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Re-Assessment of Forest Carbon Balance in Southeast Asia: Policy Implications for REDD+

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Abstract

Southeast Asia is rich in tropical forests and biodiversity but rapid deforestation and forest degradation have accelerated climate change and threatened sustainable development in the region. Carbon emission reductions through reducing deforestation and forest degradation, forest conservation, sustainable management of forests, and enhancement of forest carbon stocks (REDD+) have been a focal topic of the climate change mitigation since the Bali in 2007. However, only a handful of studies exist so far on this important issue that are suitable to inform the debate with estimates of carbon stocks and emission reductions or removals as a result of REDD+. Our study attempts to analyze the potential emission reductions and removals for a 35-year period under the REDD+ scheme. We start by developing land use change and forest harvesting models that are used to estimate carbon stock changes in natural forests and forest plantations in Southeast Asia. Carbon emissions from deforestation and forest degradation of natural forests were 1865.1, 1611.4, and 1300.4 $TgCO_2$ $year^{-1}$, respectively. With a hypothetical carbon project of 35 years beginning from 2015, carbon emission reductions were estimated at 817.6 $TgCO_2$ $year^{-1}$, of which about 10% was from reducing forest degradation. Carbon removals due to increase of forest plantations were 76.3 $TgCO_2$ $year^{-1}$ but the removals could be much higher if there is a new definition on the eligibility of forest plantations. Summing up together, about 893.9 $TgCO_2$ of carbon credits could be achieved from implementing carbon project in Southeast Asia or about US $6.6 billion annually between 2015 and 2050 if carbon price in 2012 is used. In addition to reducing emissions, there are other benefits from carbon project implementation. This study suggests that REDD+ has great potential for reducing carbon emissions and enhancing carbon stocks in the forests. Without financial incentives, carbon project would not happen and therefore climate change will continue to threaten future development.

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Keywords

Carbon Emissions, Carbon Finance, Deforestation, Forest Degradation, Tropical Forests

1. Introduction

Annual carbon emissions due to deforestation in the tropics were estimated ranging from 1.1 PgC [1] to 1.5 PgC [2], and up to 2.2 ± 0.6 PgC [3] during 1990s (1 PgC = 10^{15} gC). These emissions account for about 13.7% to 27.5% of the 8.0 PgC of global emissions. Furthermore, including selective logging, drought-induced mortality and fire in those calculations may lead to double those emissions [4] [5], accompanied by even higher losses of biodiversity. It is thus not surprising that the issue of reducing deforestation in the tropics has again become a central theme of the United Nations Framework Convention on Climate Change (UNFCCC). This is especially true after the Thirteen Conference of the Parties (COP13) of UNFCCC adopted the Bali Action Plan in 2007 (Decision 2) [6] recognizing the increasingly important role of tropical forests in greenhouse gas emissions reductions through the reduced emissions from deforestation and forest degradation, conservation of forests, sustainable management of forests, enhancement of forest carbon stocks (REDD+) in developing countries. The Action Plan encourages the parties to start implementing the REDD on a voluntary basis while negotiations for official inclusion of the REDD as a mitigation option for the post-Kyoto climate agreement [6] are continuing. Discussions on including reduced deforestation in the post-Kyoto agreement have been made [7]-[10], while discussions on reduced forest degradation are usually ignored due to difficulties in accurately detecting carbon emissions from degradation [11]. However, although the REDD has great potentials because of its remarkably low cost [8], the magnitude of carbon emissions from deforestation and forest degradation in tropical forests has been highly controversial [12]-[15] with errors likely to be as high as ±30% to ±60% [12] [16]. Most recent studies by Pan *et al*. [17] estimated carbon emissions from tropical deforestation (natural forests) at 2.9 PgC but were compensated by the increase of carbon sinks from forest plantations at 1.6 PgC annually between 1990 and 2007. Previous studies suggest the need for further research on forest carbon assessment so that uncertainties can be reduced. Reducing scale of carbon assessment from global to regional or even national scale is likely to reduce such uncertainties.

Using available data between 1980 and 2000 [18], Kim Phat *et al*. [19] developed land use change and forest carbon models to assess forest carbon stock changes affected by forest management in Southeast Asia. Their study suggests that deforestation in Southeast Asia resulted in carbon emissions of 465 TgC (1 TgC = million tonnes carbon) per year or about 29% of the global net carbon release from deforestation worldwide during 1990 and 2000. In addition to reducing deforestation, switching from conventional forest management (*i.e*. using conventional logging) to a more responsible forest management (*i.e*. using reduced impact logging) could further reduce carbon emissions depending on chosen management scenarios and financial incentives. Their findings indicate that reducing deforestation and improving logging practices can significantly contribute to reducing carbon emissions from deforestation and forest degradation while increasing timber and carbon-based revenues in Southeast Asia. As more data become increasingly available and international efforts made substantial progresses towards including reducing deforestation and forest degradation in the climate change mitigation option, re-assessment of forest carbon stock changes and emission reductions or removals or both becomes necessary for Southeast Asian countries.

The aim of this paper is, therefore, to provide a re-assessment estimate of the combined carbon emissions due to deforestation and forest degradation, the contribution of forest plantations to the forest carbon stocks in Southeast Asia. A further objective of this report is to develop a number of suitable scenarios and to estimate the results and impacts of REDD+ for a 35-year hypothetical project, which here is assumed to comprise the years 2015 to 2050.

This study will revisit the recently available data [20] with a focus on natural forests and forest plantations in Southeast Asia. The purpose is to project past changes of carbon stocks and emissions onto the period 1990 to 2050, during which a hypothetic REDD+ project is implemented from 2015 until 2050. It uses a generalized but comprehensive regional approach with representative estimates of the main factors controlling the carbon stocks under land use change and different forms of forest management, including forest protection, illegal logging, and reduced deforestation.

2. Study Materials and Methods

2.1. Forest Land Use Changes

Data on the total area of natural forests and forest plantations in the tropics in 1990, 2000, 2005, and 2010 were obtained by summing up the estimated area of all forests in Southeast Asia (**Table 1**) as reported in FAO [20]. FAO [20] categorized six forest types according to function, namely production, protection, conservation, social services, multiple purpose, and unspecific purpose. Based on those definitions (see Note under **Table 2**), we can

Table 1. Area of natural forests and forest plantations in Southeast Asia (unit: million·ha).

Country	Natural Forest				Forest Plantations				Total Forest Area			
	1990	2000	2005	2010	1990	2000	2005	2010	1990	2000	2005	2010
Brunei Darussalam	0.41	0.40	0.39	0.38	0.00	0.00	0.00	0.00	0.41	0.40	0.39	0.38
Cambodia	12.88	11.47	10.66	10.03	0.07	0.08	0.07	0.07	12.94	11.55	10.73	10.09
Indonesia	118.55	95.74	94.16	90.88	0.00	3.67	3.70	3.55	118.55	99.41	97.86	94.43
Laos	17.31	16.43	15.92	15.53	0.00	0.10	0.22	0.22	17.31	16.53	16.14	15.75
Malaysia	20.42	19.93	19.32	18.65	1.96	1.66	1.57	1.81	22.38	21.59	20.89	20.46
Myanmar	38.82	34.17	32.47	30.79	0.39	0.70	0.85	0.99	39.22	34.87	33.32	31.77
Philippines	6.27	6.79	7.05	7.31	0.30	0.33	0.34	0.35	6.57	7.12	7.39	7.67
Singapore	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thailand	16.88	15.89	15.45	14.99	2.67	3.11	3.44	3.99	19.55	19.00	18.90	18.97
Timor-Leste	0.94	0.81	0.76	0.70	0.03	0.04	0.04	0.04	0.97	0.85	0.80	0.74
Viet Nam	8.40	9.68	10.28	10.29	0.97	2.05	2.79	3.51	9.36	11.73	13.08	13.80
Southeast Asia	240.87	211.31	206.45	199.53	6.39	11.74	13.04	14.53	247.26	223.05	219.50	214.06

Source: [20].

Table 2. Primary designated functions of forest in 2010 and its use in this study.

Country	Primary designated function* (% of total forest area)						Use for this study (%)	
	A	B	C	D	E	F	Production (PdF = A + E + F)	Protection (PrF = B + C + D)
Brunei Darussalam	58	5	21	1	0	15	73	27
Cambodia	33	5	39	1	4	17	54	46
Indonesia	53	24	16	0	0	7	60	40
Laos	23	58	19	-	0	0	23	77
Malaysia	62	13	10	0	15	0	77	23
Myanmar	62	4	7	0	27	0	89	11
Philippines	76	8	16	0	0	0	76	24
Singapore	0	0	100	0	0	0	0	100
Thailand	14	7	47	1	0	32	46	54
Timor-Leste	33	42	25	0	0	0	33	67
Viet Nam	47	37	16	0	0	0	47	53
Southeast Asia (weighted average by forest area)							61	39

*: Definitions of forest functions according to FAO (2005). 1) Production (A): Forest/other wooded land designated for production and extraction of forest goods, including both wood and non-wood forest products (NWFPs). 2) Protection of soil and water (B): Forest/other wooded land designated for protection of soil and water. 3) Conservation of biodiversity (C): Forest/other wooded land designated for conservation of biological diversity. Includes, but is not limited to, protected areas. 4) Social services (D): Forest/other wooded land designated for the provision of social services. These services may include recreation, tourism, education and/or conservation of cultural/spiritual sites. 5) Multiple purpose (E): Forest/other wooded land designated for any combination goods, protection of soil and water, conservation of biodiversity of socio-cultural services, and where none of these alone being significantly more important than the others. 6) Unknown function (unspecific, F): Forest/other wooded land for which a specific function or where the designated function is unknown. For this study, No. 1, No. 5, and No. 6 above were classified as production forest (PdF), and the rest were classified as protected forest (PrF).

classify tropical forests into two types, namely production forest (PdF, comprising production, multiple-purpose, and unspecific-purpose forests) and protection forests (PrF: protection, conservation and social services forests). Protection forest is forest that is normally protected from commercial logging and forest clearing, while production forest is forest designated for commercial logging, clearing for forest plantation, agricultural cultivation, and other purposes as and when needed. Both PrF and PdF are natural forests, to which we add a third category, forest plantations (FP). The change in area of forest plantations and natural production forest are estimated according to a method modified from Kim Phat *et al*. [19]. The equations used are:

$$\frac{\mathrm{dPdF}(t)}{\mathrm{d}t} = (a+b) \times \mathrm{PdF}(t) \quad (1)$$

$$\frac{\mathrm{dPrF}(t)}{\mathrm{d}t} = 0 \quad (2)$$

$$\frac{\mathrm{dFP}(t)}{\mathrm{d}t} = a \times \mathrm{PdF}(t) \quad (3)$$

where $\mathrm{PdF}(t)$, $\mathrm{PrF}(t)$ and $\mathrm{FP}(t)$ are areas of production forest, protected forest and forest plantations in million ha at time t (in years), $a+b$ is the change rate of PdF, a is the conversion rate from PdF to FP, and b the conversion rate from PdF to other land use types, such as agricultural lands, resettlements or urban build-up. **Table 1** shows the available data for natural forest and forest plantation in 1990, 2000, 2005, and 2010 by country in Southeast Asia. Proportion of PrF between 2005 and 2009 did not change and therefore it is assumed that its area remains constant throughout the modeling period between 1990 and 2050 (**Table 2**, **Table 3**). A least-square fit to calculate $a+b$ a and initial values at time $t=0$ (corresponding to 1990) for PdF, and FP, yields: PdF(0) = 160.2 million ha, FP(0) = 6.8 million ha, a = 0.0029% or 0.29% increase year^{-1} and $a+b=-0.0146$ or 1.46% loss year^{-1} (**Table 3**).

2.2. Forest Carbon Stocks and Stock Changes

In the modeling framework developed here, carbon stocks in forests can be affected either by full land-use conversion (activity data described in Equations (1)-(3) or by change in the carbon stock within a particular forest type (emission factor). The former is related to the term "deforestation" in REDD+, the latter causes "degradation" depending on harvesting intensity and related damages. In this study, forest degradation is defined as the loss of carbon stock in a standing forest at any given time compared to the previous year. This may be due to overexploitation (legal or illegal), resulting in carbon loss from unsustainable harvesting. Additional cause is logging damages to the residual forest stands caused by logging operations that exceed natural increments (termed hereafter as the "Mean Annual Increment", MAI) of a forest in question. Although small-scale logging is carried out in protected forests for local consumption by forest dependent communities who reside in the protected forest, and carbon stocks in PrF is assumed to be constant during the modeling period; this is based on the fact that carbon loss due to small-scale logging is equally compensated by natural regeneration. A separate carbon stock model accounts for the very different dynamics of forest plantations (FP).

Table 3. Production and protected forests and forest plantations used in land use model.

Year	Production Forest (PdF)	Protected Forest (PrF)	Forest Plantations (FPl)	Total
1990	163.1	77.8	6.4	247.3
2000	133.5	77.8	11.7	223.0
2005	128.7	77.8	13.0	219.5
2010	121.7	77.8	14.5	214.0
Assumptions	Deforestation but some of the deforested area is replanted	Remain constant throughout the modeling period	Increase due to replanting on deforested land	
Parameters	a + b = −0.0146 (1.46% decrease annually)		a= 0.0029 (0.29% increase annually)	
Initials	160.2		6.8	

Although five carbon pools need to be reported by parties to the UNFCCC [21], this study only considers the following pools: aboveground, belowground, litters and deadwood. Role of soil carbon as carbon sink or source is uncertain, either a sink [22] [23] or a source [23]. For lack of data, the present study does not include soil carbon (another carbon pool). Future studies should include soil carbon when data for different land uses after deforestation become available.

Natural forest. Natural forests (PdF and PrF) are usually the state-owned forests, where logging, clearing or protection can take place depending whether it is PdF or PrF. For PdF, individual country grants concession rights to logging companies for harvesting and managing under the terms of agreement and forest management guidelines such as forest concession management, the forestry code of logging practices, or the like. Forest concessionaire (logging company) pays to government the license fees, timber royalties and other fees (see [24] for more) for the rights to manage and harvest the forests. The model for carbon stock changes in natural forests modifies the one by Kim Phat *et al*. [19]. It assumes that within a concession (*i.e*. production forest), different parcels of land undergo a cutting cycle of length CC (years), and within this parcel of land, a fraction f_H of the mature trees-themselves comprising a fraction f_M of all trees-are cut. f_H is regulated by forest harvesting law or the forestry code of logging practice. The model allows for illegal logging by defining an illegal logging rate r (see Kim Phat *et al*. [19]). Illegal logging is defined as the harvesting of wood without government-issued license.

Carbon stock, CS(t) in PdF or PrF can thus be estimated by:

$$\mathrm{CS}(t) = \mathrm{CS}_{\mathrm{above}}(t) + \mathrm{CS}_{\mathrm{below}} + \mathrm{CS}_{\mathrm{litters}} + \mathrm{CS}_{\mathrm{dead}} + \mathrm{CS}_{\mathrm{soil}} + \mathrm{CS}_{\mathrm{HWP}} \quad (4)$$

where $\mathrm{CS}_{\mathrm{above}}(t)$ is aboveground carbon, $\mathrm{CS}_{\mathrm{below}}$ is belowground carbon, $\mathrm{CS}_{\mathrm{dead}}$ is carbon in deadwood, $\mathrm{CS}_{\mathrm{litters}}$ is carbon in litters, and $\mathrm{CS}_{\mathrm{soil}}$ is carbon in soil. According to IPCC Good Practices [21] (IPCC 2006), including carbon in harvested wood product ($\mathrm{CS}_{\mathrm{HWP}}$) is optional. For this study, $\mathrm{CS}_{\mathrm{soil}}$ and $\mathrm{CS}_{\mathrm{HWP}}$ are not accounted for. Except $\mathrm{CS}_{\mathrm{above}}(t)$, logging does not significantly affect $\mathrm{CS}_{\mathrm{below}}$, $\mathrm{CS}_{\mathrm{below}}$, and $\mathrm{CS}_{\mathrm{below}}$ and therefore for simplicity, carbon in these three pools are assumed to be constant proportional to $\mathrm{CS}_{\mathrm{above}}(t)$ throughout the modeling period. REDD+ project implementation is assumed to be undertaken in 2015 for 35 years until 2050. A 35-year project cycle is a common duration of forestry carbon projects being implemented elsewhere in the tropics. All units are MgC·ha^{-1}(1 MgC = 10^6 gC), except otherwise stated. $\mathrm{CS}_{\mathrm{above}}(t)$ can be accounted by

$$\frac{\mathrm{dCS}_{\mathrm{above}}(t)}{\mathrm{d}t} = \mathrm{MAI} - \left[\mathrm{LM}(t) + \mathrm{H}(t)\right] \times \mathrm{BEF} \quad (5)$$

where t is time (year), MAI is mean annual increment (MgC·ha^{-1}·year^{-1}), $\mathrm{LM}(t)$ is logging mortality, $\mathrm{H}(t)$ is harvested carbon (MgC·ha^{-1}·year^{-1}). $\mathrm{LH}(t)$ is dependent on the amount of trees to be harvested varying according to logging practices [25] (Sasaki *et al*. 2012). $\mathrm{H}(t)$ can be derived by:

$$\mathrm{H}(t) = \frac{f_M f_H}{1-r} \times \frac{\mathrm{CS}_{\mathrm{above}}(t)}{\mathrm{CC} \times \mathrm{BEF}} \quad (6)$$

$$\mathrm{LM}(t) = \alpha \times \mathrm{H}(t) \quad (7)$$

Deciding the initial values for carbon stocks *i.e*. $\mathrm{CS}_{\mathrm{above}}(0)$ affects the results of carbon stocks, emissions or removals in Southeast Asia. Based on various sources (**Table 4**), average aboveground carbon stocks in forests in Southeast Asia are 151.1 MgC·ha^{-1} (129.6 - 172.6 for lower and upper bounce of 95% confidence interval, respectively). Aye *et al*. [26] estimated that about 15.9%, 14.2%, and 24.3% of aboveground carbon stocks in Myanmar's deciduous forests are in belowground, litters, and deadwood, respectively. We use these ratios for our study (**Table 4**).

Availability of mature trees in the forests and allowable rate for harvesting of these mature trees affect timber production and logging in the tropics. The two fractions were taken from Sasaki *et al*. [25] and set to $f_H = 0.3$ and $f_M = 0.43$ for PdF. BEF is biomass expansion factor (BEF = 1.74 taken from [37] Brown, 1997). As explained early, carbon stocks in PrF is assumed to be constant. Cutting cycle (CC) is 30 years based on Sasaki *et al*. [25].

To estimate r, a number of sources were reviewed. The Forests and the European Union Resource Network [38] released an illegal logging statement claiming about 50% of the tropical wood products imported to the European Union came from illegal source. The illegal proportion of total wood products was between 50% and

Table 4. Available data on aboveground carbon stocks in Southeast Asia.

Country	Aboveground carbon stocks ($MgC·ha^{-1}$)	Reference
Cambodia	116.6	[27]
Indonesia	243.0	[28]
Indonesia (Berau district)	199.3	[29]
Malaysia	138.0	[30]
Malaysia	166.0	[31]
Malaysia	164.0	[31]
Malaysia (Tangkulap)	126.0	[32]
Malaysia (Deramakot)	178.0	[32]
Malaysia (Pasoh)	137.0	[33]
Malaysia (Pasoh)	155.0	[33]
Myanmar	116.6	[26]
Philippines	193.0	[34]
Thailand	71.6	[35]
Vietnam	111.5	[36]
Average (CS_{above})	151.1	129.6 - 172.6 is for lower and upper bounce of 95% Confidence Interval, respectively
Below (CS_{below})	24.0	[26]
Litters ($CS_{litters}$)	21.5	[26]
Deadwood (CS_{dead})	36.7	[26]
Soil	(Not included)	
Total (CS)	233.3	

80% depending on political situation and locations on the country in the tropics [38]. Illegal logging in Cambodia was reported at 67% in 1997 [39]. While illegal logging is not constant over time, depending on political and economic situation in the countries in concern, here we assume that 50% $(r = 0.5)$ of logging in PdF is illegal for 1990 through 2050 *i.e*. for the whole period of hypothetical REDD+ implementation. Revision of the parameter r is highly recommended once data become available. Parameter values and variables for Equations (5)-(7) are given in **Table 5**.

MAI is an important indicator in forest management. Based on various studies in Southeast Asia [40]-[43] [27], a previous study by Kim Phat *et al*. [19] assumed a rate of 1 $m^3·ha^{-1}·yr^{-1}$ for the MAI of tropical natural forests of Southeast Asia between 2000 and 2050. Based on evidence of long-term plots from 1975 to 1996, a biomass increase of 0.71 ± 0.34 $MgC·ha^{-1}·yr^{-1}$ was observed for Amazonian forests [44]. The average volume increment for commercial timber in logged forests in Tapajós National Forest (Amazonia) has been estimated at 0.33 $m^3·ha^{-1}·yr^{-1}$ or about 0.09 $MgC·ha^{-1}·yr^{-1}$ [45]. Based on 12 - 17 years of measurements from experimental plots in national forests at Jarí and Tapajós, Amazonia, Alder and Silva [46] have estimated a MAI of 0.4 - 3.1 $m^3·ha^{-1}·yr^{-1}$ or about 0.11 - 0.88 $MgC·ha^{-1}·yr^{-1}$. According to recent study of Wadsworth and Zweede [47] who focused their research on 24 crop trees in eastern Amazonia, logged forests were found to have a MAI of at least 0.56 to 0.67 $m^3·ha^{-1}·yr^{-1}$. For this study, MAI is assumed to be 0.76 $MgC·ha^{-1}·yr^{-1}$.

Tree damages due to logging in relation to commercial stands were reported to be 60% for Sabah (Malaysia) by Tay *et al.* [48], 56% for Sarawak (Malaysia) by FAO [49], and 48.4% in East Kalimantan by Sist and Saridan [50]. Approximately 44% of the 60% reported by Tay *et al*. [48] were destroyed during the harvesting over a 60-year cutting cycle or about 0.7% yr^{-1}. According to Sist *et al*. [50], logging caused 24.7% in dead commercial trees and 25.4% additional trees that were injured but not dead, in addition to canopy openings and damages to the soil. Pinard and Putz [31] found that 18% of all injured trees with DBH greater than 5 cm died after 12 months of harvesting. Iskandar *et al*. [51] reported that every one m^3 of wood harvested led to the loss of 0.7 -

Table 5. Initial values and parameters used for production forest (Equations (5)-(7)).

Description	Conventional Logging (CVL)	Reduced Impact Logging (RIL)
Initial carbon stocks CS_{above} (0)	151.1	151.1
f_M (Fraction of mature trees)	0.43	0.43
f_H (Logging rate)	0.3	0.3
r (Illegal logging rate)	0.5	0.5
CC (Cutting cycle in year)	30	30
MAI (Mean Annual Increment)	0.76	0.76
BEF (Biomass Expansion Factor)	1.74	1.74
α	0.4	0.14

1.3 m^3 due to logging damages. Recent study by Kimsun [52] suggested that logging damages under the RIL was 14% of the harvested wood. For this study, α is 0.40 (40% of harvested wood) is for damages under CVL and 0.14 is for damages under the RIL. More discussion on this variable will be discussed later in the paper.

Forest Plantations. Although tropical natural forests have been cleared, part of the deforested land has been gradually replaced forest plantation [20]. According to FAO [53], major tree species being planted in the tropics are eucalypts (23%), pines (10.5%), Acacia (7.7%), and the rest comprises a mixture of fast-growing and native species. Based on various studies as seen in **Table 6**, average carbon stocks in forest plantations is 91.6 $MgC \cdot ha^{-1}$. Carbon stocks in forest plantation are therefore assumed to be constant using the average of carbon elsewhere in Southeast Asia of 92 $MgC \cdot ha^{-1}$. We use 92.0 MgC as carbon stocks in forest plantations in our study. Major forest plantations were well established before the beginning of the modeling timeframe. Carbon stocks in FPl, $CS_{FPl}(t)$ are therefore

$$CS_{FPl}(t) = CS(0) = 92 \tag{8}$$

2.3. Carbon Stocks in Natural Forests and Forest Plantation

The carbon stocks in natural forest in any given year is estimated by

$$NF_{TOTAL}(t) = CS\_PdF(t) \times PdF(t) + CS\_PrF(t) \times PrF(t) \tag{9}$$

where $NF_{TOTAL}(t)$ is the carbon stock in natural forests at time t (in TgC), $CS\_PdF(t)$ and $CS\_PrF(t)$ are the sums of all carbon pools (except soil carbon) per hectare in production and protected forests, respectively.

Clear-cut and re-plant are assumed to take place after a cutting rotation period of 10 years. Total carbon stocks in FPl after annual harvest is estimated by

$$FPl_{TOTAL}(t) = CS_{FPl}(t) \times \left[FPl(t) - \frac{FPl(t)}{10} \right] \tag{10}$$

$FPl_{TOTAL}(t)$ is the total carbon stocks in forest plantations at time t (in TgC).

The total carbon stocks in natural forests and forest plantations in Southeast Asia are therefore

$$CS_{TOTAL}(t) = NF_{TOTAL}(t) + FPl_{TOTAL}(t) \tag{11}$$

2.4. Carbon Emissions from Deforestation and Forest Degradation

Establishment of baseline emissions or reference emission level is important for any developing country planning to receive financial support from developed countries under the REDD+ scheme. Total emissions from deforestation and forest degradation can be estimated by.

Table 6. Carbon stocks in forest plantations by species in the tropics.

Carbonstocks ($MgC\cdot ha^{-1}$)	Remarks	References
	Pinuscaribaea	
130.2	Various locations across Sri Landka	[54]
80.6 (AG)	15-year-old stand in Nigeria	[55]
103.5 (AG)	10-year-old stand in Nigeria	[56]
99.3 (AG)	Mid-country Wet Zone (WM3b)	[57]
76.2 (AG)	Mid-country Intermediate Zone (IM1b)	[58]
	Eucalyptus grandis	
132.7	Various locations across Sri Landka	[54]
197.0 (AG)	27-year-old stand in New South Wales, Australia	[58]
137.0 (AG)	12-year-old stand in New South Wales, Australia	[59]
234.5	19-year-old stand in Hatton, Sri Lanka	[60]
53.5 - 70.5 (AG)	5.5-year-old stand in Brazil	[61]
	Eucalyptus camaldulensis	
26.2	Various locations across Sri Landka	[54]
13.5 - 17.5	3.5-year-old stand in Southern Brazil	[62]
22.6	3-year-old stand in Southern India	[63]
	Tectona grandis	
42.7	Various locations across Sri Landka	[54]
70.6 (AG)	15-year-old stand in Nigeria	[64]
120.0	20-year-old stand in Panama	[65]
142.0 (AG)	47-year-old stand in Costa Rica	[66]
113.0 - 191.0	Mature stand in South-Western Nigeria	[67]
70.6 (AG)	14-year-old stand in Nigeria	[64]
34.2 (AG)	Philippines	[68]
	Swietenia macrophylla	
97.6	Various locations across Sri Landka	[54]
130.5 (AG)	16-year-old stand in the Philippines	[69]
133.8	Mature stands in the Philippines	[70]
61.9 (AG)	59-year-old stand in Puerto Rico	[71]
	Acacia mangium	
110.7	Various locations across Sri Landka	[54]
45.2 (AG)	4-year-old stand in Malaysia	[72]
88.1 (AG)	Philippines	[73]
25.6 (AG)	Philippines	[74] [68]
	Acaciaauriculiformis	
87.1	Various locations across Sri Landka	[54]
76.8 (AG)	Philippines	[68]
	Assumption for this study: 92.0 $MgC\cdot ha^{-1}$	

Source: De Costa *et al*. [54]. Note: AG refers to above-ground carbon stocks.

$$\mathrm{E}_{\mathrm{TOTAL}}(tn)=\mathrm{E}_{\mathrm{DEFORESTATION}}(tn)+\mathrm{E}_{\mathrm{DEGRADATION}}(t) \tag{12}$$

Or

$$\mathrm{E}_{\mathrm{DEGRADATION}}(t)=\mathrm{E}_{\mathrm{TOTAL}}(tn)-\mathrm{E}_{\mathrm{DEFORESTATION}}(tn) \tag{13}$$

where $\mathrm{E}_{\mathrm{TOTAL}}(tn)$, $\mathrm{E}_{\mathrm{DEFORESTATION}}(tn)$, and $\mathrm{E}_{\mathrm{DEGRADATION}}(tn)$ are total emissions, emissions from deforestation, and emissions from forest degradation, respectively at time $t=n$. $\mathrm{E}_{\mathrm{TOTAL}}(tn)$ and $\mathrm{E}_{\mathrm{DEFORESTATION}}(tn)$ are obtained by

$$\mathrm{E}_{\mathrm{TOTAL}}(tn)=\left[\mathrm{PdF}(tn)\times\mathrm{CS}_{\mathrm{PdF}}(tn)-\mathrm{PdF}(tn-1)\times\mathrm{CS}_{\mathrm{PdF}}(tn-1)\right]\times\frac{44}{12} \tag{14}$$

$$\mathrm{E}_{\mathrm{DEFORESTATION}}(tn)=\left\{\left[\mathrm{PdF}(tn)-\mathrm{PdF}(tn-1)\right]\times\mathrm{CS}_{\mathrm{PdF}}(tn)\right\}\times\frac{44}{12} \tag{15}$$

where $\mathrm{PdF}(tn)$ is area of PdF at time $t=n$ in million ha (Equation (1)), $\mathrm{CS}_{\mathrm{PdF}}(tn)$ is carbon stocks of PdF in $\mathrm{MgC\cdot ha^{-1}}$, 44/12 is molecular weight of carbon dioxide per carbon unit. Unit for $\mathrm{E}_{\mathrm{TOTAL}}(tn)$, $\mathrm{E}_{\mathrm{DEFORESTATION}}(tn)$, and $\mathrm{E}_{\mathrm{DEGRADATION}}(tn)$ is $\mathrm{TgCO_2}$ (1 $Tg = 10^{12}$ g = 1 million·tonnes).

2.5. Carbon Emission Reductions and Removals

Carbon-based financial compensation under the REDD+ scheme of the UNFCCC is a performance-based mechanism requiring the known amount of carbon emission reductions or removals resulted from policy interventions and actions in the field. In this paper, emission reductions can be achieved through reducing deforestation and forest degradation, while carbon removals can be achieved through forest plantations. Emission reductions ($\mathrm{EDef_{REDUCTION}}$) can be obtained using equation developed by Ty *et al.* [75]:

$$\mathrm{EDef}_{\mathrm{REDUCTION}}(tn)=\mathrm{E}_{\mathrm{DEFORESTATION}}(tn)\times\mathrm{RPI}(t) \tag{16}$$

where $\mathrm{RPI}(tn)$ is relative project impact at time $t=n$. It is the effects of policy interventions and projections undertaken to reduce drivers of deforestation, which in turn results in reducing deforestation. For simplicity, $\mathrm{RPI}(t)$ is taken directly from Ty *et al.* [75].

To estimate reductions from reducing forest degradation, we need to understand emissions in the absence of project activities and emissions when project is implemented to reduce forest degradation. The former is forest management using conventional logging, and the latter refers to forest management using reduced impact logging as in our present study. We assume that Reduced Impact Logging (RIL) is adopted as part of the management system required to achieve "sustainable management of forests" component of the REDD+ elements. Unlike conventional logging (**Table 5**), RIL is a logging practice that uses well-defined logging planning, well-trained staff, directional felling, and strictly follows logging code of practices or logging regulation (see [25] [76] for reviews of RIL). As reviewed by Sasaki and Putz [77], RIL can significantly reduce logging damages to residual stands, reduce wood and logging wastes resulted from untrained loggers, and reduce environmental damages to sensitive social and environmental areas in the forests in question. The difference between CVL and RIL is the damage caused by logging (*i.e.* $\mathrm{H}(t)$ in Equation (6) and Equation (7); **Table 5**). As seen in **Table 5**, logging damage is 40% and 14% under CVL and RIL, respectively. Emission reductions can be estimated by

$$\begin{aligned}&\mathrm{EDeg}_{\mathrm{REDUCTION}}(tn)=\mathrm{E}_{\mathrm{DEGRADATION}}(tn)\\&-\left\{\left[\mathrm{PdF}(tn)\times\mathrm{CS}_{\mathrm{RIL}}(tn)-\mathrm{PdF}(tn-1)\times\mathrm{CS}_{\mathrm{RIL}}(tn-1)\right]-\left[\mathrm{PdF}(tn)-\mathrm{PdF}(tn-1)\right]\times\mathrm{CS}_{\mathrm{RIL}}(tn)\right\}\times\frac{44}{12}.\end{aligned} \tag{17}$$

Definition of forest plantation under the REDD+ scheme is not yet defined. Afforestation and reforestation defined in 2001 for clean development mechanism of the Kyoto protocol can not be applied on deforested lands after 31 December 1989. Since no new definition was adopted for forest plantations implemented on deforested land after 2015 (the modeling timeframe for forest management), we assume that all carbon credits (removals) as a result of planting could be eligible for financial support under the REDD+ scheme. Carbon removals can be obtained by:

$$R_{FPl}(tn) = CS_{FPl}(t) \times \left[FPl_{TOTAL}(tn) - FPl_{TOTAL}(tn-1) \right] \times \frac{44}{12} \tag{18}$$

3. Results and Discussions

3.1. Land Use Change

Parameter values of $a + b$ and a and initial values for production forest (PdF) and forest plantation (FP) were derived by performing a least-square fit and regression analysis. According to regression resultsusing available data in 1990, 2000, 2005, and 2010, $a + b$, a, initial values for PdF and FPl are −0.0146 (decreases 1.46%), 0.00286 (0.29% is converted back to forest plantation), 160.2 million ha, and 6.8 million ha, respectively. Using these parameters and initial values, area of production forest declined to 66.6 (34.3 - 129.5) million ha in 2050 from 160.2 (141.8 - 180.9) million ha, representing a loss of 1.6 million ha or about −0.97% per year (**Figure 1**). Between 1990 and 2000 and 2000 and 2010, annual loss of production forest was estimated at 2.2 and 1.9 million ha, respectively. Because area of protected forest (PrF) was assumed to remain unchanged, its change rate is zero. If no action to reducing or completely stopping deforestation, area of production forest will continue to decline and will be smaller than area of protected forest starting from 2039 onward. Consequently, even protected forest will be subject to clearing and commercially unless alternative sources are available sooner rather than later. Using data by FAO [78] (2005), Kim Phat *et al.* [19] estimated the loss of natural forests in Southeast Asia at 2.3 million ha between 1990 and 2000. By comparing the two studies, deforestation has slowed down.

In contrast, area of forest plantations increases to 25.1 (19.8 - 33.2) million ha in 2050 from 6.8 million ha in 1990. Area of forest plantations increases about 0.31 million ha per year (4.49%) over the modeling period (**Figure 2**). Forest plantations increased about 0.43 million ha (6.32%) between 1990 and 2000, and 0.37 million ha (3.33%) between 2000 and 2010.

Over the whole Southeast Asia, area of natural forests declines to 144.4 million ha in 2050 from 238.0 million ha in 1990 with annual deforestation rate or 0.66% or about 1.56 million ha (**Table 7**). More specifically, deforestation rates were 0.92% and 0.87% between 1990 and 2000 and 2000 and 2010. Loss of natural forests is being compensated by the increase of forest plantations. As shown in **Table 7** below, total area of forests (natural and plantation) in Southeast Asia declines only about 0.51% or about 1.25 million ha between 1990 and 2050. Deforestation in Southeast Asia between 1990 and 2000 and 2000 and 2010 was 1.75 (0.71%) and 1.51 (0.67%) million ha per year (**Table 7**). Our findings of deforestation were in the ranges estimated by Kindermann *et al.* [8]

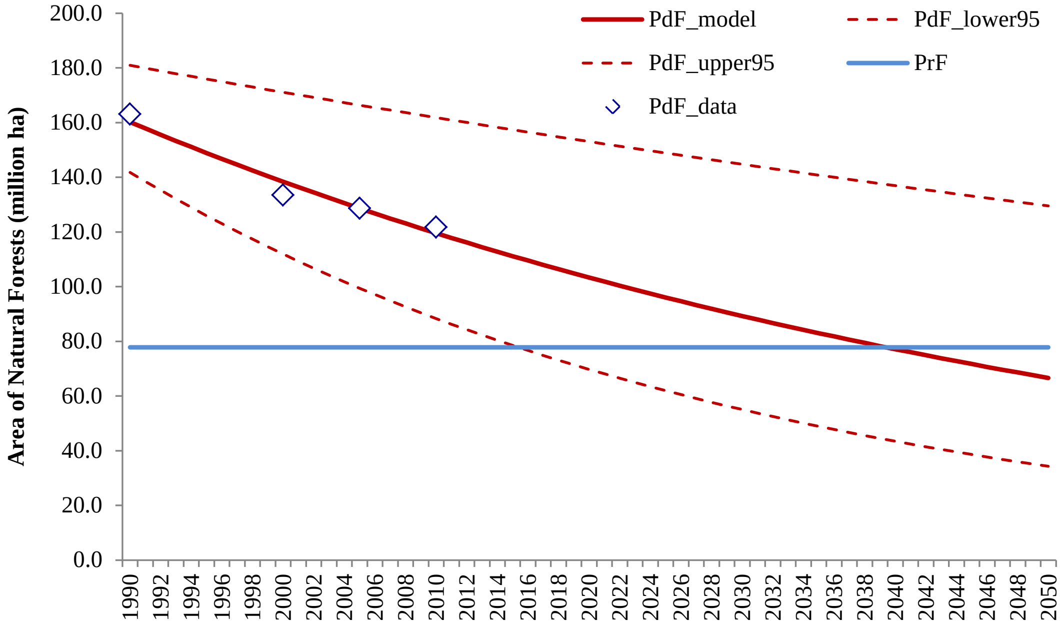

Figure 1. Area of natural forests in Southeast Asia (1990-2050).

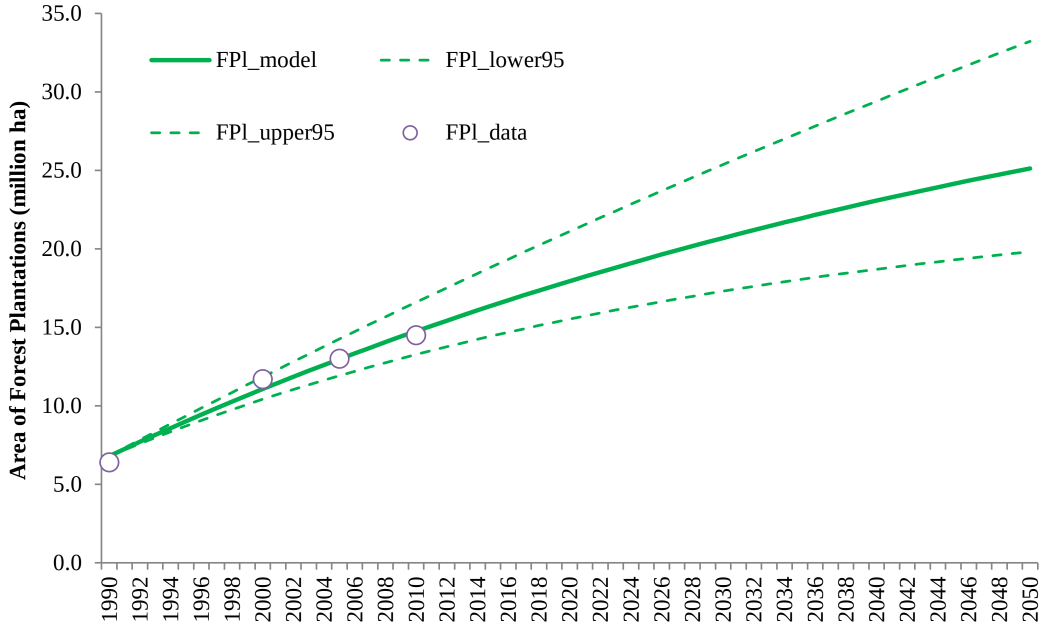

Figure 2. Area of forest plantations in Southeast Asia (1990-2050).

Table 7. Area of natural forests and forest plantations in Southeast Asia (modeling results).

Year	Natural Forests			Forest Plantations (FPl)	Total
	Production Forest (PdF)	Protected Forest (PrF)	Total		
1990	160.2	77.8	238.0	6.8	244.8
2000	138.4	77.8	216.2	11.1	227.3
2010	119.6	77.8	197.4	14.8	212.1
2050	66.6	77.8	144.4	25.1	169.6
			Annual changes		
1990-2000	−2.18	0.0	−2.18	0.43	−1.75
Change rate	−1.36%	0.00%	−0.92%	6.32%	−0.71%
2000-2010	−1.88	0.00	−1.88	0.37	−1.51
Change rate	−1.36%	0.00%	−0.87%	3.33%	−0.67%
1990-2050	−1.56	0.00	−1.56	0.31	−1.25
Change rate	−0.97%	0.00%	−0.66%	4.49%	−0.51%

Note: Area is in million ha, annual change is million ha per year, and change rate is % proportional to area in the preceding year.

who estimated the loss of forests in Southeast Asia at 1.1 - 2.2 million ha per year between 2005 and 2030 depending on chosen models. Miettinen *et al.* [79] estimated the deforestation rate in insular Southeast Asia at 1% between 2000 and 2010, which well within our estimate of deforestation of natural forest.

3.2. Carbon Emissions Due to Deforestation and Forest Degradation

Carbon stocks in forests in Southeast Asia changed dramatically during the modeling period. No change in carbon stocks was observed in protected forest (PrF) because of the study assumption. Deforestation and forest degradation led to decline of carbon stocks in production forest (PdF) from 37371.6 TgC (aboveground, belowground, litters, and deadwood) in 1990 to 13531.3 TgC in 2050, representing an annual loss of 397.3 TgC. Annual losses between 1990-2000, 2000-2010, and 2015-2050 were 508.2, 439.1, and 354.3 TgC, respectively (**Table 8**).

Table 8. Carbon stocks and changes in Southeast Asia.

Year	Production Forest (PdF)	Protected Forest (PrF)	Forest Plantation (FPl)	Total
Total carbon stocks in TgC (1 TgC = 1 million·tonnes C)				
1990	37371.6	18149.3	563.04	56083.9
2000	32289.7	18149.3	916.446	51355.4
2010	27898.8	18149.3	1221.79	47269.9
2015	25932.6	18149.3	1358.53	45440.4
2050	13531.3	18149.3	2080.69	33761.3
Annual changes in TgC $year^{-1}$ and in $TgCO_2$ $year^{-1}$in ( )				
1990-2000	−508.2 (−1865.1)	0.0	35.3 (129.7)	−472.9 (−1735.4)
2000-2010	−439.1 (−1611.5)	0.0	30.5 (112.1)	−408.6 (−1499.4)
1990-2050	−397.3 (−1458.2)	0.0	25.3 (92.8)	−372.0 (−1365.4)
2015-2050	−354.3 (−1300.4)	0.0	20.6 (75.7)	−333.7 (−1224.6)

These losses were compensated by the increase of carbon stocks in forest plantations. Over the same period, forest plantations sequestered about 20.6 - 35.3 TgC $year^{-1}$ (**Table 8**). Altogether, carbon loss due to deforestation and forest degradation in Southeast Asia was 472.9 (1990-2000), 408.6 (2000-2010), and 372.0 TgC (1990-2050), respectively.

By assuming that REDD+ project will be implemented in 2015 and ended in 2050 (35 years), carbon emission during this period can be estimated. Deforestation of production forests emitted about 1400.0 $TgCO_2$ in 2015, 1272.7 in 2020, 1054.3 in 2030, 876.2 in 2040, and 730.5 $TgCO_2$ in 2050 (**Figure 3**). On average between 2015 and 2050, deforestation emitted 1027.0 TgC $year^{-1}$. In addition, degradation of production forest also emitted 275.0 $TgCO_2$ or about 26.8% of total emissions from deforestation. Emissions from deforestation and forest degradation were estimated to be 1302.0 $TgCO_2$ $year^{-1}$ between 2015 and 2050 (**Figure 3**). This figure is highly higher than that estimated by Kindermann *et al.* [8] who estimated emissions from deforestation in Southeast Asia at 1.1 $TgCO_2$ between 2005 and 2030. This is because their study did not include loss from forest degradation.

3.3. Emission Reductions or Removals

Over a 35-year period between 2015 and 2050, emissions from project implementation designed to reduce drivers of deforestation and forest degradation were estimated at 10468.8 $TgCO_2$ or about 290.8 $TgCO_2$ $year^{-1}$. Since total emissions in the absence of project activities (baseline emissions) were 36972.8 $TgCO_2$, reduced emissions were estimated at 26504.0 $TgCO_2$ per 35 years or 736.2 $TgCO_2$ per year (**Table 9**, **Figure 4**).

Over the same period, carbon emissions due to forest degradation in the absence of project activities (baseline emissions) *i.e.* using CVL were 9898.8 $TgCO_2$ and emissions from project implementation (*i.e.* using RIL) were 6970.5 $TgCO_2$, reduced emissions from forest degradation were therefore 2928.3 $TgCO_2$ or 81.3 $TgCO_2$ per year between 2015 and 2050 (**Table 9**, **Figure 5**).

In addition to reduced emissions from deforestation and forest degradation, forest plantations in Southeast Asia gained about 2745.3 $TgCO_2$ or 76.3 $TgCO_2$ annually over the same period (**Table 9**). Altogether, carbon reductions and removals through implementing forestry project to reducing deforestation and forest degradation in Southeast Asia resulted in total reductions of 29432.3 $TgCO_2$ and removals of 2745.3 $TgCO_2$ for a 35-year project or about 817.6 and 76.3 $TgCO_2$ $year^{-1}$ (**Table 9**). With US $7.4 per $MgCO_2$ [80], total carbon revenues alone from reduced carbon emissions and increasing carbon stocks in Southeast Asia are $237.8 billion for 35-year project or about 27% of GDP in Indonesia in 2013. The annual carbon revenues are therefore $6.6 billion or about 44% of GDP in Cambodia in 2013. By implementing carbon projects designed to reducing deforestation and forest degradation, there are other benefits that could be achieved such as strengthening land tenure of local community, safeguarding of socio-economic values of local people, biodiversity, creating local employment, and improving local livelihood.

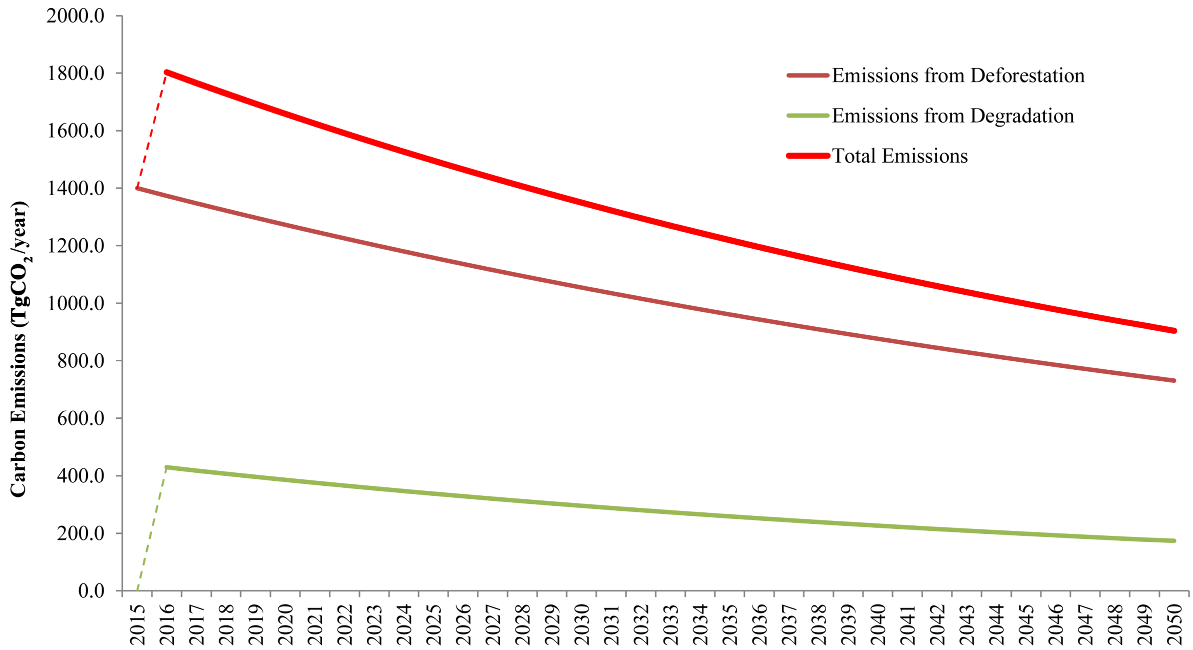

Figure 3. Annual carbon emissions from deforestation and forest degradation in Southeast Asia.

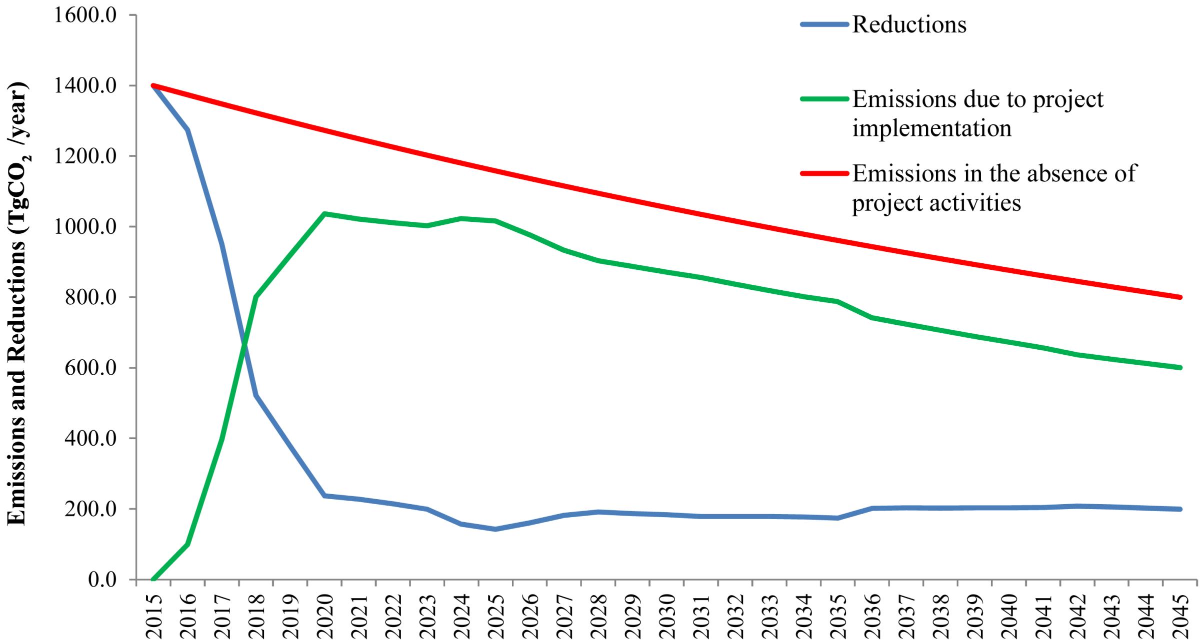

Figure 4. Emission reductions from reducing deforestation in production forest.

3.4. Policy Implications for Protected Forest

Forests in Southeast Asia are home to millions of flora and fauna. Some of flora and fauna have been threatened by the alarming loss of forests and repeated mismanagement of forests that has eventually led to rapid loss of important tree and wildlife species. In addition to such loss, deforestation and forest degradation continue to pose threats to livelihood of forest dependent communities as well as economic development in the region because of the adverse effects of climate change on agricultural production and water quality. Since the adoption of Bali Action Plan in 2007, there had been hope that REDD+ scheme would become a mitigation option for the post-Kyoto

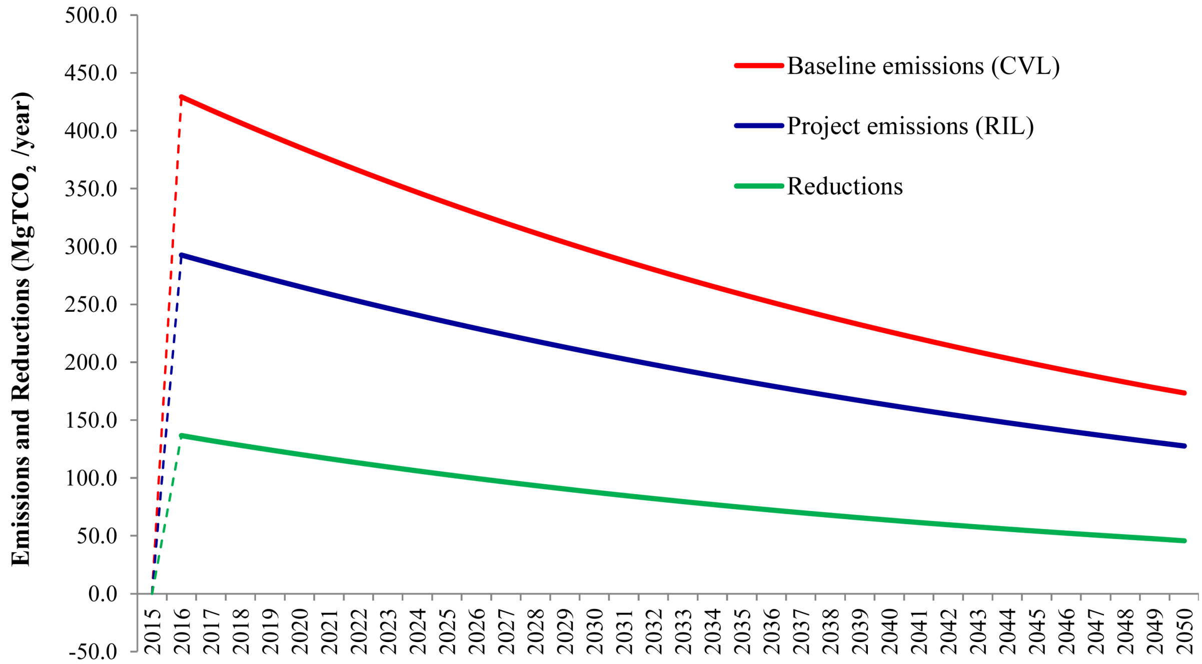

Figure 5. Emission reductions from reducing degradation in production forest.

Table 9. Baseline emissions, emission reductions, and removals in Southeast Asia.

Description	Baseline emissions	Project emissions	Reductions	Removals
		Deforestation		
35 years	36972.8	10468.8	26504.0	
Annual	1027.0	290.8	736.2	
		Forest degradation		
35 years	9898.8	6970.5	2928.3	
Annual	275.0	193.6	81.3	
		Enhancement through plantation		
35 years				2745.3
Annual				76.3
		Total		
35 years	46871.6	17439.3	29432.3	2745.3
Annual	1302.0	484.4	817.6	76.3
		Revenues (billion dollars)		
35 years	346.8	129.1	217.8	20.3
Annual	9.6	3.6	6.0	0.6

Note: Average carbon price from REDD+ project was $7.40 in 2012 and $4.20 in 2013 [80]. Carbon price was fluctuated in 2013 because global demand for carbon credits was significantly reduced due mainly to the lack of new climate agreement. Nevertheless as world leaders needed to decide on future climate regime by 2015, it is expected that a new climate regime is anticipated and thus carbon price is likely to increase. For this study, $7.40 per $MgCO_2$ (tCO_2) is used and therefore the derived number of carbon revenues should be used as indicative number. Future adjustment is needed when carbon price is known for some degree of uncertainty.

climate agreement, which was expected from 2013. Unfortunately, no agreement on future climate regime was reached and therefore REDD+ is still a voluntary scheme. Nevertheless, despite fluctuation of global carbon prices at the mandatory markets, carbon prices at voluntary markets did not change significantly compared to the former. Without losing hope, developing countries should continue to implement policies that will result in reducing deforestation and forest degradation. Well-thought policies designed to reduce drivers of deforestation and forest degradation should take into account the traditional uses of forest and non-forest products, transparency of benefit sharing that will ensure that any benefits from carbon projects will also reach local communities that are the main actors in either protecting the forests or destroying them. In addition to generating carbon revenues, world leaders have begun to discuss the payments for ecosystem services under the UN Convention on Biological Diversity.

Since constant value of forest area and carbon stocks were used, no change in area or carbon stocks was seen in protected forest during the modeling period. This is obviously true in the real world when forests are fully protected before the start of any carbon development projects, carbon-based incentives alone are not sufficient to encourage forest protection because no single carbon credit is gained. In the case of protected forests, payment for ecosystem services beyond carbon credits becomes urgently necessary. Otherwise, protected forests should be destroyed first in order to establish the baseline, against which emission reductions can be estimated and subsequently carbon-based revenues could be achieved. This scenarios is however worse because it encourages destruction of forests. As 2015 is approaching, world leaders need to consider not only carbon-based incentives but also alternative payment for ecosystem services provided by well-protected forests.

4. Conclusions

Reducing carbon emissions from deforestation and forest degradation, conservation of forests, sustainable management of forests, and enhancement of forest carbon stocks (REDD+) scheme of the UNFCCC was considered as a potential climate change mitigation options for future climate change regime. Under the REDD+ scheme, financial support to developing countries is expected to provide carbon emission reductions or removals can be achieved. We developed land use and carbon stocks models along with management scenarios to account for carbon balance, emission reductions or removals in Southeast Asia. Between 1990 and 2050, deforestation was 1.6 million ha or about 1.0% annually. Deforestation of natural forests was compensated by the increase of forest plantations whose area increased about 0.3 million ha or 4.5% annually over the same period. Carbon emissions due to deforestation and forest degradation were 1865.1, 1611.5, 1458.2, and 1300.4 $TgCO_2$ annually between 1990 and 2000, 2000 and 2010, 1990 and 2050, and 2015 and 2050, respectively. If financial support is available to implement REDD+ project, about 817.6 $TgCO_2$ $year^{-1}$ of reductions (9.9% from reducing forest degradation) could be achieved for a 35-year project between 2015 and 2050. Over the same period, removals due to increase of forest plantations were estimated at 76.3 $TgCO_2$ annually depending on eligibility of accounted carbon. Altogether, carbon credits from reducing deforestation and forest degradations and forest plantations were estimated at 893.8 $TgCO_2$ or about US $6.6 billion annually for 35 years of hypothetical carbon project if carbon is priced at $7.40 per $MgCO_2$.

Forest degradation resulted from the use of conventional logging not only poses threat to global carbon emissions, but also the biodiversity degradation because only highly valuable commercial trees are targeted. Including REDD+ as climate change mitigation option in the future climate regime has a great potential to reducing carbon emissions while safeguarding biodiversity and socio-economic values of local community in the tropics. Although forest plantations increasingly uptake atmospheric carbon, decision whether to harvest the forest at any given cutting rotation strongly affect carbon sequestration capacity. Decision for harvesting forest plantation should be based on further analysis on wood demands and wood availability from both natural forest and forest plantation. Since carbon sinks in forest plantations are credited under the first commitment period from 2008 and 2012, forest plantations are expected to continue to increase provided that future climate regime is agreed upon. Therefore, future study on carbon balance in the tropic forests should account for carbon uptakes in forest plantations separately. Nevertheless, forest plantations need better management and more attentions so as to avoid adverse impacts on local environment and biodiversity. From our study, it suggests that reducing deforestation and forest degradation has huge implications for climate change mitigation and sustainable development. Improved management of natural forests through the adoption of appropriate management system such as the use of reduced-impact logging would enhance carbon stocks in the forests and maintain or increase timber production for economic development and job generation. It is important that REDD+ be included as a climate change mitigation option and financial support for good forestry practices be made available continuously either through mandatory or voluntary markets or other form of payments.

There are however limitations to this study. Prediction of future deforestation and forest degradation is difficult to validate because future development and political uncertainty in developing countries are unpredictable. Therefore, findings in this research should be used as indicative. In addition, deciding initial carbon stocks is important but it needs more data from the field in order to reduce uncertainty that would affect overall estimation of carbon emissions from deforestation and forest degradation. Initials should be revised when more data are available.

Conflict of Interest

The authors declare no conflict of interest.

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