Doctoral Dissertation

Assessment of Forest Carbon Balance in Southeast Asia

by

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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. The issue of reducing deforestation and forest degradation (REDD+) has become a central theme of the United Nations Framework Convention on Climate Change (UNFCCC) negotiations because of its ability to mitigating climate change and achieving sustainable development. 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+.

This research attempts to analyze the potential emission reductions and removals and cumulative carbon fluxes due to selective logging in Southeast Asia for a 35-year period under the REDD+ scheme. This study starts 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. Study results suggest carbon emissions from deforestation and forest degradation of natural forests were 1865.1, 1611.4, and 1300.4 $TgCO_2$ $year^{-1}$ between 1990 and 2000, 2000 and 2010, and 2015-2050, 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 depending on 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.

In addition, selective logging in Southeast Asia also contributes cumulative carbon fluxes. Selective logging creates a large amount of wood residues in forests in addition to producing a small amount of sawn-wood for use as source of construction materials. Cumulative carbon fluxes were analyzed between 2015 and 2050 under two scenarios, namely conventional (CVL) and reduced-impact logging (RIL).

Study results suggest that CVL produced about 146.6 (±5.4) million m^3 annually. Logging created annual carbon fluxes of about 0.23, 0.23, 0.20, 0.69, and 0.15 MgC ha^{-1} $year^{-1}$ in sawn-wood, wood wastes at sawmills (SWW), wood product wastes due to logging damages remained in the forests (WPW), branches and top logs (BRA), and belowground dead root (BLD), respectively. Cumulative carbon fluxes were estimated at 281.0, 506.6, and 87.4 TgC $year^{-1}$ in sawn-wood, onsite (WPW, BRA, BLD), and offsite (SWW) pools, respectively. Except in SW, cumulative carbon fluxes in onsite and offsite pools showed a decline trend in about 10 years after logging. Switching from CVL to RIL could increase fluxes in sawn-wood 60% higher than that under CVL, while reducing fluxes in short-lived onsite and offsite wood residues. Not only RIL can increase carbon fluxes in sawn-wood, it can also increase production of sawn-wood and retain more carbon in standing forests. Selective logging can create huge carbon fluxes in various wood components. Depending on carbon accounting methods, these fluxes could be used to offset carbon emissions from deforestation and forest degradation. Including carbon fluxes (credits) in sawn-wood in climate change mitigation options would provide incentives for better utilization of harvested wood products and management of tropical forests. Otherwise, destructive logging and careless use of harvested wood will continue unabated. Providing incentives for carbon offset in harvested wood products will also stimulate the development of wood processing technology, which will eventually result in more sawn-wood production and more carbon storage in harvested wood products, while retaining more carbon in standing forests.

From this 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 and illegal logging strongly affect the amount of timber to be harvested and other wood components. More forest inventory data are important for determining initial carbon stocks in the forests in order to reduce uncertainty that would affect overall estimation of carbon emissions from deforestation and forest degradation. Rate of illegal logging is difficult to determine because of the large area of tropical forests and this rate is affected by many factors such as political stability and demand for timber production. It is recommended revisions to initial carbon stocks and rate of illegal logging be revised in future study when more data become available. To encourage utmost use of harvested timber, future climate agreement should consider cumulative carbon fluxes as carbon credits that can be used to generate additional incomes while protecting tropical forests.

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ABBREVIATION IN THIS DISSERTATION

BLD	Belowground dead root
BRA	Branches and top logs of harvested and damaged trees
COP	Conference of the parties to the UNFCCC
CVL	Conventional logging
FP	Forest plantation
FREL	Forest reference emission level
FRL	Forest reference level
HWPs	Harvest wood products
IPCC	Intergovernmental Panel on Climate Change
MAI	Mean annual increment
PdF	Production forest
PEL	Project emission level
PrF	Protection forest
REDD	Reducing emission from deforestation and forest degradation
REDD+	Reducing emission from deforestation and forest degradation, conservation of forest, sustainable forest management and enhancement of forest carbon stock
RIL	Reduced impact logging
SFM	Sustainable forest management
SW	Sawn-wood
SWW	Wood wastes at sawmills
UNFCCC	United Nations Framework Convention on Climate Change
WP	Wood products
WPW	Wood product wastes in the forest

Chapter 1 INTRODUCTION

1.1 Background

Tropical Forests are important for climate change mitigation because forests can play both roles in either carbon sinks or sources depending on forest management. A proposal for post-2012 international agreement that includes avoiding deforestation in non-Annex I countries is now undergoing public scrutiny (Kanninuen *et al.,* 2007). World leaders recently met in Lima, Peru to discuss new climate change agreement to replace the Kyoto Protocol when it expired in 2012. Although a binding commitment for greenhouse gas emission reduction was not reached, global climate change mitigation through REDD (Reducing Emission from Deforestation and forest Degradation), promoting sustainable forest management, and enhancing carbon sinks (hereafter referred to as REDD+) in the Copenhagen Accord was reached at the Fifteenth Conference of the Parties (COP 15) to the United Nations framework convention on climate change (UNFCCC) in December 2009 (Sasaki *et al.,* 2010).

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. Annual carbon emissions due to deforestation in the tropics were estimated ranging from 1.1 PgC (Achard *et al.,* 2004) to 1.5 PgC (Gillison *et al.,* 2007), and up to 2.2 ± 0.6 PgC (Houghton *et al.,* 2003) 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 (Nepstand *et al.,* 1999; Houghton *et al.,* 2000), 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 UNFCCC. This is especially true after the Thirteen Conference of the Parties (COP13) of UNFCCC adopted the Bali Action Plan in 2007 (Decision 2) (UNFCCC, 2008) 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 (UNFCCC, 2008) are continuing. Discussions on including reduced deforestation in the post-Kyoto agreement have been made (Miles *et al.,* 2008; Ebeling *et al.,* 2008), while discussions on reduced forest degradation are usually ignored due to difficulties in accurately detecting carbon emissions from degradation (De Fries *et al.,* 2007). However, although the REDD has great potentials because of its remarkably low cost (Kindermann *et al.,* 2008), the magnitude of carbon emissions from deforestation and forest degradation in tropical forests has been highly controversial (Achard *et al.,* 2002; Houghton *et al.,* 2003) with errors likely to be as high as ±30% to ±60% (Achard *et al.,* 2002; IPCC, 2000).

Sustainable forest management (SFM) is an important part of REDD+, because it maintains wood supply from the forests to meet increasing demands for wood while generating employment and revenues for owners of the forest resource or for governments in developing countries. SFM is strongly affected by logging practices (Asner *et al.,* 2006; Pearce *et al.,* 2003; Sasaki *et al.,* 2009) and logging practices are generally carried out by logging companies or concessionaire in the tropics. In fact, the majority of logging practices in the tropics are carried out under the forest concession system. If SFM is finally included in the REDD+ scheme under the new climate change agreements, a sound management system is required for managing concessions because the current logging practices were responsible for rapid forest degradation and deforestation (Asner *et al.,* 2006; Asner *et al.,* 2010). Furthermore, logging practices strongly influence the end-use wood supply and carbon stocks in concession forests in the tropics (Kim *et al.,* 2004; Sasaki *et al.,* 2006; Sist *et al.,* 2003), it is therefore necessary to understand which logging systems are both sustainable and economical. In addition to sequestering atmospheric carbon, harvested wood products (HWPs) can also store carbon for many years depending on how the products are processed and used. Accounting for carbon storage in HWPs has brought more attention because of the need for reporting sources of remissions or removals to the UNFCCC. Stockmann *et al.,* (2012) analyzed carbon storage in HWPs in the Northern region of the United States of America and found that forest management in this region alone created carbon storage in HWPs of about 25.5 TgC in 2010 increasing from just 0.3 TgC in 1910. For the whole USA, annual carbon fluxes in HWPs were estimated at 37 TgC year^{-1} (Heath *et al.,* 1996). Dymond (2012) developed accounting methods (British Columbia Harvested Wood Products version 1) for HWPs in British Columbia, Canada for 1965–2065. Based on his findings, the author argued that default accounting methods developed by Intergovernmental Panel on Climate Change (IPCC) overestimated carbon emissions in North America and suggested that IPCC modified emission factor from its current default of 1.0 to 0.52. Gundimeda (2001) estimated carbon storage in various pools of HWPs due to timber harvesting in India for 200 years. He suggested that increasing wood durability is likely to increase more carbon storage.

1.2 Statement of Research Problems

Forest in Southeast Asia is ecologically and economically important because they harbor a considerable diversity of flora and fauna and possess unique biotic communities. In the climate change viewpoint, the tropical forests make essential contribution to combating global warming with sequestering atmospheric carbon and emission reduction and removals as a result of REDD+. Moreover, selective logging creates a large amount of wood residues in forest in addition to producing a small amount of sawn-wood, although accounting for carbon fluxes in harvested wood products (HWPs) become necessary in the fight against climate change. Despite of this fact, only a few studies had been done on estimate carbon stock and emission reduction or removal. Furthermore, previous studies focused mainly on carbon fluxes in the HWPs without considering carbon storage in other wood components created by logging when forests are harvested such as in branches, top logs, belowground (i.e. dead root), and wood wastes due to wood processing at the sawmill when timber (logs) is processed to make sawn-wood for end-use products. Presently very scanty information is available on carbon stock, emission reduction or removal and carbon fluxes in various wood components. Thus this makes it difficult to discuss in the REDD+ negotiation forum and obtain incentive from REDD+, without financial incentives, carbon project would not happen and therefore climate change will continue to threaten future development.

1.3 Study Objectives

This study was designed to achieve the following objectives:

- 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.
- To estimate carbon storage (cumulative fluxes) in various wood components (sawn-wood, wood wastes at sawmills, wood product wastes due to logging damages remained in the forests, branches and top logs and belowground dead root) due to selective logging in production forest in Southeast Asia.

Chapter 2 LITERATURE REVIEWS

Most recent studies 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 (Pan *et al.,* 2011). In addition, forest degradation (the loss of commercial and large trees, trees damaged by unplanned logging and fires) may account for another 25 to 42% of carbon emissions from tropical forests in Asia (Flint and Richards, 1994; Iverson *et al.,* 1994) and 32% from Africa (Gaston *et al.,* 1998). Worldwide, people involved in the promotion of sustainable forest management and forest conservation have high expectations of the possible inclusion of Reducing Emissions from Deforestation and Forest Degradation (REDD) in the international climate convention to be agreed in December 2010 in Copenhagen (Parker *et al.,* 2008). Ongoing discussions and research have paid considerable attention to the design of methodologies enabling countries to quantify carbon stocks, carbon sequestration and emission reductions. Involved parties have requested the inclusion of regulations that guarantee environmental integrity, biodiversity conservation, indigenous rights and poverty reduction, among others (Seymour, 2008).

Land use changes and forest management activities have high potential to mitigate carbon emission. Forest management offers one of the important options for mitigating carbon emissions. Available options in forest management include avoiding emissions, conserving the existing carbon pools on the land (slowing down deforestation or improving forest harvesting), reduced deforestation and forest degradation, expanding carbon storage in forest ecosystems by increasing the area and/or carbon density of forests (e.g. by plantations, agro-forestry, natural regeneration, soil management) (Dixon *et al.,* 1994; Dixon, 1996; Brown *et al.,* 1999; Walker *et al.,* 2008), increasing storage in durable wood products and substituting sustainably grown wood for energy intensive and cement-based products (e.g. bio-fuels, construction materials) (Koluchigina *et al.,* 1995; Winjum *et al.,* 1998). Terrestrial ecosystems especially forest vegetation have the greatest potential for mitigating atmospheric CO_2 emissions through conservation and management (Brown *et al.,* 1996; Munishi *et al.,* 2000; Munishi and Shear, 2004). The potential of massive reforestation as a means to sequester carbon dioxide from the atmosphere is frequently discussed as a means to reduce the buildup of this greenhouse gas and slow the rate of global warming (Rosenfeld and Botkin, 1990). International negotiations between nations that produce large amounts of carbon dioxide through burning of fossil fuels and nations with the potential to plant large areas of forest are one indication of the interest in this process. Determining the amount of carbon stored and the rate at which forests release and sequester carbon is important or understanding the potential such uses of forests (Daniel *et al.,* 1993). Changes in forest cover use and management produces sources and sinks of CO_2 that is exchanged with the atmosphere (Haygreen and Bowler, 1989; Jackson, 1992; Chidumayo, 1993). Using available data between 1980 and 2000 (FAO, 2001; Kim Phat *et al.,* 2004) 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. Deforestation and logging were responsible for the release of about 50.3 million ton CO_2 year^{-1} from natural forests in Cambodia during the 1970s, 1980s and 1990s (Sasaki, 2006).

Sasaki and Yoshimoto (2010) focused on the opportunity costs of managing tropical forests versus clearing these forests to develop industrial plantations, and suggested that managing tropical forests for timber production under the REDD+ mechanism would be preferable because of the huge potential revenues and other benefits from the ecosystem services provided by these forests. Toni (2010) suggests the need for REDD+ decentralization in order to effectively manage the revenues from

REDD+ scheme while protecting tropical forests. Although previous studies clarified the fundamental basis for understanding the potential of REDD+, many of them failed to address the potential reductions in carbon emissions and the timber supply from sustainably managing concession forests. Estimating emission reduction potentials require the understanding of the Reference Emission Level (REL: emissions in the absence of project activities) and the Project Emission Level (PEL: emissions from project implementation). Previous studies provide important information about the current state of research on carbon accounting methods for HWPs from wood harvesting in the North America, Europe, and India. These studies agreed that HWPs stored a large amount of carbon in different forms. Considering these components is particularly important for timber harvested in tropical forests, where logging usually create huge amount of wood wastes in forests (Sist and Ferreira, 2007; Putz *et al.,* 2008; Putz *et al.,* 2012; Souza *et al.,* 2005; Asner *et al.,* 2006) and only logs with good quality are transported to the sawmills for processing. Unlike trees in temperate or boreal forests, tropical trees can be used only up to the first main branch and the majority is left in forests to decay. Whiteman *et al.,* (1999) estimated industrial round-wood production in Malaysia and Indonesia at about 83 million m^3 in 1996 and projected to increase to 95 million m^3 in 2010. Given that only about 30% of this amount was left in the forests (Sasaki *et al.,* 2012 and Sasaki and Putz, 2009 for reviews), carbon storage in HWPs associated with this amount of round-wood production could be huge.

In the discussion on policy incentives and modalities for measurements, reporting and verification (MRV), the issues of identifying drivers and activities causing forest carbon change on the national level for REDD+ monitoring and implementation have revived increasing attention in the REDD+ debate (Bendorf *et al.,* 2007; UNFCCC, 2010). The UNFCCC negotiations (UNFCCC, 2009; UNFCCC, 2010) have encouraged developing countries to identify land use, land use change and forestry activities in particular those that are linked to the driver of deforestation and forest degradation, and to assess their potential contribution to the mitigation of climate change. Understanding is needed for assessing not only how much forests are changing but also how to define proper policies, and national REDD+ strategies and implementation plans (Boucher, 2011; Rudorff *et al.,* 2011). National decision-makers in REDD+ countries have three complementary mean to affect drivers at national to local levels: incentives, disincentives and enabling measures (Borner *et al.,* 2011). A further distinction is made between policy-based and incentive-based interventions, with policy-based intervention being comprised of polices to shift the balance of profitability between agriculture and forestry, policy that directly regulate land use, and cross-sector polices that underpin the first three (Angelsen *et al.,* 2009). Whether intervention are polices or incentive-based will depend on variety of factors, include the degree which a country embraces a market or policy-based approach to REDD+, the characteristics of proximate and underlying drivers, strength of existing institution and governance, the tenure rights of forest users, and many other factors.

Chapter 3 STUDY MATERIALS AND METHODS

3.1 Forest land use changes

Southeast Asia is consisting of the country such as Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste and Vietnam (Figure 1). The population growth between 1990, 2000 and 2010 was 445.36, 523.83 and 593.41 million people (Table 1). 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 2) as reported in FAO (FAO, 2010). FAO (FAO, 2010) categorized six forest types according to function, namely production, protection, conservation, social services, multiple purpose, and unspecific purpose.

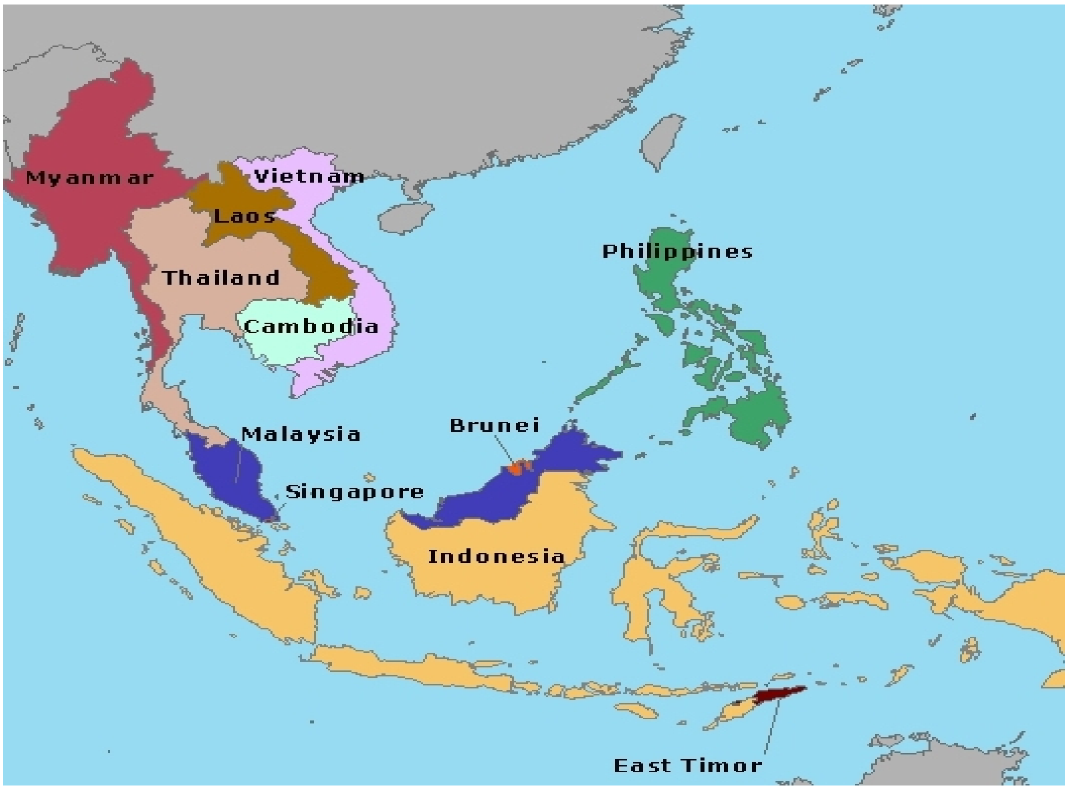

Figure 1 Map of Southeast Asia (11 Countries).

Source: https://bilography.wordpress.com

Table 1 The population growth in Southeast Asia between 1990, 2000 and 2010

Country	Population (Million)		
	1990	2000	2010
Brunei Darussalam	0.25	0.33	0.40
Cambodia	9.53	12.45	14.14
Indonesia	184.35	213.40	239.87
Lao PDR	4.19	5.32	6.20
Malaysia	18.21	23.42	28.40
Myanmar	39.27	44.96	47.96
Philippines	61.63	77.31	93.26
Singapore	3.02	3.92	5.09
Thailand	57.07	63.16	69.12
Timor-Leste	0.74	0.83	1.12
Viet Nam	67.10	78.76	87.85
Southeast Asia	445.36	523.83	593.41

Source: United Nations Population Division, 2010.

Based on those definitions (see Note under Table 3), we can 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).

Table 2 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: FAO, 2010

Production forest (Figure 2) is forest designated for commercial logging, clearing for forest plantation, agricultural cultivation, and other purposes as and when needed while Protection forest (Figure 3) is forest that is normally protected from commercial logging and forest clearing. Both PdF and PrF are natural forests, to which we add a third category, forest plantations (FP) (Figure 4).

Table 3 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
South-east 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 protection forest (PrF)

Figure 2 Photo of production forests in Katie province, Cambodia, 2014. Production forest is where logging is allowed to take place.

Figure 3 Protection forests in Seima Protection forest, Mondulkiri province, Cambodia, 2010. Protection forest is where commercial logging is prohibited.

Figure 4 Plantation forest, although tropical natural forest have been cleared, part of the deforested land has been gradually replaced forest plantation (Kompong Tom province, Cambodia, 2014).

The change in area of forest plantations and natural production forest are estimated according to a method modified from Kim Phat *et al.,* 2004. The equations used are:

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

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

$$\frac{\mathrm{dFP(t)}}{\mathrm{dt}} = a \times \mathrm{PdF(t)} \tag{3}$$

Where

PdF(t), PrF(t) and FP(t) are areas of production forest, protection 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 2 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 3, Table 4). 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 4).

Table 4 Production and protection forests and forest plantations used in land use model

Year	Production Forest (PdF)	Protection forest (PrF)	Forest Plantations (FP)	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) r^2=0.96		a= 0.0029 (0.29% increase annually)	
Initials	160.2		6.8	

3.2 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, 2, and 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+ (Figure 5), the latter causes "degradation" depending on harvesting intensity and related damages (Figure 6). 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.

Figure 5 Photo is showing deforestation in Mondulkiri province, Cambodia, 2013. The loss of forest to other form of land use (UNFCCC, 2014).

Figure 6 The forest degradation in Mondulkiri province, Cambodia. 2010, is a reduction of canopy cover or stocking within the forest (FAO, 2007).

Although small-scale logging is carried out in protection forests for local consumption by forest dependent communities who reside in the protection 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).

However, five carbon pools need to be reported by parties to the UNFCCC (IPCC, 2006), 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 (Cerri *et al.,* 2003; Guo *et al., 2002*) or a source (Guo *et al., 2002*). 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 (Kim *et al.,* 2006) 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.,* 2004. 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 (Kim Phat *et al.,* 2004). 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:

$$CS(t) = CS_{above}(t) + CS_{below} + CS_{litters} + CS_{dead} + CS_{soil} + CS_{HWP} \qquad (4)$$

Where

$CS_{above}(t)$ is aboveground carbon

CS_{below} is belowground carbon

CS_{dead} is carbon in deadwood

$CS_{litters}$ is carbon in litters

CS_{soil} is carbon in soil

According to IPCC Good Practices (IPCC 2006), including carbon in harvested wood product (CS_{HWP}) is optional. For this study, CS_{soil} (Figure 7) and CS_{HWP} are not accounted for. Except $CS_{above}(t)$, logging does not significantly affect CS_{below} (Figure 8), CS_{litter} (Figure 9), and CS_{dead} (Figure 10) and therefore for simplicity, carbon in these three pools are assumed to be constant proportional to $CS_{above}(t)$ throughout the modeling period. REDD+ project implementation is assumed to undertake in 2015 for 35 years until 2050.

Figure 7 Soil sampling for estimating carbon pool in soil (Mondulriki province, Cambodia, 2010). Soil organic matters are included organic matter in mineral and organic soils (including peat) to a specified depth chosen by the country and applied consistently through the time series (FAO, 2007).

Figure 8 Sample of Below-ground biomass, is all living biomass of live roots. Fine roots of less than (suggested) 2mm diameter are sometimes excluded because these often cannot be distinguished empirically from soil organic matter or litter (FAO, 2007).

Figure 9 Sample of litters (Mondulriki province, Cambodia, 2010), is defined as all dead organic surface material on top of the mineral soil (Timothy *et al.,* 2005).

Figure 10 Sample of deadwood (Mondulriki province, Cambodia, 2010) is includes volume of all non-living wood not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots, and stumps larger than or equal to 10 cm in diameter or any other diameter used by the country (FAO, 2007).

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. $CS_{above}(t)$ can be accounted by

$$\frac{dCS_{above}(t)}{dt} = MAI - [LM(t) + H(t)] \times BEF \qquad (5)$$

Where

t is time (year)

MAI is mean annual increment (MgC ha^{-1} $year^{-1}$)

LM(t) is logging mortality

H(t) is harvested carbon (MgC ha^{-1} $year^{-1}$)

LH(t) is dependent on the amount of trees to be harvested varying according to logging practices (Sasaki *et al.,* 2012). H(t) can be derived by:

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

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

Deciding the initial values for carbon stocks i.e. $CS_{above}(0)$ affects the results of carbon stocks, emissions or removals in Southeast Asia. Based on various sources (Table 5), 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.,* (2014) 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 5).

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.,* (2012) and set to f_H =0.3 and f_M=0.43 for PdF. BEF is biomass expansion factor, BEF=1.74 taken from (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.,*(2012).

Table 5 Available data on aboveground carbon stocks in Southeast Asia

Country	Aboveground carbon stocks (MgC ha^{-1})	Reference
Cambodia	116.6	Kim Phat *et al.,* (2000)
Indonesia	243.0	Griscom *et al.,* (2009)
Indonesia (Berau district)	199.3	Sist and Saridan (1998)
Malaysia	138.0	Berry *et al.,* (2010)
Malaysia	166.0	Pinard & Putz (1996)
Malaysia	164.0	Pinard & Putz (1996)
Malaysia (Tangkulap)	126.0	Imai *et al.,* (2009)
Malaysia (Deramakot)	178.0	Imai *et al.,* (2009)
Malaysia (Pasoh)	137.0	Okuda *et al.,* (2004)
Malaysia (Pasoh)	155.0	Okuda *et al.,* (2004)
Myanmar	116.6	Aye *et al.,* (2014)
Philippines	193.0	Lasco and Pulhin (2009)
Thailand	71.6	Petsri and Pumijumnong (2007)
Vietnam	111.5	Van Con *et al.,* (2013)
Average ($\mathbf{CS_{above}}$)	**151.1**	129.6-172.6 is for lower and upper bounce of 95% Confidence Interval, respectively
Below ($\mathbf{CS_{below}}$)	24.0	Using ratio in Aye *et al.,* (2014)
Litters ($\mathbf{CS_{litters}}$)	21.5	Aye *et al.,* (2014)
Deadwood ($\mathbf{CS_{dead}}$)	36.7	Aye *et al.,* (2014)
Soil	(Not included)	
Total (CS)	**233.3**	

To estimate r, a number of sources were reviewed. The Forests and the European Union Resource Network (FERN, 2002) 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 80% depending on political situation and locations on the country in the tropics (FERN, 2002). Illegal logging in Cambodia was reported at 67% in 1997 (DAI, 1998). 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), (6) and (7) are given in Table 6.

Table 6 Initial values and parameters used for production forest (Equations 5, 6, 7)

Description	Conventional Logging (CVL)	Reduced Impact Logging (RIL)	Remarks
Initial carbon stocks $CS_{above}(0)$	151.1	151.1	Khun and Sasaki (2014)
f_M (fraction of mature trees)	0.43	0.43	Sasaki *et al.,* (2012)
f_H (logging rate)	0.3	0.3	Kim Phat *et al.,* (2004)
r (illegal logging rate)	0.5	0.5	Sasaki *et al.,* (2012)
CC (cutting cycle in year)	30	30	Common cutting cycle
MAI (Mean Annual Increment)	0.76	0.76	Khun and Sasaki (2014)
BEF (Biomass Expansion Factor)	1.74	1.74	Brown (1997)
α (Logging Damage)	0.4	0.14	Sasaki *et al.*, (2012)

MAI is an important indicator in forest management. Based on various studies in Southeast Asia (FAO 1981; ITTO 1994; Van *et al.,* 1998; Kim Phat *et al.,* 2000; Kim Phat *et al., 2002)*, a previous study by Kim Phat *et al.,* (2004) 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 (Phillips *et al.,* 1998). The average volume increment for commercial timber in logged forests in Tapajós National Forest (Amazonia) has been estimated at 0.33m^3 ha^{-1} yr^{-1} or about 0.09 MgC ha^{-1} yr^{-1} (Van *et al.,* 2003). Based on 12–17 years of measurements from experimental plots in national forests at Jarí and Tapajós, Amazonia, Alder and Silva (2000) 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 (2006) 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.,* (2002), 56% for Sarawak (Malaysia) by FAO (2001), and 48.4% in East Kalimantan by Sist *et al.,* (2003). Approximately 44% of the 60% reported by Tay *et al.,* (2002) were destroyed during the harvesting over a 60-year cutting cycle or about 0.7% yr^{-1}. According to Sist *et al.,* (2003), 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 (1996) found that 18% of all injured trees with DBH greater than 5 cm died after 12 months of harvesting. Iskandar *et al.,* (2006) reported that every one m^3 of wood harvested led to the loss of 0.7–1.3 m^3 due to logging damages. Recent study by Kimsun *et al.,* (2011) 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 dissertation.

Forest Plantations: Although tropical natural forests have been cleared, part of the deforested land has been gradually replaced forest plantation (FAO, 2010). According to FAO (FAO, 1995), 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 7, average carbon stocks in forest plantations is 91.6 MgC 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 ha^{-1}. We use 92.0 MgC as carbon stocks in forest plantations in this study. Major forest plantations were well established before the beginning of the modeling timeframe. Carbon stocks in FPl, $CS_{FPl}(t)$ are therefore

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

Table 7 Carbon stocks in forest plantations by species in the tropics

Carbon stocks ($MgC\ ha^{-1}$)	Remarks	References
Pinus caribaea		
130.2	Various locations across Sri Landka	De *et al.,* 2012
80.6 (AG)	15 year old stand in Nigeria	Kadeba, 1991
103.5 (AG)	10 year old stand in Nigeria	Egunjobi and Bada, 1979
99.3 (AG)	Mid-country Wet Zone (WM3b)	Dharmaparakrama, 2006
76.2 (AG)	Mid-country Intermediate Zone (IM1b)	Turner *et al.,* 1983
Eucalyptus grandis		
132.7	Various locations across Sri Landka	De *et al.,* 2012
197.0 (AG)	27 year old stand in New South Wales, Australia	Turner *et al.,* 1983
137.0 (AG)	12 year old stand in New South Wales, Australia	Bitk *et al.,* 1992
234.5	19 year old stand in Hatton, Sri Lanka	Nissanka *et al.,* 2003
53.5 – 70.5 (AG)	5.5 year old stand in Brazil	Stape *et al.,* 2008
Eucalyptus camaldulensis		
26.2	Various locations across Sri Landka	De *et al.,* 2012
13.5 – 17.5	3.5 year old stand in Southern Brazil	Bernado *et al.,* 1998
22.6	3 year old stand in Southern India	Himter, 2001
Tectona grandis		
42.7	Various locations across Sri Landka	De *et al.,* 2012
70.6 (AG)	15 year old stand in Nigeria	Mbackwe *et al.,* 2008
120.0	20 year old stand in Panama	Kraenzel, 2003
142.0 (AG)	47 year old stand in Costa Rica	Perez *et al.,* 2003
113.0 – 191.0	Mature stand in South-Western Nigeria	Ola, 1993
70.6 (AG)	14 year old stand in Nigeria	Mbackwe *et al.,* 2008
34.2 (AG)	Philippines	Lasco *et al.,* 2003
Swietenia macrophylla		
97.6	Various locations across Sri Landka	De *et al.,* 2012
130.5 (AG)	16 year old stand in the Philippines	Kawahara *et al.,* 1981
133.8	Mature stands in the Philippines	Racelis, 2000
61.9 (AG)	59 year old stand in Puerto Rico	Wadsworth *et al.,* 2003
Acacia mangium		
110.7	Various locations across Sri Landka	De *et al.,* 2012
45.2 (AG)	4 year old stand in Malaysia	Tsai *et al.,*1988
88.1 (AG)	Philippines	Lasco *et al.,* 2000
25.6 (AG)	Philippines	Buante 1997, Lasco *et al.,* 2003
Acacia auriculiformis		
87.1	Various locations across Sri Landka	De *et al.,* 2012
76.8 (AG)	Philippines	Lasco *et al.,* 2003
Assumption for this study: 92.0 $MgC\ ha^{-1}$		

Source: De Costa *et al.,* (2012)

Note: AG refers to above-ground carbon stocks

3.3 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 protection forests, respectively.

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

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

Where

$FPl_{TOTAL}(t)$ 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

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

3.4 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

$$E_{TOTAL}(tn) = E_{DEFORESTATION}(tn) + E_{DEGRADATION}(t) \tag{12}$$

Or

$$E_{DEGRADATION}(t) = E_{TOTAL}(tn) - E_{DEFORESTATION}(tn) \tag{13}$$

Where

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

$$E_{TOTAL}(tn) = \left[PdF(tn) \times CS_{PdF}(tn) - PdF(tn\text{-}1) \times CS_{PdF}(tn-1)\right] \times \frac{44}{12} \tag{14}$$

$$E_{DEFORESTATION}(tn) = \left\{\left[PdF(tn) - PdF(tn\text{-}1)\right] \times CS_{PdF}(tn)\right\} \times \frac{44}{12} \tag{15}$$

Where

PdF(tn) is area of PdF at time t=n in million ha (Eq. 1)

$CS_{PdF}(tn)$ is carbon stocks of PdF in MgC ha^{-1}

44/12 is molecular weight of carbon dioxide per carbon unit

Unit for $E_{TOTAL}(tn)$, $E_{DEFORESTATION}(tn)$, and $E_{DEGRADATION}(tn)$ is $TgCO_2$ (1 Tg = 10^{12} g = 1 million tonnes).

3.5 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 ($EDef_{REDUCTION}$) can be obtained using equation developed by Ty *et al.,* (2011):

$$EDef_{REDUCTION}(tn) = \{E_{DEFORESTATION}(tn) \times [1 - RPI(tn)]\} \times CS \times \frac{44}{12} \qquad (16)$$

Where

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, RPI (t) is taken directly from Ty *et al.,* (2011) (Table8, 9).

Table 8 Effectiveness of project action to reduce the driver of deforestation and forest degradation

Driver of Deforestation and forest degradation	**Project Actions (unit: %)**										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Total**
1. Forest clearing for land sales	0	0	100	0	0	0	0	0	0	0	100
2. Conversion to cropland	0	50	0	5	0	0	30	0	10	0	95
3. Conversion to settlements	0	75	0	0	0	0	0	0	0	0	75
4. Fuel-wood gathering	0	0	25	0	8	25	0	0	0	0	58
5. Annual Forest fires induced to clean the land	0	20	20	0	0	0	0	25	0	25	90
6. Hunters inducing forest fires	0	0	50	0	0	0	0	0	0	25	75
7. Illegal logging for commercial on-sale	0	0	90	0	0	0	0	0	0	0	90
8. Timber harvesting for local use	0	20	50	20	0	0	0	0	0	0	90
9. Economic land concessions	100	0	0	0	0	0	0	0	0	0	100
10. Timber concessions	100	0	0	0	0	0	0	0	0	0	100
Total reduction in deforestation	0	27	39	2	1	3	8	3	3	4	

Source: Ty *et al.,* (2011)

Table 9 Project actions and resulting reductions of the drivers of deforestation and forest degradation

Project Actions	Description	Reduction in Driver
Project Action 1: Strengthening Land-tenure	The land-tenure is enforced through Community Forestry Agreements. These were signed in May 2009, during the second year of the crediting period. Therefore, a rate of 50% was assumed for this year. They are automatically renewed for 15 years unless the land is not managed according to the agreement.	This action is likely to result in 100% reduction of drivers 9, 10 and 11
Project Action 2: Land-use Plans	Land-use plans are fully supported by the project proponents from the first year of the project. However, it is expected that a period of 5 years is necessary before the full effect (rate) of land use plans is reached due to the often challenging negotiations to design a broadly accepted land-use plan.	This action is likely to result in reductions of 25% for driver 2, 50% for driver 3, 25% for driver 5 and 25% for driver 8
Project Action 3: Forest Protection	Forest protection measures are fully funded for the whole project period. It is assumed that full effect, or rate, of forest protection will be reached after 3 years, when all participating communities will have acquired experience to protect the forests most effectively.	This action is likely to result in reductions of 100% for driver 1, 25% for driver 4, 20% for driver 5, 50% for driver 6, 90% for driver 7, and 50% for driver 8

Project Action 4: Assisted Natural Regeneration	Assisted natural regeneration activities consist of (1) silvicultural activities such as thinning, removal of exotic and invasive species, and coppicing, and (2) enrichment planting. Silvicultural activities are planned for years 3-20, while enrichment planting is planned for years 3-30. During the first year, a number of pilot activities are planned to find out the most effective way to optimize the regeneration. Therefore, the rate of the first year is set to 50%.	This action is likely to result in reductions of 5% for driver 2, 20% for driver 8
Project Action 5: Introduction of Fuel-efficient Stoves	The project plans to distribute 500 fuel-efficient stoves annually for year 3 until 10. It is assumed that a fuel efficient stove has a lifetime of about 3 years. Therefore, from year 5 onwards, when the project activity has the greatest effect, on average 1,500 stoves will be active. During years 3-10, 500 stoves are anticipated to become defunct while still 500 stoves are introduced by the project. After 10 years, no more stoves are distributed, and the activity rate will go down with 500 per year. However, around 10 years, it is assumed that 33% of the people that once had a fuel-efficient stove will purchase or maintain a fuel-efficient stove due to the higher efficiencies, and the fewer time required to gather fuel-wood. This represents around 5% of all the households in the project area.	This action is likely to result in reductions of 7.5% for driver 4

Project action 6: Introduction of Mosquito Nets	Analogously to fuel-efficient stoves, mosquito nets are introduced from years 3 until 10. About 700 mosquito nets per year will be distributed. Similarly to fuel-efficient stoves, a lifetime of 3 years is anticipated, while no mosquito nets will remain in use in the project after subsidizing by the project has terminated.	This action is likely to result in reductions of 25% for driver 4
Project Action 7: Agricultural Intensification	Agricultural intensification measures are planned from years 3-20. Every year, 60 new farmers will be introduced in the system. In addition, it will take time to build out marketing networks for alternative crops and commodities. Therefore, the effect of agricultural intensification will increase linearly until year 20.	This action is likely to result in reductions of 30% for driver 2
Project Action 8: Water Resource Development Projects	Natural resource management practices are fully planned from year 3 until the end of the project. Due to the nature of the projects, measures will be instantly effective.	This action is likely to result in reductions of 20% for driver 5
Project Action 9: NTFP Development	Non-timber forest product development activities are supported during years 3-20. Similar as to agricultural intensification measures, a period of 10 years is assumed before these will be fully effective because marketing networks must be developed, etc. A final adoption rate of 50% is assumed after terminating the project's support for these activities.	This action is likely to result in reductions of 10% for driver 2
Project Action 10: Fire Prevention	Fire prevention activities are planned from year 4 of the crediting period until the end of the project. A learning period of 5 years is assumed until fire prevention activities are fully effective.	This action is likely to reduce of 25% for driver 5, and 25% for driver 6

Source: Ty *et al.,* (2011)

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 6), 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 (Sasaki *et al.,* 2012; Putz *et al.,* 2008). As reviewed by Sasaki and Putz (2009), 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. H (t) in Eq. 6, 7; Table 6). As seen in Table 6, logging damage is 40% and 14% under CVL and RIL, respectively. Emission reductions can be estimated by

$$\begin{aligned} EDeg_{REDUCTION}(tn) = E_{DEGRADATION}(tn) - \{ & [PdF(tn) \times CS_{RIL}(tn) - PdF(tn-1) \times CS_{RIL}(tn-1)] \\ & - [PdF(tn) - PdF(tn-1)] \times CS_{RIL}(tn) \} \times \frac{44}{12} \end{aligned} \qquad (17)$$

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't 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:

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

3.6 Carbon Fluxes Due to Selective Logging

This study obtained total area of production forest from our previous study (Khun and Sasaki, 2014) in Southeast Asia. Using forest functions defined by FAO (FAO, 2010), this study classified forestland uses to production forest, protection forest, and forest plantation. Area change and forest carbon stocks change for each forest classification were predicted up to 2050. In tropics, commercial logging is commonly carried out in production forest, where mature trees (trees with diameter greater than minimum diameter for harvesting) are selectively logged once per cutting cycle (Figure 11).

Figure 11 Selective logging (Mondulriki province, Cambodia, 2010), is the practice of cutting down one or two trees while leaving the rest intact (Mark, 2005).

3.6.1 Wood components created by selective logging

This section focuses on estimating timber harvest, logging mortality, wood products (Figure 12), sawn-wood (Figure 13), sawn-wood wastes (Figure 14), wood product wastes, belowground dead root, branches and top logs of harvested trees (Figure 15) in production forest in Southeast Asia (Figure 16) under two logging practices, namely CVL and RIL. The former is assumed to be the business-as-usual practice while the latter is assumed to be a practice adopted when financial support under the UN's REDD+ scheme is available. The difference between CVL and RIL is the amount of logging damages, wood wastes caused by logging and wood processing inefficiency (Sasaki and Putz, 2009).

Figure 12 Wood products (WP) from selective logging (Katie province, Cambodia, 2013) were cut from the forests that have the DBH bigger than 30cm.

Figure 13 Sawn-wood (SW) (Kompong Speu, Cambodia, 2014) after deliver the wood products to the factory then they convert to sawn-wood for using in country or export to other countries.

Figure 14 Branches and top logs of harvested and damaged trees (Mondulriki province, Cambodia, 2010), this is the components that remain in the forest after the logging and the components also can stock the carbon.

Figure 15 Belowground dead root (Mondulriki province, Cambodia, 2010), however the tree already dead but the belowground dead root can stock the carbon in the period of time.

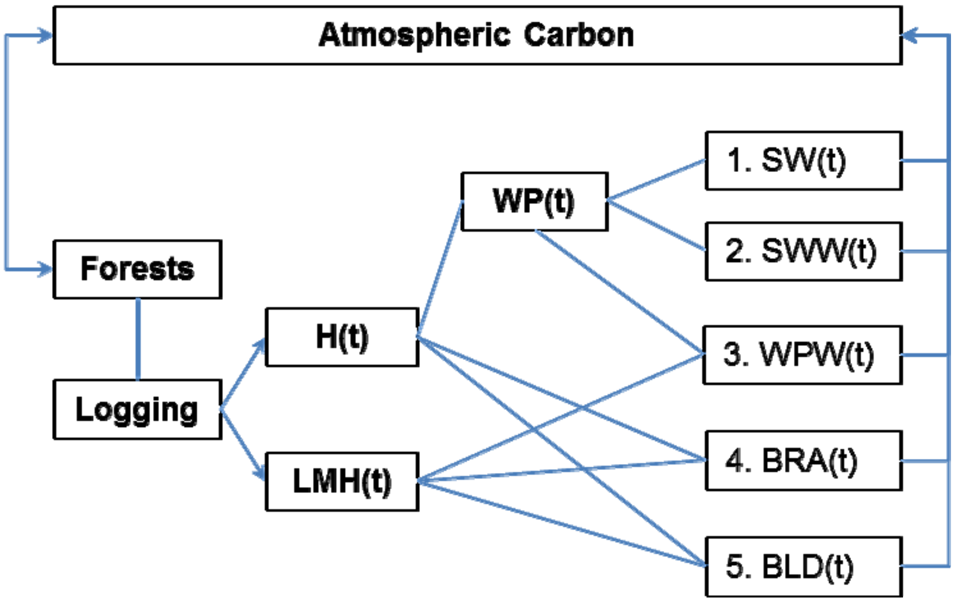

Figure 16 Five wood components created by selective logging.

Description of other values and parameters are given in Table 6.

Wood products (WP), sawn-wood (SW), wood wastes in the forests (WPW), branches and top logs of harvested and damaged trees (BRA) and belowground dead root (BLD) can be derived by

$$\mathrm{WP(t)} = (1 - \mathrm{s}) \times \mathrm{H(t)} \tag{19}$$

$$\mathrm{SW(t)} = (1 - \mathrm{a}) \times \mathrm{WP(t)} \tag{20}$$

$$\mathrm{WPW(t)} = [\mathrm{H(t)} - \mathrm{WP(t)}] + \mathrm{LM(t)} \tag{21}$$

$$\mathrm{BRA(t)} = [\mathrm{H(t)} + \mathrm{LM(t)}] \times (1 - \mathrm{BEF}) \tag{22}$$

$$\mathrm{BLD(t)} = [\mathrm{H(t)} + \mathrm{LM(t)}] \times 0.16 \tag{23}$$

Where

s: Proportion of wood wastes to harvested logs. These wastes include broken trunks and high stumps. Based on various sources, Sasaki *et al.,* (2012) adopted s=0.3 or 30% for CVL and s=0.1 or 10% for RIL. We used same value for this study

a: Wood processing efficiency at sawmills (i.e. proportion of wood waste at sawmill). We used same values adopted by Sasaki *et al.,* (2012) for wood processing inefficiency (a=0.5 for CVL, and a=0.4 for RIL)

BEF: Biomass expansion factor. We used 1.74 as reported by Brown (1997).

0.16 or 16% is the proportion of root to aboveground biomass (Aye *et al.,* 2014).

Carbon fluxes in each wood component above at every time step are estimated by first order decay function followed Grier (1978). This method was also recently used by Stockmann *et al.,* (2012) to estimate carbon storage in harvested wood products from the United States forest service northern region. Carbon remaining in any wood component created by selective logging at any time carbon is obtained by:

$$\mathrm{CF_i(t)} = \mathrm{CF_i(t0)} \times e^{-k_i \times t} \tag{24}$$

Where

$C_i(t0)$: Initial amount of carbon at year zero (i.e. starting year of the model)

t: Elapsed time (years)

k_i: constant decay rate for wood component i, which can be derived by

$$k_i = \frac{\ln(2)}{HL_i} \tag{25}$$

Where

HL_i: Half-life time (years) of wood component i. HL is the time after which half the carbon is no longer in use. Table 10 provides information on HL for various wood components.

Based on 32 native tree species in Malaysian Borneo, Mori *et al.,* (2014) estimated HL time ranging about just about 1 year to as high as 28 years for dead trees, with average of about 4.3 years. Tobin *et al.,* (2007) estimated the decay rates of 31 stumps and 51 logs at 0.0592 and 0.0466 or 11.7 and 14.9 years of HL time, respectively. Based on data from 199 dead trees in Amazonian forest, Chambers *et al.,* (2000) estimated average decay rate of medium-size trees of 0.17-0.19 per year or about 4 years of HL time. There are large variations of decay rates ranging from 0.015 (HL=46.2 years) to 0.67 (HL=1.0 year) $year^{-1}$. Annual temperature in tropical forests is warmer than that in temperate forests, and therefore the decay rate of dead trees in tropical forests is much faster. Given these large variations and for simplicity, we assumed that HL times for SWW, WPW, BRA, and BLD at 3, 5, 4, and 5 years, respectively (Table 10).

Table 10 Half-life time of five wood components considered in this study

Name	Wood Components (i)	HL (years)	Sources	k
SW	Sawn-wood	30	IPCC (2006)	0.0231
SWW	Wood wastes when logs are processed to sawn wood at sawmills	3	Assumptions based on Mori	0.2310
WPW	Wood product wastes due to logging damages left behind in the forests	5	*et al.,* 2014, Tobin *et al.,*	0.1386
BRA	Branches and top logs left behind in the forests	4	2007,Chambers *et al.,* 2000	0.1733
BLD	Belowground dead root	5		0.1386

3.6.2 Cumulative carbon fluxes

Cumulative carbon fluxes in each wood component per hectare are obtained by

$$CCF_n(tn) = CF_1(tn) + CF_2(tn-1) + ... + CF_n(t1) \quad (26)$$

Where

$CF_n(tn)$: carbon fluxes in wood component occurred at harvest time t=n (MgC ha^{-1})

Cumulative carbon fluxes in each wood component due to logging in production forest in Southeast Asia are therefore

$$TCF(tn) = PdF(t) \times CCF_n(tn) \quad (27)$$

Where

TFC(tn): Cumulative carbon fluxes in each wood component (TgC)

PdF(t): Area of production forest (million ha) taken from our previous study (Khun and Sasaki, 2014)

3.6.3 Converting from carbon to wood volume

Since existing publications on carbon stock changes affected by logging in Southeast Asia are rare, we need to convert carbon stocks in harvested timber, wood products, and sawn-wood to cubic volume so that results of this study can be validated against that in previous studies. We converted harvested timber, wood products, and sawn wood from carbon to cubic meter of wood using the following equation:

$$W_i(t) = \frac{CW_i(t)}{WD \times CT} \tag{28}$$

Where

$W_i(t)$: Amount of wood in wood component *i* (harvested wood, wood products or sawn-wood) at time *t* ($m^3\ ha^{-1}$)

$CW_i(t)$: Amount of carbon in wood component *i* ($MgC\ ha^{-1}$)

WD: Wood density ($Mg\ m^3$). WD is 0.56 (Brown 1997)

CT: Carbon content in dry wood ($MgC\ Mg^{-1}$). CT is 0.5 (IPCC 2006)

Total production for each wood component is therefore

$$TW_i = PdF(t) \times W_i(t) \tag{29}$$

Where

$TW_i(t)$: Total production of wood component *i* (million m^3)

Chapter 4 RESULTS AND DISCUSSION

4.1 Forest Carbon Stock Changes

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 results using available data in 1990, 2000, 2005, and 2010, *a+b*, *a*, initial values for PdF and FP 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 17). 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 protection 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 protection forest starting from 2039 onward. Consequently, even protection forest will be subject to clearing and commercially unless alternative sources are available sooner rather than later. Using data by FAO (2005), Kim Phat *et al.,* (2004) 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 18). 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 11). 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 11 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.

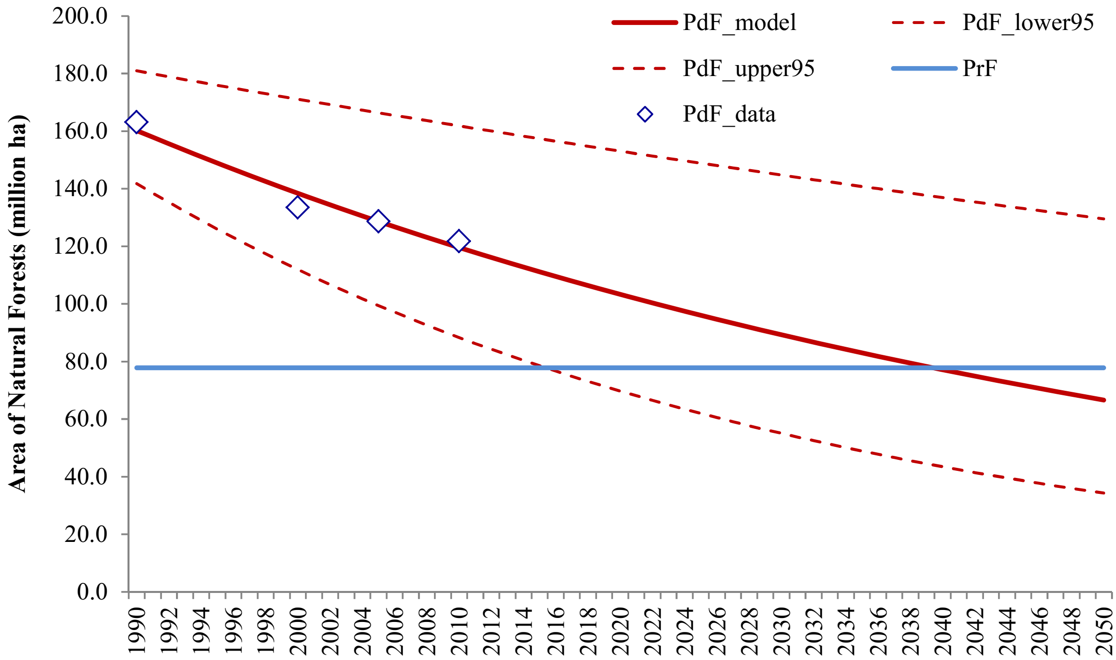

Figure 17 Area of natural forests in Southeast Asia (1990-2050).

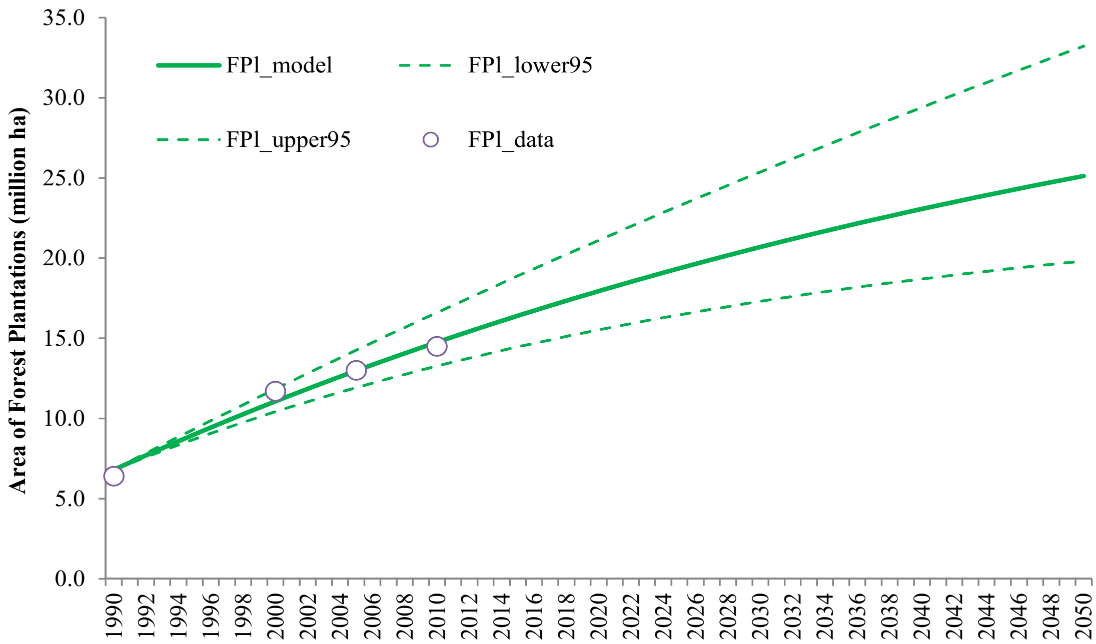

Figure 18 Area of forest plantations in Southeast Asia (1990-2050).

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 11).

Table 11 Area of natural forests and forest plantations in Southeast Asia (modeling results)

Year	Natural Forests			Forest	Total
	Production Forest (PdF)	Protection forest (PrF)	Total	Plantations (FPl)	
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.

These findings of deforestation were in the ranges estimated by Kindermann *et al.,* (2008) 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.,* (2011) estimated the deforestation rate in insular Southeast Asia at 1% between 2000 and 2010, which well within our estimate of deforestation of natural forest.

4.2 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 protection forest (PrF) because of the study assumption. Deforestation and forest degradation led to decline of carbon stocks in production forest (PdF) from 37,371.6 TgC (aboveground, belowground, litters, and deadwood) in 1990 to 13,531.3 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 12). 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 12). 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 1,400.0 TgCO_2 in 2015, 1,272.7 in 2020, 1,054.3 in 2030, 876.2 in 2040, and 730.5 TgCO_2 in 2050 (Figure 19). On average between 2015 and 2050, deforestation emitted 1,027.0 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 1,302.0 TgCO_2 year^{-1} between 2015 and 2050 (Figure 19). This figure is highly higher than that estimated by Kindermann *et al.,* (2008) who estimated emissions from deforestation in Southeast Asia at 1,100 TgCO_2 between 2005 and 2030. This is because their study did not include loss from forest degradation.

Table 12 Carbon stocks and changes in Southeast Asia

Year	Production Forest (PdF)	Protection forest (PrF)	Forest Plantation (FP)	Total
Total carbon stocks in TgC (1 TgC = 1 million tonnes C)				
1990	37,371.6	18,149.3	563.04	56,083.9
2000	32,289.7	18,149.3	916.446	51,355.4
2010	27,898.8	18,149.3	1,221.79	47,269.9
2015	25,932.6	18,149.3	1,358.53	45,440.4
2050	13,531.3	18,149.3	2,080.69	33,761.3
Annual changes in TgC $year^{-1}$ and in $TgCO_2$ $year^{-1}$				
1990-2000	-508.2 (-1,865.1)	0.0	35.3(129.7)	-472.9 (-1,735.4)
2000-2010	-439.1 (-1,611.5)	0.0	30.5 (112.1)	-408.6 (-1,499.4)
1990-2050	-397.3 (-1,458.2)	0.0	25.3 (92.8)	-372.0 (-1,365.4)
2015-2050	-354.3 (-1,300.4)	0.0	20.6 (75.7)	-333.7 (-1,224.6)

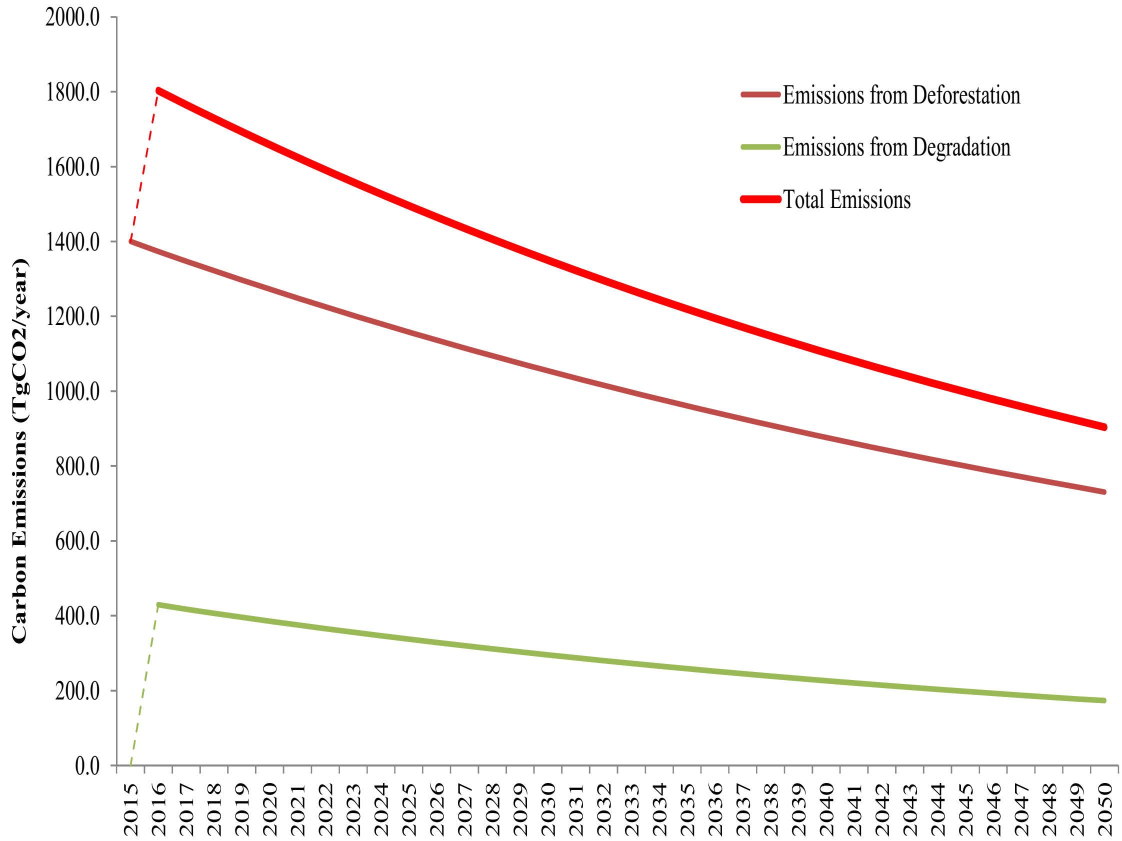

Figure 19 Annual carbon emissions from deforestation and forest degradation in Southeast Asia.

4.3 Carbon Fluxes Due to Selective Logging

4.3.1 Wood products and other wood components created by selective logging

Wood products are important sources for housing and economic development in Southeast Asia. Between 2015 and 2050 of the modeling timeframe, logging produced about (± for standard error) 0.83 (±0.01) m^3 ha^{-1}, declining about -0.57% $year^{-1}$. This decline was due to overexploitation and logging damages (harvested wood and logging damages are greater than mean annual increment). Other studies have found that selective logging in the tropics resulted in significant decrease of stand volume or carbon stocks (Asner *et al.,* 2005, Blanc *et al.,* 2009, Mazzei *et al.,* 2010, Zimmerman *et al.,* 2012).

Wood products (round-wood) from logging in production forest in Southeast Asia were 146.6 (±5.4) million m^3 $year^{-1}$ between 2015 and 2050. Overexploitation coupled with decline in area of production forests (Khun and Sasaki, 2014) caused a decrease of round-wood production of about 2.2 million m^3 annually over the same period (Figure 20). Of the 146.6 million m^3, about 73.3 (±2.7) million m^3 were processed further to sawn-wood. The remainder (50%) was wood wastes at the processing sawmills. Other wood components created by selective logging include 217.0 (±8.0), 46.5 (±1.7), and 62.8 (±2.3) million m^3 $year^{-1}$ of branches and top logs, belowground dead root, and wood wastes due to felling, trimming and transporting to sawmills, respectively (Table 13). Wood components (except sawn-wood) are usually excluded in any reports by any government and so are carbon fluxes in these wood components.

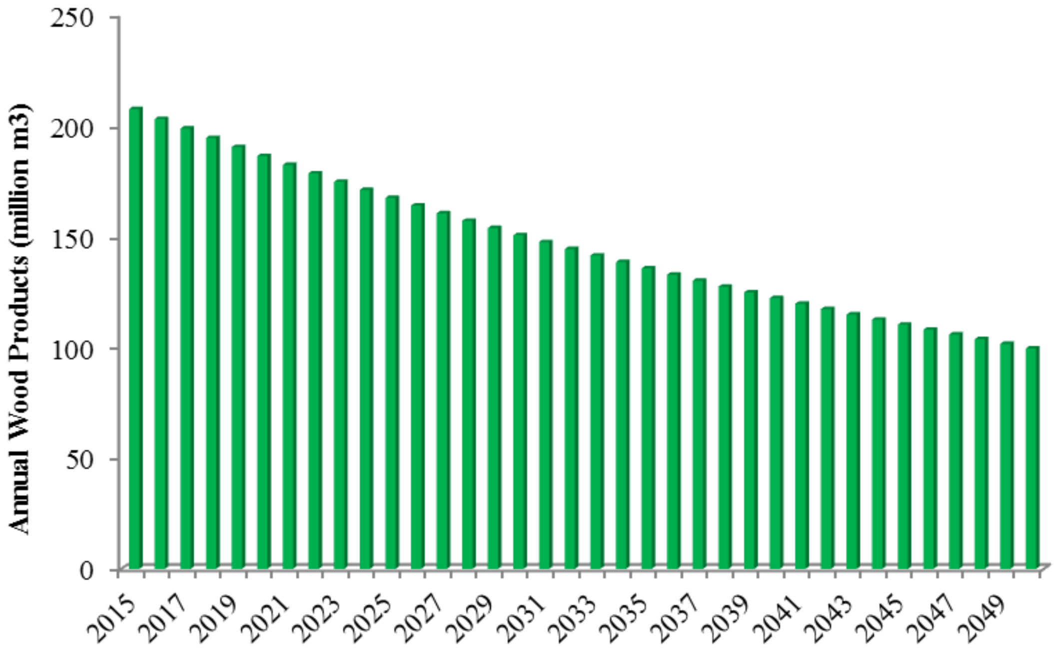

Figure 20 Annual wood products (round wood) in Southeast Asia (2015-2050).

Table 13 Mean annual productions of various wood components created by selective logging (2015-2050)

Wood Component (*i*)	Mean (Million m^3)	Standard Error	Percentage to Total	Classification
SW	73.3	2.7	15.5%	SW
SWW	73.3	2.7	15.5%	Offsite
BRA	217.0	8.0	45.9%	Onsite
BLD	46.5	1.7	9.8%	Onsite
WPW	62.8	2.3	13.3%	Onsite
Total	**473.1**		**100.0%**	

Waggener and Lane (1997) reported industrial round-wood production in Southeast Asia about 68.1 million m^3 in 1980 and increased to 87.1 million m^3 in 1992. Using these data (Figure 21) and based on linear projection, average round-wood production between 2015 and 2050 was 134.4 (±2.3) million m^3, only about 8% lower than this study estimate. This lower prediction may be due to the fact that data of Waggener and Lane (1997) did not include wood production from illegal logging. If 50% of illegal logging was included, wood production using data from Waggener and Lane (1997) went up to 268.8 million m^3. This higher value would be possible given that their data were collected when Southeast Asia still had higher forest cover and countries such as Philippines and Thailand were the among major producers of round-wood (FAO, 2011).

Since 1990s, forest resources in the Philippines and Thailand became exhausted. In addition, forest cover in Cambodia, Myanmar, Indonesia, and Laos has declined sharply over the last 15 years (FAO, 2010). As forest resources in many countries in Southeast Asia continue to decline, it is expected that round-wood product from natural forests (i.e. production forest in our study) will continue to decline. Based on data published by (FAO, 2011), round-wood production in Southeast Asia peaked at about

105 million m^3 in 1993 but decline to about 80 million m^3 in 2007. Whiteman *et al.,* (1999) projected the production of industrial round wood in Malaysia and Indonesia alone to 95.2 million m^3 in 2010. Our findings of round-wood production are well within the range of previous studies.

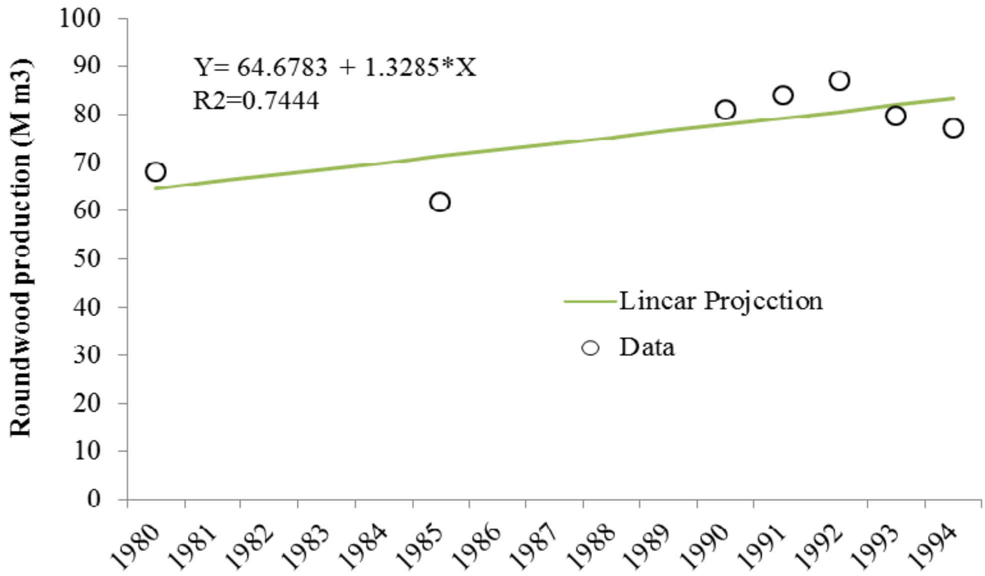

Figure 21 Industrial round-wood production reported by Waggener and Lane (1997) and linear fitting curve used to project future production. Source: Waggener and Lane (1997).

4.3.2 Carbon fluxes in wood products and other wood components

Annual fluxes in sawn-wood product declined from 0.26 MgC in 2015 to 0.21 MgC ha^{-1} in 2050 with annual decline rate of about 0.57%. Average fluxes were 0.23 (±0) MgC ha^{-1} over the same period. Cumulative carbon fluxes in sawn-wood were just 0.26 MgC ha^{-1} in 2015 but cumulatively increased to 5.68 MgC ha^{-1} in 2050 with increase rate of about 59.2% annually between 2015 and 2050 (Figure 22).

Cumulative carbon fluxes in wood wastes at sawmill (SWW) were 0.26 MgC in 2015 and 1.04 MgC in 2050 after reaching the highest point at 1.14 MgC in 2030. Similar patterns of cumulative fluxes were also seen in wood wastes in the forests

(WPW), branches and top logs (BRA), and belowground dead root (BLD). Cumulative carbon fluxes were 0.22, 0.77, and 0.17 MgC ha^{-1} in 2015 and 1.43, 4.01, and 1.06 MgC ha^{-1} in 2050 for WPW, BRA, and BLD, respectively (Figure 22). Cumulative carbon fluxes began to decline quickly and emit carbon in about 10 years after harvesting.

There models suggested that selective logging created huge amount of wood residues remained in the forests and at sawmills. Feldpausch *et al.,* (2005) found that logging produced more wood residues in the selectively logged forests. Onsite residues that include branches and top logs, wood waste due to logging (broken logs, stumps), and belowground dead root account for high cumulative carbon fluxes but these fluxes began to decline when inflow fluxes are smaller than outflow fluxes due to wood decay. Offsite fluxes in wood waste at the sawmills has same pattern to that of onsite fluxes. Fluxes in sawn-wood continue to increase depending on how sawn-wood is further utilized to further make furniture or houses or other building infrastructures.

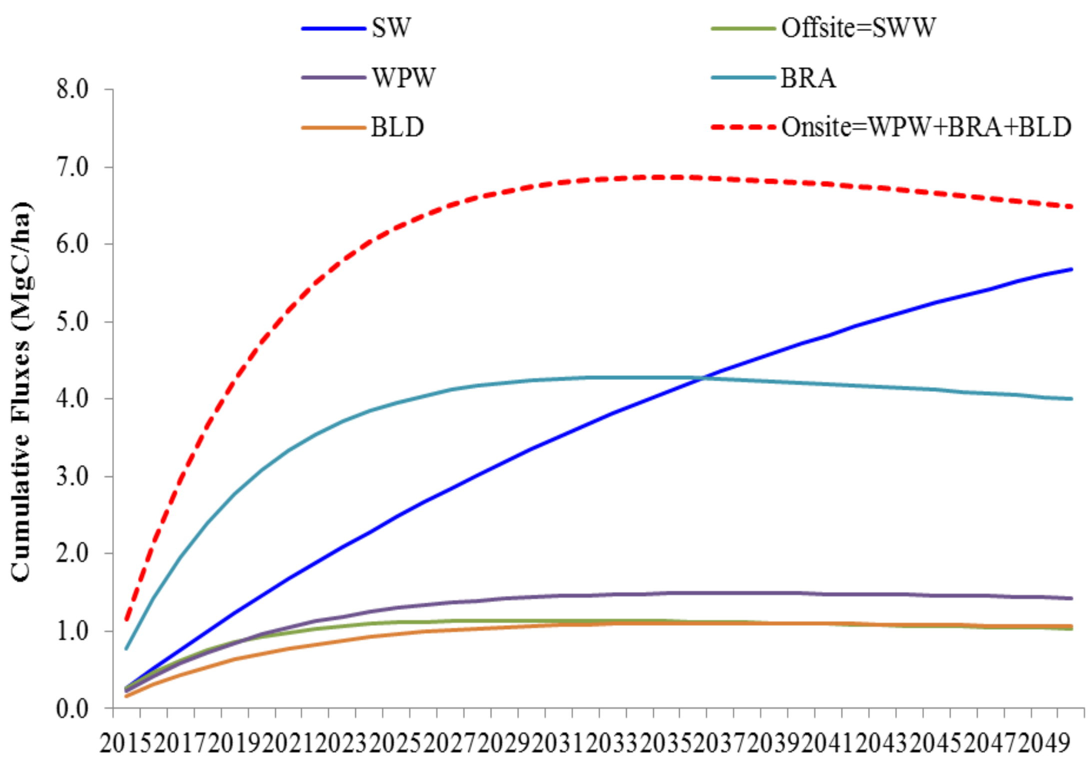

Figure 22 Cumulative carbon fluxes in various wood components created by logging.

4.3.3 Cumulative carbon fluxes due to selective logging

Cumulative carbon fluxes in sawn-wood, onsite and offsite wood components created by selective logging under CVL in production forest in Southeast Asia were estimated at 378.7, 433.0, and 69.1 TgC in 2050 increasing from 29.1, 129.4, and 29.1 TgC in 2015, respectively. Cumulative fluxes in onsite and offsite wood components declined sharply after reaching the highest level at 2028 (13 years after logging) and 2025, respectively (Figure 23). In contrast and despite decline in area of production forests (Khun and Sasaki 2014), cumulative fluxes in sawn-wood still increased and reached the highest level at 378.8 TgC in 2049. These fluxes began to decline gradually thereafter due to the decline in area of production forest in Southeast Asia (Khun and Sasaki 2014). Totally, selective logging under CVL in Southeast Asia resulted in cumulative carbon fluxes of 187.5 TgC in 2015 and 880.8 TgC in 2050. Depending on carbon accounting methods, the increase in cumulative carbon fluxes could be used to offset carbon emissions from tropical deforestation.

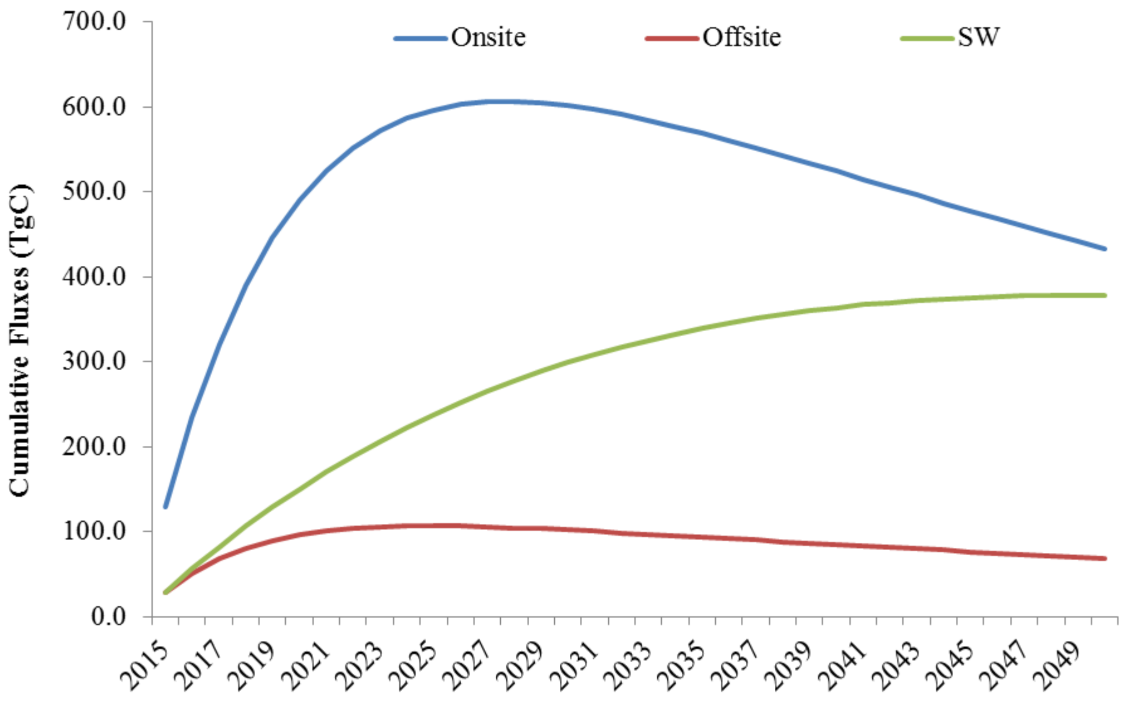

Figure 23 Cumulative carbon fluxes in onsite, offsite, and sawn-wood products.

4.3.4 Impacts of forest management on carbon fluxes

Reduced impact logging (RIL) is assumed as a logging practice that will be adopted for "sustainable management of forests" element of the REDD+ scheme. As RIL was able to significantly reduce wood wastes in the forests (WPW), wood wastes at sawmills (SWW), and logging damages, carbon fluxes in short-lived wood components can be reduced and therefore reduce emissions when inflow fluxes are smaller than outflow fluxes.

By being able to reduce damages, more sawn-wood production can be achieved from the same amount of harvested timber. Because sawn-wood has longer half-life time carbon, more carbon storage can be achieved as shown in Figure 24. Cumulative fluxes in sawn-wood under RIL and CVL increased to 608.4 and 378.7 TgC in 2050 from 44.8 and 29.1 TgC in 2015, respectively. After 35 years, cumulative fluxes under RIL were 229.7 TgC higher than that in CVL. In addition, RIL was able to reduce fluxes in short-lived wood components at 100.6 TgC (Figure 24, Table 14).

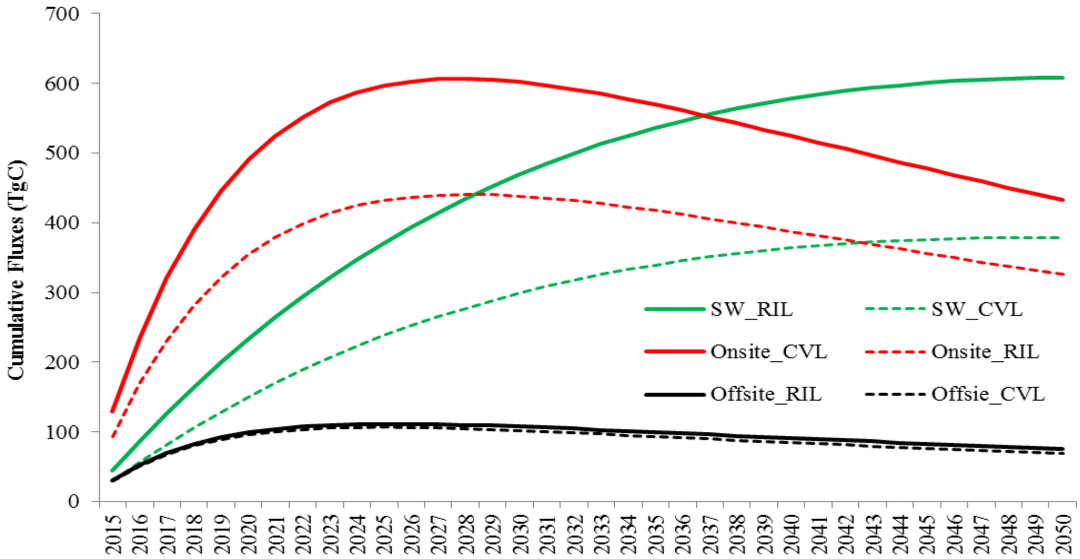

Figure 24 Cumulative carbon fluxes due to selectively logging under RIL and CVL in production forest in Southeast Asia.

Not only RIL could retain more carbon in standing forests (Sasaki *et al.,* 2012), but it can also increase sawn-wood product and carbon fluxes in sawn-wood.

This study finding suggested that adopting RIL not only lead to more carbon being retained in forests but also increase wood production and carbon storage in long-lived wood product. In addition, long-lived wood products could be achieved by technology transfer. If half-life time in sawn-wood can be lengthened, more carbon storage in harvested wood products can be further achieved.

Table 14 summary of cumulative carbon fluxes due to selectively logging under RIL and CVL in production forest in Southeast Asia

Year	Reduced Impact Logging (RIL) (TgC)				Conventional Logging (CVL) (TgC)			
	Onsite	Offsite	SW	Total	Onsite	Offsite	SW	Total
2015	93.4	29.9	44.8	168.1	129.4	29.1	29.1	187.5
2025	432.2	111.6	371.5	915.2	596.8	106.8	238.0	941.7
2035	417.5	99.6	536.1	1053.2	569.4	93.6	339.6	1002.6
2045	356.1	83.1	600.6	1039.8	477.7	76.5	376.0	930.2
2050	325.7	75.7	608.4	1009.9	433.0	69.1	378.7	880.8

Differences of cumulative fluxes under RIL vs CVL

Year	Onsite		Offsite		SW		Total	
	(TgC)	(%)	(TgC)	(%)	(TgC)	(%)	(TgC)	(%)
2015	-36.0	-27.8	0.8	2.9	15.8	54.3	-19.4	-10.3
2025	-164.6	-27.6	4.8	4.5	133.4	56.0	-26.4	-2.8
2035	-151.9	-26.7	6.1	6.5	196.5	57.9	50.7	5.1
2045	-121.5	-25.4	6.6	8.6	224.6	59.7	109.6	11.8
2050	-107.3	-24.8	6.6	9.6	229.7	60.7	129.1	14.7

4.3.5 Sensitivity analysis

There are several potential sources of uncertainty in this study. Initial carbon stocks in tropical forests vary greatly depending on many factors such as forest types, locations, and levels of disturbance. These variations could result in up to 60% biases of carbon estimates in tropical forests (Achard *et al.,* 2002; Fearnside *et al.,* 2003; Pelletier *et al.,* 2012). For instance, FAO (2010) estimated average carbon stocks in tropical Asia at 93 MgC ha^{-1}, while Friedlingstein *et al.,* (2010) and Baccini *et al.,* (2012) estimated at 160 and 115 MgC ha^{-1}, respectively. Another potential source of uncertainty is the use of illegal logging (50% of all harvested wood). Illegal logging usually is not reported in any official data of wood production in tropical countries. This is due probably to the lack of proper investigation or the difficulty in controlling illegal logging over large area of tropical forests. Using 166, 115, and 93 MgC ha^{-1} as initial value for our study, wood products in Southeast Asia were 154.6, 114.3, and 94.7 million m^3 year^{-1}, respectively between 2015 and 2050 for 50% (r=0.5) rate of illegal logging was used. Using same initial carbon stocks but different rates of illegal logging, wood products changed significantly over the same period (Table 15).

There are other factors that could affect results of our study. Not all tropical production forests are suitable for logging due to the presence of water surface, villagers, and environmentally and socially sensitive areas (such as steep slopes, buffer-zones around villagers, heritage sites, and so on). These areas are commonly referred to inoperable area, an area where logging can't be carried out. By logging regulation, logging on environmentally and socially sensitive areas is strictly prohibited.

Table 15 Average annual wood products under different initial carbon stocks and rates of illegal logging (2015-2050)

Initial Carbon Stocks ($MgC\ ha^{-1}$)	Annual wood products based on three rate of illegal logging (million $m^3\ year^{-1}$)			
	r=0.5 (50%)	r=0.3 (30%)	r=0.1 (10%)	r=0.1 (0%)
151.1 (This study)	146.6	110.1	88.1	80.1
160.0 (Friedlingstein *et al.,* 2010)	154.6	116.1	92.9	84.4
115.0 (Baccini *et al.,* 2012)	114.3	85.8	68.7	62.4
93.0 (FAO, 2010)	94.7	71.0	56.8	51.6

4.4 Carbon Balance and Loss

According to the forest carbon stock in Southeast Asia, the deforestation and forest degradation changed dramatically, the natural forest carbon stock were 45,440.4 TgC in 2015 and decline to 33,761.3 TgC in 2050. In addition, selective logging under CVL in Southeast Asia resulted in cumulative carbon fluxes of 187.5 TgC in 2015 and 880.8 TgC in 2050. Totally, carbon balance was 45,627 TgC in 2015 and 34,642.1 TgC in 2050.

In contrast, between 2015 and 2050 the carbon stock in the production forest also loss gradually (this study assume that the protection forest no change in carbon stock) from 25,932.6 TgC in 2015 to 13,531.3 TgC in 2050. The annual losses between 2015 and 2050 were 354.3 TgC or 1,300.4 $TgCO_2$.

4.5 Establishment of Reference Emission Level

Forest Reference Emission Level (FREL) or Forest Reference Levels (FRLs) defined as “benchmarks for assessing each country’s performance ” in implementing

REDD+ activities. In REDD+ negotiations, baseline methods that rely on extrapolating historic rates of deforestation have been seen as problematic, particularly by “high forest cover, low deforestation, HFLD ”. HFLD countries that are under increasing pressure from economic growth or agricultural expansion and absent additional policies or measures, would expect deforestation to increase. For this reason, it has been agreed that REDD+ FREL/FRELs should “take into account historic data ” but also can “adjust for national circumstances ” and information to substantiate such adjustment must be provided. The guidance provided to date also suggested an approach for FREL/ FRLs that is flexible (allowing for some choice in pools, gases and activities), step-wise (allowing for improvements over time in data and methodologies), and transparent (country submit through actions related to their forests (UN-REDD, 2014).

According to the UNFCCC decision, result base payment requires a forest reference level. To development the FREL/FRLs is the difficult task for developing country and also the political issues because after report to the UNFCCC, it would be difficult to change so it need to have the transparency, completeness, consistency, comparability and accuracy data. Transparency implies that the assumptions and methods used to prepare FRLs are clearly and fully described. FRLs should be complete. With respect to relevant pools and categories of activities, where pools or activities are missing, their absence should be documented along with a justification for their exclusion. FRLs should be prepared in a way that is consistent with accepted standards of carbon accounting, and that allows for comparison of FRLs among countries. To ensure accuracy, bias must be avoided and uncertainty must be reduced. So it needs to have the good data of the carbon stock in each forest type by classify which type is deforestation or degradation, the more detail the more accurate data.

Base on the assumption of the data from this research (modeling result), the total forests area were 244.8, 227.3 and 212.1 million ha in 1990, 2000 and 2010 while the population growth in Southeast Asia was 445.36, 523.83 and 593.41 million (Figure 25).

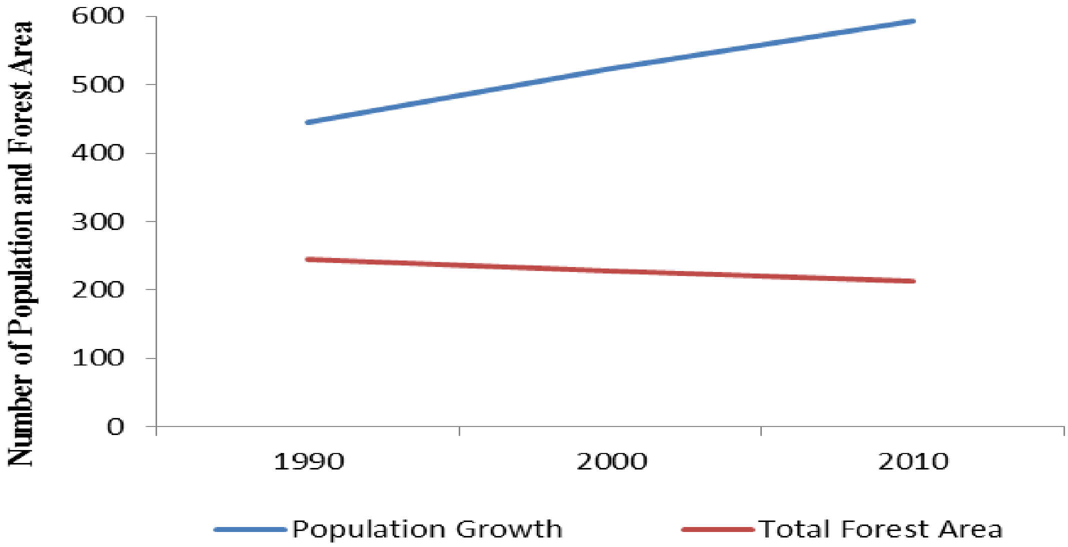

Figure 25 Population growth and total forest area.

The annual change rate of population growth between 1990-2000, 2000-2010 and 1990-2010 were 7.85, 6.96 and 7.4 million while change rate were 1.76%, 1.33% and 1.66%. For the total forest area, the annual change rate between 1990-2000, 2000-2010 and 1990-2010 were -1.75, -1.52 and -1.64 million while change rate were -0.71%, -0.67% and -0.67% (Table 16).

Table 16 Area of total forest and population growth in Southeast Asia (unit: million)

Year	Population Growth	Total Forest Area (ha)
1990	445.36	244.80
2000	523.83	227.30
2010	593.41	212.10
Annual Changes		
1990-2000	7.85	-1.75
Change Rate	1.76%	-0.71%
2000-2010	6.96	-1.52
Change Rate	1.33%	-0.67%
1990-2010	7.40	-1.64
Change Rate	1.66%	-0.67%

Source: United Nations Population Division, 2010.

Assumed that in the next 35 years from 2015 to 2050 the population and the economic in Southeast Asia will grows up such as Cambodia, Lao and Myanmar, so it will effect to the forest land area because the people need more land for other purpose such as agriculture land and habitat thus it will have more emission than the previous time. From 1990 to 2010 the change rate of forest areas were -0.67% so base on the national circumstance, it could not use the baseline emission as the REL/RLs, it assume that the REL/RLs will be more higher than the baseline 1% so the baseline emission were 46,871.6 TgCO_2 while the REL/RLs were 47,340.3 TgCO_2 in the period of 35 years and the annual change was 1,302 TgCO_2 and 1,315 TgCO_2, respectively (Figure 26).

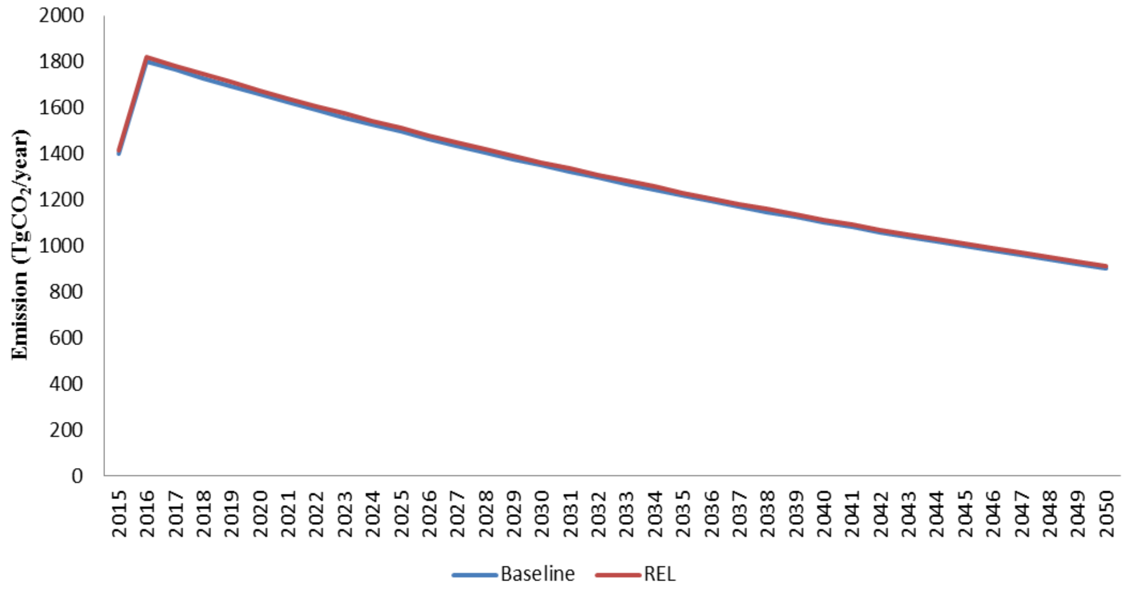

Figure 26 Baseline emission and reference emission level.

4.6 Reductions or Removals and Carbon Revenues

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 10,468.8 $TgCO_2$ or about 290.8 $TgCO_2$ $year^{-1}$. Since total emissions in the absence of project activities (baseline emissions) were 36,972.8 $TgCO_2$, reduced emissions were estimated at 26,504.0 $TgCO_2$ per 35 years or 736.2 $TgCO_2$ per year (Table 17, Figure 27).

Over the same period, carbon emissions due to forest degradation in the absence of project activities (baseline emissions) i.e. using CVL were 9,898.8 $TgCO_2$ and emissions from project implementation (i.e. using RIL) were 6,970.5 $TgCO_2$, reduced emissions from forest degradation were therefore 2,928.3 $TgCO_2$ or 81.3 $TgCO_2$ per year between 2015 and 2050 (Table 17, Figure 28).

Table 17 Baseline emissions, emission reductions, and removals in Southeast Asia

Description	Baseline Emissions	Project Emissions	Reductions	Removals
Deforestation				
35 years	36,972.8	10,468.8	26,504.0	
Annual	1,027.0	290.8	736.2	
Forest Degradation				
35 years	9,898.8	6,970.5	2,928.3	
Annual	275.0	193.6	81.3	
Enhancement through plantation				
35 years				2,745.3
Annual				76.3
Total				
35 years	46,871.6	17,439.3	29,432.3	2,745.3
Annual	1,302.0	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 (Peters and Gonzalez, 2014) and 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 $MgCO_2$ (t CO_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.

In addition to reduced emissions from deforestation and forest degradation, forest plantations in Southeast Asia gained about 2,745.3 $TgCO_2$ or 76.3 $TgCO_2$ annually over the same period (Table 17). Altogether, carbon reductions and removals through implementing forestry project to reducing deforestation and forest degradation in

Southeast Asia resulted in total reductions of 29,432.3 $TgCO_2$ and removals of 2,745.3 $TgCO_2$ for a 35-year project or about 817.6 and 76.3 $TgCO_2$ $year^{-1}$ (Table 17).

With US$7.4 per $MgCO_2$ (Peter *et al.,* 2014), 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.

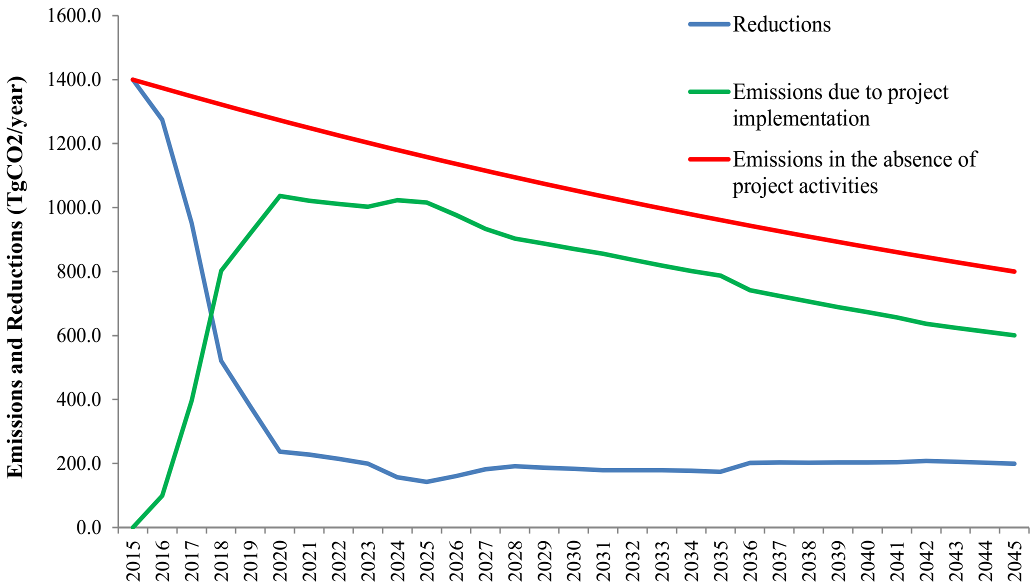

Figure 27 Emission reductions from reducing deforestation in production forest.

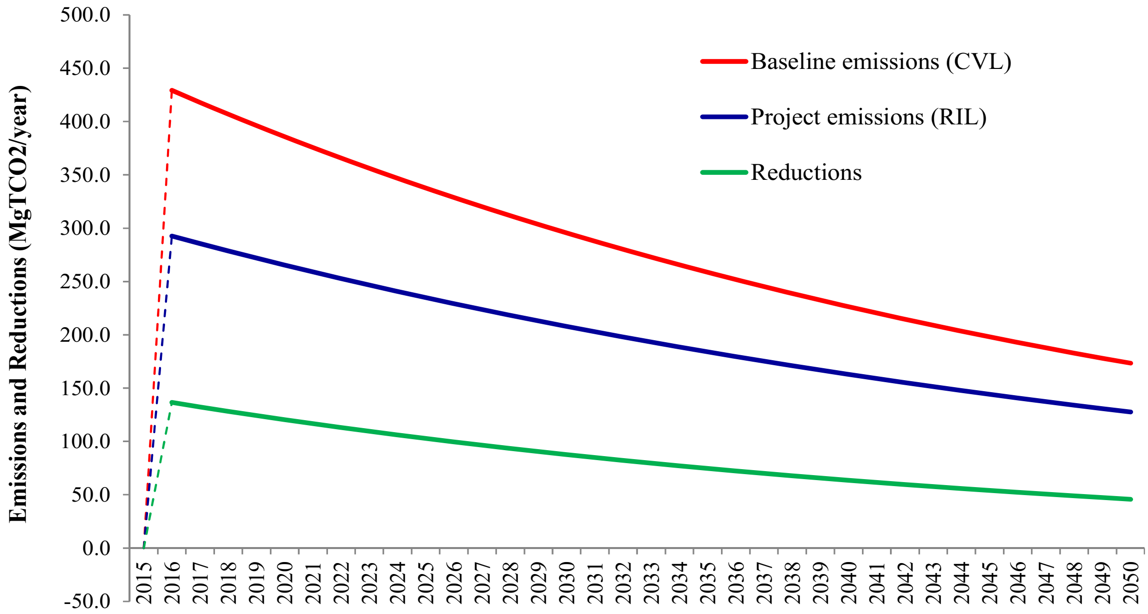

Figure 28 Emission reductions from reducing degradation in production forest.

Chapter 5 CONCLUSIONS

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. 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. REDD+ can contribute to a range of policy goals in addition to climate change mitigation. It can promote biodiversity conservation and secure the provision of ecosystem services including water regulation, timber production, erosion control and the supply of non-timber forest products. Social benefit, such as improved livelihood, clarification of land tenure, and stronger governance may also arise from implementing REDD+.

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 $MgCO_2$.

By implementing the REDD+ project, the huge carbon reduction from deforestation and forest degradation could result in more carbon revenues for the government under REDD+ scheme. Moreover, the government needs to have transparent policy interventions and enforcement so that long-term reductions and revenues can be achieved. Transparency of benefit sharing will ensure that any benefit from carbon projects will also reach local community that are the main actors in either protecting the forests or destroying them. Furthermore, the government should also pay attention on safeguard biodiversity and traditional values of forests for local communities. After implement the REDD+ project, to be sure that the people live near or inside the forest still can collect the non-timber product and they won't ask to leave from the forest or their habitat.

In addition, carbon fluxes in various harvested wood were rarely included in previous studies. We used first order decay function to estimate carbon fluxes in various wood components created by selective logging in production forest in Southeast Asia under CVL and RIL. Apart from producing about 73.3 (±2.7) million m^3 of sawn-wood, selective logging resulted in cumulative carbon fluxes of 3.5 - 5.5, 1.0 - 1.1, 0.4 - 1.3, 3.2 - 3.8, and 0.8 - 0.9 MgC ha^1 in SW, SWW, WPW, BRA, and BLD, respectively after 35 years of logging depending on logging practices (CVL or RIL). Due to fast decay rates, carbon fluxes in SWW, WPW, BRA, and BLD began to emit carbon in about 10 years after harvesting while fluxes in sawn-wood continued to increase despite decrease in area of production forest. By classifying WPW, BRA, and BLD in onsite fluxes and SWW in offsite carbon fluxes, we could estimate total fluxes due to selective logging in production forest in Southeast Asia. Total fluxes under CVL were 129.4, 29.1, and 29.1 TgC at time of logging and 433.0, 69.1, and 378.7 TgC in onsite, offsite, and sawn-wood, respectively after 35 years of logging. This study suggests that switching from conventional logging to reduced impact logging could further increase carbon fluxes in sawn-wood to 608.4 TgC after 35 years of logging while reducing short-lived onsite and offsite wood residues. This study indicates that selective logging can create huge carbon fluxes in various wood components. Depending on carbon accounting methods, these fluxes could be used to offset carbon emissions from deforestation and forest degradation. Including carbon fluxes (credits) in sawn-wood in climate change mitigation options would provide incentives for better utilization of harvested wood products and management of tropical forests. Otherwise, destructive logging and careless use of harvested wood will continue unabated. Providing incentives for carbon offset in harvested wood products will also stimulate the development of wood processing technology, which will eventually result in more sawn-wood production and more carbon storage in harvested wood products, while retaining more carbon in standing forests.

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.

Finally, REDD+ is one of the new mechanism to protect our forest because REDD+ can improve the institutional arrangement by develop the new policy or regulation and strategy such as safeguard guideline, MRV system (Measuring, Reporting and Verification) to monitor the forest. Moreover, the local people also can participate with the REDD+ project such as doing patrol, inventor and other activities. Furthermore, it also can get the revenue from selling the carbon credit. This can improve livelihood of the local people and government. Last but not least, can get both benefits such as protect our forest and also can get the fund for developing the country. So without REDD+ it would be difficult to protect the remaining forest, from time to time, the forests were decrease.

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