ORIGINAL ARTICLE

A feasibility study for determining the mean annual aboveground biomass gain of tropical seasonal forests in Cambodia

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ABSTRACT

To study the feasibility of determining the mean annual aboveground biomass gain of tropical seasonal forests at the national scale, we estimated the gain (i.e., increase due to growth of living trees) and loss (i.e., decrease due to tree death) of aboveground tree stand biomass (stand AGB) using 49 permanent sample plots distributed nationwide for 139 observation periods from 2005 to 2015 in Cambodia. In a linear mixed-effects model, stand AGB gain was predicted to increase with the initial stand AGB: Stand AGB gain = 0.0165 Stand AGB + 2.20 (n = 139, P < 0.0001, R2 = 0.4531, RMSE = 2.84), where Stand AGB gain is the sum of tree AGB growth (Mg ha⁻¹ year⁻¹), and Stand AGB is the sum of initial tree AGBs (Mg ha⁻¹). The mean estimated stand AGB gain was 4.79 Mg ha⁻¹ year⁻¹ for an average initial stand AGB of 155.5 Mg ha⁻¹. The annual stand AGB loss was <20% of the initial stand AGB and the influence of stand AGB loss on stand AGB gain was negligible. The 2006 IPCC Guidelines for National Greenhouse Gas Inventories assigned stand-age-dependent values of default annual stand AGB gain for tropical natural forests. However, age is difficult to determine in tropical trees. Our stand-age-independent approach based on the stand AGB offers a practical method for assessing the AGB gain of tropical natural forests.

Key words: 2006 IPCC Guidelines, logging, national level, REDD-plus, the gain-loss method

INTRODUCTION

Tropical seasonal forest is the predominant vegetation of Indochina. In Cambodia, various anthropogenic interventions have affected the forest (Rundel 1999), including logging (Forestry Administration 2010) and fires (Wood 2012). Information on forest biomass gain is indispensable to avoid the overuse of forest resources and manage forests sustainably, and to estimate greenhouse gas (GHG) emissions from forests to facilitate climate change mitigation initiatives such as the United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD-plus) (UNFCCC 2009). Nationwide forest carbon stocks have rarely been monitored in tropical countries using permanent sample plots (PSPs). In Cambodia, PSPs have been established nationwide, from which we can obtain a reasonably accurate estimation of the forest carbon and its changes. However, information on forest biomass gain has been reported only at the provincial level in Cambodia (Top et al. 2004).

Two methods of calculating changes in carbon stocks are described in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: the gain-loss method and the stock-difference method (IPCC 2006). For biomass carbon, the gain-loss method calculates annual biomass changes based on the difference between biomass gain (the annual increase in biomass due to biomass growth) and loss (the annual decrease by wood removal and losses from disturbances by fire, insects, diseases, etc.). In the stock-difference method, the change in biomass (which reflects biomass gains and losses) is determined from the difference in biomass measured at different time points.

The stock-difference method, in which the difference in carbon stocks at two different time points is presumed to equal the emissions and removals during the corresponding
interval, is considered more widely applicable than the gain-loss method (Sato 2012a) at higher tiers (tiers 2 and 3, IPCC 2006). However, neither the continuous maintenance of many sample plots nor frequent tree measurements for forest biomass determinations is necessarily easy in countries with frequently changing land use (e.g., when forests with PSPs are destroyed), given that a sufficient number of plots and frequent updating of the forest data are required (Kiyono et al. 2010). In addition, when unusual wood removal occurs between the tree measurements, the change in forest biomass values using the stock-difference method would likely have limited scientific meaning and generality. When, for these reasons, the stock-difference method is not practical over the long term, the gain-loss method provides an alternative for estimating forest biomass change. The gain-loss method is built on an ecological understanding of how forests grow and on information about natural and anthropogenic processes that result in carbon losses (Murdiyarso et al. 2008). The forest biomass gains should have ecological meaning. IPCC (2006) provided default forest biomass gain values for the gain-loss method at tier 1, in cases where country-specific gain values are lacking. Countries that use the gain-loss method at higher tiers (tiers 2 and 3) are required to determine the forest biomass gain and loss values as their own country-specific emission factors to calculate the forest biomass change at the country level.

In Cambodia, permanent sample plots (PSPs) have been set aside by the Forestry Administration (FA), the Ministry of Agriculture, Forestry and Fisheries (MAFF) and the Ministry of Environment (MoE) in tropical seasonal natural forests (evergreen forests, EFs; semi-evergreen forests, SEFs; and deciduous forests, DFs), which occupy around 90% of the forest land in the country (Samreth et al. 2012). The PSPs are distributed throughout Cambodia and can be used as a scientific basis for determining typical mean annual rates of biomass gain and loss as country-specific emission factors at tiers 2 and 3 (IPCC 2006).

In this study, we calculated the gain (i.e., increase due to growth of living trees), loss (i.e., decrease due to tree death), and change in the aboveground tree stand biomass (hereafter, stand AGB) in 49 PSPs located in tropical seasonal forests throughout Cambodia (Fig. 1) during 139 observation periods between 2005 and 2015. We then estimated the mean annual stand AGB gain at the country level based on the relationships between initial stand AGB and stand AGB gain considering conditions possibly affecting stand AGB gain, e.g., initial stand AGB and forest type. Finally, we used estimates of the mean annual stand AGB gain as a provisional measure of country-specific
mean annual stand AGB gain and compared these values with the corresponding IPCC default values.

STUDY SITES AND METHODS

Forest definition and forest types in Cambodia

Forests in Cambodia include three main forest-cover regions: in the Mekong basin, along the coast of Tonlé Sap Lake, and in the Krâvânh (Cardamom) Mountains (Akinaga 1943). In addition, they can be divided into lowland forests, montane forests, and azonal forest formations (Rundel 1999). All are subject to a tropical monsoon climate, with a pronounced rainy season from around May to October and a dry season from November to around April. The mean annual temperature is 26.5–30°C except at high altitudes on mountains. The geology is mainly sandy alluvium, shale and other impermeable rock, sandstone, and conglomerates in hilly regions and clayish and siltly alluvium in the lowlands (Crocker 1962). The mean annual precipitation (MAP) depends on the region but ranges from 1,400 to >4,000 mm (1990–2012, World Bank Group 2015).

For the purposes of the United Nations Framework Convention on Climate Change (UNFCCC), Cambodia defines forests as follows: a minimum tree crown cover of 10%, a minimum area of 0.5 ha, and a minimum tree height of 5 m (http://cdm.unfccc.int/DNA/index.html). Cambodian forests are classified as protected forest, valid concessions, and other designations managed by FA; protected areas for fisheries managed by MAFF; and protected areas such as national parks and wildlife sanctuaries managed by MoE (Samreth et al. 2012). Of these, the largest area is FA forests (82%), followed by MoE forests (18%); MAFF forests cover a very limited area (<1%). The main forest types are EF (34.2%) and DF (43.7%), followed by SEF (12.7%) (Samreth et al. 2012).

The mean carbon stocks of four carbon pools (above- and belowground biomass, deadwood, and litter) per unit land area were estimated in a previous study (Kiyono et al. 2010) using the MoE-PSP data for three main forest types (EF, including SEF, DF, and secondary forests). By using the FA-PSP data, the mean carbon stocks of two carbon pools (above- and belowground biomasses) of trees per unit land area were estimated for two main forest types (EF, including SEF, and DF) (Samreth et al. 2012). EFs tended to have a larger carbon stock than did DFs in terms of biomass (Kiyono et al. 2010, Samreth et al. 2012) and soils within the same geological formations (Toriyama et al. 2011).

PSP data

The census data of trees in the FA- and MoE-PSPs (Table 1), where trees have been measured at intervals of 1–2 years, were selected for use in this study. The PSPs were distributed in all three main forest-cover regions (Akinaga 1943) at 23–500 m above sea level, and were set relatively near forest roads to facilitate monitoring and to obtain data on forests disturbed in various ways by human impact.

The FA-PSPs used in this study were of two types. The 12 PSPs in the first type were clustered in groups of four PSPs (each 50 × 50 m) in three provinces (Kratie, Ratanakiri, and Mondulkiri). Data including botanical name and diameter at breast height (DBH) were collected for PSP trees with DBH ≥5 cm. The 15 PSPs (each 30 × 40 m) in the second type were established separately in Kampong Thom Province. Data on botanical name, DBH, tree height, and so on were collected for trees with DBH ≥5 cm. The 22 MoE-PSPs were nested plots set up by establishing 20 × 100-m and 5 × 40-m plots in the eight provinces (six PSPs in Kratie and two PSPs in each of Kampông Chhnang, Kampông Speu, Siem Reap, Preah Vihear, Kampot, Sihanoukville, Koh Kong, and Pursat). Data, including botanical name and DBH, were collected for trees with DBH ≥30 cm in the 20 × 100-m plots and with DBH ≥5 cm in the 5 × 40-m plots.

DBH was measured using a measuring tape at 1.3-m height, except in the case of trunk irregularities or branching, in which case it was measured below or above that height. Tree height was measured using a handheld compass (Suunto, Finland) or an ultrasound distance measure (Vertex IV: Haglöf, Sweden). Nomenclature followed the system described by Pauline (2000). Common tree species included Dehaasia cuneata, Dipterocarpus costatus, Irvingia malayana, Lithocarpus elephantum, Nephelium hypoleucum, Peltophorium dasyrhachis, and Syzygium lineatum in the EFs; Dipterocarpus intricatus, Dipterocarpus tuberculatus, Peltophorium ferrugineum, Shorea obtusa, Shorea siamensis, Terminalia mucronata, Terminalia tomentosa, and Xyli dolabriformis in the DFs; and Lagerstroemia cochinchnensis and Dipterocarpus dyeri in the SEFs. The tree census was irregularly repeated 2–9 times per PSP in the dry seasons of 2005–2015. Although no National Forest Inventory (NFI) has been carried out in Cambodia, the projected area of the Cambodian PSSPs, 0.12–0.25 ha, was similar to the 0.1–0.5 ha often used in the NFIs of other countries (Sato 2012b).

For simplification, in the following data analysis, SEF
Table 1. General description of the permanent sample plots (PSPs) used in this study.

| PSP no. | Province       | Forest type | Dominant species | Elevation m | MAP m | Plot size m² | Tree census¹ | Entity with responsibilities | PSP no. | Province       | Forest type | Dominant species | Elevation m | MAP m | Plot size m² | Tree census¹ | Entity with responsibilities |
|---------|----------------|-------------|------------------|-------------|-------|--------------|--------------|-----------------------------|---------|----------------|-------------|------------------|-------------|-------|--------------|--------------|-----------------------------|
| 1       | Kampong Thom   | EF          | Vo               | 102         | 1737  | 1200         | 2009, 2010   | FA                          | 26      | Ratanakiri     | DF          | So               | 122         | 1886  | 2500         | 2013, 2015   | FA                          |
| 2       | Kampong Thom   | EF          | Vo               | 93          | 1737  | 1200         | 2009, 2010   | FA                          | 27      | Ratanakiri     | DF          | So               | 122         | 1886  | 2500         | 2013, 2015   | FA                          |
| 3       | Kampong Thom   | EF          | Dc               | 111         | 1737  | 1200         | 2009, 2010   | FA                          | 28      | Ratanakiri     | DF          | So               | 122         | 1886  | 2500         | 2013, 2015   | FA                          |
| 4       | Kampong Thom   | EF          | Vo               | 91          | 1737  | 1200         | 2009, 2010   | FA                          | 29      | Ratanakiri     | DF          | So               | 122         | 1886  | 2500         | 2013, 2015   | FA                          |
| 5       | Kampong Thom   | EF          | Dl               | 95          | 1737  | 1200         | 2009, 2010   | FA                          | 30      | Mondulkiri     | DF          | So               | 345         | 1821  | 2500         | 2012, 2013, 2015 | FA                          |
| 6       | Kampong Thom   | EF          | Da               | 102         | 1737  | 1200         | 2009, 2010   | FA                          | 31      | Mondulkiri     | DF          | So               | 345         | 1821  | 2500         | 2012, 2013, 2015 | FA                          |
| 7       | Kampong Thom   | EF          | Co               | 76          | 1737  | 1200         | 2009, 2010   | FA                          | 32      | Mondulkiri     | DF          | So               | 345         | 1821  | 2500         | 2012, 2013, 2015 | FA                          |
| 8       | Kampong Thom   | EF          | Pf               | 66          | 1737  | 1200         | 2009, 2010   | FA                          | 33      | Mondulkiri     | DF          | So               | 345         | 1821  | 2500         | 2012, 2013, 2015 | FA                          |
| 9       | Kampong Thom   | EF          | Vo               | 105         | 1737  | 1200         | 2009, 2010   | FA                          | 34      | Kratie         | DF          | Dr               | 69          | 1795  | 2500         | 2012, 2013, 2015 | FA                          |
| 10      | Kampong Thom   | EF          | Ag               | 94          | 1737  | 1200         | 2009, 2010   | FA                          | 35      | Kratie         | DF          | Ds               | 69          | 1795  | 2500         | 2012, 2013, 2015 | FA                          |
| 11      | Kampong Thom   | EF          | Ag               | 113         | 1737  | 1200         | 2009, 2010   | FA                          | 36      | Kratie         | DF          | Tt               | 69          | 1795  | 2500         | 2012, 2013, 2015 | FA                          |
| 12      | Kampong Thom   | EF          | Dc               | 109         | 1737  | 1200         | 2009, 2010   | FA                          | 37      | Kratie         | DF          | Ds               | 69          | 1795  | 2500         | 2012, 2013, 2015 | FA                          |
| 13      | Kampong Thom   | EF          | Sc               | 95          | 1737  | 1200         | 2009, 2010   | FA                          | 38      | Preah Vihear   | DF          | Di               | 76          | 1745  | 2000         | 2005, 2006, 2008, | MoE     |
| 14      | Kampong Thom   | EF          | Sp               | 95          | 1737  | 1200         | 2009, 2010   | FA                          | 39      | Preah Vihear   | DF          | So               | 73          | 1745  | 2000         | 2005, 2006, 2008, | MoE     |
| 15      | Kampong Thom   | EF          | Vo               | 113         | 1737  | 1200         | 2009, 2010   | FA                          | 40      | Kratie         | DF          | Dt               | 68          | 1748  | 2000         | 2010, 2011, 2012, | MoE     |
| 16      | Siem Reap      | EF          | Dd               | 23          | 1486  | 2000         | 2005, 2006, 2008, | MoE     |
| 17      | Siem Reap      | EF          | Dd               | 28          | 1486  | 2000         | 2005, 2006, 2008, | MoE     |
| 18      | Kratie         | EF          | Im               | 111         | 1748  | 2000         | 2005, 2006, 2008, | MoE     |
| 19      | Kratie         | EF          | Im               | 89          | 1748  | 2000         | 2005, 2006, 2008, | MoE     |
| 20      | Kratie         | EF          | Dc               | 109         | 1748  | 2000         | 2010, 2011, 2012, | MoE     |
| 21      | Kampong        | EF          | Le               | 688         | 2530  | 2000         | 2005, 2006, 2008, | MoE     |
| 22      | Kampong        | EF          | Sl               | 675         | 2530  | 2000         | 2005, 2006, 2008, | MoE     |
| 23      | Sihanoukville  | EF          | At               | 31          | 3013  | 2000         | 2005, 2006, 2008, | MoE     |
| 24      | Koh Kong       | EF          | Nh 80           | 3100        | 2000   | 2005, 2006, 2008, | MoE     |
| 25      | Koh Kong       | EF          | Im               | 65          | 3100  | 2000         | 2011, 2012, 2013, 2014, 2015 | MoE     |

¹ Species with the largest AGB in the PSP: Ag, Anisoptera glabra; Ac, Aglaia elaeagnoides; At, Albizia thorelli; Co, Croton oblongifolius; Di, Dipterocarpus longan; Da, Dipuncus alatus; Df, Dipuncus dyeri; Ds, Dipuncus tuberculatus; Eu, Eugenia sp.; Im, Irvingia malayana; Le, Lithocarpus ekheptanum; Nh, Nephelium hypoleucum; Pf, Peltophorum ferrugineum; Sc, Syzygium cumini; Sl, Syzygium linearis; Sp, Syzygium polyanthum; So, Shorea obtusa; Ss, Shorea siamensis; Vo, Vatica odorata
² Minimum DBH measured, 5 cm
³ Mean annual precipitation (World Bank 2015)
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was included in the EF category, following previous studies (Kiyono et al. 2010, Samreth et al. 2012), given that the tree biomasses of these two forest types were similar. In the MoE-PSPs, EF included SEF, and secondary forests were considered EFs or DFs according to their tree composition.

Data from PSPs 18 and 21 during the period 2006–2008 were not used because there were some inconsistencies in tree numbering or tree size data. Overall, EF was represented by 25 PSPs, with data from 63 observation periods, and DF was represented by 24 PSPs, with data from 76 observation periods (Table 1).

Estimating tree AGB

Tree AGB was estimated using DBH data and the following generic allometry equation for tropical and subtropical trees (Kiyono et al. 2006):

\[ \text{Tree AGB} = 11545 \times DBH^{1.24} \times \text{ht}^{0.631} \times \text{ba}^{0.631} \]

where \( \text{Tree AGB} \) is the sum of the aboveground organ (leaf, branch, stem, etc.) weights (kg), and \( \text{ba} \) is the basal area of a stem at a height of 1.3 m (m\(^2\)). The equation is derived from the data of trees with 1 ≤ DBH ≤ 51 cm.

The allometry equations with parameters of tree height and/or stem wood density were not applicable in this study because some PSPs (22% of the total) lack tree height data, and others (37% of the total) lack botanical names, often used to assess stem wood density. We used the allometry equation with parameters for tree height (\( \text{ht} \), m) and stem wood density (\( D \), kg m\(^{-3}\)):

\[ \text{Tree AGB} = 2.171 \times DBH^{1.62} \times \text{ht}^{0.978} \times D^{0.631} \]

\( n = 515, R^2 = 0.987, P < 0.0001 \),

(Kiyono et al. 2006)

in the PSPs with corresponding parameter data. The difference (%) in the stand AGB results between Eqs. 1 and 2 was calculated as

\[ \frac{(\text{stand AGB by Eq. 1} - \text{stand AGB by Eq. 2})}{(\text{stand AGB by Eq. 1})} \times 100 \]

We found a mean difference of \(-9 \pm 10\%\) (\( n = 10 \)) in EFs and a mean difference of \(3 \pm 9\%\) (\( n = 12 \)) in DFs. The differences were considered small, although they suggest an influence of tree height on stand AGB.

The tree AGB values were summed to define stand AGB (AGB per unit land area). For PSPs with available tree height data, tree height for DBH of 40 cm (\( \text{ht}_{40} \)) was estimated based on the empirical relationship between DBH and tree height, without extrapolation, in each PSP.

Estimating annual gain, loss, and change in stand AGB

The biomass gain-loss method, based on estimates of annual change in biomass from estimates of biomass gain and loss (IPCC 2006), is defined as

\[ \text{Stand AGB change} = \text{Stand AGB gain} - \text{Stand AGB loss} \]

where \( \text{Stand AGB change} \) is the annual change in stand AGB, \( \text{Stand AGB gain} \) is the annual increase in stand AGB due to tree growth, and \( \text{Stand AGB loss} \) is the annual decrease in stand AGB due to tree death. Following this equation, the annual stand AGB gain of the PSP was equal to the sum of the annual AGB growth of the survivor and recruit trees in the observation period. To avoid overestimating the AGB growth in the recruit trees, the DBH of the recruit trees 1–2 year(s) before recruitment was assumed to be 5 cm (the minimum DBH measured). To avoid overestimating the stand AGB of the PSP, however, the recruited trees were not included in AGB calculation for the years before the recruitment. The sum of the AGB of the trees that died during the observation period was used to calculate the annual stand AGB loss. The cause of death was not specified because for some dead trees it was difficult to determine from the records whether death was due to wood removal or natural disturbances. Valuable timber species trees with DBH ≥40 cm were listed to calculate the tree density of timber species in the PSPs.

A linear mixed-effects model was used to determine which variables were independently associated with the stand AGB gain, where the initial stand AGB, forest type (EF or DF), and their interaction (initial stand AGB \( \times \) forest type) were incorporated into the analysis as independent effects. The linear mixed-effects model was used to consider random effects attributable to the differences in the number of observation periods per PSP because the number of observation periods per PSP differed among the PSPs (1–8, Table 1). The final predictive model was identified as that with the lowest Bayesian information criterion (BIC, Schwarz 1978).

Statistical analysis was conducted using JMP statistical software (ver. 10.0, SAS Institute, Cary, NC, USA).
RESULTS

Annual stand AGB gain

The observed stand AGB gain was 0.101–16.88 Mg ha\(^{-1}\) year\(^{-1}\) in EFs and 0.00282–9.58 Mg ha\(^{-1}\) year\(^{-1}\) in DFs (Fig. 2). The linear mixed-effects model indicated that the stand AGB gain significantly increased with the initial AGB \((P=0.0235)\). The effect of forest type was not significant \((P=0.0989)\), and there was no significant difference in stand AGB gain between EFs and DFs when the initial stand AGB was the same. The initial stand AGB \(\times\) forest type interaction was not significant \((P=0.9846)\), suggesting that the slopes of the relationships between initial stand AGB and stand AGB gain were not significantly different between EFs and DFs.

The most accurate predictive model identified by the lowest BIC was a linear mixed-effects model using the initial stand AGB as the independent variable and PSP as a random effect. The relationships between initial stand AGB and stand AGB gain (Fig. 2) were approximated by the following equations.

\[
\text{Stand AGB gain} = 0.0165 \times \text{Stand AGB} + 2.20 \quad (n=139),
\]

where Stand AGB gain is the sum of the tree AGB growth (Mg ha\(^{-1}\) year\(^{-1}\)), and Stand AGB is the sum of the initial tree AGBs (Mg ha\(^{-1}\)). The \(P\)-value of the prediction by the final linear mixed-effects model was <0.0001. \(R^2\) and the root mean squares (RMSE) of the errors of the model were 0.4531 and 2.84, respectively.

Forests with large tree \(h_{40}\) values had large stand AGBs \((\text{Stand AGB} = 12.6 \times \text{tree height}_{40} - 134.6 \quad [P=0.0042, \text{RMSE}=17.3])\) in EFs. However, there was no such significant relationship \((P=0.0784)\) in DFs (Fig. 3a) and there was no significant \((P=0.696\) in EFs and 0.504 in DFs) relationship between tree height\(_{40}\) and stand AGB gain for either forest type (Fig. 3b). DFs likely had larger AGBs than EFs when tree height\(_{40}\) was the same because DFs had a greater density of standing trees with DBH \(\geq 20\) cm than EFs when tree height\(_{40}\) was the same.
There was no significant relationship between MAP values and stand AGB gain for either forest type \((P = 0.103\) in EFs and 0.677 in DFs, Fig. 4).

**Annual stand AGB loss**

The annual stand AGB loss was <20% of the total in forests with a relatively large initial stand AGB (≥100 Mg ha\(^{-1}\)), which likely (82% in EFs and 70% in DFs) had ≥10 trees ha\(^{-1}\) of timber species (Adina cordifolia, Anisoptera costata, Calophyllum soulattri, Cratoxylum formosum subsp. formosum, Dalbergia assamica, Diospyros pilosanthera, Diospyros spp., Dipterocarpus costatus, Dipterocarpus intricatus, Dipterocarpus tuberculatus, Irvingia malayana, Lithocarpus elephantum, Nephelium hypoleucum, Pterocarpus indicus, Scaphium macropodum, Shorea guiso, Shorea obtusa, Shorea roxburghii, Shorea siamensis, Shorea vulgaris, Sindora cochinchinensis, Terminalia tomentosa, Vitex pinnata, and Xylia dolabriformis) with DBH ≥40 cm, whereas forests with a smaller initial stand AGB were very unlikely to have such timber species (0% in EFs and 5% in DFs) (Fig. 5). In forests with a stand AGB loss of 5–20% of the initial stand AGB (\(n = 5\) in EFs, Fig. 6a; \(n = 7\) in DFs, Fig. 6b), newly dead trees were timber species with large DBHs (among EFs and DFs, the maximum DBHs in the PSP were 66 ± 15 cm and 34 ± 16 cm, respectively), as listed above, suggesting that for these trees wood removal and its collateral damage were the main cause of death.

**Influence of stand AGB loss on stand AGB gain**

Selective logging can temporarily accelerate the growth of survivors (Silva et al. 1995). However, the influence of annual stand AGB loss did not significantly
impact stand AGB gain in our dataset ($P = 0.645$ in EFs and $P = 0.545$ in DFs, Fig. 7). In forests with a stand AGB loss of $5-20\%$, the stand AGB gain in a year in which there was large stand AGB loss did not significantly differ from the stand AGB gain 1 year earlier (paired t-test, $P = 0.338$, $n = 3$, EFs; $P = 0.204$, $n = 5$, DFs), 1 year later (paired t-test, $P = 0.456$, $n = 3$, EFs; data not available for DFs), or 2 years later (paired t-test, $P = 0.931$, $n = 3$, EFs; data not available for DFs).

### Estimating annual stand AGB gain

Equation 3 was used as a linear regression model to estimate annual stand AGB gain from the initial stand AGB. These estimates (Fig. 2) were in the range of $2.47-7.37$ Mg ha$^{-1}$ year$^{-1}$ in EFs and $3.09-6.42$ Mg ha$^{-1}$ year$^{-1}$ in DFs for initial stand AGBs of $16.4-313.3$ Mg ha$^{-1}$ year$^{-1}$ and $54.1-256.1$ Mg ha$^{-1}$ year$^{-1}$, respectively.

The difference in the initial stand AGB between forest types was significant ($P = 0.0103$, mean $\pm$ SE, $166.0 \pm 12.4$ in EFs and $118.8 \pm 12.5$ Mg ha$^{-1}$ in DFs). The estimated stand AGB gain corresponding to the average initial stand AGB of each forest type was $4.94 \pm 0.77$ (95% confidence interval, CI) Mg ha$^{-1}$ year$^{-1}$ in EFs and $4.16 \pm 0.81$ (95% CI) Mg ha$^{-1}$ year$^{-1}$ in DFs. The mean estimated stand AGB gain was $4.55$ (95% confidence interval [CI] $3.80-5.30$) Mg ha$^{-1}$ year$^{-1}$ for an average initial stand AGB of $142.6$ Mg ha$^{-1}$ without distinguishing between forest types.

### Annual stand AGB change

Overall, the stand AGB increased (Fig. 8) during most observation periods (83% in EFs and 80% in DFs). The initial stand AGB biomass was not significantly correlated with the annual stand AGB change ($P = 0.351$ in EFs and 0.564 in DFs). The stand AGB usually increased even in forests with the largest stand AGB class, by $\sim 300$ Mg ha$^{-1}$ in EFs and $\sim 250$ Mg ha$^{-1}$ in DFs, suggesting that most forests in the present PSPs were not fully mature.

Intense wood removal and its collateral damage strongly decreased the stand AGB (Fig. 8). To estimate these

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Fig. 6. Relationship between initial stand AGB and stand AGB loss in permanent sample plot forests (a) Evergreen forest. (b) Deciduous forest. Circles, forest with stand AGB loss $5-20\%$ year$^{-1}$ compared to the initial stand AGB of $\geq 100$ Mg ha$^{-1}$. Small circles, forest with more than two observation periods.

Fig. 7. Relationship between stand AGB loss and stand AGB gain in permanent sample plot forests (a) Evergreen forest. (b) Deciduous forest. Open circle, forest with stand AGB loss $5-20\%$ year$^{-1}$ compared to the initial stand AGB of $\geq 100$ Mg ha$^{-1}$. Small circles, forest with more than two observation periods.
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was expected to be large when the land was fertile and therefore to serve as an index of climate and/or soil conditions. Although forests with large tree height values had large stand AGBs in EFs, there was no significant relationship with stand AGB gain for either forest type (Fig. 3). MAP is positively and significantly correlated with net primary productivity (NPP) when MAP is < 3,000 mm, as determined by the empirical global NPP–

Fig. 8. Initial stand AGB and annual stand AGB change in permanent sample plot forests
(a) Evergreen forest. (b) Deciduous forest. Open circle, forest in which the stand AGB loss was 5–20 % y⁻¹ compared to the initial stand AGB of ≥100 Mg ha⁻¹. Small circles, forest with more than two observation periods.

intense wood removal cases, the mean annual stand AGB change was 5.19 ± 4.94 Mg ha⁻¹ year⁻¹ (mean ± SD, n = 58) in EFs and 2.80 ± 2.98 Mg ha⁻¹ year⁻¹ (mean ± SD, n = 69) in DFs. When all cases were included, the mean annual stand AGB change decreased to 3.17 ± 8.83 Mg ha⁻¹ year⁻¹ (mean ± SD, n = 63) in EFs and 1.30 ± 6.60 Mg ha⁻¹ year⁻¹ (mean ± SD, n = 76) in DFs.

Samreth et al. (2012) estimated forest tree carbon stocks at the country level in Cambodia in 1998 and 2000 using data from 100 FA-PSPs, but not our PSP data. Based on their estimates of biomass at the two time points, we estimated the mean annual stand AGB change by the stock-difference method (reflecting biomass gains and losses) using the default values for the ratio of belowground biomass to AGB (0.28 for a tropical dry forest, with AGB >20 Mg ha⁻¹, IPCC 2006) and a carbon fraction of 0.5. The mean annual stand AGB change was 3.60 ± 70.92 Mg ha⁻¹ year⁻¹ (mean ± SD, n = 85) for EFs and 0.72 ± 26.82 Mg ha⁻¹ year⁻¹ (mean ± SD, n = 15) for DFs. These mean values for EFs were comparable (113 %) to ours, whereas those for DFs were smaller (56 %) than ours, which were obtained using the gain-loss method: 3.17 ± 8.83 Mg ha⁻¹ year⁻¹ in EFs and 1.30 ± 6.60 Mg ha⁻¹ year⁻¹ in DFs.

Comparison of the country-level mean annual stand AGB gain in this study vs. the IPCC default values

We used estimates of the mean annual stand AGB gain as a provisional measure of the country-specific mean annual stand AGB gain to compare these values with the corresponding IPCC default values. According to the IPCC (2006), tropical seasonal forests in Cambodia belong to the ecological zone of tropical dry forests with a dry period of 5–8 months, mostly during the winter. The default gain value in the gain-loss method provided for this ecological zone of Asia (continental) is 6.0 Mg ha⁻¹ year⁻¹ for forests with a stand age ≤20 years and 1.5 Mg ha⁻¹ year⁻¹ for forests with a stand age >20 years. The stand AGB gains estimated in this study (2.47–7.37 Mg ha⁻¹ year⁻¹ in EFs and 3.09–6.42 Mg ha⁻¹ year⁻¹ in DFs, Fig. 2) were several times higher than the IPCC default value for stand age >20 years (1.5 Mg ha⁻¹ year⁻¹).

DISCUSSION

Country-level annual stand AGB gain in tropical seasonal forests in Cambodia

In this study, we used data from 139 observation periods to calculate annual stand AGB gain and loss in 49 PSPs in the tropical seasonal forests of Cambodia. The results can be considered representative at the country level because the PSPs were distributed nationwide and the observation period was 10 years. In a linear mixed-effects model with parameters of initial stand AGB and forest type, the effect of forest type was not significant, and there was no significant difference in annual stand AGB gain between EFs and DFs when the initial stand AGB was the same (Eq. 3). The mean stand AGB gain was 4.94 Mg ha⁻¹ year⁻¹ and 4.16 Mg ha⁻¹ year⁻¹ in EFs and in DFs, respectively, based on the average initial stand AGB by forest type.

Tree height was expected to be large when the land was fertile and therefore to serve as an index of climate and/or soil conditions. Although forests with large tree height values had large stand AGBs in EFs, there was no significant relationship with stand AGB gain for either forest type (Fig. 3). MAP is positively and significantly correlated with net primary productivity (NPP) when MAP is < 3,000 mm, as determined by the empirical global NPP–
climate relationships (Schuur 2003). Therefore, under the higher MAP conditions of the studied forests, the stand AGB gain was expected to be large (1,486 ≤ MAP ≤ 3,100 mm, Table 1). However, this was not the case for either forest type (Fig. 4).

Stand AGB loss was presumed to influence stand AGB gain. In a tropical rainforest in the Amazon (terra firme), stand AGB gain increased in logged forests in which 23% (range, 8–35%) of the AGB was lost under the management of reduced-impact logging compared to control forests (Mazzei et al. 2010). In a young (30 years old) temperate broad-leaved deciduous forest in Japan, removal of 44% of the wood via thinning significantly decreased stand AGB gain, whereas removal of 13% of the wood had no significant influence on the subsequent stand AGB gain (Takiya 2002). Our results are similar to the latter case. In our study, in which the annual stand AGB loss was <20% of the total stand AGB, the influence of stand AGB loss on stand AGB gain was negligible (Fig. 7). Nevertheless, there is insufficient information on stand AGB gain when >20% of the wood is removed in tropical seasonal forests in Cambodia. As Shibuya and Masuchi (1991) suggested regarding the effects of thinning on temperate deciduous broad-leaved forests, stand AGB loss was considered not to affect the stand AGB gain greatly, except in cases with a high ratio of stand AGB loss.

**Country-level annual stand AGB change in tropical seasonal forests in Cambodia**

The largest observed stand AGB loss was 39.6 Mg ha⁻¹ year⁻¹ in EFs and 47.6 Mg ha⁻¹ year⁻¹ in DFs. For a stand with a relatively large AGB, this was equivalent to the sum of several tens of years’ estimated stand AGB gain (4–7 Mg ha⁻¹ year⁻¹ in EFs with a stand 300 > AGB ≥ 100 Mg ha⁻¹ year⁻¹ and 4–6 Mg ha⁻¹ year⁻¹ in DFs with a stand 250 > AGB ≥ 100 Mg ha⁻¹ year⁻¹; Fig. 2). It should be noted that large trees require a longer recovery period (Mazzei et al. 2010, West et al. 2014). Relatively large stand AGB losses are likely to occur by logging for select large timber tree species, whereas stand AGB gain occurs in all survivor and recruited trees.

The mean annual changes in stand AGB were positive in both EFs and DFs, even when the losses were taken into account (Fig. 8). This suggests that the forests were not fully mature and provided a significant carbon sink, thus reducing the rate of increase in atmospheric carbon dioxide. Our study showed the country-level mean annual changes in stand AGB using the gain-loss method with stand AGB gain (Fig. 2) and loss (Fig. 6) data in tropical seasonal forests in Cambodia. The validity of the method was confirmed by the similarity of 113% in EFs and 56% in DFs between the resulting values and those obtained using the stock-difference method and the dataset of Samreth et al. (2010) as shown above, which was independent of ours. We have only two comparisons at present, and the similarity in DFs was not high. Further analyses are required to fully validate the method.

**An approach to estimating country-level stand AGB gain in tropical seasonal forests**

The IPCC (2006) divides tropical natural forests into those ≤20 years and >20 years to provide specific default gain values using the gain-loss method. Young forests have larger gain values than old forests do. However, the age of tropical trees is difficult to estimate accurately, except for a few species. Thus, our stand-age-independent approach is of particular value in studies of tropical natural forests. If we choose 1.5 Mg ha⁻¹ year⁻¹ as a conservative measure of AGB gain, applying the IPCC default values (for stand ages >20 years) for tier 1 to Cambodian tropical seasonal forests, then this value greatly underestimates the mean stand AGB gain (4.94 Mg ha⁻¹ year⁻¹ in EFs and 4.16 Mg ha⁻¹ year⁻¹ in DFs) obtained in this study. Specifically, stand AGB gain in Cambodia can be calculated according to empirical Equation 3, which was based on stand AGB for evergreen forests, including semi-evergreen forests (<300 Mg ha⁻¹) and deciduous forest (<250 Mg ha⁻¹).

However, our information on annual stand AGB gain is limited to cases in which wood removal was <20%. Furthermore, our method requires further data (e.g., estimation of stand age) for its verification.

**CONCLUSIONS**

We determined a provisional stand AGB gain in the tropical seasonal forests of Cambodia and introduced a new approach for estimating country-level stand AGB gain in a tropical seasonal forest. Detailed information on forest cover and forest cover change exists for major forest types in Cambodia (Forestry Administration, Ministry of Agriculture, Forestry and Fisheries 2011). Nonetheless, additional studies are needed to determine the applicable range of the provisional mean annual stand AGB gain introduced in this work and to develop a country-specific mean annual stand AGB gain whose values for Cambodian
natural forests are more accurate than the IPCC default values. In addition, as data on the amount of country-specific wood removal become available from other sources, such as statistics on wood products production, it will be possible to use the gain-loss method to calculate the rate of forest biomass change at a given time point. The new approach and the values of annual stand AGB gain introduced in this study will extend the availability of the gain-loss method and contribute to sustainable forest management in tropical forest countries, including Cambodia.

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