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Practicalities of Non-Destructive Methodologies in Monitoring Anthropogenic Greenhouse Gas Emissions from Tropical Forests under the Influence of Human Intervention

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Abstract

We examined non-destructive methodologies for practicalities in monitoring anthropogenic greenhouse gas (GHG) emissions from tropical dry-land forest under the influence of various forms of human intervention. Spaceborne SAR withstood comparison with Landsat ETM+ in land cover classification of degraded tropical forest. For measurement of carbon stock and GHG flux per unit land area, the gain-loss method requires both growth rate and removal rate of forest carbon stock. However, the latter has rarely been obtained in tropical forest. For the stock-difference method, permanent sampling plot data can be used to estimate mean carbon stock per unit land area of each forest type. For cyclic land use that includes a clear-cutting stage such as slash-and-burn agriculture, chronosequential changes in carbon stock can be predicted by determining the time and spatial-distribution of cleared land. Changes in forest biomass by logging, storm-damage, etc., may be identified by monitoring the presence and diameter of the crowns of overstory trees. We developed five equations containing the parameter for crown diameter for estimating tree biomass. Overstory height can be a parameter for estimating ecosystem carbon stock of various plant communities, and forest height can be measured by airborne and spaceborne sensors, etc. Generic equations containing the parameter for overstory height are available for estimating community biomass of tropical and subtropical forests. PALSAR has an advantage over other remote systems by enabling frequent sensing and semi-direct biomass estimation using backscattering coefficients. However, no reasonable remote sensing methods exist for monitoring the amount of carbon loss by forest conversion and logging in forests

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with high biomass. To compensate for the faults of the present PALSAR methodologies and to enable practical and frequent monitoring of all types of forests by humans, it is vital to devise a new methodology to detect changes in high-biomass forests.

Discipline: Forestry and forest products
Additional key words: biomass, carbon, forest degradation, PALSAR, REDD

Introduction

Reducing Emissions from Deforestation in Developing Countries[38] and REDD-plus[39] (REDD is an abbreviation for Reducing Emissions from Deforestation and Forest Degradation) are new mechanisms to foster reduction of deforestation and forest degradation by allocating international support funds using the market mechanism, etc., to developing countries under pressure of deforestation and forest degradation. The amount of anthropogenic greenhouse gas (GHG) emissions from deforestation and forest degradation must be predicted and reduced by anthropogenic efforts and scrutinized by means of appropriate operational procedure for monitoring, reporting, and verification (MRV), keeping in mind that values relating to forest degradation depend on the degradation activity and forest composition[29]. Requirements for methodologies to monitor GHG emissions from deforestation and forest degradation may include accuracy (not only in terms of less errors in each element but also covering all important elements), large scale, frequency (semi-real time), and options (in accordance with the cause of deforestation and forest degradation, data availability, cost, etc.). Kiyono et al.[23] assessed the potential amount of GHG emissions from deforestation and forest degradation at test sites in Cambodia (dry land) and Indonesia (peat swamp) following the Tier 1 method in the IPCC National Greenhouse Gas Inventories Programme[14]. They showed that CO_2 from biomass and soil organic matter and N_2O from mineralization of soil organic matter were important to consider due to their large potential emissions and related uncertainty. Important subcategories of dry-land forest were CO_2 emissions from biomass and soil organic matter.

A simplified method[19] for estimating CO_2 emissions from deforestation and forest degradation is the calculation of carbon stock change by monitoring forest land and periodically summing the land area and its averaged carbon stock for important forest types. This method can be achieved by the following three steps. Step 1: Forest area and carbon stock (and GHG flux) are measured per unit land area and multiplied for main forest types at two points in time; Step 2: GHG emissions are estimated by calculating the difference in the sum of carbon stock (and GHG flux) between the two points in time; and Step 3: The trend of GHG emissions is estimated by repeating Steps 1 and 2. However, the amount of GHG emissions from forests may have increased due to various forms of human intervention such as forest conversion to agricultural land, reduction in fallow period of slash-and-burn agriculture, logging, and fuel wood collection. Compared to forest conversion for farming, etc., changes in the fallow period of slash-and-burn agriculture, logging, and fuel wood collection are difficult to detect in tropical forests where remote sensing is less available and few roads are available for ground-based measurement.

In this study, we analyzed existing non-destructive methodologies usable for estimating forest ecosystem carbon stock, collected supplemental data for devising additional methodologies, and then discussed the merits and demerits of each methodology for use in monitoring anthropogenic GHG emissions from tropical dry-land forest under the influence of various forms of human intervention. However, the influence of forest fire, which is also an important cause of forest degradation[12], is outside the scope of this paper due to limited data.

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Methods and study sites

1. Existing non-destructive methodologies and additional field data collection

The proposed simplified method of forest monitoring[19] requires objective variables of stratified forest area and carbon stock (and GHG flux) per unit land area. We reviewed literature on methodologies usable for the non-destructive estimation of carbon stock in tropical forests. Approaches for determining carbon stock per unit land area are classified into gain-loss methods and stock-difference methods[15] with the latter divided into five types (PSP data, community age, crown diameter, overstory height, and backscattering coefficients). We collected additional field data for approaches that use crown diameter and community age as follows:

2. Crown diameter

Due to the limited available data on tropical rainforest trees[13,42] for crown diameter, we supplemented it with data on trees in a deciduous forest at the Baluran National Park[16] in East Java Province, Indonesia. The deciduous forest was formed under a drier climate, with less than 1,000 mm in precipitation per year[41], and twelve various-sized large trees of eight species were selected for measuring DBH, tree height, and crown diameter. Each tree was identified by its botanical name, and the tree biomass was estimated using the following generic equations (Kiyono et al.[21], revised with data on tropical rainforest trees[13,42]; applicable to tropical and subtropical dry land trees having DBH: 1-133 cm)

$$\text{Tree biomass} = 1.77 \times ba^{1.05} \times D^{1.11} \times ht^{0.535} \quad (n = 530,\ R^2 = 0.986,\ p < 0.0001) \tag{1}$$

$$\text{Tree biomass} = 4.08 \times ba^{1.25} \times D^{1.33} \quad (n = 530,\ R^2 = 0.981,\ p < 0.0001) \tag{2}$$

where ba is the basal area of a stem at a height of 1.3 m (m^2), D is the basic density (kg m^{-3}) of stem wood, and ht is tree height (m). Following the methodologies (e.g., AR-AMS0004/Version 01) approved by the CDM Executive Board[7], D values were chosen giving priority for (a) to (b) preference as follows: (a) species-specific or group of species-specific from neighboring countries with similar conditions (i.e., Morikawa[27] in this study); (b) globally species-specific or group of species-specific (i.e., IPCC National Greenhouse Gas Inventories Programme[14]).

The biomass ratio of trees detectable by airborne or spaceborne sensors to total vegetation may differ among forest types. To determine the biomass ratio, we set a research plot of 30×80 m land area in a lowland semi-evergreen rainforest and in a lowland deciduous forest, both of which are located in Kampong Thom Province, Cambodia. For each tree in the plots having DBH < 5 cm, we noted the botanical name, measured the DBH and tree height, and recorded the layer in which the crown belonged according to the degree of crown exposure to sunlight (layer 1: crown almost fully exposed to sunlight; layer 2: exposure partly suppressed by other trees; layer 3: exposure fully suppressed by other trees).

3. Community age

To verify the model prediction in the methodology using the parameter for community age[18], carbon stock data on slash-and-burn fallow land were collected in northern Laos (Xiang Ngeun District, Luang Prabang Province). In this survey, we measured the overstory height of plant communities in the field and estimated community carbon stock (aboveground and belowground biomass, deadwood, and litter) using the relationship of overstory height to the sum of carbon stock in the four carbon pools[20]. We also collected other necessary information for the estimation (e.g., elevation above the sea level of the sites and for grazing, local government regulations and whether or not the fallow land at the sites was used for grazing). The surveyed community sites can be classified into two groups: (i) sites without grazing practice and at an elevation of around 500 m above sea level; (ii) sites with grazing and around 900 m above sea level.

Results and discussion

1. Measurement of forest area

Forest land cover classification can be achieved at reasonable cost using remote sensors with medium resolution such as Landsat. Detecting land where the soil is bare (e.g., slash-and-burn fields under preparation for cropping[17]) is particular easy[1]. Man-made objects such as logging infrastructure (roads and landings) and slash-and-burn fields are visible when they are at a relatively large scale and may be used as indicators to estimate forest area with logging operations and fuel wood collection, respectively. However, successful imaging by means of optical sensors depends on the weather conditions, e.g., the probability of cloud-free image acquisition was calculated in the Brazilian Amazon[2,33].

Active microwave sensors (Synthetic Aperture Radar; SAR) can overcome the cloud problem and are expected to enable frequent monitoring of tropical forests with less regard to clouds. Recent research shows that spaceborne SAR withstands comparison with Landsat ETM+ in land cover classification of degraded tropical forest[30,35]. The Japan Aerospace Exploration Agency (JAXA) has provided data from PALSAR (Phased Array L-band SAR) at no charge, and therefore the cost for using PALSAR could be low. However, a single SAR image hardly provides reliable information on steep mountains[10] because SAR backscatter signals are affected by topography, land use, etc.[3].

2. Measurement of carbon stock and GHG flux per unit land area

The IPCC National Greenhouse Gas Inventories Programme[15] recommends two options for measuring changes in carbon stock in LULUCF: the gain-loss method and the stock-difference method.

(1) Gain-loss method

The gain-loss method requires both the growth rate and removal rate of forest carbon stock. However, the latter has rarely been obtained in tropical forests[25,37]. Systematic sampling in accordance with human intervention in forests is needed and local residents' participation in data collection may increase the accuracy of carbon stock estimation.

(2) Stock-difference method

(i) Approach using permanent sampling plot (PSP) data

Permanent sampling plot (PSP) data can be used to estimate mean carbon stock per unit land area of each forest type. Kiyono et al.[19] estimated the mean carbon stock of four carbon pools (aboveground and belowground biomasses, deadwood, and litter) per unit land area for two main types of forest (evergreen and deciduous) using data from PSPs established by the Ministry of Environment to monitor forests in Cambodia. The study suggests that by multiplying the averaged carbon stock and forest area[9] for the nation's main forest types, reliable forest carbon stock values can be obtained less expensively at the national level. The number of PSPs depends on the desired level of precision, deviation of carbon stock for each stratum, etc. By moderately classifying forest types by means of satellite imagery, a reasonably accurate estimation of carbon stock can be expected. If a sufficient number of systemically and secretly set PSPs are available, highly reliable estimation is possible. However, if this is not the case, PSP data will be limited in terms of representation and interpretation of samples. Monitoring costs include that for road construction to access forests. Systematic sampling with a sufficient number of plots and frequent updating of averaged carbon stock data is vital for an accurate estimation of CO_2 emissions from forests under pressure of land-use change and forestry activities[19]. Consequently, when the ground-based measurement costs are high, large-scale monitoring may not be feasible. Local residents' participation in the monitoring[28] with development of simplified methodologies may increase the accuracy of carbon stock estimation by PSPs.

(ii) Approach using parameter for community age

For cyclic land use that includes clear-cutting stage (e.g., slash-and-burn agriculture, clear-cutting methods for plantation forestry, etc.), chronosequential changes in carbon stock can be estimated by determining time and spatial-distribution of cleared land. Inoue et al.[17] detected slash-and-burn fields using a time series of Landsat images and a model containing the parameter for community age, and estimated chronosequential changes in carbon stock in fallow land in northern Laos. A revised model (Fig. 1, Kiyono et al.[18]) predicted that the carbon stock would increase rapidly in the initial stages of fallow land and then would become slower about five years after the last cropping. The growth rates would be higher in the montane than in the lowland and would become low when the fallow land is used for grazing.

As a result of the verification in this study, the model prediction for fallow land without grazing was appropriate, while that for fallow land with grazing was considered to be overestimated (Fig. 1). About ten years ago, the local government (Xiang Ngeun District) introduced regulations making it mandatory for every village to have pastures. Consequently, grazing in fallow land has gradually stopped in the region (we are presently investigating the process). This could be the reason for the overestimation mentioned above.

The land where this approach can be applied is usually controlled by the local community and therefore vegetation changes are relatively predictable. Access for obtaining ground data is relatively easy. However, monitoring is necessary at least once a year and failure to detect bare land can be fatal to the accuracy of estimation. Thus, this approach may involve a medium cost level.

(iii) Approach using parameter for crown diameter

Crowns of tall and/or separate trees in forests can be distinguished by airborne or high-resolution spaceborne sensors. Changes in forest biomass by logging, storm-damage, etc., may be identified by monitoring the presence and diameter of the crowns. We developed five equations for estimating tree biomass containing a parameter for crown diameter and other parameters using samples of trees from a rainforest[13,42] and a seasonal forest (this study) (Table 1). The equation containing the single parameter for crown diameter (Eq. 3) had the smallest determination coefficient, R^2 (0.671), among the five equations. Adding a parameter for basic density (Eq. 4) or tree height (Eq. 5) increased R^2, and the equation containing three parameters (crown diameter, basic density, and tree height) (Eq. 6) had the highest R^2 (0.820). Crown diameter was closely correlated with DBH (R^2 = 0.856, $p < 0.0001$), and interestingly, the relationship was almost the same among regions under different climates (Fig. 2, left). However, the relationship of crown diameter to tree biomass clearly differed among regions (Fig. 2, right), and R^2 became low (0.671) when we sweepingly applied the equation containing the single parameter for crown diameter to all samples (Eq. 1). On tropical dryland, rainforests with tall trees are usually established at locations with abundant water supply; toward the drier climate, the tree height decreases[6]. Trees grow tall under wetter climate with fewer dry months (based on climatic diagram by Walter et al.[40]) (Table 1). Therefore, adding the parameter for dry months per year increased R^2 (0.763, Eq. 7). Compared to basic density and tree height, the data on dry months may easily be obtained for regions where sufficient meteorological data is available.

$$\text{Tree biomass} = 0.0707 \times CD^{3.93} \quad (n = 22, R^2 = 0.683, p = 0.0001) \tag{3}$$

$$\text{Tree biomass} = 0.0000126 \times CD^{4.10} \times D^{1.30} \quad (n = 22, R^2 = 0.769, p < 0.0001) \tag{4}$$

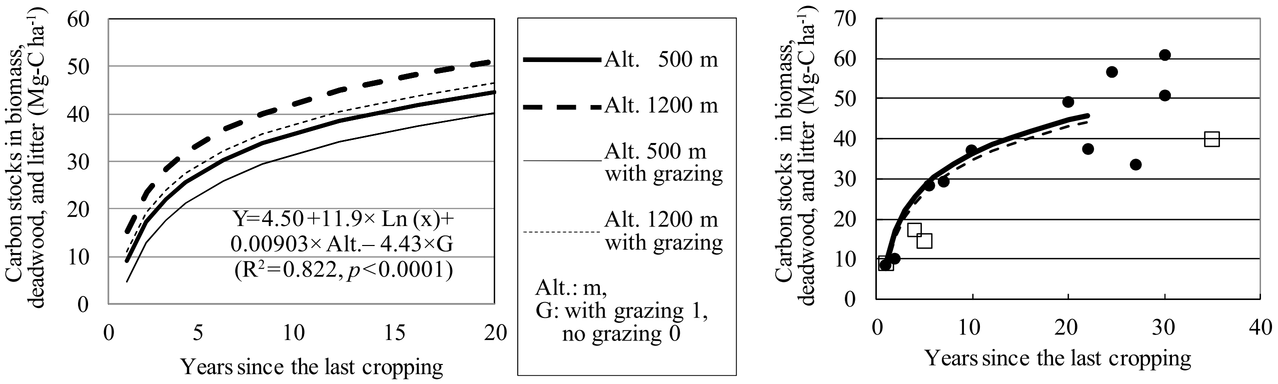

Fig. 1 Model for predicting carbon sequestration rates in slash-and-burn fallow land in northern Laos[18] (modified by the authors) (left) and the results of verification (right)

Left: Sum of carbon stock in aboveground and belowground biomass, deadwood, and litter predicted by the following equation: Carbon stock = 4.50 + 11.9 Ln (Y) + 0.00903 × Alt − 4.43 G (R^2 = 0.822, p < 0.0001) where Y: years since the last cropping, Alt: elevation above sea level (m), G: 1 when with grazing activities and 0 (zero) when without grazing activity. The thick solid line is the model prediction at 500 m above sea level without grazing, the solid line is for 500 m above sea level with grazing, the broken line is for 1,200 m above sea level with grazing, and the dotted line is for 1,200 m above sea level without grazing. Right: ● communities in lowland without grazing activity (solid line is the model prediction for land at 500 m above sea level), communities in montane with grazing activity (broken line is the model prediction for land 900 m above sea level).

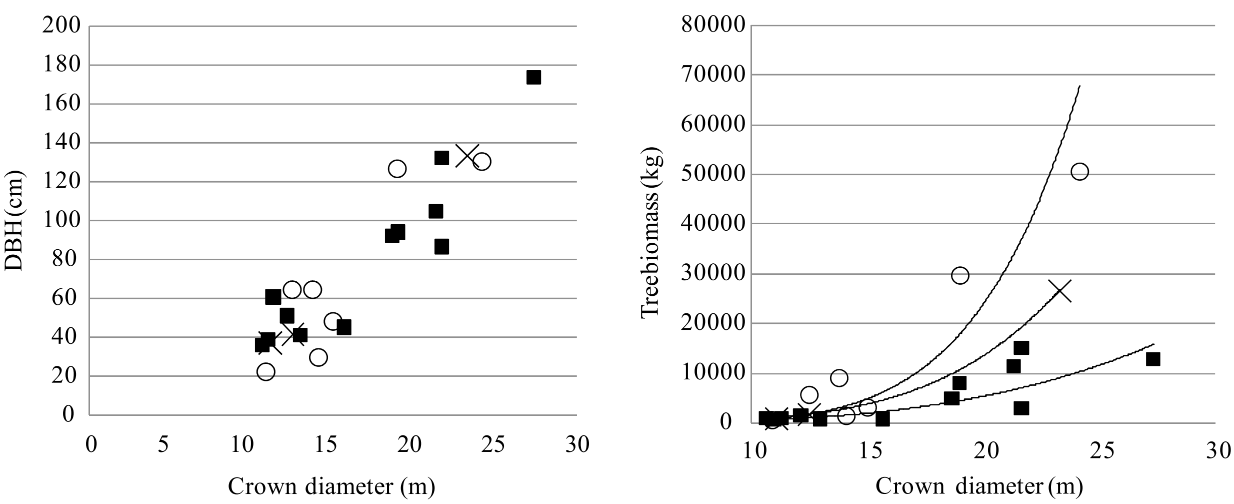

Fig. 2 Relationship of crown diameter to DBH (left) and tree biomass (right)

○ : Rainforest (Kalimantan, Indonesia[42]), × : Rainforest (Cambodia[13]), ■ : Deciduous forest (Java, Indonesia; this study).

$$\text{Tree biomass} = 0.0424 \times CD^{3.10} \times ht^{0.911} \quad (n = 22, R^2 = 0.807, p < 0.0001) \tag{5}$$

$$\text{Tree biomass} = 0.0000210 \times CD^{3.31} \times ht^{0.842} \times D^{1.15} \quad (n = 22, R^2 = 0.874, p < 0.0001) \tag{6}$$

$$\text{Tree biomass} = 0.00711 \times CD^{4.08} \times (12-DM)^{0.959} \quad (n = 22, R^2 = 0.757, p < 0.0001) \tag{7}$$

Tree biomass: kg, *CD*: crown diameter (m), *ht*: tree height (m), *D*: basic density (kg m^{-3}), *DM*: dry months per year based on climatic diagram in Walter et al.[40].

The biomass ratio of trees with crowns almost fully exposed to sunlight to total vegetation was 55% in semi-evergreen forest and 64% in deciduous forest (when including trees with exposure partly suppressed by other trees, the ratio was 68% and 86%, respectively) in the PSPs in Cambodia. The biomass ratio of detectable trees to total vegetation may be small in forests that develop a distinct crown layer. Using this percentage, a rough estimation of entire forest biomass may be possible by adding the biomass of the undetected understory vegetation. The percentage of detectable biomass depends on many conditions including forest type and sensors. Gnau[11] demonstrated the difficulties involved in the application of this method to young (15 and 25 years old) tropical secondary forests in Laos. Bamboo is quite difficult to measure by using this method[11] although the bamboo community is a dominant vegetation in the region[20]. Carbon stock removal by fuel wood collection cannot be determined by this method. Optical sensors cannot detect tree crowns under poor weather conditions.

(iv) Approach using parameter for overstory height

Overstory height can be used as a parameter for estimating biomass and ecosystem carbon stock in various plant communities[20]. As forest height can be measured by airborne and spaceborne sensors, etc., Kiyono et al.[22] prepared generic equations containing a parameter for overstory height for various tropical and subtropical forests to estimate community biomass and discussed various issues related to estimating biomass and carbon stock change from overstory height change. The relationship between overstory height and biomass did not differ between rainforest and seasonal forest where tall tree species dominated the communities. However, the relationship between tall forest, bamboo forest, and shrub communities differed considerably, and thus when the generic equation is used for the estimation, the values for the bamboo forest can be overestimated, while the values for the shrub community are underestimated. Considering this, the life form of dominant species in biomass estimation would reduce the uncertainty of estimates. In addition, the accuracy of forest carbon stock estimates would be affected by inconsistency in the definition of overstory height, lack of information about the amount of carbon in the understory, and some specific uncertainties of carbon amount in each carbon pool (biomass, deadwood, litter, and soil organic carbon).

Airborne LiDAR can measure three-dimensional forest structures in detail including overstory height[8]. Although the forest monitoring method using airborne LiDAR is expensive and difficult to up-scale, it may be applicable for a wide range of biomass and for detecting forest conversion, slash-and-burn use, logging, etc.

Both stereo mapping remote sensors (Digital Surface Model; DSM)[34] and multi-polarized SAR[5,24,31] have the potential to monitor overstory height and detect its change by forest conversion, slash-and-burn use, logging, etc. However, few reports have verified the use of this method in tropical forests.

Ground-based measurement of overstory height is an option for monitoring forest change as one of the most simplified methodologies. Systematized monitoring may involve considerable cost, but local residents' participation in the monitoring can reduce the operation costs[28].

(v) Approach using backscattering coefficient of PALSAR

Takahashi et al.[36] demonstrated the close correlation between the values of backscattering coefficients of PALSAR and airborne LiDAR metric, which relates to aboveground biomass although the values of PALSAR backscattering coefficients became saturated when the biomass became large. Since the airborne LiDAR metric, which relates to aboveground biomass, is closely related to cross sectional area and volume of forest stand (e.g., Mclean and Krabill[26]; Nelson et al.[32]), biomass estimation equations using PALSAR backscattering coefficients (e.g., Awaya et al.[4]) can be a powerful tool for monitoring tropical forests. In this sense, PALSAR has an advantage over other measures in terms of large-scale, frequent-sensing, and semi-direct biomass estimation. However, because of unresolved technical difficulties associated with the application of PALSAR backscattering coefficients to steep-slope areas, PALSAR indexes are only partly usable for biomass monitoring at present. The development of tools for full forest coverage is necessary, such as by combining PALSAR backscattering coefficients and a supplemental methodology.

3. Choice of method for estimating anthropogenic greenhouse gas emissions from forests under various forms of human intervention

The results of this study were compiled in a matrix (Table 2). Both Landsat and SAR can be used for land cover classification and mapping of land cover types.

Table 1. Trees in rainforest[13,42] and seasonal forest (this study)

Species	DBH	Tree height	Crown diameter	Basic density[*1]	Tree biomass	Precipitation	Dry months[*2]	Location	Sources	Remarks
		ht	*CD*	*D*			*DM*			
	cm	m	m	Kg m^{-3}	Kg	mm $year^{-1}$	$Year^{1}$			
Myristica sp.	37	24	11.1	530	871	3726	3	Cheko, Koh Kong, Cambodia	Hozumi et al. (1969)	Because only fresh weights were available for branch+fruit and stem in the original data, they were converted to dry weights assuming the dry/fresh weight ratio at 0.6 for branch+fruit and 0.55 for stem. Belowground biomass was then estimated assuming the root-to-shoot ratio (*R*) was 0.1778.
cf. *Calophyllum* sp.	41.3	24.7	12.5	530	1727	3726	3			
Anisoptera sp.	133.2	44.2	23.3	540	26522	3726	3			
Shorea laevis	130.5	70.7	24.2	700	50471	1862	0	Sebulu, East Kalimantan, Indonesia	Yamakura et al. (1986)	Belowground biomass was estimated assuming the root-to-shoot ratio (*R*) was 0.1778.
Dipterocarpus crinitus	127	46.5	19	550	29389	1862	0			
Dialium platycephalum	64.1	43.5	13.8	800	8928	1862	0			
Hopea mengerawan	64.3	42.5	12.5	640	5594	1862	0			
Hopea mengerawan	48.1	38.3	15	640	2788	1862	0			
Santiria tomentosa	29.5	30	14.1	530	1170	1862	0			
Polyalthia glauca	22.1	19.3	10.9	510	374	1862	0			
Acacia leucophloea	39.1	10	11.0	500	655	1000	7	Baluran, East Java, Indonesia	This study. Precipitation is less than 1000 mm a year (Whitten et al. 1996)	Tree biomass was estimated using values of DBH (cm), *ht* (m), *D* (Mg m^{-3}) and a generic equation for tree biomass estimation (Kiyono et al. 2006, revised): Tree biomass $= 1.77\ ba^{1.05}\ D^{1.11}\ ht^{0.535}$ (n = 530, $R^2 = 0.986$, $p < 0.0001$), *ba*: basal area of stem at 1.3 m high (m^2).
Erythrina sp.	60.8	17	11.3	240	962	1000	7			
Tamarindus indica	94.1	19	19.0	750	9072	1000	7			
Tamarindus indica	104.8	24	21.3	750	12878	1000	7			
Acacia leucophloea	92.4	18	18.7	500	5407	1000	7			
Ficus sp.	132.0	22	21.7	650	17034	1000	7			
Sterculia foetida	86.6	22	21.7	310	3092	1000	7			
Azadirachta indica	41.3	10	13.0	550	828	1000	7			
Zizyphus rotundifolia	51.3	7	12.2	760	1508	1000	7			
Acacia leucophloea	45.4	8	15.7	500	787	1000	7			
Sterculia foetida	173.3	24	27.3	310	13888	1000	7			
Schleichera oleosa	36.3	9	10.7	960	1082	1000	7			

[*1] Morikawa (2003) for *Azadiracta indica* and IPCC National Greenhouse Gas Inventories Programme (2006) for the others.
[*2] In Walter's climatic diagram (Walter 1971).

Table 2. Matrix for choices of methods for estimating anthropogenic greenhouse gas emissions from forests under various forms of human intervention

Objective variables	Approaches		Requirements	Costs	Getting data in a large land area	Technical difficulties	Applicability of the method in estimating anthropogenic GHG emissions by each activity				Inprovement in accuracy expected by local people participating in the monitoring
							Conversion to crop land	Reducing fallow period of slash-and-burn agriculture	Logging	Fuel wood collection	
Forest area	Land cover classification		Optical remote sensor with medium or higher resolution	Medium	Easy	・Not applicable when clouded	Possible	Possible	Partially possible	Partially possible	Low
			SAR with microwaves longer than L-band	Medium	Easy	・Not applicable to areas with steep slopes	Possible	Possible	?	?	Low
Carbon stocks and GHG fluxes per unit land area	Gain-loss method	Growth rate, removal rate	Measurement on the ground	?	Difficult	・Methods are not tested	?	?	?	?	High
	Stock difference method	PSP data	Measurement on the ground	High	Difficult	・Limitation in representativeness and secretness of plot	Possible	Possible	Possible	Possible	High
		Community age	Remote sensor with medium or higher resolution	Medium	Easy	・Applicable to land use with periodical naked land stages e.g. slash-and-burn farming	Impossible	Possible	Impossible	Impossible	Low
		Crown diameter	Remote sensor with high resolution Aerial photograph	High	Medium	・Not applicable when clouded ・Crowns are hardly recognized in some forests	Partly possible	Impossible	Partly possible	Impossible	Low
		Overstory height	Multi-polarization SAR	Low	Medium	・Methods are not tested ・Applicable to small parts of globe	?	?	?	Impossible	Low
			Airborne LiDAR	High	Difficult	・Nothing in particular	Possible	Possible	Possible	Impossible	Low
			Stereo mapping remote sensor (DSM)	Medium	Easy	・Not applicable when clouded ・Methods are not tested	?	?	?	Impossible	Low
			Measurement on the ground	?	Difficult	・Methods are not tested	Possible	Possible	Possible	Impossible	High
		Backscattering-coefficients	SAR with microwaves longer than L-band	Low	Medium	・Not applicable to areas with steep slopes ・Not applicable to high biomass forest	Partly possible	Partly possible	Impossible	Impossible	Low

This table is applicable to dry land forest.

Landsat has an advantage over SAR in that it is less sensitive to slope effects. However, optical sensors cannot detect forest under poor weather conditions, and therefore SAR has an advantage over Landsat due to its potential for frequent monitoring. Consequently, Landsat and SAR can complement each other in forest monitoring.

As for carbon stock, PALSAR is at an advantage by enabling semi-direct measuring using backscattering coefficients although it is limited to forests with medium or low biomass. There are no practical methods for monitoring the amount of carbon loss by forest conversion and logging in high-biomass forests. An inexpensive method available at present is applicable only to monitoring carbon stock in cyclic land use that includes clear-cutting stage, such as in slash-and-burn agriculture. It is suggested that the practical method should be chosen from adaptive options with considerations of available data and resources in the target region. Although the approach using PSP data may cost more than the other methods, the combination of forest area estimation using mid- to higher resolution remote sensing images and carbon stock estimation using PSPs shows high feasibility under the present circumstances.

Conclusion

We examined non-destructive methodologies for practicalities in monitoring anthropogenic greenhouse gas (GHG) emissions from tropical dry-land forest under the influence of various forms of human intervention. Compared to non-destructive methodologies for land cover classification, those available for carbon stock estimation have low-level practicalities in monitoring anthropogenic GHG emissions from tropical forests under the influence of human intervention. To compensate for the faults of PALSAR methodologies at present and to enable practical and frequent monitoring of all types of forest vegetation by humans, it is vital to devise a new methodology to detect changes in high-biomass forests.

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