was developed for the Japanese forest ecosystem and applied in the study of the Yahagi River, Ise Bay basins, and Toyota City, Japan, by one of the authors (Ooba et al., 2010, 2012a, 2014). This biogeochemical model was designed to simulate water, carbon, and nitrogen cycles in forest ecosystems. Submodels within the BGC-ES model incorporate tree populations and an allometric scale and both were validated by observations of gaseous fluxes and water quality in forests; mass cycles were considered as dynamic processes. Therefore, the feedback effects between forest management practices and effects of mass circulations can be clearly quantified using the model. The temporal impact of a long-term change of biomass productivity in a forest caused by a change in management and harvesting practices can be simulated with the model.

Environmental impacts may change with ecological and forestry processes depends on the selected forest management scenario. In this study, a temporal aspect of biomass production was introduced with the life-cycle assessment approach.

In our study, a combined forest ecosystem and cost calculation model (Ooba et al., 2012a) was used to estimate various ecosystem services and the production of wood biomass. Using this model, we were able to conduct regional-scale simulations of a long-term woody biomass production (wood chip) under various forest management scenarios. The results were assessed using ORT assuming carbon was offset by the combustion of woody biomass. Finally, we proposed the development of a policy that would be based on multiple parameters, including ecological and economical systems.

2. Models and study site

Forest ecosystems change dynamically over a relatively long time period ($10–10^2$ years); temporal changes in environmental and social impacts arise from the production of woody biomass. Many process-based ecological forest models have been proposed in agricultural science and forest meteorology. Studies of these models indicate a direct correlation between carbon sequestration rate and forest management practices (e.g., Ueyama et al., 2011).

The following models and index that evaluate temporal changes under various forest management scenarios were used in this study.

2.1. Biogeochemical forest model (BGC-ES)

The BGC-ES model (version 1.1; Ooba et al., 2010, 2012b) was used to simulate a forest ecosystem. The model can evaluate the dynamic effects of forest management (arbitral timing and degree of thinning and clear cutting).

This model consists of four submodels: biomass, water cycle, carbon–nitrogen cycle, and forest management. The smallest simulation unit of the forest ecosystem was assumed to consist of homogeneous tree species without understory vegetation. Parameter sets of the model were provided for four needleleaf forests in a major plantation (Japanese cedar; Japanese cypress, Japanese red and black pine, and Japanese larch). Broadleaf forest was represented by parameter set of species of *Quercus*, (e.g., *Q. acutissima* and *Q. serrata*).

2.1.1. Biomass submodel

We assumed that an increase in average tree height depends on forest age and site coefficient. In a plant ecosystem consisting of a single species, maximum population number is related to maximum trunk volume as shown by Yoda et al. (1963). The population number and volume are given by solving the simultaneous equations derived from published charts of forest growth.

An individual tree has leaf, branch, trunk, root, and fine root components. The aboveground biomass is related to the tree volume, which can be calculated from the allometric equations.

2.1.2. Water cycle submodel

The radiation balance and water balance were estimated from the daily meteorological data. Potential evapotranspiration rate was estimated by the Penman–Monteith equation (Monteith and Unsworth, 1990). The actual evapotranspiration rate was estimated from the amount of intercepted water, day length, leaf area index, and soil dryness.

To calculate a daily runoff that includes surface and subsurface layer flows, we assumed a relatively simple model with two critical values.

2.1.3. Carbon and nitrogen cycle submodel

This submodel calculates the yearly carbon and nitrogen (CN) fluxes. Leaf litter and dead trees were added to litter pools and coarse woody debris pools, respectively, and the soil pools had influx of decomposed mass from the litter pools. 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).