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SIMULATION STUDY FOR ASSESSING THE CARBON SEQUESTRATION POTENTIAL OF DIFFERENT TREES FOR REFORESTATION

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Abstract. *Carbon sequestration through reforestation is a significant technique that plays important role in reducing atmospheric carbon. In reforestation project, environmental conditions of the site as well as tree characteristic used will determine the extent of carbon can be sequestered. In this paper, we will demonstrate the use of CENTURY model in assessing the capacity of different trees in sequestering carbon on a mountain ecosystem of West Java, Indonesia. The paper will firstly address the capacity of Pinus merkusii forest to sequester carbon and, secondly, the effect plant characteristics, i.e. biomass allocation and C/N ratio, on the pattern of carbon sequestration of two hypothetical species.*

Introduction

Reforestation is an important technique for climate change mitigation. During forest growth, atmospheric carbon is taken up by plants and incorporated into their biomass and the soils and it resides on the ecosystem for a period of time. In this manner, reforestation is a means for carbon sequestration.

The ‘service’ provided by forest to sequester carbon has increasingly been appreciated and its value can now be sold through various carbon trading mechanisms. A tool is required to facilitate assessment of the potential of carbon sequestration on various reforestation settings. Such information is very valuable for practitioners and policy makers when formulating reforestation strategy.

CENTURY model developed by Parton *et al.* (1993) is one of the available tools suitable for that purpose. This model has been used for various ecosystem in the world and proven to be effective for simulating carbon cycle (e.g. Song & Woodcock, 2003). The most appealing feature of this model is that it allows the effects of different environmental settings and plant characteristics on carbon sequestration to be investigated. Despite its potential, the use of CENTURY model in Indonesia, to our knowledge, has so far been limited.

Our research attempted to study the pattern of carbon sequestration in various reforestation settings using the CENTURY model. On the previous research, we have used the model to assess the effect of changing climate setting on carbon sequestration (Hidayanto, 2006). In this paper, we will demonstrate the use of CENTURY model to assess, firstly, the capacity of *Pinus merkusii* forest to sequester carbon and, secondly, the effect plant characteristics i.e. biomass allocation and C/N ratio, on the pattern of carbon sequestration.

CENTURY model

CENTURY is a mechanistic model developed by Parton *et al.*, (1993). This model simulates key processes of nutrient cycling of an ecosystem, including plant production and litter-fall, and decomposition. Here, we only describe the essential features of the model; more detailed description of the model can be seen in Matherell *et al.* (1994).

CENTURY consists of several submodels i.e. plant production, climate, soil organic matters, dead plant materials. Those submodels represent pools that exist in real systems. Flows of nutrient between the pools are mainly regulated by functions of climate and plant nutrient/characteristics and parameters. Pools representation as submodels can be viewed in Figure 1.

Plant production submodel calculates biomass production and nutrient allocation. CENTURY simulates plant production for crop, forest and grassland. In this study, however, we only used the forest production submodel. The biomass production is simulated as a function of nutrient availability and climate conditions. The biomass produced is allocated into aboveground and belowground compartments. The aboveground compartment is further divided into leaves, stems, and branch compartments, whereas the belowground compartment is divided into coarse and fine roots (Matherell *et al*., 1994). The biomass allocation to each compartment follows certain rules as set in the model parameters.

Following the death of plants, there is a transfer of nutrients to dead-plant material pools, which is simulated in the decomposition submodel. The rate of decomposition is a function of plant material characteristic (e.g. lignin and nutrient content) and climate conditions. Decomposition submodel also calculates the nutrients that will in the end be available again for the plant. CENTURY model can simulate the dynamics of carbon (C), nitrogen (N), phosphor (P) and sulfur (S), but in this research we only focus on the carbon dynamics.

This model operates in monthly time step but the outputs can be presented in a monthly or yearly basis. Main model inputs are monthly precipitation, maximum and minimum air temperatures, soil texture, and plant chemistry (Metherell *et al.* 1994). Those main inputs are subsequently used to derive other variables such as soil temperature, which is calculated as a function of air temperature and precipitation.

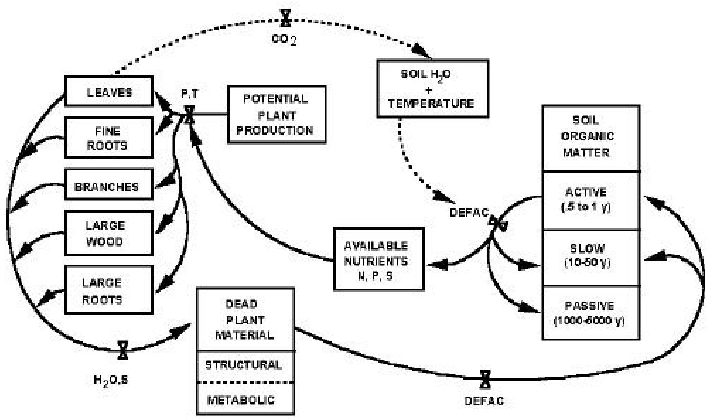

Figure 1. CENTURY model structure that represents plant production (leaves, branches, stem (large woods), roots, dead plant materials, soil organic matters, and climate/atmosphere. Source: Matherell *et al*. (1994).

Methodology

Study site

The model was set up to reflect the condition of the study site, i.e. Mount Papandayan ecosystem. Mount Papandayan is an active volcano located in West Java Province of Indonesia. Its peak lies of 07^o 18’ 55” S dan 107^o 43’ 24” E. The major vegetation types in this area is (natural) mixed forest surrounded by several forest plantations of mainly pine (*Pinus merkusii*) and rasamala (*Altingia exelsa*) trees. This area has experienced major land-encroachments and clearings for conversion to agricultural lands (Sulistyawati *et al.*, 2006). At the moment, there are large tract of abandoned lands need to be reforested to restore the ecosystem structure and function. Mount Papandayan has cold and wet climate with the average of annual rainfall of 3,900 mm, whereas the average maximum and minimum monthly temperature of 24^{o}C and 4^{o}C respectively.

Configuring the model

The use of model in this research is facilitated by the application software and source codes provided by the developers (Parton *et al.*). Century has more than 100 parameters. Fortunately, it is distributed with some “default” set of parameters reflection settings of various ecosystem types in the world. When the model is adopted for a new site or vegetation, it has to be re-parameterized. Given the extensive data used for parameterization, often it is not easy to conduct complete parameterization. The limitation of data often forces the modelers to re-parameterize only selected keys parameters and uses the default values supplied by the developers for the rest.

In this study, we parameterized the model to reflect the site condition of Mount Papandayan ecosystem and the tree *Pinus merkusii*. In general, we used the data taken from the field supplemented by the data from secondary resources. In case when there were no data available, we use the most suitable "default set of parameters" supplied by the developers. In this context, we mostly used the default set of parameters defining tropical evergreen forest in Luquillo Experimental Forest (Metherell *et al*., 1994).

Simulation setting

The model was firstly used to assess the capacity of *Pinus merkusii* forest to sequester carbon. *Pinus merkusii* has been selected for examination in this study because, apart from being planted in Mount Papandayan, this species is commonly used for tree plantation in many parts of Java.

Subsequently, the model was used for "a simulation experiment" to assess the effect of biomass allocation rule on the pattern of carbon sequestration. The model depicts forest trees as a unit consists of five compartments, i.e. leaves, fine roots, fine branches, large wood (large branch and stem), and coarse roots with carbon and nutrients allocated to the different components using a fixed allocation scheme. In this experiment, the performance of *Pinus merkusii* was compared to a "hypothetical species" having the same plant characteristics as *Pinus merkusii* except the biomass allocation rule, which reflects the biomass allocation strategy of *Gmelina arborea* (Swamy *et al.*, 2005). This species is called Gmelina-like thereafter. Although not currently found in Mount Papandayan, *Gmelina arbore*a is increasingly common for tree planting in many parts of Indonesia (Rosteko, 2003). One may argue that this does not represent a realistic condition as apart from biomass allocation strategy, other plant characteristics of Gmelina may also differ to *Pinus merkusii*. Nevertheless, such simplification has been taken in order to focus the examination of the effect of biomass allocation strategy.

In the second set of simulation experiment, the performance of *Pinus merkusii* was compared to a "hypothetical species" having the same plant characteristics as *Pinus merkusii* except the C/N ratios, which reflects the C/N ratios of rasamala (*Altingia exelsa)*. Rasamala is currently planted in Mount Papandayan and several other mountain forests in West Java. The C/N ratio data of rasamala were gathered from the field measurements. This species is called Rasamala-like thereafter. The simulations begin with condition reflecting an early planting phase of reforestation and was run for 200 years.

Results and Discussions

The pattern of total carbon accumulation of *Pinus merkusii* forest, which is a sum of carbon stored in aboveground and belowground biomass, soil organic matters (SOM), dead wood and forest litter, shows an initial rapid carbon accumulation but it tends to stabilize towards the end of simulation (Figure 2). This simulation demonstrates that reforestation using *Pinus merkusii* can accumulate carbon at the rate of 3.91 mega-gram carbon (ton) per hectare (Mg C/ha/year) during the first 20 years of forest growth and this equals to the rate of CO2 sequestration of 14.35 Mg CO2/ha/year. The rate of carbon accumulation tends to be slower at later stages. During year 20 – 40, the rate of carbon accumulation is 2.39 Mg C/ha/year, while the rate for the entire simulation period is 1.08 Mg C/ha/year. At the end of simulation (year 200), the total carbon on the forest system level is around 291 Mg C/ha.

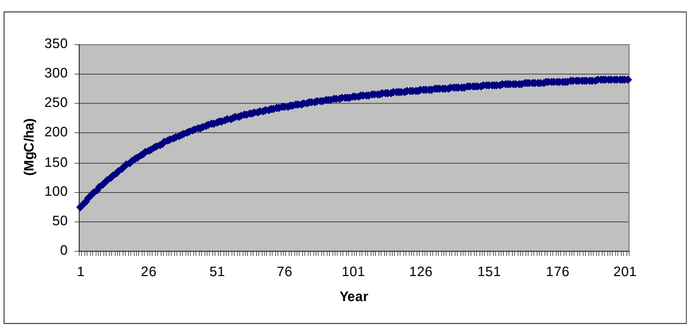

Figure 2. Total carbon at *Pinus merkusii* forest

Figure 3 suggests that most of the biomass carbon is held in the large wood compartment and the proportion of carbon held in this compartment increases as the forest grows. When the pattern of carbon distribution is presented in terms of aboveground, belowground biomass and carbon incorporated as soil organic matter (SOM) (Figure 4), it is clear that most carbon is held as aboveground biomass, which accounts for around 54 % of the total forest carbon at the end of simulation. It is interesting to note that the soil can in fact hold a significant amount of carbon. Toward the end of simulation, the soil can hold around 70 Mg C/ha, which makes up around 24 % of the total forest carbon.

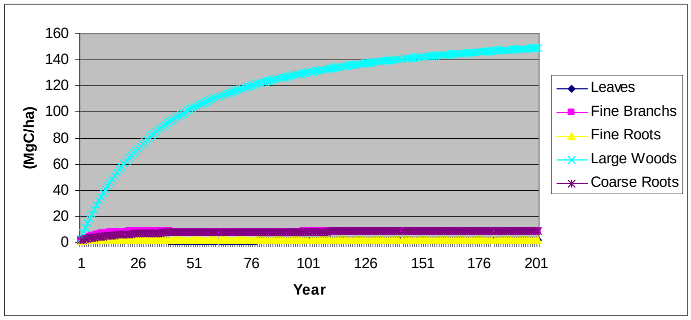

Figure 3. Carbon accumulation on *Pinus merkusii* forest by plant compartments.

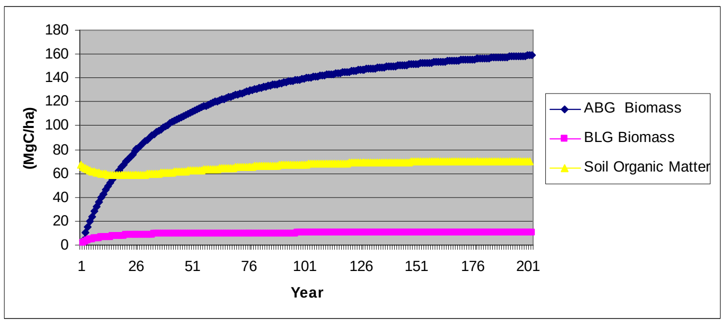

Figure 4 Carbon accumulations on aboveground biomass, belowground biomass and SOM on *Pinus merkusii* forest.

An assessment of plausibility of the model to simulate carbon sequestration in reforestation setting can be done by comparing the simulated values with comparable empirical data available (Table 1). When compared to the aboveground carbon accumulation on tropical secondary forests, the simulated values are generally lower than those estimated by Brown and Lugo (1990 cited in Silver, *et al.*, 2000). In contrast, the simulated rate of carbon sequestration tends to be higher than the estimation of Silverton *et al.* (2000) based on the empirical data from all over the world.

Table 1. Comparison between the simulated values and empirical estimates

No.	Type of forest	Location	Source	Parameter	Unit	Value	Comparable estimates from this simulation study
1	Tropical secondary forest	n.a	Brown & Lugo (1990 cited in Silver *et al.*, 2000)	Average of the annual aboveground C accumulation	Mg C/ha/yr	2-3.5	1.59
2	Tropical secondary forest	sites worldwide	Silver *et al.* (2000)	Annual aboveground C accumulation during the first 20 years	Mg C/ha/yr	3.09	3.30
3	Tropical secondary forest	sites worldwide	Silver *et al.* (2000)	Annual aboveground C accumulation during the first 80 years	Mg C/ha/yr	1.45	1.59
4	Tropical plantation	n.a	Lugo *et al.* (1998 cited in Silver *et al.*, 2000)	Annual aboveground C accumulation during the first 26 years	Mg C/ha/yr	0.8 - 15	3.00
5	*Pinus merkusii* plantation	Mount Papandayan	Sulistyawati & Ulumudin (unpublished data)	Aboveground C stock in 12 year-old stand	Mg C/ha	53	49.1
6	*Pinus merkusii* plantation	East Java	Forestry Departmen (unpublished data)	Aboveground C stock in 14 year-old stand	Mg C/ha	74	54.95
7	*Pinus merkusii* plantation	Mount Tangkubanparahu	Hidayanto (2006)	Aboveground C stock in 20 year-old stand	Mg C/ha	48	69.93
8	Tropical secondary forest	sites worldwide	Silver et al. (2000)	Average soil C during the first 20 years	Mg C/ha	60 ± 4	60.65
9	Tropical secondary forest	sites worldwide	Silver et al. (2000)	Average soil C during year 20 - 80	Mg C/ha	74 ± 6	62.81
10	Tropical secondary forest	sites worldwide	Silver et al. (2000)	Annual soil C accumulation during the first 20 years	Mg C/ha/yr	1.30	-0.44
11	Tropical secondary forest	sites worldwide	Silver et al. (2000)	Annual soil C accumulation during year 20 - 100	Mg C/ha/yr	0.20	0.11
12	*Pinus merkusii* plantation	Mount Papandayan	Sulistyawati & Ulumudin (unpublished data)	Soil carbon stock in 12 year-old stand	Mg C/ha	84.47	59.24

Table 1 also presents carbon data of several *Pinus merkusii* plantations. Before making the comparison, it is important to note that in tree plantation setting, management action particularly in the form of stand thinning can also affect the level of biomass in forest stand. This factor may explain the peculiar trend in the level of carbon stock in pine plantations in which the oldest site (in Mount Tangkubanparahu) has the lowest aboveground carbon stock. In general, the comparison suggests that the simulated values tend to be lower than the empirical estimates. Nevertheless, the simulated annual rate of carbon sequestration is within the range reported by Lugo *et al.* (1998 cited in Silver *et al.*, 2000) for other tropical plantations.

In terms of the level of soil organic matters (SOM), in all cases, the simulated values tend to be lower than the empirical estimates. The range of simulated soil carbon level (58 – 70 Mg C/ha/year during 200 years period) within the range reported for the soil on pine and rasamala forests in Mount Papandayan, i.e. 68 – 84 Mg C/ha/yr (Sulistyawati and Ulumudin, unpublished data).

The comparisons above suggests that despite tends to be underestimate, the simulated values are close to comparable values based on empirical estimates. This could be taken as indication that the CENTURY model is able to plausibly simulate the carbon dynamics of *Pinus merkusii* plantation.

Subsequently, we compared performance of *Pinus merkusii* with a hypothetical species having more biomass allocated to large wood, i.e Gmelina-like tree. The biomass allocation for leaves, fine branches, fine roots, large stems and coarse roots for *Pinus merkusii* are 0.17, 0.1, 0.15, 0.52, and 0.06 respectively. Meanwhile, those of Gmelina-like tree are 0.04, 0.1, 0.11, 0.65, and 0.1 respectively. The result of this simulation experiment (Figure 5) shows that reforestation with Gmelina-like tree results in higher carbon sequestration than with *Pinus merkusii.* The difference in carbon sequestration between them is more pronounced as the forest stand reaches old phase. Inspection on the patterns of the carbon distribution by plant compartments indicates that the major differences among those two species lies on aboveground carbon biomass rather than carbon on belowground biomass and soil organic matters (Figure 6). These findings suggest that biomass allocation strategy of plant can significantly affect the rate of carbon sequestration with higher carbon sequestration will be achieved when planting tree with high biomass allocation to large woods.

One may argue that such pattern is merely a consequence of the model representation and simple simulation setting, which only differentiates one factor, i.e. biomass allocation rule. It is true that in reality other plant characteristics may vary, nevertheless it sends a message that one should also consider such morphological characteristic in selecting species for reforestation.

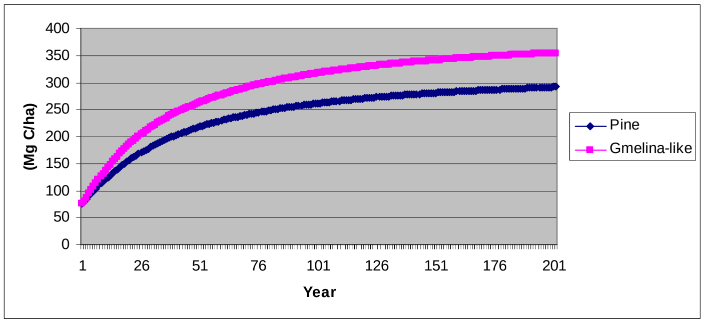

Figure 5. Total carbon on pine (*Pinus merkusii*) and Gmelina-like forests

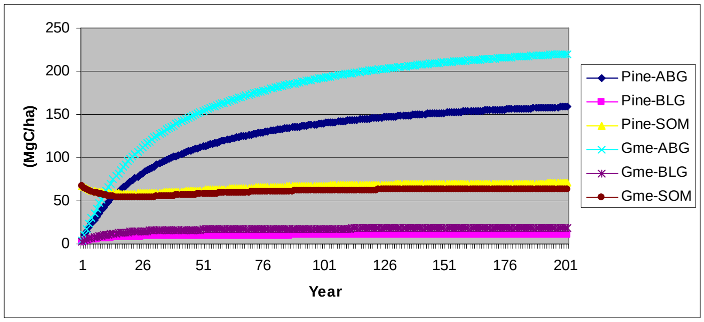

Figure 6 Carbon accumulations on aboveground, belowground biomass and SOM on *Pinus merkusii* and Gmelina-like forests

In the second simulation experiment, we compared two species having contrasting characteristic in terms of C/N ratios. In general, C/N ratios of Rasamala-like species in almost all plant compartments are higher than those of *Pinus merkusii*. The most distinct difference is on the C/N ratio on large woods compartment in which C/N ratio of Rasamala-like is 40 % higher than that of *Pinus merkusii*.

The result shows that unlike in the previous simulation experiment, the higher C/N ratios of Rasamala-like tree only yield a slightly higher (up to 6%) total carbon in forest system. This subtle difference occurs mainly on the aboveground biomass rather than in soil organic matters (Figure 7).

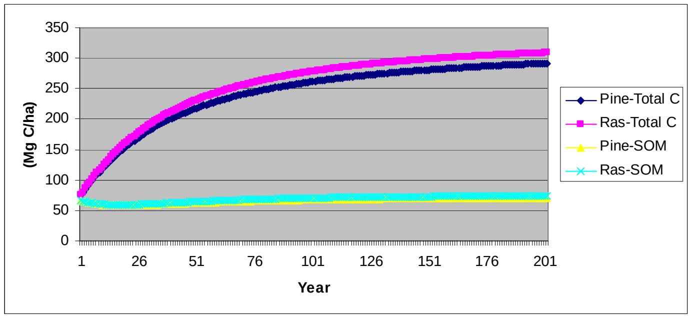

Figure 7. Total carbon and carbon in SOM on pine (*Pinus merkusii*) and Rasalama-like forests.

Concluding Remarks

This study reveals that the CENTURY model is able to plausibly simulate the dynamics pattern of reforestation using *Pinus merkusii*. This was judged by the proximity of the simulated values with the comparable data reported by other studies. The rate of carbon sequestration on reforestation using *Pinus merkusii* is at least 3.91 mega-gram carbon (ton) per hectare (Mg C/ha/year) during the first 20 years and this equals to rate of CO2 sequestration of 14.35 Mg CO2/ha/year. This study also shows that characteristic of tree particularly the biomass allocation can significantly affect the amount of carbon sequestered in forest ecosystem with higher allocation to large wood brings about higher amount of carbon sequestered. Belowground (biomass and soil) also plays an important role as carbon storage. This study shows that soil is able to hold 20 – 24 % of the total forest carbon. Therefore, it is important to include belowground carbon storage when valuing the capacity of forest in sequestering carbon.

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