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Review paper

Forest reference emission level and carbon sequestration in Cambodia

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ABSTRACT

Adoption of the Paris Agreement suggests the urgent need for developing countries to establish a forest reference emission level (FREL) if they wish to seek financial support to reduce carbon emissions from deforestation and forest degradation. Analysis of past trends of deforestation is important for establishing a FREL, but so far only a handful of studies exist on such analysis at the commune level. We used the available data of forest cover in 2002 and 2006 and forest inventory data to analyze forest cover and carbon stock changes according to seven forest types at commune level in Cambodia. Carbon stocks were estimated in four carbon pools, namely aboveground, belowground, litter and deadwood pools. This analysis formed the basis for determining the FREL at national and provincial levels in Cambodia. We found that carbon emissions due to deforestation were 82.2 $TgCO_2$ yr^{-1}, but carbon sinks (removals) due to increase of forest cover were 72.3 $TgCO_2$ yr^{-1}, representing the net emission loss of 9.9 $TgCO_2$ yr^{-1} between 2002 and 2006. Taking the trend of deforestation between 2002 and 2006 as a baseline, FREL for a 30-year timeframe was estimated for six time intervals. FRELs at national level were estimated to be 26.8 to 69.2 $TgCO_2$ yr^{-1} or up to 36% of the total greenhouse gas emissions in Cambodia. Our study provides a first look at how to set subnational and national FRELs for Cambodia using a retrospective approach. Such a framework could form a useful basis for Cambodia to adopt the national and subnational FRELs, for which effective policies can be developed to address the drivers of deforestation and forest degradation.

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1. Introduction

International efforts have been made to reduce tropical deforestation and forest degradation because of the concern over the threats to livelihoods of forest dependent communities, loss of biodiversity, and climate change and its effects on sustainable development. Accordingly, a number of agreements have been reached. Most notably, the adoption of the REDD+ scheme, which is an initiative referring to Reducing Emissions from Deforestation and Forest Degradation PLUS (+) forest conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries (Christoff, 2008), in the Bali Action Plan at the thirteenth conference of the parties (COP13) to the United Nations Framework Convention on Climate Change (UNFCCC) in 2007, emphasizes that accounting for carbon emissions from deforestation and forest degradation is increasingly important (Margono et al., 2014; Pedroni et al., 2009; Pelletier and Goetz, 2015). In addition, Decision CP.16/1/Add. 1/par. 71 of the UNFCCC requires developing countries to develop four elements if they aim to undertake REDD+ activities for financial compensation (Sandker et al., 2014): (1) a national strategy or action plan; (2) a national forest reference emission level (FREL) and/or forest reference level (FRL); (3) a robust and transparent national forest monitoring system for the monitoring and reporting of the REDD+ activities; and (4) a system for providing information on how the safeguards are addressed or respected. The UNFCCC has defined FREL as the benchmark for carbon emissions against which a country's performance in implementing REDD+ activities can be assessed (Sandker et al., 2014). FREL could be developed using the UNFCCC's guideline provided at the COP17 (Herold et al., 2012). In addition to establishing a national FREL, Decision 12/CP.17 also acknowledges the importance of establishing subnational or provincial FRELs as an interim measure (Herold et al., 2012). The adoption of the Paris Agreement at the COP21 (Brauers and Richter, 2016), along with the submission of the Intended Nationally Determined Contribution (INDC) by parties to the UN convention, especially by developing country parties, suggests the urgent need for the development of FRELs.

In recent years, a number of studies have attempted to estimate carbon emissions from deforestation and forest degradation in the tropics to provide the needed information for establishment of the baseline emissions, against which mitigation measures and performance can be assessed. Based on recent studies, carbon emissions from tropical deforestation are estimated to account for between 8% and 10% (Achard et al., 2014; Baccini et al., 2012; Houghton et al., 2012) to as high as 20%–26% of global carbon emissions (Houghton, 2003; Pan et al., 2011). Despite progress in the study of carbon emissions in the tropics globally, only a handful of studies have attempted to quantify the country-level baseline emissions for the purpose of determining the FRELs. For instance, Romijn et al. (2013) discussed the impacts of different forest definitions on setting up the FRELs in Indonesia. They found that FRELs varied from 484.6 $TgCO_2$ to 753.3 $TgCO_2$. Using national data of forest cover changes and the standard partial equilibrium model, Busch et al. (2009) discussed the impacts of setting up the FRELs on cost per reduction unit under six FREL scenarios for tropical countries. Although previous studies provide useful information on the magnitudes of carbon emissions and the range of possible FRELs in the concerned countries, none of them focused on developing the FRELs for national or subnational level using commune-level data, especially in Cambodia. Such small-scale data are important for understanding forest cover and carbon stock changes and for measuring the implementation performance of the REDD+ activities at small, regional, subnational, and national levels.

Cambodia is a non-Annex I country (i.e., a low-income developing country with no legally binding emission reductions by 2020) to the UNFCCC. Cambodia ratified the UNFCCC in December 1995 and the Kyoto Protocol in August 2002. Cambodia submitted its INDC to the UNFCCC in September 2015, proposing to reduce 3.1 million tCO_{2e}, compared to the 2010 emission level, by 2030 (Uy, 2015a). Apart from introducing policies to reduce emissions from energy and transport sectors, Cambodia has actively participated in reducing carbon emissions from deforestation and forest degradation through the REDD+ scheme. Although Cambodia has made remarkable progress in preparation for the full implementation of the REDD+ activities (Chuop, 2015), FRELs are presumably still under development. Thus it is impossible to know what methods and data are being used and how FRELs are decided in Cambodia. Using limited available data, this paper aims to analyze forest cover and carbon stock changes at the commune level and discuss the timely important issue of FREL development. We hope to stimulate discussions on future carbon emissions in various provinces in Cambodia and how FRELs may be determined in the respective provinces. This study uses 2002 and 2006 forest cover data to analyze forest cover change starting from the commune level in Cambodia. Changes in forest cover and carbon stocks in four carbon pools according to seven forest categories are analyzed to provide a basis for estimating carbon emission and removal (carbon sequestration) in Cambodia. We also discussed the causes of deforestation, carbon emissions, and policy implications for the establishment of national and subnational FRELs in Cambodia.

2. Study methods and materials

Although remote sensing is commonly used to estimate carbon emissions from tropical forests at various scales (Asner et al., 2011; Zolkos et al., 2013; Hansen et al., 2013), data were not available for the current study. Forest cover spatial data produced by Cambodia's Forestry Administration (FA hereafter, FA is a government agency responsible for forest management in Cambodia) (FA, 2008; Pak et al., 2010) were used to estimate the baseline emissions and the FRELs.

2.1. Introduction to forest cover change and REDD+ in Cambodia

Forests have been the main source for timber harvesting and revenues in Cambodia (Kim et al., 2006; Singh, 2014) in addition to providing habitats for 2308 species, 123 species, 545 species, 63 species, 88 species, and 874 species of known vascular plants, mammals, birds, amphibians, reptiles, and fishes found in Cambodia. However, clearing of natural forests for industrial plantations (Neef et al., 2013; Davis et al., 2015) has posed great concerns over the loss of natural forests and their ecosystems whose healthy functions are important for sustaining Cambodia's agriculture-dependent economic development. Due to deforestation and forest degradation, 31 species, 37 species, 24 species, 3 species, 13 species, and 28 species are classified as threatened (Kapos et al., 2010).

Cambodia has experienced a rapid decline of forest cover over the last 10 years. Official data show that forest cover in Cambodia was 10.4 million ha in 2010, declining from 11.1 million ha in 2002 (Leng, 2011), representing an annual loss of 92,562.7 ha (0.8%) between 2002 and 2010. Other studies estimated forest cover at 10.2 million ha in 2010 and 9.6 million ha in 2015 (FAO, 2015). Deforestation and forest degradation were responsible for 50.3 $TgCO_2$ per year of carbon emissions between 1993 and 2003 in Cambodia (Sasaki, 2006). As part of its efforts to reduce deforestation and forest degradation, Cambodia submitted its Readiness Preparation Proposal or R-PP to the Forest Carbon Partnership Facility (FCPF) of the World Bank in late 2008, which was accepted in early 2009. In October 2009, Cambodia joined the UN-REDD programme as a partner country. Subsequently, Cambodia has received a total grant of US$3.8 million from the FCPF, in addition to about $2.3 million from the UN-REDD program, for developing and enhancing the government's capacity to address deforestation and forest degradation, as well as for measuring, reporting and verifying emission reductions in Cambodia. Until recently, one REDD+ project in Oddar Meanchey Province was verified by the Verified Carbon Standard (VCS) and the Climate, Community & Biodiversity Alliance (CCBA) in 2013. Another REDD+ project in Mondulkiri was validated by CCBA in November 2015, and three more REDD+ projects are under different stages of preparation (Bradley and Shoch, 2013).

2.2. Data availability and land use classification

Data on forest cover at the commune level in Cambodia were available only for 2002 and 2006. We used these data to determine the trend of past change of forest cover. Methods for the analysis of forest covers in 2002 and 2006 were reported in FA (2008) and Pak et al. (2010). According to Pak et al. (2010), FA employed the method of visual analysis digitization using ArcView software, ERDAS 9.1 with a minimum mapping unit of 25 ha in addition to using the satellite band SPOT-4 432. To ensure accuracy, FA sent three teams to groundtruth 102 points throughout the country. In very remote areas, Quickbird images were used in lieu of site visits. Assessment of forest cover change between 2002 and 2006 was done from commune to national levels. Cambodia defines administrative boundaries by village, commune, district, and provincial boundaries. Village boundaries are not clearly defined as villages or even communes are often merged or newly created as directed by the government.

The FA classified forest cover in 2002 and 2006 into seven forest land-use categories, namely evergreen, semi-evergreen, deciduous, other forests, bamboo, dry woody shrubland, and evergreen woody shrubland. Fig. 1 shows forest cover according to seven forest land use categories, non-forest land and surface water. Evergreen forest is a category containing multi-story forests, where more than 80% of tree species keep their leaves during the entire year. This category includes lowland tropical rain forests, hill evergreen forests and dry evergreen forests. The semi-evergreen forest category incorporates a variable percentage of evergreen and deciduous trees. It includes mixed evergreen and mosaic forests. The deciduous forest category contains forests where more than 80% of tree species shed their leaves during the dry season spanning from November to April. It consists of dry mixed deciduous forests and dry dipterocarp forests. The other forests category contains different types of forests, including forest re-growth, inundated forest re-growth, inundated forests, mangrove forests, forest plantations, and inundated mosaic forests. Forest regrowth is a naturally regenerated forest found mainly in the remote abandoned areas. Inundated forests are found along the freshwater ways such as long the Tonle Sap great lake, the Mekong River and its tributaries. Mangrove forests are found along the coastal areas. Forest plantation includes rubber, pine, teak, and other forms of tree crops. Although mangrove and inundated forests may contain higher carbon stocks in the soil (Donato et al., 2011; Kurnianto et al., 2015), the areas of the two forest types in this category are not available. The evergreen woody shrubland category is a mixture of shrubs, grass and trees, but tree cover remains between 10% and 20%. The dry wood

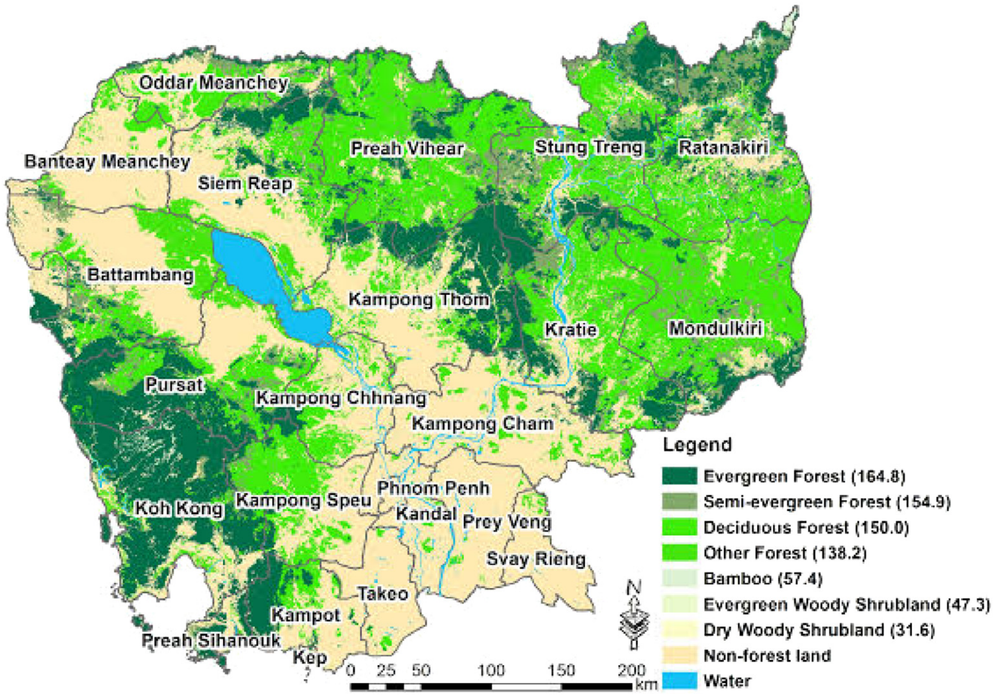

Fig. 1. Forest cover map by province according to nine land use categories. Number in the parenthesis of the Legend is the initial values of carbon stocks (aboveground, belowground, litter, and deadwood) used in our study. Cambodia may use different or the same values for official reporting purposes.

shrubland category is similar to that of wood and shrub evergreen but it is found in dry plains or on plateaus, as well as on dry and sun exposed slopes. The bamboo category is bamboo forest usually found in the southeastern part of Cambodia. The non-forest land category contains grasslands, mosaics of cropping, agriculture land, barren lands, rock outcrops, urban areas, water, wetlands, and other areas that were covered with clouds in the satellite imagery, and are therefore not considered in this study.

2.3. Communes, districts, and provinces in Cambodia

In 2006, Cambodia had 23 provinces and one capital. Each province is composed of districts; each district consists of communes; and each commune consists of villages. There were 168 districts divided into 1618 communes in 2006. Since Phnom Penh (consisting of seven districts) contained no forests, it was not included in our study. Due to civil wars and administrative reforms, many villages in Cambodia still do not have fixed administrative boundaries, making it impossible to find consistent data of forest cover by villages even in the forest cover data 2002 and 2006. In our study, forest areas by category at the commune level were summed to calculate forest areas at the district level. Carbon stocks by forest category at district, provincial, and national levels were then calculated for both years.

2.4. Carbon pools

The Intergovernmental Panel on Climate Change (IPCC, 2006) recommends five carbon pools for greenhouse gas inventories in the forest sector. Due to lack of information, only four of the five carbon pools were considered in this study: aboveground biomass, belowground biomass, deadwood, and litter. Based on 12-year data in the primary forests and deforested lands in the lowland tropical rain forest in Southeast Asia, a recent study found no change of soil carbon in both land types (Yonekura et al., 2010). Due to data limitations and for simplicity, carbon in soil is not included.

Total vegetation carbon stocks (CS) in 2002 and 2006 were estimated by summing the four carbon stocks by land use categories as follows:

$$\mathrm{CS} = \sum_{k=1}^{23}\sum_{i=1}^{161}\sum_{e=1}^{7} \mathrm{FA}_{e,i,k} \times \mathrm{CS}_e \quad (1)$$

where, $\mathrm{FA}_{e,i,k}$ is the area of forest category e in district i, and province k (ha) (Phnom Penh and its seven districts were excluded from our study because they contained no forest cover); CS_e is the carbon stocks in forest category e (MgC ha^{-1}). Again the carbon stocks include aboveground biomass, belowground biomass, deadwood and litter.

Annual carbon emissions (CE) between 2002 and 2006 are obtained using the stock-change method (method 2) of the IPCC Guidelines (IPCC, 2006):

$$CE = \frac{[CS_{2006} - CS_{2002}]}{2006 - 2002} \times \frac{44}{12} \quad (2)$$

where, CS_{2002} and CS_{2006} are total carbon stocks in 2002 and 2006, respectively, obtained through Eq. (1) ($TgCO_2$ and 1 $TgCO_2$ is one million tCO_2); the ratio 44/12 is the molecular weight ratio of carbon dioxide to carbon.

2.5. Forest reference emission level (FREL)

FREL is an important component of the REDD+ scheme. Developing countries must develop a FREL for their respective countries before they can obtain financial compensation, which is based on reduced emissions (reductions) or increased carbon stocks (carbon sequestration or removals). Developing countries need to lower their emissions from deforestation and forest degradation below the FREL to qualify for financial compensation. FRELs are the CO_2 emissions from deforestation and forest degradation in the absence of project activities undertaken to reduce deforestation and forest degradation. FRELs can be developed based on the past trends of deforestation, a "retrospective approach", or future trends a "prospective approach" (Huettner et al., 2009). The former can be done using available data and extrapolating into the future, but the latter is more dynamic, taking into consideration the national circumstances of the countries in question. For this study, a retrospective approach is used.

In this study, FREL was calculated at provincial level, which can be considered as a subnational FREL, while the sum of FRELs at provincial level is the national FREL. To avoid confusion with the official FRELs that only the government in developing countries can decide, we used the terms total FREL and subtotal FREL instead of national FREL and subnational/provincial FREL, respectively. The national and subnational FRELs will be determined and decided by developing countries, where different datasets, methods and/or approaches may be used.

To estimate FREL, removals, and FRL, the annual increase or decrease of forest area by category must be estimated. Using the retrospective approach (past trend) as a baseline, the following equations are used to derive forest area changes:

$$FAD_{e,k}(t) = FA_{e,k}(t_0) \times e^{a_{e,k} \times t} \quad (3)$$

$$FAI_{e,k}(t) = FA_{e,k}(t_0) \times t^{a_{e,k}} \quad (4)$$

where, $FAD_{e,k}(t)$ is the area of forest category e in decreasing trend (ha); $FAI_{e,k}(t)$ is the area of forest category e in increasing trend (ha); $FA_{e,k}(t_0)$ is the initial area of forest category e i.e. area in 2002 (ha); $a_{e,k}$ is the change rate of area of forest category e. If $a < 0$ (decrease), Eq. (3) is used, Eq. (4) otherwise. Eq. (4) is used with the assumption that increase of area of forest category e will slow down when land availability for such increase is reduced. If $a = 0$, there is no change in forest area; t it the time step (1 year). Timeframe of the modeling period is 30 years. This 30-year timeframe is consistent with a common duration of REDD+ projects currently adopted by VCS (www.vcsprojectdatabase.org). t_0 is for the year 2002.

The Gain-Loss Method (IPCC, 2006) was used to obtain carbon emissions by forest category:

$$CE_{e,k}(t) = \left[FAD_{e,k}(t_2) - FAD_{e,k}(t_1)\right] \times CS_e \times \frac{44}{12} \quad (5)$$

$$CI_{e,k}(t) = \left[FAI_{e,k}(t_2) - FAI_{e,k}(t_1)\right] \times CSI_e(t) \times \frac{44}{12} \quad (6)$$

where, $CE_{e,k}(t)$ is the carbon emissions from deforestation of forest category e ($MgCO_2$ $year^{-1}$); $CI_{e,k}$ (t) is the carbon sequestration (it is sometimes called removals) due to increase in area of forest category e ($MgCO_2$ $year^{-1}$); CS_e is the carbon stocks of forest category e (MgC ha^{-1}). According to methodology used by the VCS for REDD+ projects; CS_e can be used as constant average value for forest with decreasing trend over time (VCS, 2009; Estrada, 2011). It is therefore assumed to be constant for this study over the modeling period; $CSI_{e,k}(t)$ is the carbon stocks in increasing trend due to natural regrowth or plantations (MgC ha^{-1}). Forest with increasing trend is usually protected (Soares-Filho et al., 2010), abandoned (Poorter et al., 2016), or planted forests (Pan et al., 2011). Therefore, carbon stocks in forest with increasing trend in this study are assumed to following logistic equation:

$$CSI_e(t) = \frac{CSI_{MAXe} \times CSI_e(t_0) \times e^{r_e \times t}}{CSI_{MAXe} + CSI_e(t_0) \times (e^{r_e \times t} - 1)} \quad (7)$$

where, $CSI_e(t_0)$ is the initial carbon stocks of forest category e having increase in area (MgC ha^{-1}); $CSI_{MAXe}(t)$ is the maximum carbon stocks of forest category e having increase in area (MgC ha^{-1}); r_e is the growth rate of forest category e with increasing trend.

Subsequently, the forest reference emission level for each province can be estimated by

$$FREL_k(t) = \frac{\sum_{e=1}^{7} CE_{e,k}(t)}{1000\,000} \quad (8)$$

where, $FREL_k(t)$ is the forest reference emission level in the province k at time t ($TgCO_2\ yr^{-1}$), $CE_{e,k}(t)$ is provided in Eq. (5).

And the Total FREL for Cambodia is therefore

$$FREL_{CAMBODIA}(t) = \sum_{k=1}^{24} FREL_k(t) \tag{9}$$

where, $FREL_{CAMBODIA}(t)$ is the total FREL for the whole country at time t ($TgCO_2\ yr^{-1}$).

Carbon gained due to increase in forest area or carbon sequestration in provincial level are derived by

$$RM_k(t) = \frac{\sum_{e=1}^{7} CI_{e,k}(t)}{1000\,000} \tag{10}$$

where, $RM_k(t)$ is the carbon sequestration (removals) in the province k at time t ($TgCO_2\ yr^{-1}$), $CI_{e,k}(t)$ is provided in Eq. (6).

Total carbon sequestration (or removals) for Cambodia are therefore

$$RM_{CAMBODIA}(t) = \sum_{k=1}^{24} RM_k(t) \tag{11}$$

where, $RM_{CAMBODIA}(t)$ is the total Removals (sequestration) for the whole country at time t ($TgCO_2\ yr^{-1}$).

The forest reference level (FRL_k) for each province can be obtained by $FRL_k = FREL_k + RM_k$. Estimates of FRL for the whole of Cambodia can be determined from $FREL_{CAMBODIA} + RM_{CAMBODIA}$. FRL provides an indication of the magnitude of net carbon emissions, where financial incentives are provided for carbon credits from a reduction in emissions below the FREL or from carbon sequestration (i.e. enhancement of forest carbon stocks).

For estimating carbon emissions from deforestation, initial carbon stocks for each forest category shown in Table 1 and Fig. 1 are assumed to be constant over the 30-year period of the project cycle. This assumption is based on the fact that the natural increase in biomass through growth is equally removed for local use either for housing or cooking energy. This assumption is consistent with REDD+ methodology of the VCS (VCS, 2009; Estrada, 2011). In contrast, sequestration due to an increase of forest area is estimated differently in each case because regenerated forests or plantations have lower initial carbon stocks, but higher biomass growth rates than natural forests (Aryal et al., 2014). Eq. (7) was used to estimate the increment of carbon stocks for any forest category of increasing area. As forest biomass for young regrowth/regenerated forests (including plantations) is usually small (Poorter et al., 2016), we assume that the initial carbon stocks are 10% of the mean carbon stocks in respective forest categories. Mean annual increments (MAI) in tropical countries range from 0.1 to 0.9 MgC $ha^{-1}yr^{-1}$ in Panama (Meyer et al., 2013), 1.3 $ha^{-1}\ yr^{-1}$ in Amazonia forests (Mazzei et al., 2010), 1.6 MgC $ha^{-1}\ yr^{-1}$ in Northern Borneo (Berry et al., 2010), and 2.3 $MgCha^{-1}\ yr^{-1}$ in Kampong Thom province of Cambodia (Top et al., 2004). A recent study using about 1500 sample plots in 45 forest sites of secondary forests in the Neotropics found a MAI of 3.0 Mg C $ha^{-1}\ yr^{-1}$ (Poorter et al., 2016). For this study, MAIs for all forest categories (forests with increasing trend) were assumed to be 1.5 MgC $ha^{-1}\ yr^{-1}$. The $r_{e,k}$ was obtained by dividing MAI by the initial carbon stock values of respective forests showing an increasing trend. Maximum carbon stocks of increased forests are assumed to reach same level of mean carbon stocks prior to the commencement of the project.

3. Results

3.1. Forest cover and carbon stocks changes

An analysis of forest cover change by commune according to seven forest categories showed that forest cover in Cambodia was 11.4 million ha, occupying about 62.7% of the country's total land area in 2002. Forest cover declined to 10.9 million ha in 2006. The annual rate of loss was 132,038.6 ha or about 1.2% between 2002 and 2006 (Table 2). This rate of change is in agreement with that estimated (1.2%) by the FAO Forest Resource Assessment project for the period 2000–2015 (FAO, 2015). Annual loss rate (1.2%) in Cambodia is similar to forest cover changes during the 1990s and 2000s in Indonesia and Malaysia (Miettinen et al., 2011; Stibig et al., 2014).

Among the three main forest types in Cambodia, semi-evergreen forest area decreased 1.6% per year (23,114.3 ha yr^{-1}); deciduous forest, 0.7% per year (35,258.7 ha); and evergreen forest, 0.3% per year (12,903.6 ha) between 2002 and 2006. Semi-evergreen forest contains several commercial timber species. Because it is located close to the populated area, this forest type is subject to both logging and land clearing. Although deciduous forest contains less commercial timber species, this forest can be easily accessible by local people and land migrants. In addition, land economy concessions are commonly found in deciduous forests. Therefore deciduous forests are subject to timber extraction for charcoal making, land clearing, and burning for industrial crop plantations (Forest Trends, 2015). Over the same period, the other forest category experienced significant loss at 2.2% or about 23,489 ha per year despite the increase in area of rubber plantations (Hang, 2009). Although detailed data are not available, specific decline or increase by forest types in this forest category is unknown.

Table 1
Initial carbon stocks for forest land use category by pools in 2002.

Land use categories (j)	Carbon pools (MgC ha^{-1})				Total CS_j	
	Above ground	Below ground	Dead wood	Litters	(MgC ha^{-1})	($MgCO_2$ ha^{-1})
Evergreen forest	96.2[a]	27.8	27.2	13.6	164.8	604.3
Semi-evergreen	98.1[b]	29.8	14.5	12.4	154.9	567.9
Deciduous forest	95.1[c]	28.9	14.1	12.0	150.0	550.2
Bamboo	36.4[d]	11.1	5.4	4.6	57.4	210.4
Other forest	87.6[e]	26.6	13.0	11.0	138.2	506.9
Evergreen woody shrubland	30.0[f]	9.1	4.4	3.8	47.3	173.6
Dry woody shrubland	20.0[g]	6.1	3.0	2.5	31.6	115.7

Note for Table 1.
[a] Based on the mean stand volume of 194.0 m^3 ha^{-1} from 162 sample plots (20 m × 60 m) in evergreen forests in Kampong Thom (Kim Phat et al., 2000) and from 120 sample plots (20 m × 60 m) in evergreen forests in Preah Vihear Provinces (Kao and Iida, 2006) in Cambodia. Carbon stocks (92.2) were derived by 194.0 ∗ 0.57 (wood density) ∗ 1.74 (biomass expansion factor) ∗ 0.5 (carbon content) using formula of Brown (1997).
[b] Based on Chheng et al. (2016) who estimated the average carbon stocks of 98.1 ± 3.6 MgC ha^{-1} from 179 sample plots (25 m × 40 m) in semi-evergreen forests in Kratie, Rattanakiri, and Stung Treng provinces in Cambodia.
[c] Based on average stand volume of 191.7 m^3 ha^{-1} from six sample plots in deciduous forest in Mondulkiri province in Cambodia (Khun et al., 2012). Carbon stocks, 95.1 = 191.7 ∗ 0.57 ∗ 1.74 ∗ 0.5. A recent report based on data from 41 clusters (3 plots per cluster) in Seima protection forests estimated the average carbon stocks for open forest (comprising of mixed deciduous forest, deciduous dipterocarp forest and open woodland) to be 150.7 MgC ha^{-1} (±15.6% CI90) (FA, 2013) or only 0.7 MgC higher than our estimate in Table 1.
[d] We used average biomass of bamboo forest in Bangladesh for this study (Altrell, 2007) because no data is available for bamboo forest in Cambodia.
[e] Based on (Sasaki, 2006).
[f] Based on mean biomass of shrubland in the Brazilian Savanna Woodland (de Miranda et al., 2014) but this biomass is very similar to average stocks of semi-natural woody scrubland located in Seima protection forest in eastern Cambodia (FA, 2013).
[g] Dry woody shrubland is subject to frequent fires. Its carbon stocks were assumed to be 10 MgC smaller than that of evergreen woody shrubland carbon stocks in belowground, dead wood, and litters in Table 1 were calculated as proportion to aboveground biomass based on (Kiyono et al., 2010) for litters and deadwood and (Khun et al., 2012) for belowground biomass.

Table 2
Changes in forest cover and carbon stocks by forest category (2002–2006).

Forest category	Total area		Change		
	2002	2006	2002–2006	yr^{-1}	% yr^{-1}
Evergreen forest					
Area (ha)	3,720,475.3	3,668,860.7	−51,614.6	−12,903.6	−0.3%
Carbon stocks (TgC)	613.1	604.6	−8.5	−2.1	−0.3%
Semi-evergreen forest					
Area (ha)	1,455,080.1	1,362,622.7	−92,457.4	−23,114.3	−1.6%
Carbon stocks (TgC)	225.4	211.1	−14.3	−3.6	−1.6%
Deciduous forest					
Area (ha)	4,833,118.7	4,692,084.1	−141,034.6	−35,258.7	−0.73%
Carbon stocks (TgC)	725.0	703.8	−21.2	−5.3	−0.7%
Other forest					
Area (ha)	1,065,679.6	971,313.7	−94,366.0	−23,591.5	−2.2%
Carbon stocks (TgC)	147.3	134.2	−13.0	−3.3	−2.2%
Bamboo					
Area (ha)	28,950.5	35,799.9	6849.4	1712.4	5.9%
Carbon stocks (TgC)	1.7	2.1	0.4	0.1	5.9%
Dry woody shrubland					
Area (ha)	138,931.6	36,975.2	−101,956.4	−25,489.1	−18.3%
Carbon stocks (TgC)	4.4	1.2	−3.2	−0.8	−18.3%
Evergreen woody shrubland					
Area (ha)	150,014.6	96,439.9	−53,574.7	−13,393.7	−8.9%
Carbon stocks (TgC)	7.1	4.6	−2.5	−0.6	−8.9%
All forests					
Area (ha)	11,392,250.4	10,864,096.1	−528,154.3	−132,038.6	−1.2%
Carbon stocks (TgC)	1723.9	1661.5	−62.4	−15.6	−0.9%
Percentage of total land area	62.7%	59.8%			

Note: Data of forest cover in 2002 and 2006 were obtained from Forestry Administration in Cambodia.

The dry woody shrubland and evergreen woody shrubland categories dramatically lost 18.3% per year and 8.9% per year, respectively, over the same period between 2002 and 2006. These last two categories are commonly found in accessible areas. They are also subject to annual clearing and burning for crop cultivation and claims of ownership rights. Other forest types, especially flooded forests along the Mekong and Tonle Sap Rivers, are commonly cleared for rice and crop plantations (Evans et al., 2004).

Rainfall is an important climatic variable affecting plant distributions (Borchert, 1998). Our analysis found that about 22.2% and 30.6% of evergreen forest and evergreen woody shrubland, respectively, were found in Koh Kong Province, where mean annual rainfall exceeds 2000 mm (ADB, 2014). Many other provinces have annual rainfalls of less than 2000 mm

Table 3
Forest cover change by province (2002–2006).

Province	Forest area (ha)		Area change (ha)		
	2002	2006	2002–2006	Annual	Rate
Oddar Meanchey	521,411.2	460,173.4	−61,237.8	−15,309.5	−2.9%
Banteay Meanchey	160,220.0	103,112.6	−57,107.4	−14,276.9	−8.9%
Battambang	593,027.9	537,388.8	−55,639.1	−13,909.8	−2.3%
Siem Reap	541,449.0	485,841.8	−55,607.2	−13,901.8	−2.6%
Pailin	87,394.8	51,403.3	−35,991.5	−8997.9	−10.3%
Ratanakiri	1,002,551.5	967,892.8	−34,658.7	−8664.7	−0.9%
Kratie	972,377.6	940,827.5	−31,550.1	−7887.5	−0.8%
Kampong Cham	192,198.1	165,377.4	−26,820.7	−6705.2	−3.5%
Preah Vihear	1,337,064.3	1,310,675.7	−26,388.6	−6597.2	−0.5%
Stung Treng	1,084,352.8	1,059,570.9	−24,781.9	−6195.5	−0.6%
Koh Kong	1,021,633.4	1,000,916.5	−20,716.9	−5179.2	−0.5%
Mondulkiri	1,266,408.4	1,249,653.0	−16,755.4	−4188.8	−0.3%
Kampong Spueu	427,668.9	412,148.0	−15,520.9	−3880.2	−0.9%
Takeo	30,028.8	15,607.2	−14,421.6	−3605.4	−12.0%
Kandal	31,467.4	18,854.0	−12,613.4	−3153.4	−10.0%
Kampong Thom	656,059.4	644,433.3	−11,626.1	−2906.5	−0.4%
Kampot	237,723.4	228,368.7	−9354.8	−2338.7	−1.0%
Pursat	899,202.8	891,559.5	−7643.4	−1910.8	−0.2%
Kampong Chhnang	216,349.9	211,052.9	−5297.0	−1324.2	−0.6%
Preah Sihanuk	86,316.0	84,320.1	−1996.0	−499.0	−0.6%
Keb	4765.8	3629.1	−1136.7	−284.2	−6.0%
Svay Rieng	12,921.2	11,980.8	−940.4	−235.1	−1.8%
Prey Veng	9656.1	9307.3	−348.8	−87.2	−0.9%
Total	11,392,248.8	10,864,094.6	−528,154.3	−132,038.6	
Annual change rate				−1.2%	

(ADB, 2014). Semi-evergreen forest was found in Stung Treng Province, accounting for 19.6% of the total area of semi-evergreen forest, while deciduous forest was mainly found (19.2%) in Preah Vihear Province. About 16.9% of other forests (mainly inundated forests along the Tonle Sap great lake and rivers) were found in Kampong Thom. About 26.4% of bamboo forests occurred in Mondulkiri Province and 20.4% of dry woody shrublands were found in Ratanakiri Province.

Oddar Meanchey, Banteay Meanchey, Battambang, and Siem Reap Provinces had the highest forest cover losses: 15,309.5 ha, 14,276.9 ha, 13,909.8 ha, and 13,901.8 ha, respectively. Altogether, deforestation in these four provinces accounted for 43.5% of the total deforestation in Cambodia between 2002 and 2006 (Table 3). Land migrants were largely responsible for deforestation in these provinces (Dulioust, 2011). Between 2002 and 2008, provinces with less forest cover, such as Takeo, Prey Veng, and Kandal, had an outflow of people seeking lands in the provinces of Oddar Meanchey, Banteay Meanchey, and Battambang (Dulioust, 2011), which were previously under the control of Khmer Rouge guerillas, whose movement ended in 1998 after Pol Pot (its leader) died. In Pailin alone, migrants from other parts of Cambodia sharply elevated the population by 28% between 2002 and 2008. About 74% of the 70,486 people in this province were migrants whose daily subsistence came from logging, mining, and land clearing (Dulioust, 2011). A rapid increase of tourists in Siem Reap Province, location of the world heritage Angkor Archaeological Park, resulted in inflow of migrants seeking better employment from the boom of the tourist industry and construction of hotels to accommodate the increasing tourists (Gaughan et al., 2009).

Generally, clearing forest under the umbrella of economic land concession (ELC) is the main driver of deforestation and forest degradation in Cambodia (Davis et al., 2015; Dhiaulhaq et al., 2014; Poffenberger, 2009). Other drivers of deforestation include illegal logging, agricultural expansion, and growing population (Michinaka et al., 2015; Poffenberger, 2009).

In 2002, total carbon stocks in forests were estimated to be 1723.9 TgC (1 TgC = one million tonne C), of which aboveground, belowground, litter, and deadwood pools account for 61.6%, 18.4%, 11.9%, and 8.1%, respectively of the total carbon pools. Total carbon stocks declined to 1661.5 TgC in 2006. Carbon loss due to deforestation was estimated at 82.2 $TgCO_2$ annually between 2002 and 2006. Over the same period, annual carbon gains were −72.3 $TgCO_2$ (the negative sign refers to carbon sequestration or removals). Specifically, carbon gains due to increase of evergreen forest and bamboo exceeded carbon loss from deforestation, resulting in carbon gains of −20.1 $TgCO_2$ and −0.4 $TgCO_2$, respectively (Table 4). Because carbon loss from the decline of deciduous forest was partially compensated by an increase of the same forest types, the loss of semi-evergreen and other forests was responsible for annual carbon emissions of 10.9 $TgCO_2$ and 10.7 $TgCO_2$, respectively, between 2002 and 2006. Over the same period for the whole of Cambodia, forest cover change was responsible for carbon emissions of about 9.9 $TgCO_2$ yr^{-1} (Table 4). Nevertheless, the amount of these overall emissions varies depending on the approach used to calculate them. If we derived the overall emissions in Cambodia by simply multiplying annual forest loss with carbon density, the overall emissions are an estimated 57.2 $MgCO_2$ yr^{-1} between 2002 and 2006. The magnitude of overestimation demonstrates why any estimation of country-level emissions should be based on detailed district or commune-level data. Separate calculations of both carbon emissions and sequestration should be performed to avoid overestimation of carbon emissions in any country.

Table 4
Annual carbon emissions or sinks due to forest cover changes (2002–2006).

Category	Area change (ha yr^{-1})	Carbon pools ($TgCO_2 yr^{-1}$)				
		Above	Below	Litters	Deadwood	Total
Increase in forest area and carbon removals						
Evergreen	24,347.4	−24.9	−7.2	−7.0	−3.5	−42.6
Semi-evergreen	1949.7	−2.1	−0.6	−0.3	−0.3	−3.4
Deciduous	3384.1	−11.2	−3.4	−1.6	−1.4	−17.6
Other forest	11,421.4	−4.5	−1.4	−0.7	−0.6	−7.1
Wood shrub evergreen	4649.9	−0.5	−0.2	−0.1	−0.1	−0.8
Bamboo	3703.6	−0.5	−0.1	−0.1	−0.1	−0.8
Total	49,456.0	−43.7	−12.9	−9.8	−6.0	−72.3
Decrease in forest area and carbon emissions						
Evergreen	−37,251.0	13.1	3.8	3.7	1.9	22.5
Semi-evergreen	−25,064.0	9.0	2.7	1.3	1.1	14.2
Deciduous	−38,642.8	13.5	4.1	0.2	1.7	21.2
Other forest	−35,012.9	11.3	3.4	1.7	1.4	17.7
Wood shrub evergreen	−18,043.5	2.0	0.6	0.3	0.2	3.1
Wood shrub dry	−25,489.1	1.9	0.6	0.3	0.2	2.9
Bamboo	−1991.2	0.3	0.1	0.0	0.0	0.4
Total	−181,494.5	51.0	15.3	9.3	6.6	82.2
Overall carbon emissions or removals						
Evergreen	−12,903.6	−11.7	−3.4	−3.3	−1.7	−20.1
Semi-evergreen	−23,114.3	6.9	2.1	1.0	0.9	10.9
Deciduous	−35,258.7	2.3	0.7	0.3	0.3	3.6
Other forest	−23,591.5	6.8	2.1	1.0	0.9	10.7
Wood shrub evergreen	−13,393.7	1.5	0.4	0.2	0.2	2.3
Wood shrub dry	−25,489.1	1.9	0.6	0.3	0.2	2.9
Bamboo	1712.4	−0.2	−0.1	0.0	0.0	−0.4
Total	−132,038.6	7.3	2.4	−0.5	0.7	10.0

Note: "+" (plus) refer to carbon emissions while "−" to carbon sequestration (carbon uptake by increase of land area).

3.2. FREL, removals, and FRL

The Forest Reference Emission Level (FREL) is an important benchmark of emissions, against which developing countries need to reduce carbon emissions. The more they reduce emissions, the more financial support they would receive, because REDD+ schemes base payments on performance (Norman and Nakhooda, 2014). If the FREL is set high, developing countries would receive more financial incentives when actual emissions are greatly reduced. On the other hand, if FREL is set low, developing countries may risk not being able to reduce emissions below the FREL.

Until recently, there was no global agreement upon the approach for deciding FRELs. Brazil, the first country that submitted a FREL to the UNFCCC in 2014, used a historical average of gross emissions from deforestation over a 10-year period between 1996 and 2005 in the calculation. Thereafter, baseline deforestation was recalculated every five years. For example, the baseline for 2011–2015, would be calculated as the mean of the annual gross deforestation from 2001 to 2010; the baseline for 2016–2020, as the mean of the annual gross deforestation from 2006 to 2015 (Sandker et al. 2014). In our study, we recalculated the baseline emissions every five years (i.e. between 0–5, 6–10, 11–15, 16–20, 21–25, and 26–30) and took the average as the FRELs for the respective period. Over a 30-year period, total FRELs were estimated to be 69.2, 51.9, 42.1, 35.4, 30.5, and 26.8 $TgCO_2$ yr^{-1} for each respective interval above (Table 5).

Cambodia submitted its Intended Nationally Determined Contributions (INDC) to the UNFCCC in 2015. The INDC proposed to reduce carbon emissions by 27%, relative to the emission level in 2005. This reduction is equivalent to 3.1 $TgCO_2$ by 2030 (Uy, 2015b). This reduction target is only about 4.5%–11.6% of the FRELs. Seven provinces, namely Battambang, Oddar Meanchey, Preah Vihear, Siem Reap, Banteay Meanchey, Kampong Thom, and Rotanak Kiri Provinces, have higher FRELs (Table 5) accounting for about 65.0%–68.7% of the total FREL over a period of 30 years (Fig. 2). As clearing forests by land migrants and clearing under the form of ELC are the main drivers of deforestation in these provinces (Dulioust, 2011; Gaughan et al., 2009; Davis et al., 2015; Dhiaulhaq et al., 2014; Poffenberger, 2009), controlling illegal migrants and requiring LEC holders to reforest before clearing could result in significant reductions of carbon emissions.

Fig. 3 shows the percentage of subtotal FRELs by provinces in Cambodia according to the six periods listed above. Although Battambang had a higher share of FRELs in the first five years (0–5), its share declines as forest area declines. In contrast, shares of FRELs in Preah Vihear, Rotanak Kiri, Siem Reap and Oddar Meanchey increase because these four provinces maintain a large area of forest cover (Fig. 1).

In addition to reducing carbon emissions, the REDD+ scheme also provides financial incentives for increasing carbon stocks in the forests, which is referred to as carbon sequestration or removals. Although forest area generally declines, some forest categories were predicted to increase in the next 30 years. As a result, carbon sequestration (or loss) can be achieved in Cambodia, depending on the degree to which these forests are harvested, cleared or protected. In the case of forest plantations in the tropics, a system of 10-year cutting and replanting rotation is commonly practiced (FAO, 2000).

Table 5
Total and total FRELs in Cambodia based on 2002 and 2006 forest cover statistics.

Provincial names	Subtotal FRELs (in 1000 $MgCO_2$ yr^{-1})					
	0–5	6–10	11–15	16–20	21–25	26–30
(1) Battambang	10,852.4	7677.1	5738.2	4362.0	3366.9	2636.5
(2) Oddar Meanchey	6333.9	5032.6	4247.3	3651.7	3176.1	2785.8
(3) Preah Vihear	6229.6	5411.9	4925.2	4558.7	4261.4	4007.8
(4) Siem Reap	5805.7	4981.6	4393.3	3895.9	3466.3	3091.6
(5) Banteay Meanchey	5617.3	3390.7	2219.8	1486.8	1013.6	700.4
(6) Kampong Thom	5450.1	4214.2	3380.1	2728.8	2214.4	1805.5
(7) Rotanak Kiri	4725.1	4228.2	3897.6	3625.8	3389.3	3176.5
(8) Pailin	3760.8	2069.2	1248.5	773.5	490.9	318.9
(9) Koh Kong	3520.4	2412.9	1742.0	1272.4	940.0	703.1
(10) Kampong Cham	2900.1	1516.1	849.9	478.7	271.0	154.1
(11) Kratie	2682.9	2218.4	1991.7	1841.7	1731.4	1644.7
(12) Kampong Spueu	2343.0	2198.3	2077.1	1963.9	1857.7	1757.9
(13) Stung Treng	2007.8	1836.2	1737.2	1667.2	1613.8	1570.1
(14) Takeo	1199.8	358.8	122.3	41.9	14.6	5.2
(15) Kampot	1196.0	957.4	802.6	685.6	594.6	521.7
(16) Kandal	1184.8	681.4	415.7	254.1	155.5	95.3
(17) Mondol Kiri	1049.3	563.6	359.3	250.6	187.5	147.7
(18) Pursat	1046.5	923.6	854.9	802.2	757.4	717.5
(19) Kampong Chhnang	645.2	618.7	597.2	577.4	558.8	541.2
(20) Preah Sihanuk	409.5	387.2	368.2	350.2	333.2	317.2
(21) Prey Veng	132.4	112.0	96.1	82.6	70.9	60.9
(22) Keb	104.3	55.6	33.5	21.0	13.5	9.0
(23) Svay Rieng	33.6	20.0	15.4	13.1	11.7	10.7
(24) Phnom Penh	–	–	–	–	–	–
Total FRELs	**69,230.8**	**51,865.7**	**42,113.0**	**35,385.7**	**30,490.5**	**26,779.2**

Note: 0–5, 6–10, 11–15, 16–20, 21–25, and 26–30 are intervals in years for assessing FRELs. UK's 2013 emissions were taken Statistical Release of Department of Energy and Climate Change (2015).

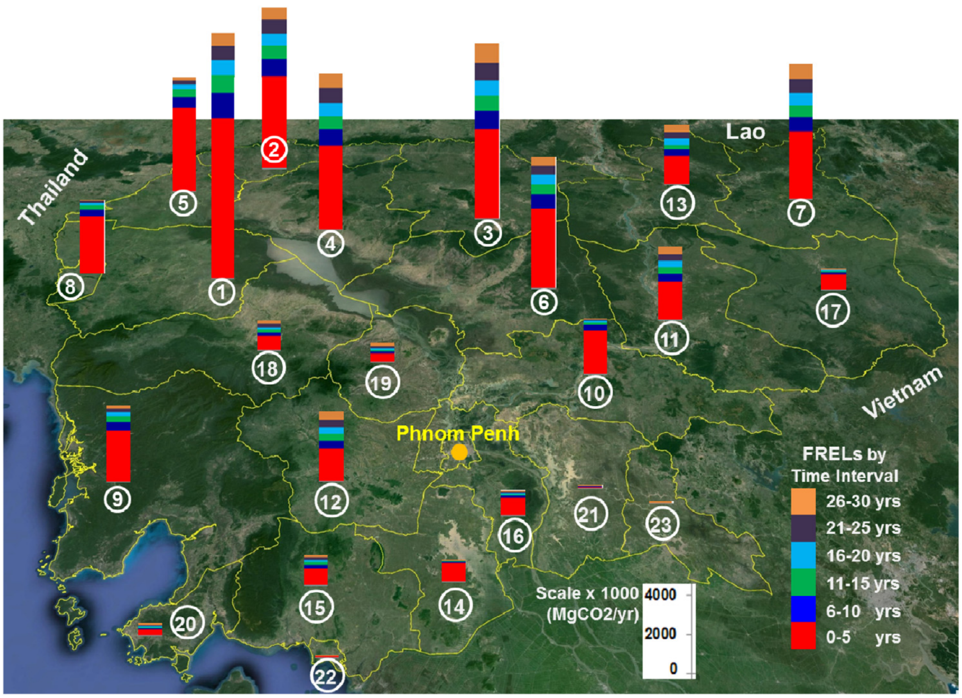

Fig. 2. Distribution of FRELs by province in Cambodia according to six time intervals. Note: Number corresponds to names of the provinces shown in Table 5. This map suggests that deforestation and related emissions are found mostly in the northern part of Cambodia. Background map was produced using Google Earth Pro.

In fact, many plantations in the tropics have a cutting rotation of between 5 and 15 years depending on planted species (Brown, 2000). Similarly, naturally regrown forests have been subject to cycles in and out of deforestation (Nelson et al., 2000), suggesting that naturally regrown forests are also subject to clear cut and regrowth. For our study, we assumed that

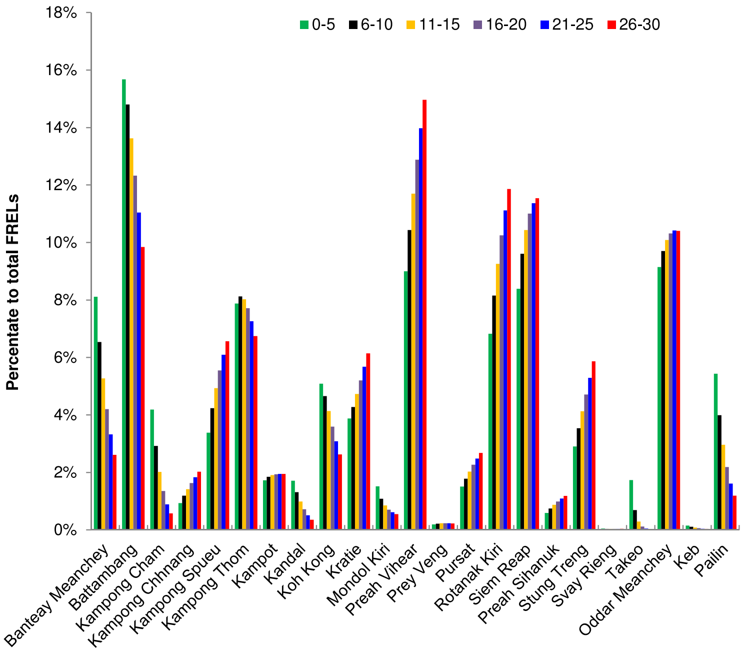

Fig. 3. Changes of percentage of subtotal FRELs by province in six time intervals.

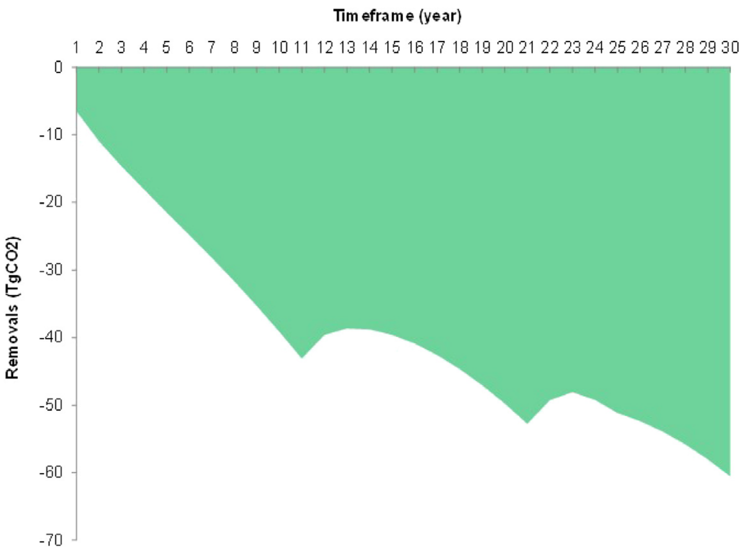

Fig. 4. Total carbon sequestration (removals) due to increase in forest area over a 30-year period.

forests with the increasing trend are clear cut and re-planted every 10 years starting from the year 10th of the initial year of the model (i.e. in 2002). With the assumption of cutting and replanting every 10 years, we estimate carbon sequestration (removals) at −16.1, −35.5, −39.5, −47.4, −50.0, and −58.3 $TgCO_2$ yr^{-1} for 0–5, 6–10, 11–15, 16–20, 21–25, and 26–30 intervals, respectively (Fig. 4). This level of carbon sequestration suggests that future emissions in the Cambodian forest sector could be compensated by an increase in forest cover if the current rate of forest cover increase is maintained (i.e. deforested areas are replanted).

4. Discussions

It is possible that data limitation and the approaches used to estimate the FRELs bias our results. Obtaining forest cover statistics at the commune level in Cambodia is difficult because deforestation and illegal logging area politically sensitive issues among political parties (McCargo, 2005). To provide a range of future deforestation rates, we compared the results of this study with that of Michinaka et al. (2015), who used panel data analysis to estimate future deforestation rates in

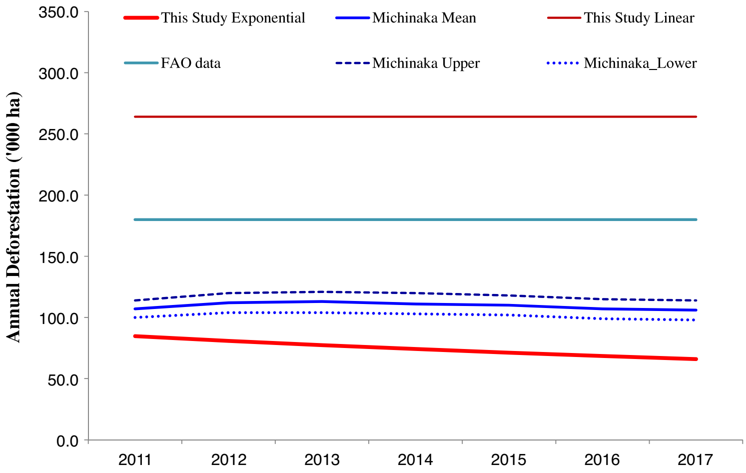

Fig. 5. Annual deforestation affected by methods used for future projection. Note: Linear fitting line for "FAO" is $y = -155.3 * x + 13\,302$, $R^2 = 0.9957$. Linear fitting line for "This Study Linear" is $y = -132.0 * x + 11\,392.2$, $R^2 = 1$. Michinaka_Lower and Michinaka_Upper refer to lower and upper bounces of the 95% confidence interval (Michinaka et al., 2015).

Cambodia. As seen in Fig. 5, their mean deforestation estimate was approximately 101,400–117,400 ha between 2011 and 2018, or about 18%–35% higher than in our study over the same period. If we used a linear projection with the available data, mean annual deforestation increases to 264,077.2 ha, which is even higher than that projected by Michinaka et al. (2015). Furthermore, if we extrapolate linearly using forest cover data in Cambodia in 1992, 1996, 2002, and 2005 (FAO, 2015), mean annual deforestation is 179,940.0 ha over the same period (2011 and 2018). Nevertheless, linear projection is likely an unrealistic approach because such projections will result in further deforestation, even if forests no longer exist.

In Vietnam, forest cover change showed an exponential decline between 1943 and 1990 before it stabilized then reversed its trend (Pham et al., 2012). Similarly, an exponential trend was also observed in Thailand between 1961 and 1998, before the trend reversed (Ongprasert, 2016). Studies also confirm that global deforestation has slowed as the total forest area declined (Boucher, 2014; FAO, 2015). These comparisons suggest that estimation of deforestation and related carbon emissions is affected by the choice of approach and data availability. The more data available showing past trends of forest cover, the relationship can be established to estimate FREL (Sandker et al., 2014).

Another bias may result from our assumption of a decline in the trend of forest cover in Cambodia and the effect of short-term data series. Using a retrospective approach, we assumed that both deforestation and forest plantation will continue at the current rate into the next 30 years, at a time when total forest cover will decline to about 50% of the country's total land area. Although forest transition theory suggests that the decline in forest cover should reverse to an increase after a threshold level has been reached (Mather, 2007; de Jong, 2010; Redo et al., 2012), the decline trend in our study is likely to continue even after this 30-year period of time span until the forest reaches about 20%, unless great efforts by the Cambodian government are undertaken. Previous studies suggest that a reversal of the trend is likely to occur when forest cover reaches about 20% of the country's total land area. For instance, forest cover changes in Vietnam reversed (began increasing) after it reached 24.9% in 1990 (de Jong et al., 2006). In Thailand, a reversal in the trend of forest cover change occurred when it reached 25.1% in 1999 (Lakanavichian, 2001). Therefore, our assumption should be revised when more data are gathered.

Furthermore, FRELs are affected by the adopted definitions of forests. Adopting definitions of forests for the future climate regime have an important role to play in determining whether the forest is deforested or degraded (Romijn et al., 2013; Sasaki and Putz, 2009). Accordingly, both the FREL and amount of carbon sequestration are affected by which definitions are adopted. Currently, Cambodia uses a definition of forest as having minimum canopy of 10% on an area of greater than 0.5 ha, and with tree height of at least 5 m (Sasaki and Putz, 2009). Any change in these thresholds will result in significant changes of reported forest cover, and therefore, FRELs in Cambodia. For example, annual loss of forest cover in Cambodia would be 124,691 ha, 123,327 ha, and 121,653 ha if 10%, 15%, and 25% of tree canopy cover are used, respectively, in the calculation (Hansen et al., 2013).

5. Conclusion

Using data of forest cover at the commune level, this study estimated the forest cover changes and carbon stock changes, carbon emissions due to deforestation, carbon sequestration due to increase of forest cover, and FRELs at subnational and national levels over a period of 30 years in Cambodia. Carbon emissions due to deforestation were significantly compensated by the carbon sequestration due to an increase of forest cover in some communes throughout Cambodia. Our study shows that overestimation of net carbon emissions can be avoided by using data of specific forest types determined at small scales such as at the commune or district level. Estimation of carbon emissions is strongly affected by the choice of estimation approach and data availability. Using a retrospective approach, this study provides a first look at how to estimate and set subnational and national FRELs for Cambodia. Our results could stimulate discussion about determining the FRELs at subnational and national levels, which will eventually be done by the Cambodian government. Our approach can be replicated, but detailed data by forest type at administrative boundary (i.e. commune or similar) will reduce the uncertainty for predicting future deforestation baseline, which is important for estimating and deciding the FRELs. Having subnational and national FRELs allows developing countries to introduce effective policies to address the drivers of deforestation and forest degradation, which will eventually result in carbon emission reductions. In addition to reducing emissions from deforestation, protecting the natural regrowth of forests and reforestation on the degraded lands could enhance carbon stocks and therefore provide additional sources of income in developing countries.

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