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Assessment of carbon stocks of semi-evergreen forests in Cambodia

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ABSTRACT

Understanding carbon stocks relative to tree species is important for managing tropical forests in a way that will result in the carbon emission reductions and biodiversity conservation required under the REDD+ scheme. Here we analyse inventory data from 179 sample plots in semi-evergreen forests of three provinces in Cambodia. Across all study sites, 5,995 trees with a diameter at breast height (DBH) $\geq$10 cm, comprising 79 species from 38 families, were analysed. Tree species of the Dipterocarpaceae were most common (10 species), followed by the species of Caesalpinaceae, Combretaceae and Ebenaceae. Analysis of relative carbon stocks (RCS) suggested that *Lagerstroemia calyculata* Kurz (RCS $=$ 14.3%), *Syzygium* sp. (6.8%), *Shorea vulgaris* (5.0%), *Irvingia malayana* (4.8%), *Anisoptera costata* Kort (4.6%), *Vatica astrotricha* (4.2%), and *Dehaasia cuneata* Blume (3.8%) together accounted for 43.6% of the total average carbon stocks of 99.8 $\pm$ 4.8 MgC ha^{-1}. We found that carbon stock is highly correlated to basal area ($R^2 = 0.993$) but not to stem density ($R^2 = 0.153$). Using carbon stock values, we estimated the carbon emission due to deforestation of semi-evergreen forests to be 8.3 TgCO$_2$ year^{-1} in Cambodia between 2002 and 2010. These emissions and the loss of 79 tree species in our study sites could be avoided if financial incentives were available for protecting semi-evergreen forests in Cambodia.

1. Introduction

Although tropical forests cover only 6% of the Earth's total land surface, they are home to the richest biodiversity on the planet, comprising a major component of our trees, plants, birds, insects and mammals (Laurance et al., 2012). Tropical forests also contribute substantially to the global economy, to local human welfare and to the global carbon budget. Based on 109 case studies from across the tropics, tropical forests are considered important sources of ecosystem services whose annual value has been estimated at US$ 6120 ha^{-1} (TEEB Climate Issues Update, 2009, as cited in Sukhudev, 2010). Unfortunately, the capacity of tropical forests to provide these services is gradually declining each year because of rapid

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deforestation (FAO, 2010; Lambin et al., 2003) and forest degradation, mainly due to uncontrolled and in many cases illegal logging (Asner, 2011; Asner et al., 2009; FAO, 2010; Gaston et al., 1998; Robinson et al., 2013; Tacconi, 2007) and fires (Nepstad et al., 1999; Siegert et al., 2001). Between 2000 and 2005, at least 392 million ha (or 20%) of the total area of humid tropical forests was logged, and approximately 50% of standing humid tropical forests retained <50% forest cover as of 2005 (Asner et al., 2009; FAO, 2010). Reducing deforestation and forest degradation has been at the forefront of negotiations of the Conferences of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) because such reduction will result in carbon emission reduction, protection of biodiversity and improvement of the livelihoods of forest-dependent communities in developing countries.

The adoption of the Bali Action in 2007 and the subsequent recognition of REDD+ (reducing emissions from deforestation and forest degradation, conservation of forests, sustainable management of forests and enhancement of forest carbon stocks) at COP13 paved way for financial incentives for the protection of tropical forests. REDD+ is a results-based financial compensation scheme requiring emission reductions while safeguarding biodiversity. Four of the seven decisions made at COP19 under the Warsaw Framework for REDD+ emphasised the importance of forest carbon monitoring and safeguarding (Decision 9/CP.19). With the requirement for biodiversity safeguards, information on the relationship between tree species and carbon stocks, and how this has been affected by management in developing countries, is important for the successful implementation of any REDD+ activity (Entenmann et al., 2014; Kapos et al., 2012). However, until recently, there was little information available on this relationship. In a review of 24 studies from across the globe, Thompson et al. (2014) found that only one study (from Panama) focused on the relationship between tree species and carbon storage in natural tropical forest. In that study, up to 61 species were found with above-ground biomass of up to 200 MgC ha^{-1} (Ruiz-Jaen and Potvin, 2010). In Cambodia, several studies have examined stand structure in evergreen, semi-evergreen and deciduous forests in Kampong Thom province (Kao and Iida, 2006; Kim Phat et al., 2000, 2002a,b; Top et al., 2004) and in evergreen forest in Preah Vihear province (Kao and Iida, 2006); however, measurements were limited to tree species, stem density and stand volume. Sasaki (2006) analysed carbon emissions due to human activities in Cambodia, but the effect of tree species was not considered. Although previous studies provide useful information on the current status of forest stand structure and carbon emissions in Cambodia, information on the relationship between these parameters, i.e. stand structure (tree species, stem density and basal area) and carbon storage, is lacking. This lack of information makes the implementation of REDD+ projects difficult, thus jeopardising carbon emission reductions, local biodiversity and the livelihoods of local people.

The aims of this study were to analyse stand structure and carbon stocks in semi-evergreen forests in Cambodia, and to discuss the policy implications for the successful implementation of REDD+ activities. This paper is structured as follows: forest inventory data from 179 sample plots were analysed according to tree species and diameter at breast height (DBH) classes; the relationships among stem density, basal area and carbon storage were evaluated following Cottam and Curtis (1956) and the policy implications for REDD+ activities and biodiversity safeguards are discussed.

2. Study methods and materials

2.1. Forests and forest cover in Cambodia

The total 2015 population of Cambodia was estimated to be approximately 15.4 million, increasing from 13.4 million in 2008. Cambodia is a heavily forested country in Southeast Asia, having a total forest area of 10.4 million ha in 2010 (approximately 57.1% of the country's total land area). Forests are socially, environmentally and economically important resources for national development in Cambodia (Kim et al., 2008, 2006; San et al., 2012a,b). Approximately 85% of the Cambodian population lives in rural areas and almost 100% of the total population uses fuelwood for daily cooking. In rural areas, fuelwood is collected from nearby forests (San et al., 2012a), but the distance to forests is increasing as the accessibility to nearby forests decreases. Per capita annual wood consumption in Cambodia has been estimated as approximately 0.66 m^3 (World Bank et al., 1996). As the Cambodian population continues to grow, a greater demand for wood is expected posing further pressure on the remaining forests. Between 2002 and 2010, approximately 0.8% of forest cover was lost annually. The annual deforestation rate accelerated between 2006 and 2010, increasing to 0.9% (Table 1). As shown in Table 1, three major forest types are recognised in Cambodia: evergreen, semi-evergreen and deciduous. Other minor forest types exist, including woody dry shrubland, woody evergreen shrubland, bamboo, forest plantation, flooded and mangrove forests. Semi-evergreen forests have a total area of 1.3 million ha (12.5% of the total forest area) in Cambodia.

The remaining 10.4 million ha of forests are classified under the land-use categories of production forests (36.1% of the total forest area), protected forests (43.1%) and conversion forests (20.8%). Production forests include concession and community forests, where timber may be harvested subject to approval from the Forestry Administration (FA). Protected forests are managed for biodiversity conservation and local development. Conversion forests are forests whose management objectives are not clearly specified. Depending on the need for economic development and settlement of a growing population, conversion forests may be converted to social land concession and/or economic land concession. However, allocation of new economic land concession was banned by the Cambodian government in 2012. Two REDD+ projects were validated in Cambodia, one of which received triple-gold verification for its contribution to emission reductions, improving local livelihoods and biodiversity conservation (Terra Global, 2013).

Table 1
Forest area in Cambodia (2002–2010).
Source: Forestry administration, unpublished data.

Forest type	Forest area						Annual area change		
	2002		2006		2010		2002–2006	2002–2010	2006–2010
	(million ha)	(%)	(million ha)	(%)	(million ha)	(%)	(%)	(%)	(%)
Evergreen forest	3.7	20.5	3.7	20.2	3.5	19.3	−0.3	−0.7	−1.2
Semi evergreen forest	1.5	8.0	1.4	7.5	1.3	7.0	−1.6	−1.5	−1.6
Deciduous forest	4.8	26.6	4.7	25.8	4.5	24.7	−0.7	−0.9	−1.1
Other forest	1.1	6.0	1.0	5.5	1.1	6.1	−2.0	0.2	2.5
Total forest area	**11.10**	**61.1**	**10.7**	**59.1**	**10.4**	**57.1**	**−0.8**	**−0.8**	**−0.9**
Non-forest land	7.1	38.9	7.4	40.9	7.8	42.9	1.3	1.3	1.2
Total	18.2	100.0	18.2	100.0	18.2	100.0	0.0	0.0	0.0

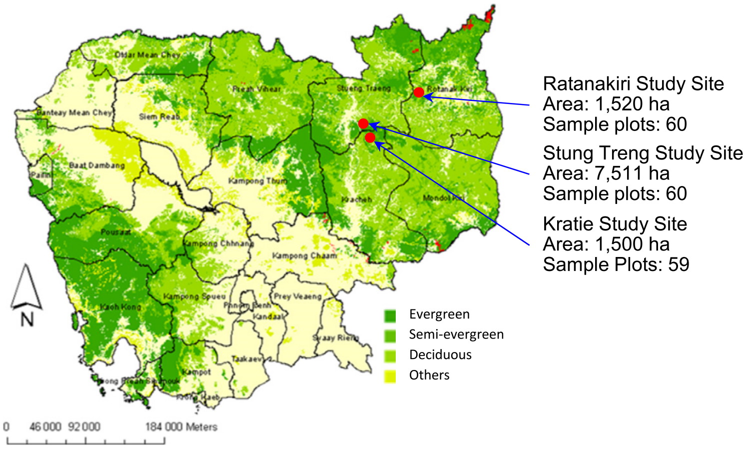

Fig. 1. Forest cover map showing locations of the study sites.

2.2. Description of the study sites

In 2007 and 2008, the FA conducted logging experiments using reduced impact logging techniques in three coupes of the former concession forests of Kratie (covering an area of 1500 ha), Ratanakiri (1520 ha) and Stung Treng (7511 ha) provinces of Cambodia (Chheng et al., 2015) (see Fig. 1). The three coupes were logged prior to the 2002 logging ban. The three provinces still have the highest forest cover when compared to other provinces in Cambodia, covering approximately 79%, 82% and 88% of the provinces' total land area, respectively (FA, 2011). Average annual deforestation in the three provinces was 7888.0 ha, 8665.0 ha and 6195.5 ha, respectively, between 2002 and 2006. Further description of the study sites can be found in Chheng et al. (2015).

Trees were selectively logged in accordance with logging guidelines under reduced impact logging practice (see Holmes et al., 2002 and Medjibe and Putz, 2012 for the practices of reduced-impact logging and associated costs). To assess logging damage, a sample plot of 25 m × 40 m was laid out along each felled tree, corresponding to branch width and tree height, respectively. Tree measurements and assessment of logging damage were carried out from April 2007 to September 2008 by the Department of Forests and Community Forestry Management of the FA. All trees with a DBH ≥ 10 cm were recorded in all sample plots. At Kratie, trees were measured in 59 sample plots in the O'Preah production coupe (13° 13′53″–13° 16′51″N, 106° 11′22″–106° 13′29″E) of the O'Kreang commune in Sambo district. In Stung Treng, trees in 60 sample plots were measured in the O'leang Krous production coupe (13° 23′90″–13° 21′30″N, 106° 11′27″–106° 14′41″E) of the Kbal Ro Meas commune in Se San district. Another 60 sample plots were laid out in the 4650 ha Toen Trapang Kraham production coupe (13° 42′57″–13° 48′24″N, 106° 41′35″–106° 44′52″E) of the Toen commune in the Kon Mom district of Ratanakiri province. Geographic locations of sample plots were recorded with the aid of the global positioning system (GPS). Plot boundaries were demarcated by the inventory team before tree measurements were conducted.

2.3. Data analysis

All trees were measured and recorded for species, DBH and location. Analysis of stand structure was performed in the following order: stem density, basal area, carbon stock. Carbon biomass for individual trees can be obtained by

$$\mathrm{CS}_i = \frac{\sum \mathrm{AB}_i \times 0.5}{1000 \times 0.1} \tag{1}$$

where

CS_i: Above-ground carbon stock for tree species i (MgC ha^{-1})
AB_i: Above-ground biomass for tree species i (kg^{-1})
0.5: Carbon content in dry biomass (MgC Mg^{-1})
0.1: Plot size of $(25 \times 40)/10{,}000$ (or 0.1 ha).

Allometric equations are commonly used to estimate above-ground biomass of individual trees in the tropics (Basuki et al., 2009; Chave et al., 2005, 2003; Kenzo et al., 2010; Brown, 1997). Basuki et al. (2009) developed allometric equations for specific lowland Dipterocarp forests in East Kalimantan, Indonesia. Their equations may not be appropriate for tropical monsoon forests in our study sites. Models developed by Chave et al. (2005) required wood density for forests by type. For simplicity, we used equations developed for generic tropical moist forest by Brown (1997) because these equations require only one variable, DBH.

$$AB_i = 42.69 - 12.800 \times DBH_i + 1.424 \times DBH_i^2 \quad (2)$$

where
DBH_i: DBH for tree species i (cm).
Carbon stocks in the forests of a study site were obtained by summing the carbon stocks of individual tree species within the site.
To assess dominancy of tree species, analysis of relative stem density (RSD), relative dominance (RD), and relative carbon stock (RCS) was performed following Cottam and Curtis (1956) as follows:

$$RSD_i = \frac{SD_i}{TSD} \times 100 \quad (3)$$

$$RD_i = \frac{BA_i}{TBA} \times 100 \quad (4)$$

$$RCS_i = \frac{CS_i}{TCS} \times 100 \quad (5)$$

where

RSD_i: Relative stem density of species i (%)
SD_i: Stem density of species i (trees ha^{-1})
TSD: Total stem density (trees ha^{-1})
RD_i: Relative dominance of species i (%)
BA_i: Basal area of species i (m^2 ha^{-1})
TBA: Total basal area (m^2 ha^{-1})
RCS_i: Relative carbon stock of species i (%)
CS_i: Carbon stock of species i (MgC ha^{-1})
TCS: Total carbon stock (MgC ha^{-1}).

3. Results

3.1. Kratie study site

At Kratie, all trees with a DBH $\geq$ 10 cm were measured in 59 sample plots. A total of 86 tree species were found in this study site, of which 55 species were identified to the level of their scientific name. However, 26 species were identified only by their local name. Mean stem density was estimated at 245.9 $\pm$ 21.3 trees ha^{-1} ($\pm$ is the confidence interval 90%) and ranged from 80 to 630 trees ha^{-1}. In Cambodia, all commercial tree species are assigned a four-capital-letter code, which is used for logging planning and timber harvest. These four codes are used throughout this paper. Tree species codes and the local, botanical and family names of trees found in all three study sites are given in Table 2. Based on relative stem density (RSD), the top 10 tree species at Kratie were *Vatica astrotricha* (Dipterocarpaceae) (RSD = 10.7%), *Lagerstroemia calyculata* Kurz (Lythraceae) (RSD = 9.1%), *Syzygium sp.* (Myrtaceae) (RSD = 4.7%), *Anisoptera glabra* (Dipterocarpaceae) (RSD = 4.3%), *Hopea recopei* (Dipterocarpaceae) (RSD = 4.3%), *Irvingia malayana* (RSD = 3.9%), *Diospyros bejaudi* (Ebenaceae) (RSD = 3.9%), *Cratoxylon prunifolium* (Hypericaceae) (RSD = 3.7%) and *Parinarium annamensis* (Rosaceae) (RSD = 2.9%). Unidentified or unknown species represented 11.9% of all stem density (Fig. 2(A), Table SI1A). As shown in Fig. 2(A), trees with DBH classes of 10–19, 20–29 and 30–39 were dominant; this is a common pattern found in selectively logged forests (Kim Phat et al., 2000).

Mean basal area for the Kratie site was 19.5 $\pm$ 1.2 m^2 ha^{-1}. *Lagerstroemia calyculata* was the most dominant, having a relative dominance (RD) of 18.6%. This was followed by *Irvingia malayana* (RD = 12.3%), *Anisoptera costata* Kort (RD = 6.1%), *Vatica astrotricha* (RD = 5.3%), *Parinarium annamensis* Hance (RD = 4.6%), *Syzygium sp.* (RD = 4.3%), *Dipterocarpus intricatus* Dyer (RD = 3.9%), *Dipterocarpus alatus* (RD = 3.8%), *Shorea cochinchinensis* Pierre (RD = 3.4%) and *Xylia dolabriformis* Benth

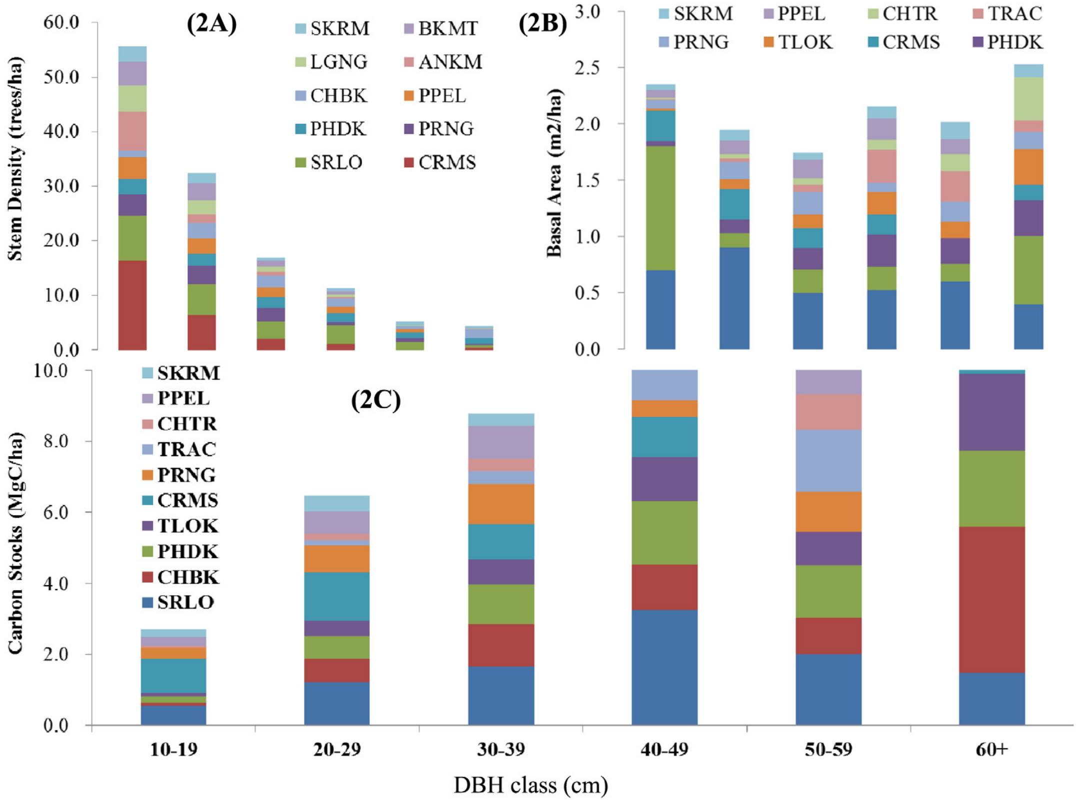

Fig. 2. Distribution of stem density (2A), basal area (2B) and carbon stock (2C) by DBH class for the top 10 species at Kratie study site. Note: Refer to Table 2 for scientific names and families of tree species corresponding to the commercial tree codes shown.

(RD = 3.0%). Unknown species (UNKN) accounted for approximately 5.6% of the basal area. *Lagerstroemia calyculata*, the typical tree species found in semi-evergreen forests in Cambodia, was dominant in all DBH classes (Fig. 2(B), Table SI1B). The average carbon stock was 95.8 ± 6.6 MgC ha^{-1}. Relative carbon stock (RCS) of *Lagerstroemia calyculata*, *Irvingia malayana*, *Anisoptera costata*, *Parinarium annamensis* and *Vatica astrotricha* was 10.6%, 8.7%, 7.6%, 5.8% and 5.6%, respectively. Carbon stocks for the top 10 species accounted for more than 60% of the total carbon stock (Fig. 2(C), Table SI1C).

3.2. Ratanakiri study site

Data from 60 sample plots were analysed for the Ratanakiri site. A total of 64 tree species were recorded. The mean stem density of trees with a DBH ≥ 10 cm was 433.7 ± 25.3 trees ha^{-1}, ranging from 200 to 730 trees ha^{-1}. For this site, the top 10 species based on RSD were *Xylopia vielana* (Annonaceae) (RSD = 11.3%), *Lagerstroemia calyculata* (RSD = 10.5%), *Euphoria cambodiana* (Euphorbiaceae) (RSD = 7.8%), *Diospyros nitida* (Ebenaceae) (RSD = 7.2%), *Ternstroemia sp.* (Theaceae) (RSD = 4.6%), *Xylia dolabriformis* (Leguminosae) (RSD = 4.2%), *Vatica astrotricha* (RSD = 4.0%), *Barringtonia sp.* (Lecythidaceae) (RSD = 3.9%) and *Grewia paniculata* (Tiliaceae) (RSD = 3.2%). While all 10 species were dominant in smaller DBH classes, only *Lagerstroemia calyculata* was dominant in larger DBH classes (Fig. 3(A), Table SI2A). The mean basal area for all trees with a DBH ≥ 10 cm was 23.8 ± 1.7 m^2 ha^{-1}. *Lagerstroemia calyculata* accounted for the highest proportion of the basal area, having an RD of 21.7%. This was followed by *Xylopia vielana* (RD = 8.0%), *Syzygium sp.* (RD = 4.5%), *Irvingia malayana* (RD = 4.2%), *Anisoptera costata* (RD = 3.5%), *Euphoria cambodiana* (RD = 3.5%), *Sindora cochinchinensis* Baill (RD = 3.0%), *Mangifera duperreana* Pierre (RD = 2.9%), *Barringtonia sp.* (RD = 2.7%) and *Dipterocarpus intricatus* (RD = 2.6%) (Fig. 3(B), Table SI2B). The average carbon stock was 101.5 ± 9.2 MgC ha^{-1}. RCS of *Lagerstroemia calyculata*, *Xylopia vielana*, *Syzygium sp.*, and *Irvingia malayana* was 24.3%, 7.3%, 4.8%, and 4.7%, respectively (Fig. 3(C), Table SI2C).

3.3. Stung Treng study site

Data from 60 sample plots were analysed for the Stung Treng site. In total, 51 species were recorded, but unknown species accounted for 11.9% of the total stem density. The mean stem density for all trees with a DBH ≥ 10 cm was 353.5±16.0 trees ha^{-1}, ranging from 180 to 490 trees ha^{-1}. Based on RSD, the top 10 species were *Syzygium sp.* (RSD = 8.9%), *Euphoria cambodiana* (RSD = 8.8%), *Dehaasia cuneata* Blume (Lauraceae) (RSD = 7.5%), *Vatica astrotricha* (RSD = 7.4%),

Table 2
Families, botanical names, commercial species codes and local names of tree species found at the three study sites.

Family	Botanical name	Species code	Local name	Study sites		
				Kratie	Ratanakiri	Stung Treng
Anacardiaceae	*Buchanania arborescens*	KMPD	Komping Doung	No	Yes	No
Anacardiaceae	*Bouea oppositifolia*	MAKP	Makprang	No	Yes	No
Anacardiaceae	*Mangifera duperreana* Pierre	SWPR	Sway Prey	Yes	Yes	No
Annonaceae	*Uvaria purpurea*	CHPM	Chhek Sampouch	No	Yes	Yes
Annonaceae	*Xylopia vielana* Pierre	KRAY	Kray	Yes	Yes	Yes
Annonaceae	*Melodorum fruticosum*	RODL	Rumdul	Yes	Yes	Yes
Annonaceae	*Dasymachalon lamentaceum*	CCHB	Cheung Chaab	No	No	Yes
Bignoniaceae	*Markhamia pierrei*	DKPO	Dokpoar	Yes	No	Yes
Bombaceae	*Bombax ceiba* L.	ROKA	Rokar	Yes	Yes	No
Caesalpinaceae	*Cassia siamensis*	ANKN	Ang kanh	Yes	No	No
Caesalpinaceae	*Afzelia xylocarpa* (Kurz) Craib	BENG	Beng	No	Yes	No
Caesalpinaceae	*Sindora cochinchinensis* Baill	KRKO	Kra Koh	Yes	Yes	Yes
Caesalpinaceae	*Dialium cochinchinensis* Pierre	KRLA	Kra Lanh	Yes	No	Yes
Caesalpinaceae	*Crudia chrysantha*	SDEY	Sdey	No	Yes	No
Caesalpinaceae	*Peltophorum ferrugineum* Benth	TRSK	Traseik	Yes	Yes	No
Clusiaceae	*Calophyllum calaba*	PHON	Phaong	Yes	Yes	No
Combretaceae	*Terminalia tomentosa*	CHLK	Chhliik	No	Yes	No
Combretaceae	*Terminalia mucronata*, Graib et Huth	PRDL	Pram Damleng	Yes	Yes	No
Combretaceae	*Terminalia nigrovenulosa*	PRPN	Preas Phnauv	Yes	Yes	Yes
Combretaceae	*Combretum quadrangulare*	SANK	Sang Ke	Yes	Yes	No
Combretaceae	*Terminalia chebula*	SRMO	Sramor	No	Yes	No
Connaraceae	*Roureopsis stenopetala*	CHEY	Chey	No	Yes	No
Crypteroniaceae	*Crypteronia paniculata* Blume	TRTM	Trabb Tum	Yes	Yes	No
Datiscaceae	*Tetrameles nudiflora* R.Br	SMPN	Sam Pung	No	Yes	No
Dilleniaceae	*Dillenia ovata*	PLUU	Pluor	Yes	No	No
Dioscoreaceae	*Dioscorea hispida*	KDCH	Kdouch	Yes	No	Yes
Dipterocarpaceae	*Shorea vulgaris*	CHRH	Chor Chong	Yes	No	Yes
Dipterocarpaceae	*Dipterocarpus alatus*	CHTR	Chheutiel Thngor	Yes	Yes	Yes
Dipterocarpaceae	*Vatica astrotricha*	CRMS	Chramas	Yes	Yes	Yes
Dipterocarpaceae	*Dipterocarpus tuberculatus*	KHLG	Khlong	Yes	No	No
Dipterocarpaceae	*Hopea odorata*	KKMS	Koki masao	No	Yes	No
Dipterocarpaceae	*Shorea farinose*, C.Fisch	LMBI	Lumbor	No	Yes	Yes
Dipterocarpaceae	*Anisoptera costata* Kort	PHDK	Phdeak	Yes	Yes	Yes
Dipterocarpaceae	*Shorea cochinchinensis* Pierre	PPEL	Po Pel	Yes	Yes	No
Dipterocarpaceae	*Dipterocarpus intricatus* Dyer	TRAC	Trach	Yes	Yes	No
Dipterocarpaceae	*Vatica philastreana* Pierre	TRLT	Tra Lat	Yes	Yes	No
Ebenaceae	*Diospyros bejaudi* Lecomte	ANKM	Angkot Kmao	Yes	Yes	Yes
Ebenaceae	*Diospyros crumenata*	CHKM	Chheu Khmao	No	No	Yes
Ebenaceae	*Diospyros nitida*	CHPL	Chhoeu Phloeung	No	Yes	Yes
Ebenaceae	*Diospyros helferi*	TRYG	Traying	Yes	Yes	No
Euphorbiaceae	*Aporusa filicifolia Bail*	KRON	Krong	Yes	No	Yes
Euphorbiaceae	*Euphoria cambodiana*	MNPR	Mien Prey	Yes	Yes	Yes
Flacourtiaceae	*Hydnocarpus anthelmitica*	KRBO	Kra Bao	No	Yes	No
Hypericaceae	*Cratoxylon prunifolium* Dyer	LGNG	Lo Ngeang	Yes	Yes	No
Irvingiaceae	*Irvingia malayana*	CHBK	Chambak	Yes	Yes	Yes
Lauraceae	*Dehaasia cuneata* Blume	ATIT	Atit/Neang Pha Ack	Yes	Yes	Yes
Lauraceae	*Crytocarya oblongifolia*	SEDA	Seda (Kraham)	Yes	No	No
Lauraceae	*Cinnamomum cambodianum*	TEPI	Tep Phirou	No	No	Yes
Lecythidaceae	*Barringtonia sp.*	RINM	Raing Phnum	No	Yes	No
Loganiaceae	*Fagraea fragrans* Roxb	TTRV	Ta Trav	No	No	Yes
Lythraceae	*Garcinia ferrea*	PRUS	Prus	Yes	Yes	Yes
Lythraceae	*Lagerstroemia calyculata* Kurz	SRLO	Sralao	Yes	Yes	Yes
Lythraceae	*Garcinia schomburghi*	TRMN	Tra Muung	Yes	Yes	Yes
Meliaceae	*Aglaia cambodiana*	BGKW	Bangkuv	No	No	Yes
Meliaceae	*Sandoricum indicum*	KMPR	Kampiing Reach	Yes	Yes	Yes
Mimosaceae	*Albizzia lebbek*	CHRS	Chreis	Yes	No	Yes
Mimosaceae	*Xylia dolabriformis* Benth	SKRM	Sokrom	Yes	Yes	No
Moraceae	*Artocarpus asperula*, Gagn	KNPR	Khnol Prey	No	Yes	Yes
Moraceae	*Artocarpus sempervirens*	SPOR	Sam Por	No	No	Yes
Myristicaceae	*Knema corticosa* Lour	SMKB	Smaa Krabey	No	Yes	No
Myrtaceae	*Careya sphaerica* Pierre	KNDL	Kandol	Yes	No	Yes
Myrtaceae	*Syzygium sp.*	PRNG	Pring	Yes	Yes	Yes
Myrtaceae	*Melaleuca leucadendron*	SMCH	Smach	Yes	Yes	Yes
Papilionaceae	*Dalbergia bariensis*, Pierre	NNON	Neang Nuon	No	Yes	No
Papilionaceae	*Dalbergia nigrescensis*	SNOL	Snuol	No	Yes	Yes
Papilionaceae	*Pterocarpus pedatus*	THNG	Thnong	Yes	Yes	No

(continued on next page)

Table 2 (*continued*)

Family	Botanical name	Species code	Local name	Study sites		
				Kratie	Ratanakiri	Stung Treng
Papilionoideae	*Dalbergia horrida*	KNAY	Knaymon	No	Yes	No
Rhizophoraceae	*Carallia lucida* Roxb	TREN	Tra Maeng	No	Yes	Yes
Rosaceae	*Parinarium annamensis* Hance	TLOK	Tlork	Yes	Yes	Yes
Salicaceae	*Homalium tomentasum*	PLNG	Pluv Neang	No	No	Yes
Sapindaceae	*Lepisanthes tetraphylla*	KRAK	Krachok Andeuk	No	Yes	No
Sapindaceae	*Schleichera oleosa*	PGRO	Pungro	Yes	No	No
Sapindaceae	*Nephelium hypoleucum*	SEMN	Semon	Yes	Yes	Yes
Sapotaceae	*Payena elliptica* Lecomtc	SRKM	Srakum	No	Yes	No
Sterculiaceae	*Tarrietia javanica*	DCSP	Doun Chaem	Yes	No	Yes
Theaceae	*Ternstroemia sp.*	PLOG	Plong	Yes	Yes	Yes
Tiliaceae	*Grewia paniculata*	POPL	Po Plear	Yes	Yes	Yes
Verbenaceae	*Vitex sp.*	PPUL	Phnul	Yes	Yes	Yes
Unknown	*Unknown*	BKMT	Bakmort	Yes	No	No
Unknown	*Unknown*	CHEM	Choueem	No	No	Yes
Unknown	*Unknown*	CHNL	Chnoul	Yes	No	No
Unknown	*Unknown*	CKTR	Chanka Trong	No	No	Yes
Unknown	*Unknown*	DGTE	Daungte	No	No	Yes
Unknown	*Unknown*	KRCS	Krochas	Yes	Yes	Yes
Unknown	*Unknown*	KTOM	Ktom	Yes	Yes	No
Unknown	*Unknown*	PANG	Pang	No	Yes	No
Unknown	*Unknown*	PHUT	Prohut	No	No	Yes
Unknown	*Unknown*	RANG	Rang	No	Yes	No
Unknown	*Unknown*	SARG	Samrong	No	No	Yes
Unknown	*Unknown*	SEW	Sew	No	Yes	No
Unknown	*Unknown*	SNKH	Snok Kluok	No	No	Yes
Unknown	*Unknown*	SRTP	Srotuap	Yes	No	No
Unknown	*Unknown*	SVDL	Svay Del	Yes	No	No

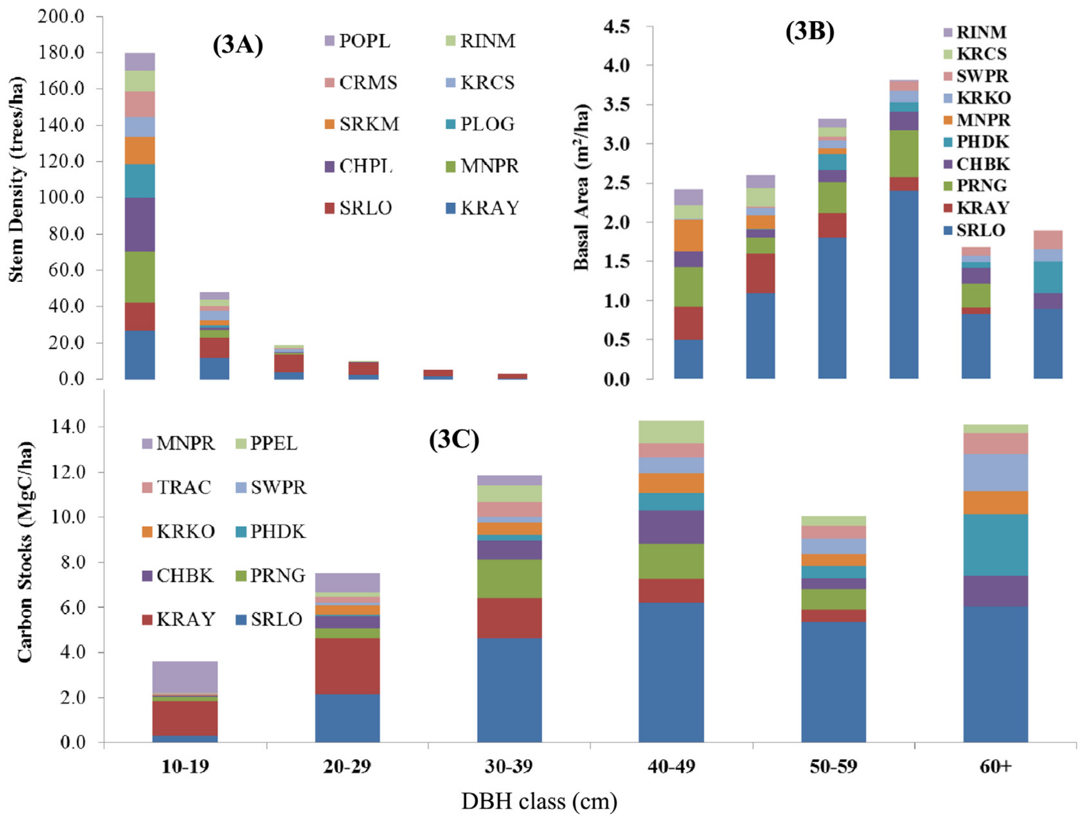

Fig. 3. Distribution of stem density (3A), basal area (3B) and carbon stock (3C) by DBH class for the major species at Ratanakiri study site. Note: Refer to Table 2 for scientific names and families of tree species corresponding to the commercial tree codes shown.

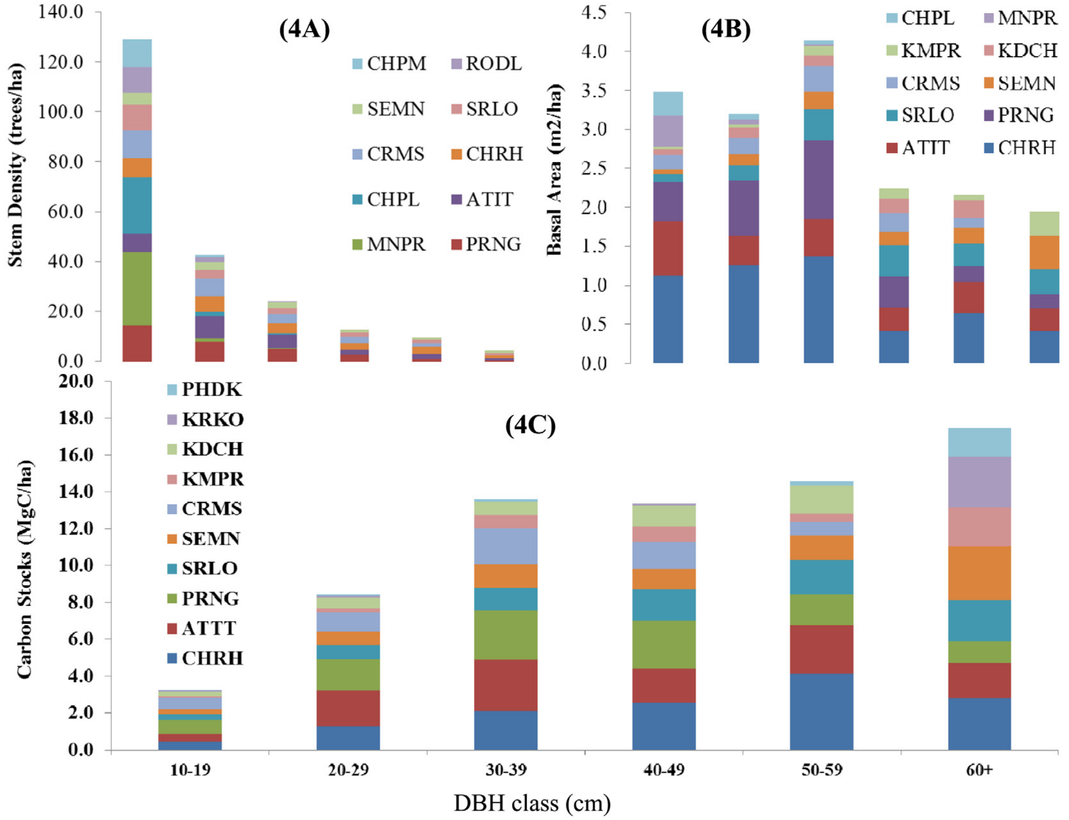

Fig. 4. Distribution of stem density (4A), basal area (4B) and carbon stock (4C) by DBH class for the major species at Stung Treng study site. Note: Refer to Table 2 for scientific names and families of tree species corresponding to the commercial tree codes shown.

Diospyros nitida (Ebenaceae) (RSD = 7.0%), *Shorea vulgaris* (Dipterocarpaceae) (RSD = 7.0%), *Lagerstroemia calyculata* (RSD = 5.5%), *Nephelium hypoleucum* (Sapindaceae) (RSD = 4.0%), *Melodorum fruticosum* (Annonaceae) (RSD = 3.4%) and *Uvaria purpurea* (Annonaceae) (RSD = 3.4%) (Fig. 4(A), Table SI3A). Mean basal area was 23.2 ± 1.8 m^2 ha^{-1}, of which *Shorea vulgaris* had an RD of 22.4%. This was followed by *Dehaasia cuneata* (11.1%), *Syzygium sp.* (12.8%), *Lagerstroemia calyculata* (7.4%), *Nephelium hypoleucum* (5.5%), *Vatica astrotricha* (4.6%), *Dioscorea hispida* of Dioscoreaceae (3.2%), *Sandoricum indicum* of Meliaceae (3.0%), *Euphoria cambodiana* (2.1%) and *Diospyros nitida* (1.9%). Unknown species accounted for approximately 8.1% of the total basal area (Fig. 4(B), Table SI3B). The average carbon stock for the Stung Treng site was 102.2 ± 8.9 MgC ha^{-1}. RCS of *Shorea vulgaris*, *Dehaasia cuneata*, *Syzygium sp.*, *Lagerstroemia calyculata* and *Nephelium hypoleucum* was 13.0%, 11.3%, 10.4%, 7.9%, and 7.5%, respectively (Fig. 4(C), Table SI3A).

3.4. All study sites

Across all study sites, 5995 trees (DBH ≥ 10 cm), belonging to 79 species from 38 families, were measured. Analysis of relative stem density suggests that trees in Dipterocarpaceae were dominant (10 species), followed by Caesalpinaceae (6 species), Combretaceae (5 species), Ebenaceae (5 species), Annonaceae (4 species) and Papilionaceae (4 species). Fifteen more species were identified by local names only (Table 2). Average stem density, basal area and carbon stock were 344.9 ± 15.4 trees ha^{-1} ($P = 0$ for ANOVA single factor), 22.2 ± 0.9 m^2 ha^{-1} ($P = 0.00367$) and 99.8 ± 4.8 MgC ha^{-1} ($P = 0.63524$), respectively (Table 3). Trees of the following species were dominant in terms of relative carbon stocks: *Lagerstroemia calyculata* Kurz (14.3%), *Syzygium sp.* (6.8%), *Shorea vulgaris* (5.0%), *Irvingia malayana* (4.8%), *Anisoptera costata* Kort (4.6%), *Vatica astrotricha* (4.2%), and *Dehaasia cuneata* Blume (3.8%), altogether accounting for 43.6% of total carbon stocks.

Using 99.8 MgC ha^{-1} as the carbon stock level, deforestation of semi-evergreen forests in Cambodia between 2002 and 2010 resulted in annual carbon emissions of 8.3 $TgCO_2$. These emissions are approximately 8.5% of the Kyoto reduction target of the United Kingdom for the first commitment period of the Kyoto protocol (2008–2012). Fig. 5 shows the distribution of carbon stocks relative to stem density in 179 sample plots across all study sites. There is a low correlation between carbon stock and stem density at all the study sites ($R^2 = 0.0521$–0.1529), suggesting that stem density cannot be used as an indicator of carbon stock. In contrast, Fig. 6 shows a strong correlation between carbon stock and basal area across all study sites ($R^2 = 0.9724$–0.9931), suggesting that basal area is an important indicator of carbon stock. Since basal area can be simply obtained by $\pi \times DBH^2/4$, DBH alone could be measured during field inventories; this would save time and costs.

Table 3
Mean stem density, basal area and carbon stock at all study sites (per hectare).

Statistics	Kratie			Ratanakiri			Stung Treng			Mean ALL		
	SD	BA	CS	SD	BA	CS	SD	BA	CS	SD	BA	CS
Total plots		59			60			60			179	
Mean	245.9	19.5	95.9	433.7	23.8	101.5	353.5	23.2	102.2	344.9	22.2	99.8
CI90	21.3	1.2	6.6	25.3	1.7	9.2	16.0	1.8	8.9	13.9	0.9	4.8
Percentage of the mean	8.6%	6.3%	6.8%	5.8%	7.3%	9.1%	4.5%	7.6%	8.7%	4.0%	4.0%	4.8%
Min	80.0	9.5	56.0	200.0	12.6	67.0	180.0	8.6	44.9	233.3	14.5	81.8
Max	630.0	35.2	216.8	730.0	48.8	322.0	490.0	59.4	396.6	506.7	34.3	216.8
ANOVA single factor (95%) for all study sites							SD		BA		CS	
F values							53.19032		5.79076		0.45492	
P values							0.00000		0.00367		0.63524	

Note 1: Units for SD (stem density), BA (basal area) and CS (carbon stock) are trees ha^{-1}, m^2 ha^{-1} and MgC ha^{-1}, respectively.
Note 2: UNFCCC's Allowable Percentage of the Mean is 10% (UNFCCC, 2002).

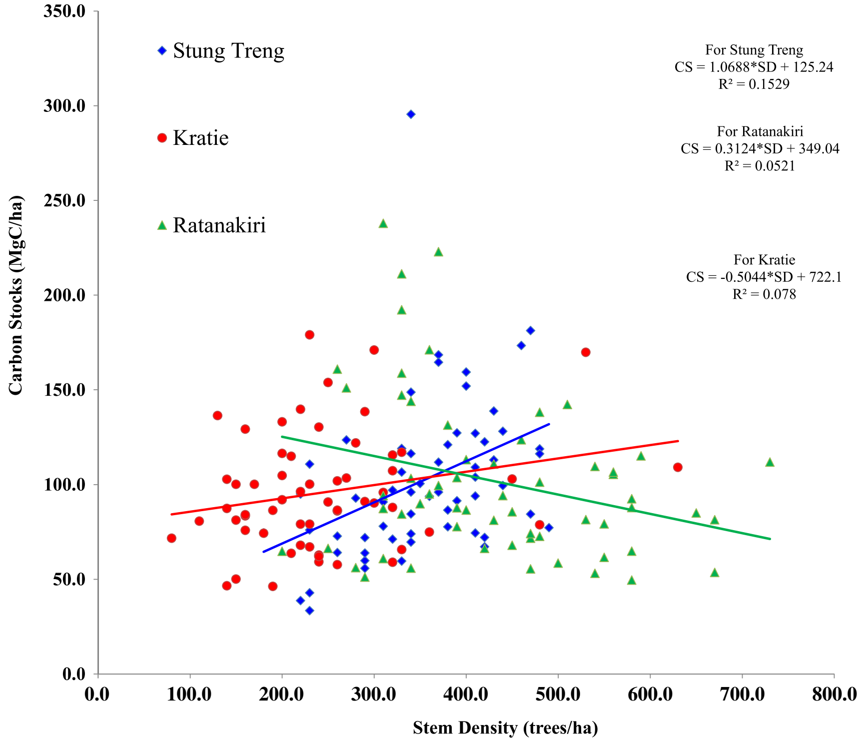

Fig. 5. Distribution of carbon stocks and stem densities at all study sites.

4. Discussion

4.1. Study uncertainties

Previous studies in Cambodia found that there were 37–154 tree species in the evergreen forest of Kampong Thom province (Kim Phat et al., 2000; Top et al., 2009, 2004) and 57 species in Preah Vihear province (Kao and Iida, 2006). Other studies found similar numbers of species in Costa Rican rain forest (Finegan et al., 1999), Western Ghats in South India (Pélissier et al., 1998) and in a community forest in Bhutan (Buffum et al., 2008). Our study found 79 tree species, with 56, 63 and 51 species at the Kratie, Ratanakiri and Stung Treng sites, respectively, well within the range of previous studies. By comparison, approximately 200 species are reported for primary lowland dipterocarp forests in Borneo (Sist and Saridan, 1999) and Amazonian rain forests (Brewer et al., 2002; Phillips and Gentry, 1994). Forests in Borneo and the Amazon are tropical rain forests, and therefore, may contain more species because the forests in our study are monsoon forests, where there is less rainfall and a poorer soil condition than found in typical tropical rain forests.

The results of our data analysis showed variations in stem density, basal area and carbon stock for trees with a DBH ≥ 10 cm. Stem density at the study sites was well within the range of previous studies from the tropics (Table 4). For instance, mean stem density was estimated to be 356.0, 530.0, 503.0, 480.0, 508.0, 448.4 and 530.2 trees ha^{-1}, respectively, in central Cambodia (Kim Phat et al., 2000); East Kalimantan, Indonesia; Amazon, Brazil; South India (Pélissier et al., 1998); Sarawak,

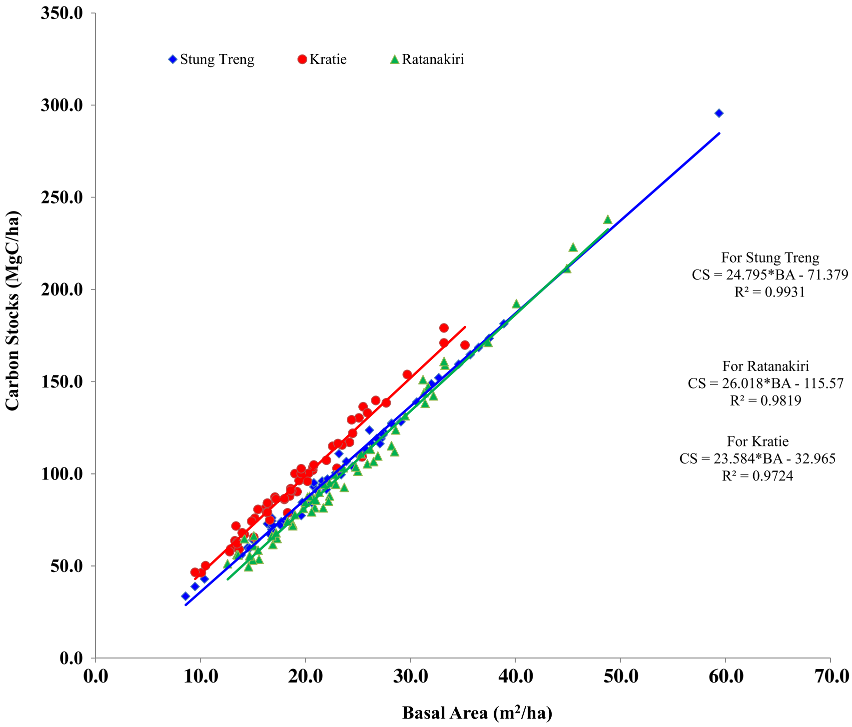

Fig. 6. Distribution of carbon stocks and basal areas at all study sites.

Malaysia and Kampong Thom Province, Cambodia (Kammesheidt et al., 2003; Kao and Iida, 2006; Kim Phat et al., 2000; Pélissier et al., 1998; Sist and Ferreira, 2007; Sist and Nguyen-Thé, 2002; Top et al., 2004; Van Gardingen et al., 2003).

Mean basal areas (19.5 ± 1.2, 23.8 ± 1.7 and 23.2 ± 1.8 m^2 ha^{-1}) at our study sites (Kratie, Ratanakiri and Stung Treng, respectively) were lower than those in previous studies of primary tropical rain forests, i.e. 31.5 ± 4.2 m^2 ha^{-1} (±SE; standard error) in East Kalimantan (Sist and Nguyen-Thé, 2002), 32.3 m^2 ha^{-1} in West Kalimantan (Cannon et al., 1994), 35.5±2.8 m^2 ha^{-1} for 11 locations in Borneo and Peninsular Malaysia, 34.4±1.4 m^2 ha^{-1} for 15 plots in Central Kalimantan (Van Gardingen et al., 2003) and 28.1 m^2 ha^{-1} in Amazonia (Lewis et al., 2004). Our values were closer to the values reported for logged-over forests, i.e. 16.4 m^2 ha^{-1} in West Kalimantan (Cannon et al., 1994), 25.2 m^2 ha^{-1} in East Kalimantan (Van Gardingen et al., 2003), 26.0 ± 6.4 m^2 ha^{-1} and 24.1 ± 7.1 m^2 ha^{-1} in Sarawak, Malaysia (Kammesheidt et al., 2003) and 20.3–25.9 m^2 ha^{-1} in the Brazilian Amazon (Silva et al., 1995). To some extent, the forests in all study sites had been logged prior to this reduced impact logging experiment in 2007. As shown in Fig. 6, some plots had a basal area comparable to that in primary tropical rain forests (basal area greater than 30 m^2 ha^{-1}), suggesting that these plots had not been logged prior to the current logging experiment. A lower basal area could also be due to the geography of the forests in our study; forests in Cambodia are monsoon forests, where rainfall and other natural conditions are less favourable than those in tropical rain forests such as those in Indonesia, Malaysia, lowland Amazonia and the Congo Basin.

Deciding what allometric equations to use for estimating aboveground biomass and carbon stocks in forests can also affect the results of our study. For instance, Basuki et al. (2009) found that use of equations developed by Brown (1997) and Chave et al. (2005) resulted in overestimating aboveground biomass of 43%–107% in their study sites. However, if equations developed by Ketterings et al. (2001) were used instead, aboveground biomass was underestimated. To increase accuracy of estimation of forest biomass as well as carbon stocks, developing equations based on data from the forests in question becomes necessary.

4.2. Implications for ecosystem services

Achieving emission reductions. Carbon is an important ecosystem service provided by forests. Although REDD+ scheme is not a mandatory mitigation option, the Bali Action Plan encourages the voluntary implementation of REDD+ activities to generate carbon credits for sales. Carbon credits from REDD+ projects totalled 22.6 $TgCO_2$, increasing approximately 35% from the previous year, and had an average carbon price of US$4.2 per $MgCO_2$ in 2013 (Peters-Stanley et al., 2014). Using US$4.2, and by assuming that 50% of deforestation of semi-evergreen forests in Cambodia can be avoided, carbon revenues were estimated to be US$17.4 million annually or about 0.1% of Cambodian GDP in 2014.

Achieving biodiversity safeguards. REDD+, through the Cancun Agreement reached at COP16, also includes safeguards to ensure that its activities do not cause negative impacts on biodiversity and social or environmental values. In addition, the

Table 4
Carbon stocks by DBH class across the tropics (MgC ha^{-1}).

DBH (cm)	≥50	30–49	20–29	10–20	Total	Source
Asia						
Carbon stocks in unlogged evergreen forest in Preah Vihear, Cambodia (DBH ≥ 10 cm, MgC)	37.29	17.01	14.88	22.91	92.09	Kao and Iida (2006)
Stand volume of logged evergreen forest in Preah Vihear, Cambodia (DBH ≥ 10 cm, MgC)	26.28	14.28	13.39	21.32	75.28	Kao and Iida (2006)
Carbon stocks in unlogged evergreen forest in Kampong Thom, Cambodia (DBH ≥ 5 cm, MgC)	65.63	22.47	16.03	17.11	121.25	Kim Phat et al. (2000)
Carbon stocks in forests in East Kalimantan, Indonesia (MgC)	112.02	45.62	22.76	18.94	199.35	Sist et al. (1998)
Carbon stocks in forests in Southeastern Sabah (Malaysia) prior to conventional logging	121.5 (40+ cm)	23.3 (20–40 cm)		11.5	156.3	Pinard and Putz (1996)
Carbon stocks in forests in Southeastern Sabah (Malaysia) after to conventional logging	43.0 (40+ cm)	14.5 (20–40 cm)		5.5	63.0	Pinard and Putz (1996)
Carbon stocks in forests in Southeastern Sabah (Malaysia) prior to reduced impact logging	118.0 (40+ cm)	23.0 (20–40 cm)		12.5	152.5	Pinard and Putz (1996)
Carbon stocks in forests in Southeastern Sabah (Malaysia) after reduced impact logging	70.5 (40+ cm)	21.0 (20–40 cm)		8.0	99.5	Pinard and Putz (1996)
Latin America						
Carbon stocks in forests in Panama (DBH ≥ 1 cm, MgC)	69.45	31.85	15.25	20.25	136.80	Chave et al. (2005)
Carbon stocks prior to harvesting in Precious Woods Amazon, Brazil (MgC)	55.44	47.26	21.52	26.33	150.56	Wellhöfer (2002)
Forests in Central Amazon (DBH ≥ 10 cm, MgC)	45.52	60.69	32.25	24.31	162.75	Nascimento and Laurance (2002)
Carbon stocks in eastern Brazilian Amazon forests prior to conventional logging. Logging reduced 26% of carbon stocks but carbon stocks recovered to 100.1 MgC after 16 years of logging					130.0	West et al. (2014)
Carbon stocks in eastern Brazilian Amazon forests prior to reduced-impact logging. Logging reduced 17% of carbon stocks but carbon stocks recovered to 132.0 MgC after 16 years of logging					132.0	West et al. (2014)
This Study						
Kratie	7.3	15.5	37.5	35.5	95.8	
Ratanakiri	13.4	17.3	37.8	33.0	101.5	
Stung Treng	10.7	14.7	36.7	40.1	102.2	
Mean	**10.5**	**15.8**	**37.3**	**36.2**	**99.8**	

Convention on Biological Diversity at COP11 recognised the importance of biodiversity safeguards and effective design of REDD+ activities in safeguarding biodiversity. Locally specific information, such as tree species, relative carbon stocks, level of threat to individual tree species, wood demand and price, is obviously needed. In 2006, Cambodia's FA, in collaboration with the Cambodia Tree Seed Project of the DANIDA (Denmark's Development Corporation), identified 34 tree species as priorities for gene conservation in Cambodia (FA, 2006). Of these, 17 were found in the study sites (Table 5). Cambodia classifies commercial tree species into four grades: luxury, grade I, grade II and grade III (Kim et al., 2006). Trees whose utilisation is not known are classified as 'out of grade'. Tree species in the luxury grade are significantly threatened, but they usually have higher prices, ranging from US\$1000 to US\$50, 000 m^{-3} depending on where they are sold. Trees of commercially valuable species are the main target for illegal loggers who sell timber at various prices according to the location of the sale. A timber royalty is applied according to grade, ranging from US\$32 m^{-3} (grade III) to US\$210 m^{-3} (luxury grade). It is obviously important that any management interventions explicitly state the threat levels of individual tree species and the necessity to safeguard such species in any REDD+ activities that not only result in carbon emission reductions but also safeguard biodiversity.

5. Conclusion

We analysed data from 179 sample plots in semi-evergreen forests of three provinces in Cambodia. On average, stem density, basal area and carbon stock were 344.9 ± 13.9 trees ha^{-1}, 22.2 ± 0.9 m^2 ha^{-1} and 99.8 ± 4.8 MgC ha^{-1}, respectively. In total, 51–63 species, belonging to 39 families, were found. *Lagerstroemia calyculata* Kurz, *Syzygium sp.*, *Shorea vulgaris*, *Irvingia malayana* and *Vatica astrotricha* were dominant in terms of stem density, and *Lagerstroemia calyculata* Kurz was dominant in terms of basal area and carbon stock. We found that basal area is an important indicator of carbon stock, exhibiting a high correlation, whereas stem density had a weak correlation with carbon stock. Using the average carbon stock found in our study, we estimated annual carbon emissions due to deforestation of semi-evergreen forest to be 8.3 $TgCO_2$ between 2002 and 2010.

Since the error in our findings (i.e. confidence interval) for carbon stocks is well within the error allowed under the UNFCCC methodological guidelines, the carbon stocks reported here may be used for estimating forest carbon stocks, stock changes and baseline emissions in Cambodia. These baseline emissions are important for Cambodia, as well as other developing countries, in deciding the forest reference emission level, which is required under the REDD+ scheme of the UNFCCC. Information on tree species relative to carbon stocks and levels of threat is useful for designing effective REDD+ activities to safeguard tree biodiversity and related socioeconomic values for local people.

Table 5
Levels of threat, timber grades and timber prices of species found at the study sites.

Botanical name	Level of threat[a]	Timber grade	Timber royalty[b] (US$ m^{-3})	Price of sawnwood at roadside near village (US$ m^{-3})	Price of sawnwood at various locations (US$ m^{-3})
Dalbergia bariensis, Pierre	5	Luxury	112–210		3900–50,000[c]
Afzelia xylocarpa (Kurz) Craib	5	Luxury	112–210		14,000–20,000[c]
Diospyros crumenata	5	Luxury	112–210		
Pterocarpus pedatus	5	Luxury	112–210		
Hopea odorata	4	I	60		
Shorea cochinchinensis Pierre	4	I	60		
Dasymachalon lamentaceum	4	Luxury	112–210		
Diospyros bejaudi Lecomte	4	Luxury	112–210		
Fagraea fragrans Roxb	4	Luxury	112–210		
Albizzia lebbek	4	Luxury	112–210		
Cinnamomum cambodianum	4				
Diospyros nitida	3	Luxury	112–210		
Tarrietia javanica	3	I	60		500[d]
Xylia dolabriformis Benth	3	I	60		
Shorea vulgaris	3	II	40		
Dipterocarpus alatus	2	II	40		460[d]
Anisoptera costata Kort	2	II	40	250[d]	430[d]
Cassia siamensis		Luxury	112–210		
Diospyros helferi		Luxury	112–210		
Sindora cochinchinensis Baill		I	60	350[d]	550[d]
Lagerstroemia calyculata Kurz		I	60		500[d]
Crudia chrysantha		I	60		
Dialium cochinchinensis Pierre		I	60		
Peltophorum ferrugineum Benth		I	60		
Terminalia tomentosa		I	60		
Artocarpus sempervirens		I	60		
Vitex sp.		I	60		
Dipterocarpus intricatus Dyer		II	40		
Dipterocarpus tuberculatus		II	40	120[d]	
Shorea farinose, C.Fisch		II	40		
Vatica astrotricha		II	40		
Vatica philastreana Pierre		II	40		
Calophyllum calaba		III	32		
Terminalia mucronata, Graib et Huth		III	32		
Crypteronia paniculata Blume		III	32		
Hydnocarpus anthelmitica		III	32		
Cratoxylon prunifolium Dyer		III	32		
Garcinia schomburghi		III	32		
Aglaia cambodiana		III	32		
Sandoricum indicum		III	32		
Artocarpus asperula, Gagn		III	32		
Carallia lucida Roxb		III	32		

Note:.
[a] Based on FA (2006).
[b] Based on Kim et al. (2006).
[c] Based on So et al. (2010).
[d] Based on Blackett (2008).

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.gecco.2015.11.007.

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