Woody Biomass and Bioenergy Potentials in Southeast Asia between 1990 and 2020

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Abstract

Forests in Southeast Asia are important sources of timber and other forest products, of local energy for cooking and heading, and potentially as sources of bioenergy. Many of these forests have experienced deforestation and forest degradation over the last few decades. The potential flow of woody biomass for bioenergy from forests is uncertain and needs to be assessed before policy intervention can be successfully implemented in the context of international negotiations on climate change. Using current data, we developed a forest land use model and projected changes in area of natural forests and forest plantations from 1990 to 2020. We also developed biomass change and harvest models to estimate woody biomass availability in the forests under the current management regime. Due to deforestation and logging (including illegal logging), projected annual woody biomass production in natural forests declined from 815.9 million tons (16.3 EJ) in 1990 to 359.3 million tons (7.2 EJ) in 2020. Woody biomass production in forest plantations was estimated at 16.2 million tons yr^{-1} (0.3 EJ), but was strongly affected by cutting rotation length. Average annual woody biomass production in all forests in Southeast Asia between 1990 and 2020 was estimated at 563.4 million tons (11.3 EJ) yr^{-1} declining about 1.5% yr^{-1}. Without incentives to reduce deforestation and forest degradation, and to promote forest rehabilitation and plantations, woody biomass as well as wood production and carbon stocks will continue to decline, putting sustainable development in the region at risk as the majority of the population depend mostly on forest ecosystem services for daily survival.

Keywords: Woody biomass; wood bioenergy; deforestation; forest degradation; land use change; selective logging; Southeast Asia

1. Introduction

International concerns about global warming caused by excessive emissions of greenhouse gases led to the adoption of the Kyoto Protocol to the United Nations Convention on Climate Change (UNFCCC) in 1997. The protocol commits industrialized countries, known as Annex I countries, to reduce greenhouse gas emissions during the first commitment period between 2008 and 2012. As the first year of the first commitment period ended, discussions for the post-Kyoto climate change agreements were carried out in December 2008 in Poznan, Poland. Several industrialized countries have pledged to reduce carbon emissions by up to 80% [1]. In addition to increasing energy efficiency and increased reliance on renewable energy sources such as wind and solar power, reducing emissions from deforestation and forest degradation (REDD) is likely to be a important mitigation option in the post-Kyoto agreements, because deforestation and forest degradation are responsible for the release of about 1.5 to 2.2 Gt C yr^{-1} [2, 3] or about up to 25% of annual global emissions.

In addition to increasing carbon emissions, deforestation and forest degradation reduce availability of woody biomass, on which approximately 2.5–2.7 billion people [4, 5] depend for daily cooking fuel. Given the widespread dependency on wood for energy and the importance of forests to mitigate climate change, there is a strong need to assess the future availability while developing a path toward the sustainable use and management of forests. Canadell and Raupach [6] proposed four strategies for managing forests for climate change mitigation. One of the strategies is to expand the use of woody biomass to replace the use of fossil fuels. Smeets *et al*. [7] provided an assessment of wood bioenergy potentials on a global scale, concluding that there is high potential of woody biomass from forests. Kinoshita *et al.* [8] evaluated the utilization of thinned wood as bioenergy in Japan and concluded that bioenergy is increasingly important in substituting for the use of oil. Utilization of woody biomass has a potential role in global warming mitigation because of its low emissions of greenhouse gases compared to the utilization of oil or coal for power generation [7, 8, 9]. To avoid power shortages such as occurred in 2001 in Brazil, the Brazilian government has launched incentive programs to encourage the utilization of biomass (including woody biomass) as bioenergy [10]. All these studies show the importance of woody biomass in climate change mitigation and sustainable development.

Although the Food and Agricultural Organization of the United Nations' Regional Wood Energy Development Program (referred to as FAO-RWEDP hereafter, [5]) provided an estimate of woodfuels in South and Southeast Asia, their estimate did not incorporate the illegal logging activities and significant logging damages that occur commonly in the region [11, 12, 13]. Their estimate also did not consider local uses of wood, an important consideration given the fact that the availability of woody biomass is directly linked to daily survival in this region. About 30–90% of the population in individual countries in Southeast Asia depends entirely on woody biomass for daily cooking and heating [14]. Furthermore, as deforestation and forest degradation continue, the future availability of wood for this region is at risk. Between 1990 and 2005, forest area in Southeast Asia declined approximately 2.6 million ha annually (about 1.2%) to 216.4 million ha in 2005 [15]. In addition, forest degradation due to logging (including illegal logging) and related damages causes the gradual loss of forest biomass and carbon stocks [16]. As the population and the demand for woody biomass continue to rise, the current and future availability of woody biomass need to be assessed so that appropriate policies can be introduced.

The aim of this study is to provide an assessment of the availability of woody biomass and bioenergy in eleven countries in Southeast Asia under current forest management regime, which includes illegal logging and logging damages. The paper is structured as follows: 1) forest land use change models are developed to estimate the rate of deforestation and reforestation through forest plantations; 2) woody biomass and harvesting models are developed to estimate the biomass changes under current management regimes, and potential woody biomass for bioenergy generation is estimated.

2. Materials and Methods

2.1. Forests in Southeast Asia

Southeast Asian countries in our study include Brunei, Burma, Cambodia, East Timor, Indonesia, Laos, Malaysia, Philippines, Singapore, Thailand, and Vietnam. This region has experienced fast economic development and the gradual loss of forest resources. Changes in areas of natural forests and forest plantations between 1990 and 2005 are given in **Table 1**. According to FAO [15], natural forests consist of production, multiple-purpose, and unspecified forests, protected forest, conservation forest, and forest for social services. The first three categories are grouped as production forest (*PdF*), where commercial logging and land development can take place, while the latter three categories are grouped as protected forest (*PrF*), where traditional firewood collection and small-scale logging for housing by local forest communities can take place. There are two types of forest plantations (FP) in the tropics, namely fast growing species plantation (*FPf*), which account for 47% of the total plantations and slow growing species plantation (*FPs*), which account for the rest [17]. For our study the proportion of fast and slow growing plantation remains unchanged during the modeling period between 1990 and 2020.

Table 1

2.2. Land use models

Over the last 15 years, although area of natural forests in Southeast Asia continued to decrease, area of forest plantations slowly increased as shown in Table 1. It could be argued that part of the deforested lands was replaced by forest plantations. Therefore, for our study, it is assumed that deforested lands are partially replaced by forest plantations (see **Fig.1** for illustration). With this assumption, the change in area of natural forests and forest plantations can be estimated using models developed by Kim Phat *et al*. [16]:

$$\frac{dPdF(t)}{dt} = -(k_a + k_b) \cdot PdF(t) \qquad (1)$$

$$\frac{dPrF(t)}{dt} = 0 \qquad (2)$$

$$\frac{dFP(t)}{dt} = k_a \cdot PdF(t) \qquad (3)$$

where *PdF(t)* is production forest at time *t*, *PrF(t)* is protected forest, *FP(t)* is forest plantation, -(k_a+k_a) is the change of *PdF(t)*, and k_a is the change of *FP(t)*

Data in Table 2 are used to derive –(k_a+k_b), k_a, and the initial values (t=0 in 1990) for areas of *PdF* and *FP* using linear regression methods. According to FAO [15], the area of protected forests in the tropics increased by approximately 0.07% from 1990 to 2005. During the modeling period of this study, *PrF* is considered to remain unchanged.

Fig. 1

Table 2

2.3. Woody biomass models

Standing biomass refers to all above-ground biomass in tons of dry matter, woody biomass refers to biomass available for bioenergy generation, and bioenergy refers to energy content in woody biomass. Leaves and root biomass are not included.

2.3.1. Natural forests:

A conceptual diagram illustrating the allocation of biomass is given in **Fig. 2**.

Fig. 2.

To estimate the standing biomass change in Southeast Asia, the following equations modified from Kim Phat *et al.* [16] are used:

$$\frac{dSB_i(t)}{dt} = MAI_i - H_i(t) - ddB_i(t) \qquad (4)$$

$$H_i(t) = \frac{f_w \cdot f_T}{1-r} \cdot \frac{SB_i(t)}{CC} \qquad (5)$$

$$ddB_i(t) = H_i(t) \qquad (6)$$

$$WAS_i(t) = s \cdot H_i(t) \qquad (7)$$

where $SB_i(t)$ is standing biomass in i forest (*PdF*, *PrF*) (ton ha^{-1}), MAI_i is mean annual biomass increment, $H_i(t)$ is harvested biomass, $ddB_i(t)$ is dead biomass caused by logging, $WAS_i(t)$ is biomass waste due to trimming, felling, skidding and/or transporting, f_W is the fraction of harvested stand biomass, f_T is the fraction of mature-tree stand biomass, *CC* is the cutting cycle, *r* is the illegal logging rate, *s* is the rate of biomass waste. It is unlikely that illegal loggers will harvest immature trees because of no market demand for such trees, and therefore $r \le 1 - f_W$. In our study the values for *MAI*, *WAS*, f_W, f_T, *CC*, and *r* (**Table 3**) are based on various country reports [16]. Under conventional logging in East Kalimantan, every one cubic meter of harvested wood resulted in the dying of 0.9–1.2 m^3 of life biomass [18]. In the same region, Sist *et al.* [19] estimated that logging 10 trees caused damage to other 309 trees all with a diameter at breast height over 10 cm, of which 206 trees were killed immediately. Therefore, for this study, $ddB_i(t)$ is assumed to be the same as $H_i(t)$ for every time step. An energy content of 20 GJ ton^{-1} of dry woody biomass [20] is used for energy estimates for biomass from natural forests and forest plantations.

Table 3

Total woody biomass available for bioenergy (BIE) in natural forests (NF) is estimated as:

$$BIE(t) = \sum_{i=1}^{2} [ddB_i(t) + WAS_i(t) + iuWAS_i(t)] \cdot NF_i(t) \qquad (8)$$

where $iuWAS_i(t)$ is iuWPi is iuWASi is in-use wasted wood due to wood processing at the wood processing factories (see Fig. 2), $NF_i(t)$ is *PdF(t)* and *PrF(0)*

Total biomass available for furniture making (BIF) is estimated as:

$$BIF(t) = \sum_{i=1}^{2} iuWP_i(t) \cdot NF_i(t) \qquad (9)$$

where $iuWP_i$ is in-use wood product (see Fig. 2)

2.3.2 Forest plantations:

Unlike natural forests, mean annual increment is faster in forest plantations, where a clear-cut system is applied. For this study, a logistic model is used to estimate biomass in forest plantations:

$$\frac{\mathrm{dSB_j(t)}}{\mathrm{dt}} = \alpha_j \cdot SB_j(t) \cdot (1 - \frac{SB_j(t)}{SB_{MAX,j}}) \tag{10}$$

where $SB_j(t)$ is standing biomass in j plantations (j is fast-growing plantation, *FPf* and slow-growing plantation, *FPs*) (ton ha^{-1}), α_j is the growth rate of a forest plantation, $B_{MAX,j}$ is the maximum wood biomass that a plantation can reach. Based on Brown [26] in Table 4, average standing biomass increment is 7.7 and 5.9 ton ha^{-1} yr^{-1} (see note under Table 4 for calculation) over 10-yr and 40-yr cutting rotation (*CR*) (**Table 4, Table 5**) for *FPf* and *FPs*, respectively (see note under Table 4 for calculation). In reality, $B_{MAX,j}$ is unknown because forest plantations are usually harvested before they reach maturity age. For this study, $B_{MAX,j}$ is assumed at 200 and 300 ton ha^{-1} for *FPf* and *FPs*. With these assumptions, α and $SB_j(0)$ for *FPf* and *FPs* are derived at 0.2765 and 0.1337, and 7.7 and 5.9 ton ha^{-1} yr^{-1}, respectively. All harvested stem biomass is assumed to be used for pulp production (PPL_j), and the rest in branches and top logs are summed to be woody biomass for bioenergy generation (ddB_j) (see **Fig. 2**). Biomass in leaves (1.9% of the total above-ground biomass [23]) is left behind in the field.

Table 4, Table 5

Total standing biomass in forest plantation j, $SBFP_j(t)$ at time t, is

$$\mathrm{SBFP_j(t_n)} = \mathrm{FPA_j(t_0)} \times SB_\mathrm{j}(\mathrm{t_n}) + \mathrm{FPA_j(t_1)} \times SB_\mathrm{j}(\mathrm{t_{n-1}}) + \ldots + \mathrm{FPA_j(t_n)} \times SB_\mathrm{j}(\mathrm{t_0}) \tag{11}$$

where $FPA_j(t)$ is the actual planted area at time t (million ha).

Total standing biomass in all plantations ($SBFP_{TOTAL}$) is therefore:

$$\mathrm{SBFP}_{\mathrm{TOTAL}}(t_n) = \sum_{j=1}^{2} \mathrm{SBFP}_j(t_n) \qquad (12)$$

Once each forest plantation reaches the *CR* age (t=*CR*), all biomass is harvested. Plantations established in 1990 (start of the model) will be harvested in 1999 for *FPf* and in 2029 for *FPs*. Replanting is assumed to be carried out one year after harvesting.

Total biomass available for pulp production (*BIP*) at time t=n in forest plantations is

$$\mathrm{BIP}(t_n) = \sum_{j=1}^{2} \frac{\mathrm{SBFP}_j(t_n)}{\mathrm{BEF}_j} \qquad (13)$$

where BEF_j is a biomass expansion factor (see note under Table 4)

And woody biomass available for bioenergy (*BIE*) at time t=n is

$$\mathrm{BIE}(t_n) = \sum_{j=1}^{2} \mathrm{SBFP}_j(t_n) - \mathrm{BIP}_j(t_n) \qquad (14)$$

3. Results and Discussions

3.1. Changes in area of forests

Over the modeling period, the area of natural forests declines from 245.9 million ha (231.1 for the 95% lower bound and 262.3 for the upper bound) in 1990 to 173.7 million ha (165.6–182.6) in 2020, losing annually about 2.0% [$-(k_a+k_b)= -0.0202$]. Mean annual changes in area of natural forests and forest plantation are estimated at 2.8 million ha yr^{-1} between 1990 and 2005, and 2.4 million ha yr^{-1} between 1990 and 2020 (**Table 6**). The area of forest plantations slowly increases to 16.0 million ha (15.2–16.8) from 10.1 million ha (9.8–10.2) in 1990, increasing about 0.2 million ha yr^{-1} (**Fig. 3**). Because only about 0.09% (k_a=0.0009) of deforested forestland is converted to forest plantations, our results suggest that most of the deforested land is converted to other types of land uses. Altogether, Southeast Asia loses about 2.2 million ha yr^{-1} (2.0–2.4) of forests over the modeling period (**Table 6**). A previous study by Kim Phat *et al*. [16] estimated deforestation in this region at 1.6 million ha yr^{-1} between 1980 and 2050. This variation may be due to the different modeling timeframe and the data used. Deforestation between 1990 and 2005 is estimated at 2.6 million ha yr^{-1} by our model, which matches very well with that estimated by FAO [15].

Fig. 3

Table 6

3.2. Standing biomass changes

Owing to deforestation and forest degradation, standing biomass in natural forests rapidly declines from 45858.7 million tons (about 957.2 EJ) in 1990 to 26597.4 million tons

(531.9 EJ) in 2020, losing about 708.7 million tons yr^{-1}(14.2 EJ) or about 1.5% yr^{-1}. Standing biomass in forest plantations is strongly influenced by cutting rotation, increasing to 1013.8 million tons (20.3 EJ) in 2020 from merely 67.8 million tons (1.3 EJ) in 1990. Altogether, Southeast Asian forests are projected to lose about 677.2 million tons yr^{-1} (13.5 EJ) between 1990 and 2020 (**Table 7**).

Table 7

3.3. Annual woody biomass and bioenergy production

In terms of woody biomass, natural forests produce, an average of 547.2±24.6 million tons yr^{-1} (± is standard error) (10.9 EJ) between 1990 and 2020, decreasing from 657.8±23.0 million tons yr^{-1} (13.1 EJ) between 1990 and 2005 (**Fig. 4**, **Table 8**). Forest plantations produce another 16.2±7.5 million tons yr^{-1} (0.3 EJ) between 1990 and 2020. Altogether, total annual production of woody biomass is 563.4 million tons (11.3 EJ) over the same period between 1990 and 2020. Total energy consumption in Southeast Asia was estimated at 6.4 EJ in 1990 and 15.7 EJ in 2006, increasing about 9.0% yr^{-1} [30]. Energy from woodfuels in Southeast Asia (excluding Singapore and Brunei) was estimated at 2.4 EJ in 1993 [14] or about 33.1% of the total energy consumption in that year [30]. Energy from woodfuels in this region increased, on average about 2.5% yr^{-1} between 1992 and 1995 [14]. Therefore, without effective policy to reducing deforestation and forest degradation, energy shortage is likely to occur in Southeast Asia.

Fig. 4

Using carbon coefficients of 25 KgC GJ^{-1} for coal, 20 KgC GJ^{-1} for petroleum products, and 15 KgC GJ^{-1} for natural gas [31], carbon emission reductions associated with using woody biomass instead of fossil fuels for energy generation are estimated at 281.7 TgC yr^{-1} for replacing coal, 225.3 TgC yr^{-1} for replacing petroleum products, and 169.0 TgC yr^{-1} for replacing natural gas throughout the modeling period (Table 8).

Table 8

3.4. Comparison with previous studies

Our models project 92.0±4.1 (52.4 million tons) and 64.8±30.2 million m^3 (33.3 million tons), of wood for furniture making and pulpwood production over the modeling period (**Table 8**). Industrial roundwood in Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Thailand, and Vietnam between 1991 and 2001 was reported at 77.2±5.6 million m^3 yr^{-1} [32]. With the addition of roundwood from illegal logging (r=0.53), the above figure would have been 164.2 million m^3 [=77.2/(1-0.53)], which is equivalent to about 82.2 million m^3 (=164.2*0.5, 0.5 is wood processing efficiency) of end-use wood products, about 9.8 million m^3 lower than our estimate. This difference may be due to the unreported wood production from illegal logging in some countries in the region.

Results from previous studies on wood bioenergy using different methods and assumptions are also compared here. Surrounded by uncertainties as identified by Koopmans [5], FAO-RWEDP estimated the potential wood bioenergy from forested land in Southeast Asia at about 6.7 EJ in 1994. If no illegal logging would take place, our model estimates wood bioenergy at 7.0 EJ in 1994 and 5.9 EJ yr^{-1} between 1990 and 2020 in the same region (Table 9). Smeets & Faaij [7] estimated the loss of wood bioenergy due to tropical deforestation at 13.0 EJ yr^{-1} between 1998 and 2050. Our estimate of wood bioenergy loss due to deforestation and forest degradation is 18.1 EJ yr^{-1} between 1990 and 2020. This difference may result from different methods and assumptions (Table 9). Using a global land-use and energy model (GLUE), Yamamoto *et al*. [33] estimated wood bioenergy in all developing countries worldwide at 45.9–85.2 EJ in 2100. Because of the difference in study methods, assumptions, and scales, the results of their study are expected to be higher than our estimate for Southeast Asia only.

Table 9

4. Sensitivity Analysis

Illegal logging is strongly affected by the political stability and governance in Southeast Asia. If an illegal logging rate of 73% (r=0.73) as reported in Indonesia [37] is used in all natural forests (NF), standing biomass in NF declines from 47858.7 million tons (957.2 EJ) in 1990 to 20652.2 million tons (413.0 EJ) in 2020, a loss of about 1.9% annually. If illegal logging is eliminated (r=0), standing biomass declines to 32393.3 million tons (647.9 EJ), losing only about 1.1% as a result of deforestation (**Fig. 5**). In terms of woody biomass production, our models project the mean annual production from all forests at 301.0 (6.0 EJ), 563.8 (11.3 EJ), and 831.7 million tons (16.6 EJ) for r=0, r=0.53 (r=0.53 was used in our study), and r=0.73, respectively (**Fig. 6**). According to Fig. 6, illegal logging is likely to cause a significant decline in annual woody biomass production. This suggestion is also supported by Meyfroidt and Lambin [41] who found a sharp decline in stand density of natural forests in Vietnam. International policy may influence biomass production. For example, if ongoing discussions lead to the inclusion of the reduced emissions from deforestation and degradation (REDD) in the post-Kyoto climate change agreement period from 2013 to 2020, a large amount of biomass loss as well as carbon emissions could be prevented. Therefore, woody biomass production will also change. Once slow growing plantations become harvestable, woody biomass production is expected to increase as well.

Another uncertainty of our study relates to the potential increase of woody biomass obtaining from forest rehabilitation as being increasingly implemented in Indonesia [38], Philippines [39], and Vietnam ([40], but see Meyfroidt and Lambin [41]). Forest rehabilitation could bring the deforested land or severely degraded forest back to its pre-harvest level, and therefore would eventually increase woody biomass. Annual or biannual re-assessment may reduce the future uncertainties regarding biomass projection.

Fig. 5

Fig. 6

5. Policy Implications for Woody Biomass Production under REDD

The current climate change agreement discussions include REDD in the post-Kyoto agreements and give hope for tropical forest conservation. The Bali Action [42] and the sustained interest in REDD during the 14th conference of the parties in Poznan in December in 2008 [43] have led to increased attention to REDD [44, 6]. If REDD is finally adopted, well-defined land use and logging planning that addresses the causes of deforestation is required. The causes of deforestation in Southeast Asia could be classified to be 1) the need for land for agricultural cultivation to feed increasing population [45], 2) industrial plantation development [46], and 3) indiscriminate logging [12, 24, 47]. The former is unavoidable because of the need for survival and requires well-assessed planning and policies to encourage sustainable practices. The latter two may be due to policy failures or the lack for incentives for long-term conservation of tropical forests. Economic, social, and ecological assessments of different land use options that take into consideration the financial incentives for protecting natural forests under REDD agreements are necessary so that resource managers–be they government or companies– will have a clear picture in terms of the financial returns and long-term social and ecological consequences of their decisions.

In order to control indiscriminate logging and its associated forest degradation, incentives are needed to promote reduced impact logging (RIL) which has been proven to reduce damages [12, 24] to residual trees and soil, reduce wood waste (the latter is due to untrained trimming, skidding, and transporting), and increase carbon sinks [47]. The REDD agreements are likely to result in decreases in woody biomass, as overexploitation and illegal logging would be gradually brought under control and the perpetual flow of ecosystem services for sustainable development could be ensured. As forest rehabilitation projects have been increasingly implemented in Indonesia [38], Philippines [39], and Vietnam [40, 41], incentives for further promoting the widespread implementation of such projects in other countries in the region could also lead to increase in woody biomasses as well as wood production. Furthermore, alternative sources of energy such as wind and solar power, and bioenergy through accelerating the development of plantations on deforested lands should be sought. Financial incentives made available through REDD agreements should be used wholly or partially for such alternatives.

Incentives or investment in plantations of hybrid species which, grow faster and are environmentally adaptable on already deforested lands would lead to the increase of woody biomass and pulpwood production for bioenergy and paper. Plantations could also decrease the pressure on natural forests whose ecosystem services and functioning are vital to sustainable development. Mean annual increment of some hybrid fast growing species of Eucalyptus (such as *E. grandis*) reaches 53–60 m^3 h^{-1} yr^{-1} (about 39.7–45.0 tons of all above-ground biomass) [48]. If this growth rate could be achieved, future supplies of woody biomass and pulp are likely to come from forest plantations, while natural forests are managed for full ecosystem services.

6. Conclusion

This study developed models to estimate forest land use changes, standing biomass, and woody biomass (for bioenergy generation) in Southeast Asia between 1990 and 2020. It also discussed the incentives for reducing deforestation and implementing sustainable forest management in the region. Our study methods could be applicable to any country or region where selective logging is practiced.

The results show that Southeast Asian forests produce about 563.8 million tons yr^{-1} (11.3 EJ) of woody biomass for the period spanning 1990 to 2020. The annual production of woody biomass decreases about 1.5% over the same period. Without appropriate measures to reduce deforestation and bring forests under sustainable management, Southeast Asia is likely to face a shortage of woody biomass. Furthermore, if the current deforestation and forest degradation continue, wood production, woody biomass, climate regulation (including carbon sequestration), watershed protection, and ecosystem functioning will be adversely affected, which, in turn could put sustainable development in the region at risk because a large part of population in this region depend on forests and their ecosystems for daily survival. Countries in the region should take advantages of the international agreements such as the Kyoto Protocol or post-Kyoto agreements, i.e. REDD, to reduce deforestation and forest degradation. At the same time, alternative sources of woody biomass, i.e. from forest rehabilitation and plantations, should be made available, because, currently only 0.08% of the 2.4 million ha deforested land is converted to forest plantations, and the majority of these lands are still available for plantation.

Our results also suggest that using wood biomass to replace the use of fossil fuels for energy generation could prevent carbon emissions of about 169.0–281.7 TgC yr^{-1} between 1990 and 2020.

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Figures and Captions

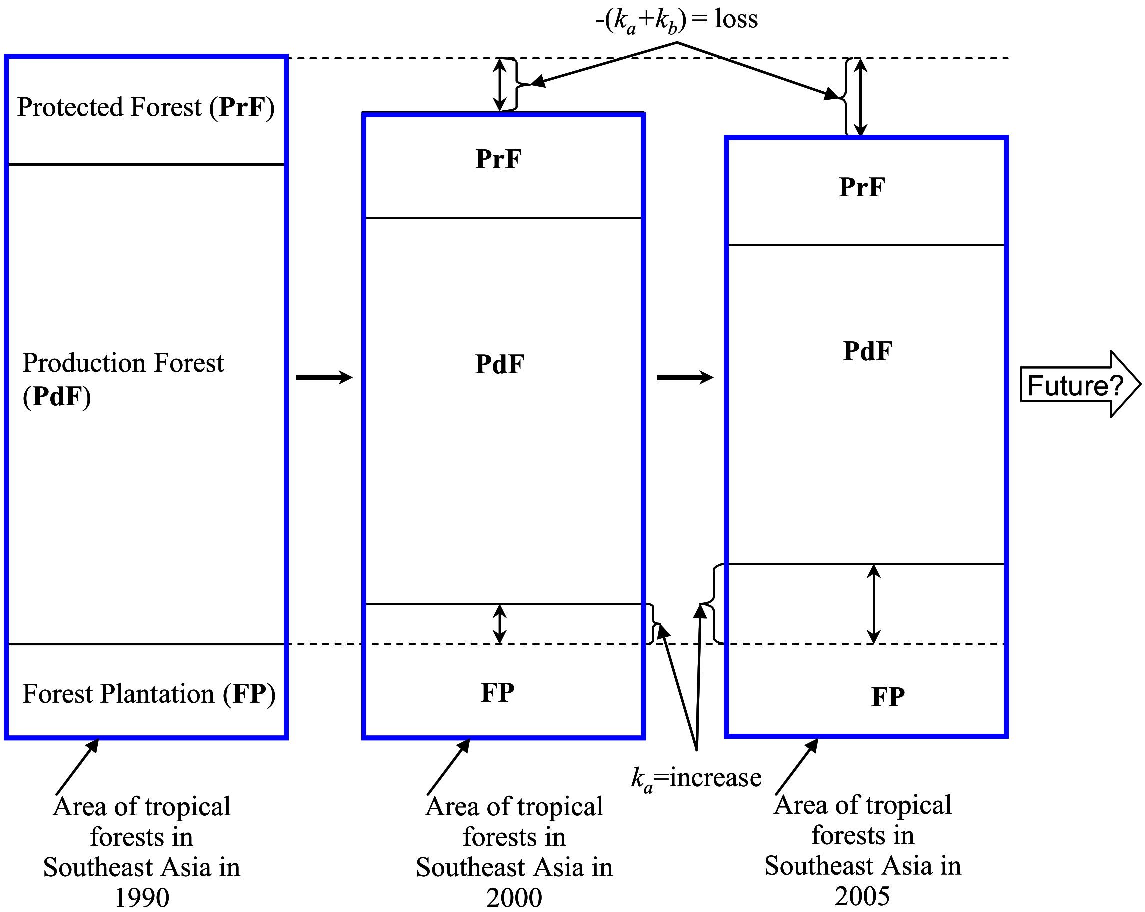

Fig. 1. Illustration of forest land use change model

Note: it is assumed that new plantations are established on deforested land only (i.e. deforested PdF).

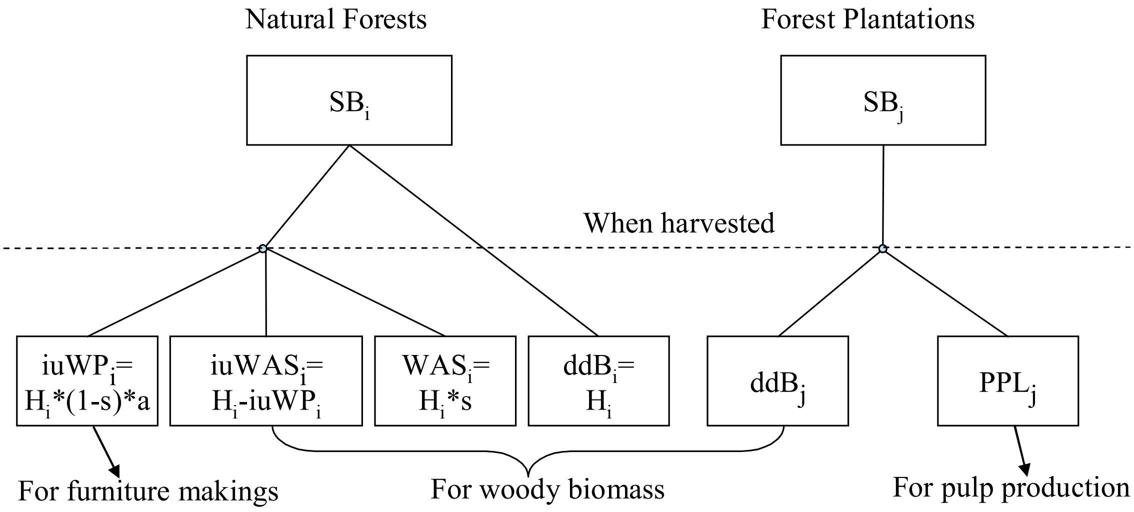

Fig. 2. Conceptual diagram for biomass allocation

Note

SB_i is standing biomass in natural forest *i*, *$iuWP_i$* is in-use wood product; *$iuWAS_i$* is in-use wasted wood, *WAS_i* is wasted wood due to felling, skidding, trimming and/or transporting; *ddB_i* is dead woody biomass caused by logging

SB_j is standing biomass in forest plantation *j*, *ddB_j* dead woody biomass in branches and top logs, *PPJ_j* is biomass in stem for pulp production ($PPJ_j = SB_j / BEF_j$, where BEF is biomass expansion factor. *BEF_j* values are presented in Table 4).

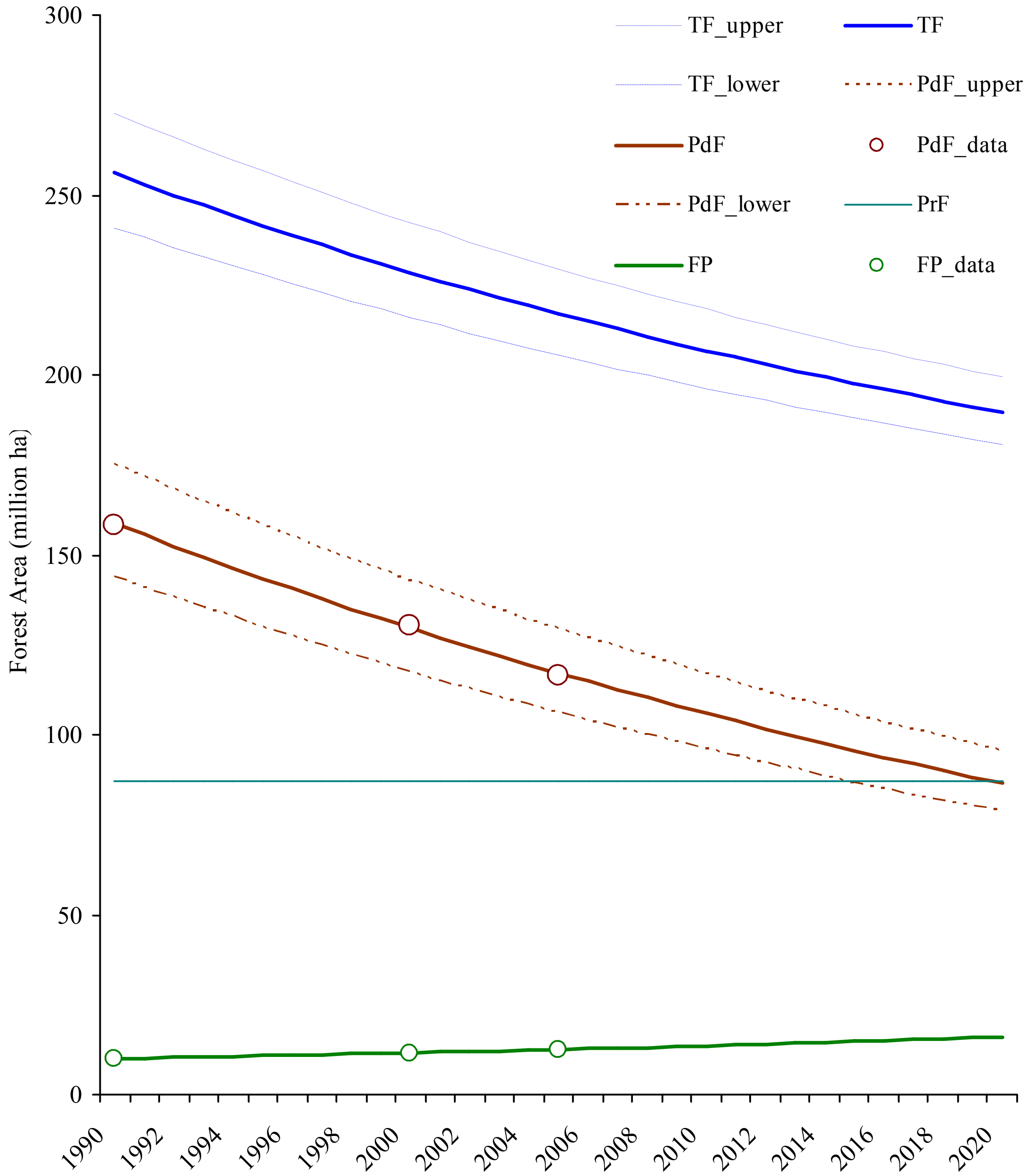

Fig. 3. Changes in area of forests in Southeast Asia (1990-2020)

Note: Confidence intervals for FP are not included because they are very small

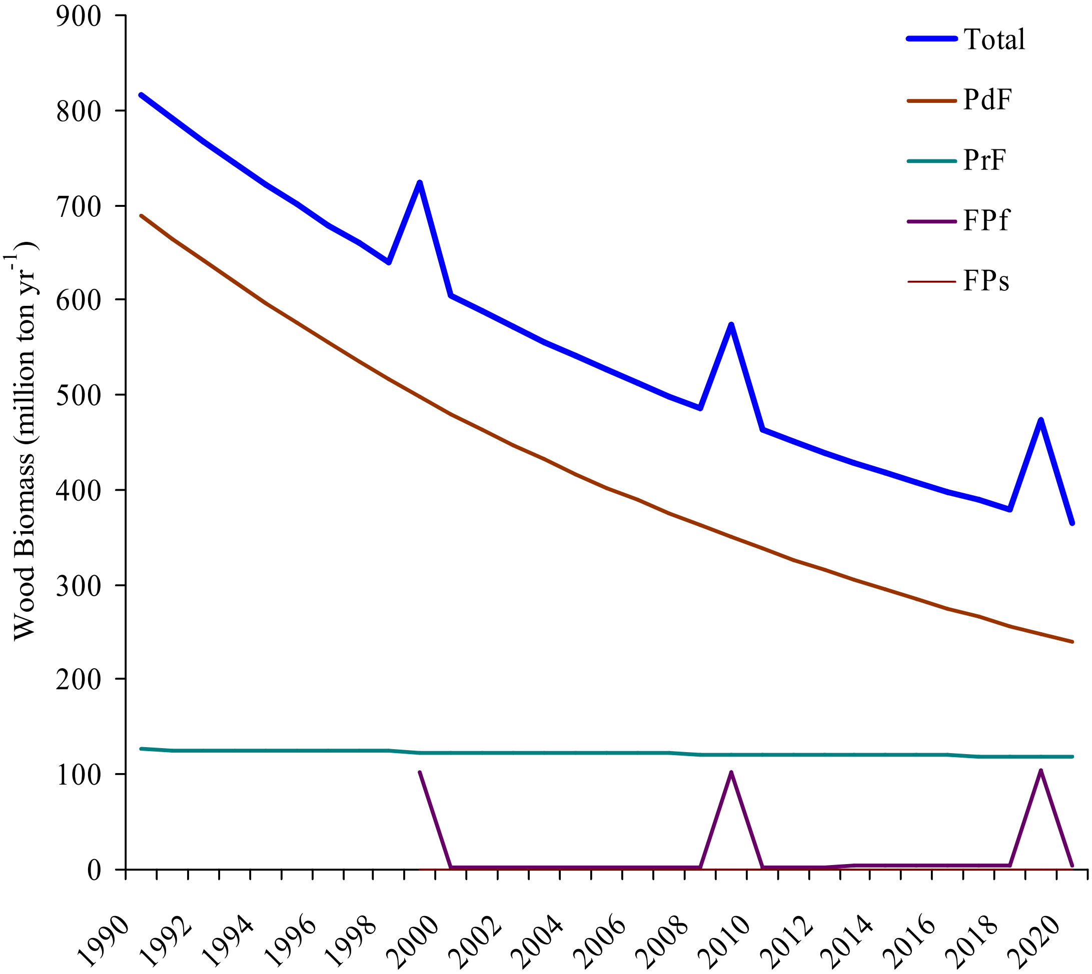

Fig. 4. Annual wood bioenergy production in Southeast Asia

Note

Fast growing plantation established in 1990 become harvestable in 1999. Its annual woody biomass production is strongly affected by cutting rotation. Slow-growing plantation will become harvestable in 2029, and therefore more woody biomass production is expected thereafter.

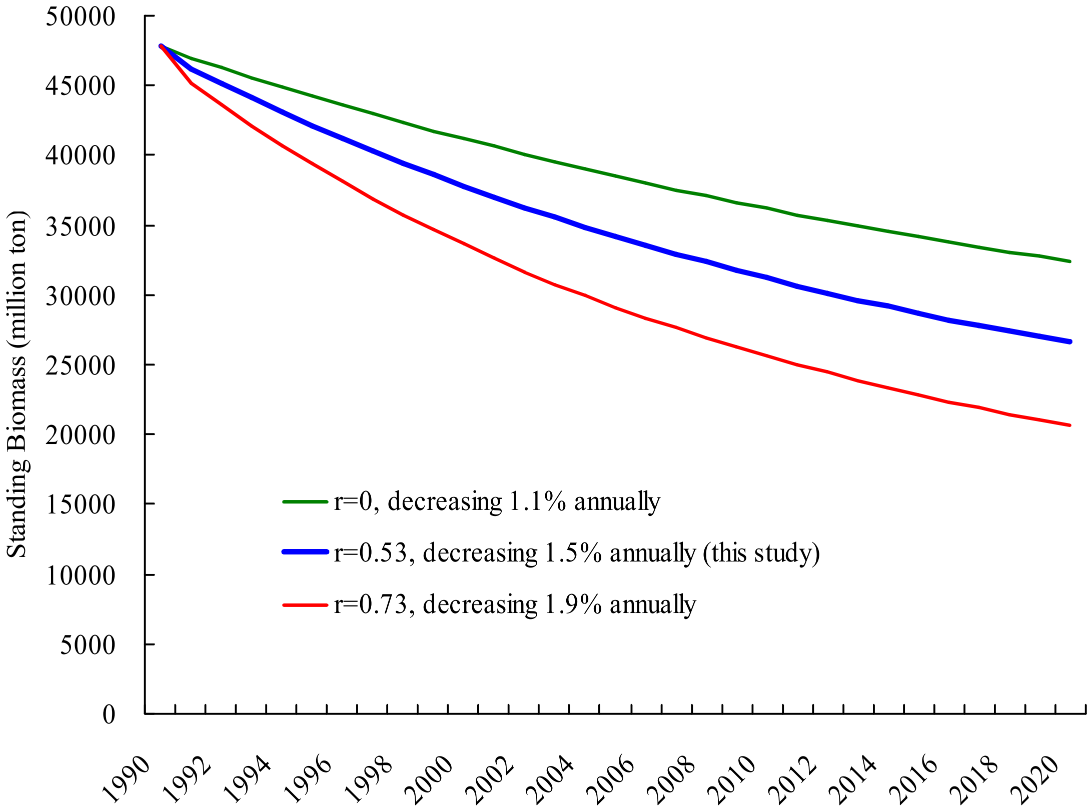

Fig. 5. Standing biomass in natural forests under different rates of illegal logging

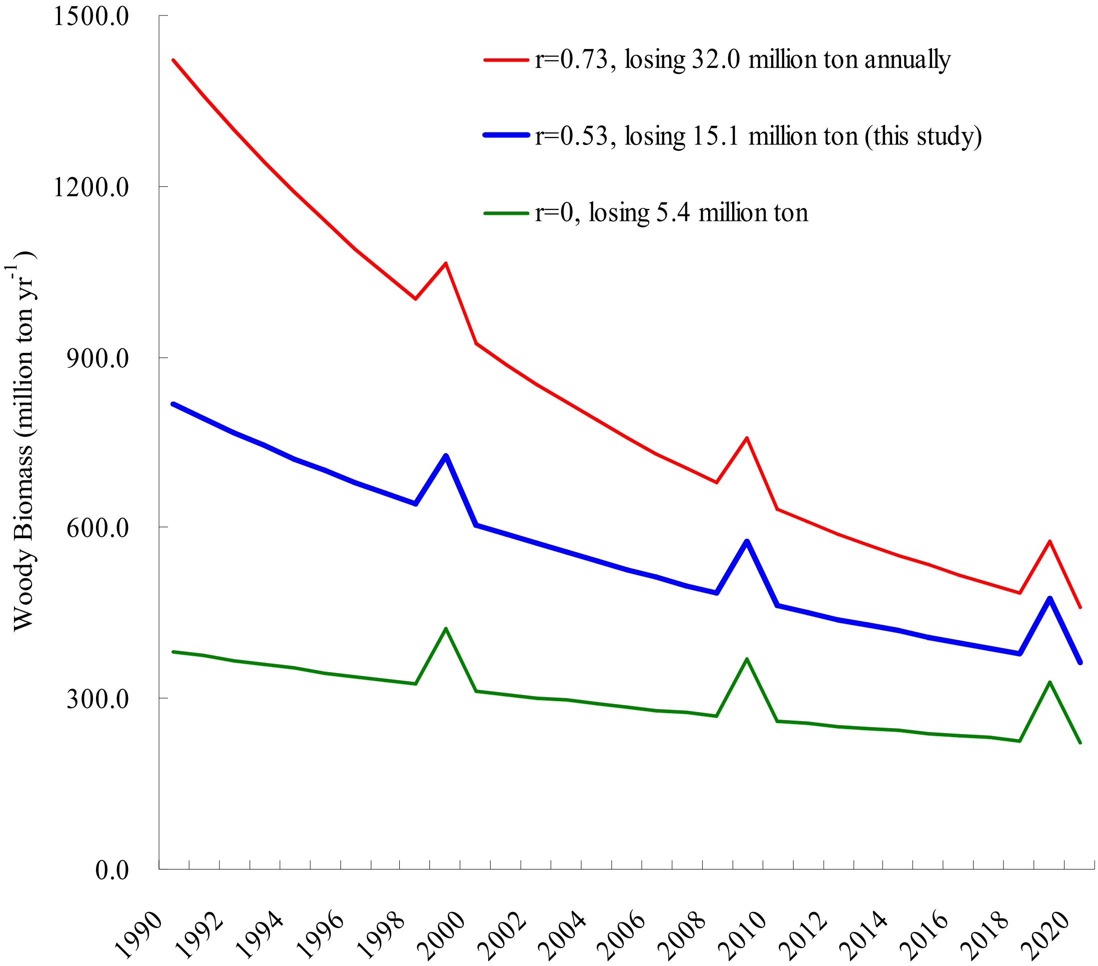

Fig. 6 Woody biomass production from all forests under different rates of illegal logging

Note

Illegal logging leads to more production of woody biomass in the beginning, but it starts to decline sharply. Additionally, deforestation is also responsible for the gradual loss of woody biomass as seen in the figure above (green line) when all illegal logging is halted.

Tables and Captions

Table 1 Changes in area of forests in Southeast Asia 1990-2005

	1990 ('000 ha)				2005 ('000 ha)		
Country	NF	FP	Total	Total	NF	FP	Total
Brunei Darussalam	313.0	0.0	313.0	288.0	278.0	0.0	278.0
Cambodia	12946.0	67.0	13013.0	11613.0	10447.0	59.0	10506.0
Indonesia	116567.0	2209.0	118776.0	100854.0	88495.0	3399.0	91894.0
Laos	17314.0	4.0	17318.0	16631.0	16142.0	224.0	16366.0
Malaysia	22376.0	1956.0	24332.0	23250.0	20890.0	1573.0	22463.0
Myanmar	39219.0	394.0	39613.0	35250.0	32222.0	849.0	33071.0
Philippines	10574.0	1780.0	12354.0	8801.0	7162.0	620.0	7782.0
Singapore	2.0	0.0	2.0	2.0	2.0	0.0	2.0
Thailand	15965.0	2640.0	18605.0	17891.0	14520.0	3099.0	17619.0
Timor-Leste	966.0	29.0	995.0	897.0	798.0	43.0	841.0
Viet Nam	9363.0	967.0	10330.0	13775.0	12931.0	2695.0	15626.0
Total	245605.0	10046.0	255651.0	229252.0	203887.0	12561.0	216448.0
Total (million ha)	245.6	10.0	255.6	229.2	203.9	12.6	216.4

Source: FAO [15]

Table 2 Data used to derive*[1] land use model's initial values and parameters

Year	NF (million ha)			FP (million ha)			Tropical Forests (million ha)
	PdF	PrF	Subtotal	FPf	FPs	Subtotal	
1990	158.4	-	245.6	-	-	10.0	255.7
2000	130.5	-	217.7	-	-	11.6	229.3
2005	116.7	87.2	203.9			12.6	216.4
Initial value	158.7	87.2				10.1	
Parameters	$-(k_a+k_b)=$ -0.0202					k_a=0.0009	

Note

*[1] Least square method was used to derive initial values and parameters

NF: Natural forests

PdF: Natural production forest

PrF: Natural protected forest

FP: Forest plantations

FPf: Fast growing forest plantation

FPs: Slow growing forest plantation

Table 3 Initial values and parameters for modeling biomass in natural forests

	PdF	PrF	Unit	Remarks and Sources
Stem Volume	200	200	$m^3\ ha^{-1}$	Taken from Kim Phat *et al*. [16]
SB(0)*[1] (stand biomass at t=0)	194.6	194.6	ton ha^{-1}	dry wood including branches, but without leaves
MAI*[2] (mean annual increment)	1.0	1.0	ton $ha^{-1}\ yr^{-1}$	dry wood including branches (no leaves, 1.9% of all; converted from [16]
f_W (fraction of harvested stand biomass)	0.3	0.1	%	30% of stand biomass of mature trees ([16] for PdF, 10% is assumed for PrF
f_T (fraction of mature-tree stand biomass)	0.5	0.5	%	50% mature biomass take from [Kim Phat *et al*. 16]
CC (cutting cycle)	30	30	yrs	[16]
r (rate of illegal logging)	0.53	0.53	%	[16]
s*[3] (fraction of wasted wood)	0.3	0.3	%	See *[3]
a*[4] (see Fig. 1) (processing efficiency)	0.5	0.5	%	[21]
WD (wood density)	0.57	0.57	ton m^{-3}	[22]
BEF (biomass expansion factor)	1.74	1.74		[22]
Leaves, l*[5]	0.019	0.019		[23]
Energy Content	20		GJ per oven try ton	[20]

Note
*[1]= V*WD*BEF*(1-*l*), leaves are considered as litters that are left behind as nutrients
*[2]= 1*WD*BEF*(1-*l*), MAI in stem is 1 $m^3\ ha^{-1}\ yr^{-1}$ (based on Kim Phat *et al*. [16])
*[3]: based on FAO [13], Homes *et al*. [24], and Sist and Sridan [25]
*[4]: Based on Loehnertz *et al*. [21]
*[5]: based on Nascimentoa and Laurance [23]

Table 4 Mean annual increments and cutting rotations for forest plantations

Species	MAI Range (ha^{-1} yr^{-1}) X (m^3)		Y (ton)		Rotation (yrs)*	Countries
	Min	Max	Min	Max		
Acacia auriculiformis	6.5	10.0	4.8	7.4	15	Myanmar, Philippines, Thailand and Vietnam
Acacia mangium	12.0	19.0	8.8	14.0	8	Indonesia, Malaysia and Papua New Guinea
	8.0	12.5	5.9	9.2		Laos, Philippines, and Vietnam
Eucalyptus species	8.0	12.5	5.9	9.2	5-15	Philippines,Thailand
	6.5	10.0	4.8	7.4		Malaysia
Mean	*8.2*	*12.8*	*6.0*	*9.4*		
For this study (fast growing species)			7.7		10	
Casuarina species	5.0	7.5	4.9	7.3	15-35	India and Vietnam
	1.5	2.5	1.5	2.4		Angola, Benin, Cuba, Kenya, Madagascar, Mauritius, Mozambique, Senegal, Somalia and Thailand
Dalbergia sissoo	3.0	5.0	2.9	4.9	24	Bangladesh, Bhutan, Burkina Faso, India, Nepal, Nigeria and Pakistan
Swietenia macrophylla	5.0	7.5	4.9	7.3	32	Indonesia and Philippines
Terminalia species	5.0	7.5	4.9	7.3		Bhutan, India and Jamaica
Tectona grandis	8.0	18.0	7.8	17.5	44	Colombia, Costa Rica, Jamaica, Nicaragua, Panama and Trinidad and Tobago
	4.0	6.0	3.9	5.8		Indonesia, Laos, Malaysia, Myanmar, Philippines, Thailand, and Vietnam
Mean	4.5	7.7	4.4	7.5		
For this study (slow growing species)			5.9		40	

Source: Brown [26]

Note:
Y=X×WD×BEF×(1-0.019) where WD is wood density, WD= 0.5 based on Miranda *et al.* [27] and Arroja *et al.* [28] for fast growing species and WD=0.57 [22] for slow growing species; and BEF is biomass expansion factor, BEF=1.50 [26]. (2006) and 1.74 [22] for fast growing and slow growing species, respectively, 0.019 is 1.9% in leaves [23]

*: Rotation length was taken as an average of rotation length of major species reported in Varmola and Del Lungo [29]

Table 5 Parameters for modeling biomass in forest plantations

	FPf	FPs	Unit	Remarks and Source
B_{MAX}	200	300	ton ha^{-1}	Maximum standing biomass (all aboveground but without leaves)
B(0)	7.7	5.9	ton ha^{-1}	All aboveground but without leaves
α	0.2765	0.1337		
MAI	7.7	5.9	ton ha^{-1} yr^{-1}	[26]
CC	10	40	yrs	[26]
WD	0.50	0.57		[27] for fast, [22] for slow growing plantation
BEF	1.50	1.74		[28] for fast, [22] for slow growing plantation
Litters	0.019	0.019		[23]
Energy Content	20	GJ per oven try ton		[20]

Table 6 Mean annual changes in area of natural forests and forest plantations (1990-2020)

Forests	1990-2005		1990-2020	
	(million ha)	(% to 1990)	(million ha)	(% to 1990)
Natural Forests	-2.8	-1.7	-2.4	-1.5
PdF	-2.8	-1.7	-2.4	-1.5
PrF	0	0	0	0
Forest Plantations	0.2	1.7	0.2	2.0
PFf	0.1	0.8	0.1	0.9
PFs	0.1	0.9	0.1	1.0
Total	-2.6	-1.0	-2.2	-0.9

Table 7 Total standing biomass in natural forests and forest plantations (1990-2020)

Forest Type	1990	2005	2020	Annual Change 1990-2005	Annual Change 1990-2020
		million tons		million tons yr^{-1}	
Natural Forests	47858.7	34202.9	26597.4	-910.4	-708.7
PdF	30884.7	17765.9	10611.6	-874.6	-675.8
PrF	16974.1	16436.9	15985.8	-35.8	-32.9
Forest Plantations	67.8	367.4	1013.8	20.0	31.5
PFf*[1]	36.4	150.2	92.5	7.6	1.9
PFs*[2]	31.4	217.2	921.3	12.4	29.7
Total	**47926.6**	**34570.3**	**27611.2**	**-890.4**	**-677.2**
Total (EJ*[3])	**958.5**	**691.4**	**552.2**	**-17.8**	**-13.5**
In terms of carbon stock changes (TgC yr^{-1})*[4]					
Natural Forests	23929.4	17101.4	13298.7	455.2	354.4
Forest Plantations	33.9	183.7	506.9	-10.0	-15.8
Total	**23963.3**	**17285.1**	**13805.6**	**445.2**	**338.6**

Note:
*[1]: Standing biomass is strongly affected by cutting rotation
*[2]: Standing biomass will be harvested in 2029, thereafter standing biomass will be reduced.
*[3]: EJ is exajoule (1 EJ = 10^9 GJ)
*[4]: Multiplying by 0.5 carbon content in dry woody biomass. One Tetragram Carbon (TgC) is one million tons of carbon
*[5]: Minus sign (-) refers to carbon sinks

Table 8 Mean annual woody biomass and bioenergy production, end-use wood and pulp production in Southeast Asia

Year	1990-2005				1990-2020			
Forests	million tons yr^{-1}		EJ yr^{-1}		million tons yr^{-1}		EJ yr^{-1}	
	Mean	s.e.*[3]	Mean	s.e.	Mean	s.e.	Mean	s.e.
Natural Forests								
BIE	657.8	23.0	13.2	0.5	547.2	24.6	10.9	0.5
BIF (million m^3)*[1]	110.6	3.9			92.0	4.1		
PdF								
BIE	533.4	22.7	10.7	0.5	424.5	24.3	8.5	0.5
BIF (million m^3)*[1]	89.7	3.8			71.4	4.1		
PrF								
BIE	124.4	0.3	2.5	0.0	122.6	0.4	2.5	0.0
BIF (million m^3)*[1]	20.9	0.1			20.6	0.1		
Forest Plantations								
BIE	15.7	14.3	0.3	0.3	16.2	7.5	0.3	0.2
BIP (million m^3)*[1]	62.8	57.2			64.8	30.2		
FPf								
BIE	15.7	14.3	0.3	0.3	16.2	7.5	0.3	0.2
BIP (million m^3)*[1]	62.8	57.2			64.8	30.2		
FPs								
BIE	0				0			
BIP (million m^3)*[1]	0				0			
Total								
BIE (million ton)	673.5		13.5		563.4		11.3	
BIF (million m^3)	110.6				92.0			
BIP (million m^3)	62.8				64.8			
In terms of carbon emissions reductions*[2] (in TgC yr^{-1}) by using wood bioenergy to replace:								
Coal			336.7				281.7	
Petroleum products			269.4				225.3	
Natural gas			202.0				169.0	

Note

*[1]: is converted by taking biomass dividing by wood density

*[2]: is derived by multiplying bioenergy (1 EJ = 10^9 GJ) with carbon coefficients of 25 KgC GJ^{-1} for coal, 20 KgC GJ^{-1} for petroleum products, and 15 KgC GJ^{-1} for natural gas [31] and dividing by 10^9 (1 TgC = 10^9 KgC)

*[3]: s.e. is standard error

BIE: woody biomass available for bioenergy
BIF: biomass available for furniture making
BIP: biomass available for pulp production (*BIP*)

Table 9 Previous studies on wood bioenergy

Authors	Methods	Major variables	Scale	Results
This study	Land use change model, biomass stock change model, biomass harvesting model	Natural forests, forest plantation, illegal logging, forest degradation	Regional	Deforestation and forest degradation reduce about 18.1 EJ yr^{-1} between 1990-2020. Potential bioenergy is 10.9 EJ yr^{-1} between 1990 and 2020. Potential wood bioenergy (no illegal logging) is 7.0 EJ in 1994 and 5.9 EJ yr^{-1} between 1990 and 2020.
FAO-Regional Wood Energy Development Program Koopmans [5] (2005)	Extrapolation using data 1990-1995. Biomass growth is assumed to increase 1% every year. Biomass growth of plantation was assumed at 6-10 m^3 ha^{-1} yr^{-1}. 80% of non-wooded lands also produce woodfuels	Natural forests, forest plantations, non-wooded lands. No illegal logging	Regional	Potential wood bioenergy is 6.7 EJ in 1994 from forested land in Southeast Asia
Smeets & Faaij (2007) [7]	Potential woody biomass in all forests is obtained by multiplying forest area and gross annual increment (GAI) under various scenarios. Data on forest area and GAI were taken from FAO [34], [35], [36]	Natural forests, forest plantations, and tree outside forests. Only GAI is harvested.	Global	Deforestation reduces about 13.0 EJ yr^{-1} between 1998 and 2050
Yamamoto *et al*. (1999) [33]	Global land-use and energy model (GLUE)	Natural forests, forest plantations, arable lands	Global	Potential wood bioenergy is 45.9-85.2 EJ in 2100 in all developing countries worldwide