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Forest biomass in Cambodia: from field plots to national estimates

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By

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EXECUTIVE SUMMARY

As part of the efforts to maintain 60 % forest cover in its country, Cambodia engaged in several projects and initiatives that require accurate estimate of forest services such as the potential to climate change mitigation, conserving biodiversity, and sustainable forest management. A quantitative assessment of most of these services will be realized with the implementation of a full-scale multi-purpose National Forest Inventory (NFI).

To support the NFI and provide initial estimates of forest biomass across the country, this study aimed to harmonise forest inventory data collected by the Royal Government of Cambodia (RGC) in partnership with different institutions, in 30 forest areas, with 15 different methodologies; secondly, test different approaches and combinations of allometric equations to estimate forest biomass; and thirdly to develop local tree height-diameter relationships when possible, and provide recommendations to improve forest biomass estimates.

The results show that differences among forests mostly concern tree diameter and height, and to a large degree related to the management regime. Community Forestry (CF) sites assessed are probably located in more degraded forests with low tree diameter ranges and very small tree height for equivalent diameter, compared to REDD conservation projects and permanent sampling plots. Therefore forests in community forestry have average biomass of 30 to 50 tons per ha while the average biomass other forests ranges from 150 to 400 tons per ha. Estimates are provided for three major forest types of Cambodia: evergreen, semi-evergreen and deciduous forest and subdivided per FAO global ecological zones and provinces.

None of the local allometric equations was found suitable for estimating tree biomass from their diameter and height. The most reliable and conservative estimates came from a combination of locally developed tree height diameter relationships together with pantropical models. Data quality could not be assessed most of the time and several recommendations are provided to improve forest inventory datasets, allometric equations and *in fine* forest biomass estimates in Cambodia.

ACRONYMS AND ABBREVIATIONS

AGB	Aboveground biomass in kg or ton/ha of dry matter
AIC	Akaike Information Criterion
BA	Basal Area
CF	Community Forest(ry)
CFMP	Community forestry management plan
DBH	Diameter at breast height (usually 1.3 m) in cm
GPS	Global positionning system
H	Tree height in m
MRV	Measurement, Reporting and Verification
NFI	National forest inventory
NGO	Non-governmental organisation
PSP	Permanent sampling plot
R	R statistical software package
REDD	Reducing emissions from deforestation and forest degradation
REDD+	REDD plus conservation, sustainable management of forests and enhancement of forest carbon stocks
SSE	Sum of squared errors
TCP	Technical cooperation programme
WD	Wood density, in this report it refers to the dry mass of the fresh volume

CI	Conservation International
FA	Forest administration of the Royal Government of Cambodia
FAO	Food and Agriculture Organisation of the United Nations
FFI	Fauna and Flora International
FiA	Fisheries Administration of the Royal Government of Cambodia
GDANCP	General Department of Administration for Nature Conservation and Protection of the Royal Government of Cambodia
GERES	Groupe Energies Renouvelables, Environement et Solidarités
IPCC	International panel on Climate Change
MAFF	Ministry of Agriculture, Forestry, and Fisheries of the Royal Government of Cambodia
MoE	Ministry of Environment of the Royal Government of Cambodia
RECOFTC	Center for People and Forests
WA	Wildlife Alliance

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The authors would like to acknowledge the Forest administration of the Royal Government of Cambodia for collecting and sharing the available forest inventory data. We also would like to thank all the General Department of Administration for Nature Conservation and Protection of the Royal Government of Cambodia and the Fisheries Administration of the Royal Government of Cambodia, and projects and institution that contributed to the effort: WCS, WA, CI, Pact, GERES, RECOFTC, FAO, FFI and USAID supported HARVEST project. All together the datasets cover almost the entire country with an interesting range of forest conditions.

We thank all the field teams, donor institutions and various contributors to the tremendous effort of collecting the field measurements, it is crucial to better understand and manage forests, especially in the tropical context.

We finally thank the Food and Agriculture Organisation of the United Nations and the UN-REDD Programme for their continuous support on improving forest biomass estimates and emission factors.

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1 CONTEXT

Cambodia's forest cover is one of the largest in Southeast Asia relatively to its country area (57 %) (FAO, 2010). Maintaining forest coverage at the 2000 level of 60 % of total land area through 2015 is one of the target objectives of the Royal Government of Cambodia as part of the 7th Cambodian Millennium Development Goals to Ensure environmental sustainability. The country has been proactive to be involved early in the REDD+ mechanism (Reducing Emissions from Deforestation and Forest Degradation, "plus" conservation, sustainable management of forests and enhancement of forest carbon stocks) and became a partner country of the UN-REDD Programme in 2011. One of the goals of the Programme in Cambodia is the development of a Monitoring System for national Monitoring, Reporting and verification (MRV) of greenhouse gas (GHG) emission and removals from the forestry sector. The design and implementation of a National Forest Inventory (NFI) is a key component in the context of REDD+ (UN-REDD, 2013). It aims to collect forestry data from the field to develop accurate estimates GHG emissions and removals for REDD+ related activities (Output 4.4 of the National Programme Document). In addition to the UN-REDD Programme, Cambodia received support from the Food and Agriculture Organisation of the United Nations (FAO) through the Technical Cooperation Programme (TCP to design a multipurpose NFI.

This study aims to support the NFI design and measurement component in MRV, in providing forest carbon stock estimates for a wide range of Cambodian forests. The specific objectives are to harmonise existing forest inventory data from government institutions and projects, develop local height diameter models using the data available and compare different sets of allometric equations to convert inventory data into carbon stocks estimates.

2 METHODOLOGY

2.1 Origin of the forest inventory data and methodological differences

A large dataset of forest measurement was collected. These forest inventories were conducted by eight institutions to meet three types of objectives: assessing forest biomass for conservation projects via the REDD mechanism (called REDD conservation or REDD in this study), measuring forest trends through permanent sampling plots (PSP), and designing community forestry management plans (called CFMP or CF in the report). The institutions can be grouped in four different groups depending on their status and mission:

- **Governmental bodies**: Forest administration of the Kingdom of Cambodia (FA). FA supported several community forestry projects and a large network of permanent sampling plots across Cambodia.
- **Environmental protection NGOs**: Conservation International (CI), Wildlife Conservation Society (WCS), Wildlife Alliance (WA) and Fauna and Flora and Flora International (FFI). They supported mainly REDD projects on forest conservation in partnership with FA and MoE.
- **Development NGOs**: Groupe Energies Renouvelables Et Solidarité (GERES), the Center for People and Forests (RECOFTC), and Pact. All these institutions supported community forestry projects. Pact supported REDD projects for groups of community forestry sites.
- **International organisations**: Food and Agriculture Organisation of the United Nations (FAO). FAO supported also community forestry projects within a watershed programme.

The sampling design and the plot locations used in these studies are presented in Figure 1, Table 1 and further explanations are provided in the next subsections.

2.1.1 Data from the Forest Administration

The Forest administration provided inventory data from five community forestry projects (called CFMP – FA in this study) and two groups of permanent sampling plots (PSP) (called FA in this study).

Among the 112 permanent sampling plots established in five regions by the Forest administration (FA, 2004), only data from 40 plots have been accessible. 20 plots were located in Koh Kong region and 20 others in Siem Reap. Measurements were carried out in Koh Kong in 1998, 2002, 2006, 2010 and both mortality and recruitment was registered. To avoid over representing these field measurements, only the latest inventory was used for this analysis. In Siem Reap forest measurements were carried out in 1998, 2000, 2005, 2011 and 2012, yet recruitment was not measured (no new trees on the post 1998 field data collection), therefore only the inventory in 1998 was used for biomass assessment. Permanent sampling plots were nested rectangular with a maximum size of 50 x 50 m (FA, 2004).

Regarding the community forestry projects, one was located in Kampot region and the four others in Svay Rieng. Inventory plot design followed the Guidelines on Community Forestry and its Relevant Policies (FA, 2006) and was composed of nested rectangular plots with a maximum size of 50 x 50 m recommended in the guidelines for deciduous forest measurements.

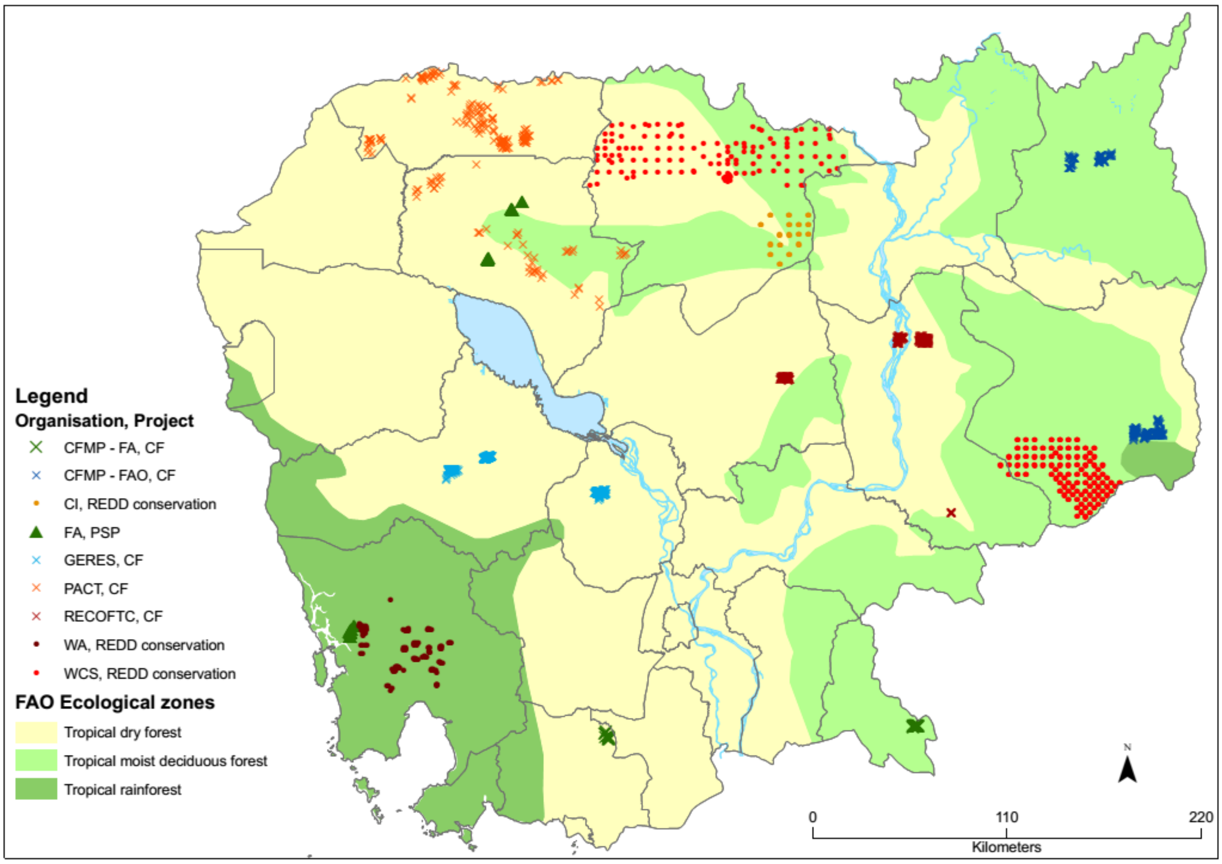

Figure 1: Location of the forest inventories over Cambodia (Source: this study).

NB: FFI inventory was implemented in the Cardamoms, close to WA projects, but could not be represented.

2.1.2 Data from Conservation International, Wildlife Conservation Society, Wildlife Alliance and Fauna and Flora International supported projects

As part of its Prey Long REDD+ Project, Conservation International implemented together with the Forest Administration a forest inventory in the South East of Preah Vihar Region in 2012 (CI, 2011). The field inventory followed a methodology developed by Winrock International (CI, 2012) (Walker et al., 2012). It was characterized by nested circular plots with a maximum plot radius of 20 m (0.126 ha area).

In the same region (Preah Vihar), WCS prepared a conservation finance project under the REDD framework and the voluntary carbon standard for the Northern plains landscape (Rainey et al., 2013). Field inventories of 119 plots were conducted in Preah Vihar Protected Forest (PVPF) and Kulen Promtep Wildlife Sanctuary (KPWS) following the same methodology as CI (CI, 2012), i.e. nested circular plot of maximum 20 m radius (Rainey et al., 2013). Data from another field inventory, made in 2004 by the Cherndar logging company, was also collected. Trees were measured in 15 rectangular plots of 250 x 20 (, which were not nested (unpublished study). WCS also conducted a forest inventory in 308 plots in Seima Protection forest in Mondolkiri region (WCS, 2013a). The same field inventory plot shape previously presented was used (circular nested of 20 m radius maximum size).

Wildlife Alliance prepared a REDD+ pilot project in the Cardamoms in Koh Kong region. A forest inventory was carried out in 2010 and covered 105 inventory plots. The methodology was prepared with the support of ONF International (ONFI). Each inventory plot was composed of two nested rectangular sub plots with a maximum size of 200 x 25 meters (ONFI, 2010).

Detailed information was not available for the forest inventory of FFI. The plot design applied by FFI was circular and nested with small trees measured in a 5 m radius plot whereas trees with a DBH bigger than 10 cm were measured inside 15 m radius circular plots. Detailed information was not available for the forest inventory of FFI.

2.1.3 Data from the Groupe Energies Renouvelables Et Solidarités, the Center for People and Forests, and Pact supported projects

GERES and RECOFTC supported the creation of community forestry (CF) projects in Cambodia and provided forest inventory data made in community forests to prepare their management plans.

GERES provided forest data for three community forestry projects, one in Kampong Chnang Region (KCN), and two in Pursat region: Prey Mouy (PM) and Pur Ou Baktra (POB). In total, forest measurements were conducted in 350 forest plots (with additional 153 plots without trees). The plot shape methodology followed the recommendation of the draft "Community Forest Management Planning Manual" (FA, 2011) for community forests smaller 1500 ha (called option 2), i.e. nested rectangular plots with a maximum size of 20 x 30 m.

RECOFTC provided data of four community forestry projects. Three were located in Kratie Region: Anh Chanh (AC), Okrasang (OS) and Okrieng (OE), and one in Kampong Thom region (KT). In total, forest was measured in 249 plots following the methodology of the "Guidelines on Community Forestry and its Relevant Policies" (FA, 2006). All plots had a nested rectangular shape, however Anh Chanh and Kampong Thom CF were located in evergreen forest, meaning that the maximum plot size was 50 x 100 meters, whereas Okrieng and Okrasang CF were located in deciduous forest and had half sized plots compared to those in evergreen and semi-evergreen forests.

Pact worked on REDD projects through community forestry (TGCapital, 2012a) and implemented two forest inventories following different methodologies in Oddar Manchey and Siem Reap provinces. In Oddar Meanchey 10 community forestry sites conducted forest inventories with 151 rectangular plots, 50 x 50 m size (TGCapital, 2012b). These plots are not nested. In Siem Reap, forest was measured in 51 inventory plots. The plot shape measured here, was nested rectangular and the maximum nested level size was 25 x 25 meters (TGCapital, 2011).

2.1.4 Data from the Food and Agriculture Organisation of the United Nations supported project

Finally, FAO provided forest data from CF projects in Kratie, Mondolkiri, Ratanakiri and Stung Treng regions. No documentation or metadata was associated to the data and many inventories had missing plot coordinates and inconsistencies in the values. Therefore only two CF in Ratanakiri (Yakpoy and Undong) and four in Mondolkiri (Pukreng, Pukroch, Puradet and Pulung) were considered for the analysis. The inventory methodology followed the Guidelines on Community Forestry for evergreen and semi evergreen forests (FA, 2006), i.e. nested rectangular plot shapes with a maximum size of 50 x 100 meters.

Table 1. Plot characteristics of various forest inventories in Cambodia.

Institution	Project	Plot shape	Nested	Level 1 Condition	Level 1 shape	Level 1 area (ha)	Level 2 condition	Level 2 shape	Level 2 area (ha)	Level 3 condition	Level 3 shape	Level 3 area (ha)	# of plots	# of trees	Min DBH (cm)	Max DBH (cm)	Tree height
WA	Cardamom	rectangle	Yes	DBH >= 30 cm	25x200m (twice)	1	DBH: 5 - 29 cm	10x25m (twice)	0.05	DBH <= 5 cm	10x6m (twice)	0.012	105	20124	1	462	Sample
CFMP-FAO	All	rectangle	yes	DBH >= 30 cm	50x100m	0.5	DBH: 10 - 29 cm	50x50m	0.25	DBH <= 10 cm	50x25m	0.125	218	16485	2	209	No
CFMP-RECOFTC	Kampong Thom CF	rectangle	yes	DBH >= 30 cm	50x100m	0.5	DBH: 10 - 29 cm	50x50m	0.25	DBH <= 10 cm	50x25m	0.125	79	4904	10	150	Sample
CFMP-RECOFTC	Anh Chanh CF	rectangle	yes	DBH >= 30 cm	50x100m	0.5	DBH: 10 - 29 cm	50x50m	0.25	DBH <= 10 cm	50x25m	0.125	7	753	10	131	No
WCS	Cherndar PV	rectangle	No	No	250x20m	0.5	No	No	No	No	No	No	15	1465	20	150	No
CFMP-FA	All	rectangle	Yes	DBH >= 30 cm	50x50m	0.25	DBH: 10 - 29 cm	25x50m	0.125	DBH <= 10 cm	25x25m	0.0625	40	2717	10	166	Yes
CFMP-RECOFTC	Okrasang CF	rectangle	yes	DBH >= 30 cm	50x50m	0.25	DBH: 10 - 29 cm	25x50m	0.125	DBH <= 10 cm	25x25m	0.0625	57	1419	10	75	No
CFMP-RECOFTC	Okrieng CF	rectangle	yes	DBH >= 30 cm	50x50m	0.25	DBH: 10 - 29 cm	25x50m	0.125	DBH <= 10 cm	25x25m	0.0625	106	3488	10	100	No
FA-PSP	Koh Kong and Siem Reap	rectangle	yes	DBH >= 30 cm	50x50m	0.25	DBH: 15 - 29 cm	20x20m	0.04	DBH < 15 cm	10x10m	0.01	40	1570	7.1	133.4	No
PACT	Oddar Meanchey	rectangle	no	No	50x50m	0.25	No	No	No	No	No	No	151	12063	2.5	200	No
PACT	Siem Reap	rectangle	yes	DBH >= 20 cm	25x25m	0.0625	DBH: 5 - 19 cm	15x15m	0.0225	DBH <= 5 cm	10x10m	0.01	51	1949	1	124	No
CFMP-GERES	All	rectangle	Yes	DBH >= 30 cm	20x30m	0.06	DBH: 10 - 29 cm	10x10m	0.001	DBH <= 10 cm	2x2m	0.0004	350	3648	5	216	No
WCS	Kulen Promtep WS	circles	Yes	DBH >= 30 cm	20m radius (3 times)	0.377	DBH: 15 - 29 cm	15m radius (3 times)	0.212	DBH < 15 cm	5m radius (3 times)	0.024	57	3573	5	190	No
WCS	Preah Vihear PF	circles	Yes	DBH >= 30 cm	20m radius (3 times)	0.377	DBH: 15 - 29 cm	15m radius (3 times)	0.212	DBH < 15 cm	5m radius (3 times)	0.024	61	3523	5	161	No
CI	Prey Long	circles	yes	DBH >= 30 cm	20m radius	0.126	DBH: 15 - 29 cm	15m radius	0.071	DBH < 15 cm	5m radius	0.0079	51	1056	5	143.6	No
WCS	Seima PF	circles	Yes	DBH >= 30 cm	20m radius	0.126	DBH: 15 - 29 cm	15m radius	0.071	DBH < 15 cm	5m radius	0.0079	308	7819	5	217	No
FFI	CCPF	circles	Yes	DBH >= 10 cm	15m radius	0.071	DBH < 10 cm	5m radius	0.0079	-	-	-	71	1476	5	104	No

Data are ordered by plot shape and then by decreasing size of the first level of plot size.

Given the huge variability of institutions, projects and methodologies driving the forest inventories, all the data were harmonised following one template to find potential data entry errors and to be able to merge all information in one table. Additional information was later associated at tree level to test a wider range of biomass models.

2.2 Data Harmonisation and additional tree and plot characteristics

2.2.1 Data harmonisation

All the plots information and trees measurements were harmonised to prepare the biomass calculations at tree and plot level. The following information was collected for each tree: Institution, Project, Original file name, Cluster, Plot code (Plot ID), Location name, Forest tenure, Forest type, Plot size in meter, Scale factor (to extend results to hectare level), GPS coordinates of the plot, Species name (scientific name: Family, Genus, Species), Quality of the tree, Diameter at breast height (DBH) in cm, Tree height (H) in meter, Year of the inventory.

Various data entry errors were found for essential tree characteristics: plot ID, GPS coordinates, DBH and H. Plot ID errors included automatic transformation into date in Excel and inconsistent spacing between letters in the plot names. All these errors were reviewed and corrected. The GPS coordinates were harmonised with a recalculation of plot center coordinates and the remaining errors (10 plots) were corrected using the location of the neighbour plots in the same inventories. Errors in DBH included: tree circumferences entered as DBH (one full inventory), DBH missing or equal to 0 (337 and 1897 trees, respectively), and DBH bigger than 6 meters (10 trees). Tree circumferences were converted into diameter. Data entries showing other errors were removed, therefor the number of trees and plots found in Table 1 may differ from the final results. Unrealistic tree heights (more than 100 meters) were found for 8 trees and were removed. Tree height was also removed for trees with a DBH smaller than 30 cm in WA forest inventory as it was not part of the field measurement methodology (ONFI, 2010).

Almost all institutions recorded the tree species names, at least partly, except for the CFs supported by FA and FAO. The complete scientific names (Family, Genus and Species) were not checked or harmonised due to the complexity of the task. The potential of errors is quite high given the need for translation from Khmer alphabet to Latin, and checking almost 100,000 trees is an enormous task to be undertaken.

In addition to tree diameter at breast height, various allometric models use the tree height and wood density to predict tree biomass. Other variables can also be used such as the crown diameter (Henry et al., 2010), (Kiyono et al., 2011), but wood density and tree height are the second and third most important input variables after tree diameter (Chave et al., 2005). Annual rainfall is an important climate characteristic to choose the appropriate model when using allometric equations from pantropical studies (Chave et al., 2005), (Brown, 1997). These studies differentiate biomass allometry for three climatic zones: dry (less than 1500 mm per year), moist (between 1500 and 3500 mm a year) and wet (more than 3500 mm a year). In Cambodia the three climatic areas are presented (see the FAO biomes in Figure 1).

2.2.2 Estimation of tree wood density

As very few trees had their height measured and none of them their wood density, both variables were estimated from external sources. Wood density from the Global Wood Density Database (Chave et al., 2009) in the Dryad digital repository (Zanne et al., 2009) was associated to each tree based on its scientific name. An average wood density was associated to each tree, at the lowest level (species, genus or family) matching with the information available in the global database. All the trees whose scientific name did not match or without scientific name (more than half of the data) were given a basic wood density value of 0.57. 0.57 is the average value for Tropical Asia (Reyes et al., 1992) found to be conservative in Cambodia (WCS, 2013b).

2.2.3 Tree height estimates

Tree height was estimated with the regional model developed by Feldpausch and colleagues for Asia (Feldpausch et al., 2010). The model estimated tree height (H) in meters from its diameter (DBH) in cm with the following equation:

$$H = exp\left(1.2156 + 0.5782 \times ln(DBH)\right)$$

As both height and diameter were available for part of the available inventories, both in community forestry lands (usually degraded forests) and natural forest in conservation areas (Wildlife Alliance's project), local models were also developed in this study. Four model types were tested: a power model (same equation shape as Feldpausch) and three other types of model, known to be asymptotic. As very big trees were measured in the forest inventories (Table 1), asymptotic models could provide more realistic estimates of these big trees' height, even though they tend to give bad results for small trees (Feldpausch et al., 2010). The four asymptotic models selected were Prodan, Weibull, Mickaelis Menten and Ratkowsky (Huang et al., 1992), (Zeide, 1993):

$$\text{(Power) } H = hd + a \times DBH^{b}$$

$$\text{(Prodan) } H = hd + \frac{DBH^2}{a + b \times DBH + c \times DBH^2}$$

$$\text{(Weibull) } H = hd + a \times \left(1 - e^{-b \times DBH^{c}}\right)$$

$$\text{(Michaelis Menten) } H = hd + \frac{a \times DBH}{b + DBH}$$

$$\text{(Ratkowsky) } H = hd + a \times e^{\frac{-b}{(DBH+c)}}$$

Where H is the tree height in m, DBH its tree diameter at breast height in cm, hd is the height at which the diameter is measured (usually at 1.3 m) and a, b and c the parameters.

These four models were selected among 16 different height-diameter models coming from an R package called lmfor (Mehtatalo, 2012) – package dedicated to tree height diameter relationship – because they generally gave the best fitting results for five national forest inventories over the tropics (unpublished study). The selection of the best model for this study was based on several indicators: convergence of the model, no visual default in the plot of estimated values against input variable, residuals against predicted values and of predicted values against observed values, smaller sum of squared errors (SSE) and lowest Akaike Information Criterion (AIC) (Akaike, 1974).

2.2.4 Annual rainfall, FAO biomes, WWF ecoregions, Forest types and vegetation classes at plot level

Annual rainfall was compiled at plot level using corrected GPS coordinates of each plot and the climatic raster data from Worldclim[1] (Hijmans et al., 2005). Average monthly rainfall (interpolations of observed data, representative of 1950-2000) at a 30 second resolution was summed into annual rainfall in mm with the raster package in R (Hijmans et al., 2014). From these values the climatic zones were determined as follows: dry zone have an annual rainfall under 1500 mm per year, moist have an annual rainfall from 1500 to 3500 mm, and wet zone receive more than 3500 mm of rain per year (Chave et al., 2005).

[1] Data accessible at: http://www.worldclim.org/

FAO biomes were associated to each plot based on its GPS location and the updated Global ecological zones' shapefile[2] (FAO, 2012). WWF ecoregions (Olson et al., 2001) were also associated to each plot based on GPS coordinates. The forest type map from the Forestry Administration 2010 and the Vegetation maps from the Ministry of Environment 2007 were used to extract the forest and vegetation types of the plots.

2.3 Methodology for assessing forest biomass

2.3.1 Review of existing allometric equations

Several institutions worked on allometric equations in Cambodia. WCS validated the pantropical model of Chave et al. 2005 for the Seima project in Mondulkiri (WCS, 2013b). The Japan International Cooperation Agency (JICA) proposed a decision tree to select among several models (one local and several equations from Chave) the most adapted to each climatic and anthropic conditions in Cambodia (JICA, 2012). FAO also supported the collection of all existing equations for Cambodia (Sarin et al., 2012) to contribute to the GlobAllomeTree[3] international database of allometric equations (Henry et al., 2013).

As a result, 40 equations were developed for Cambodia from five publications from 1962 to 2011. Only five equations had tree aboveground biomass as output variable (most equations were developed for volume). The biomass equations were developed with 22 trees whose DBH ranged from 22 to 133 cm (Kiyono et al., 2011) and used tree crown diameter, tree height and wood density as input variables. As tree crown diameter was not available in the forest inventory data, these equations could not be used in this study. In the same study two other models estimated trees biomass from their basal area and wood density. These models were developed with 530 trees across dryland over subtropical and tropical countries (DBH from 1 to 133 cm). Very little information was found about the proposed models. Model quality indicators could not be found and it was unclear if tree biomass represented total tree biomass (aboveground and underground together) or only its aboveground biomass. As one of these models was used in several studies (JICA, 2012), (Samreth et al., 2012) it was selected for this analysis.

The volume models developed by the Forest administration (FA, 2004) provided estimates of tree volume based on tree diameter, forest type (evergreen semi-evergreen or deciduous) and tree family (Dipterocarpaceae or not). As forest type and trees family were not available for all tree data, these volume equations could not be applied to the whole dataset. The equations developed by Khun and his colleagues (Khun et al., 2008) were specific to rubber trees plantations and de facto not appropriate for this study. Finally the volume equations produced by the USAID in 1962 (USAID, 1962), were constructed with a large sample size (584 trees in Humid and Semi-humid zones, 534 trees in Dry zone) but due to their DBH range from 1 to 50 cm, they were not suitable for our analysis (many trees had a DBH bigger than 50 cm and up to 450 cm).

As a conclusion, none of the equations available could be used for calculating trees biomass, except the equation developed by Kiyono and colleagues. This equation should be limited to the permanent sampling plots from FA as suggested in the JICA report (JICA, 2012).

2.3.2 Biomass calculation

Four different approaches were developed to estimate trees above ground biomass (noted AGB_01 to AGB_04). These approaches were designed to fit with different levels of information available and to use combinations of pantropical models and locally developed models in their range of validity. AGB is

[2] Data accessible at: http://www.fao.org/geonetwork/
[3] Data accessible at: www.globallometree.org

calculated in kg, and the input variables used in the models are DBH in cm, BA (basal area) in m^2, H in m, and WD in g/cm^3.

AGB_01 was calculated using the IPCC default allometric equation for tropical moist forest, available in Table 4.A.1 of the 2003 guidelines (IPCC, 2003). In case no information is available about tree height, wood density and climatic zone, AGB_01 can still be calculated at a level of uncertainty accepted by IPCC. For moist tropical forest the formula was:

$$AGB_{01} = exp\left(-2.289 + 2.649 \times ln(DBH) - 0.021 \times \left(ln(DBH)\right)^2\right)$$

where AGB_01 is the aboveground biomass in kg and DBH the diameter at Breast height in cm.

The second approach (AGB_02) followed the Guide to calculate forest living biomass (JICA, 2012). Aboveground biomass was estimated using Chave equations with diameter and wood density as input variables and climatic zone for model parameters. In addition to these equations, Kiyono's formula was recommended for PSP in dry zones. AGB_02 was calculated as follow:

- Dry zone (Annual rain < 1500 mm) and permanent sampling plots:

$$AGB_{02} = 4.08 \times BA^{1.25} \times (WD \times 1000)^{1.33}$$

- Dry zone (Annual rain < 1500 mm):

$$AGB_{02} = WD \times exp(-0.667 + 1.784 \times \ln(\mathrm{DBH}) + 0.207 \times (\ln(\mathrm{DBH}))^2 - 0.0281 \times (\ln(\mathrm{DBH}))^3)$$

- Moist zone (1500 mm ≤ Annual rain ≤ 3500 mm):

$$AGB_{02} = WD \times exp(-1.499 + 2.148 \times \ln(\mathrm{DBH}) + 0.207 \times (\ln(\mathrm{DBH}))^2 - 0.0281 \times (\ln(\mathrm{DBH}))^3)$$

- Wet zone (Annual rain > 3500 mm):

$$AGB_{02} = WD \times exp(-1.239 + 1.980 \times \ln(\mathrm{DBH}) + 0.207 \times (\ln(\mathrm{DBH}))^2 - 0.0281 \times (\ln(\mathrm{DBH}))^3)$$

The third approach (AGB_03) was based on Chave equations that include tree height (H) in addition to DBH and WD as input variable. If not measured in the field, tree height was estimated using the Feldpausch equation for Asia (see previous section). The required tree information was then: DBH, WD and climatic zone. AGB_03 was calculated as follow:

- Dry zone (Annual rain < 1500 mm):

$$AGB_{03} = WD \times exp(-2.187 + 0.916 \times \ln(\mathrm{WD} \times \mathrm{DBH}^2 \times \mathrm{H})$$

- Moist zone (1500 mm ≤ Annual rain ≤ 3500 mm):

$$AGB_{03} = WD \times exp(-2.977 + \ln(\mathrm{WD} \times \mathrm{DBH}^2 \times \mathrm{H})$$

- Wet zone (Annual rain > 3500 mm):

$$AGB_{03} = WD \times exp(-2.557 + 0.940 \times \ln(\mathrm{WD} \times \mathrm{DBH}^2 \times \mathrm{H})$$

With tree height estimated when not measured using the Feldpausch formula for Asia (Feldpausch et al., 2010):

$$H = exp\left(1.2156 + 0.5782 \times ln(DBH)\right)$$

The fourth approach (AGB_04) is based on a combination of local and pantropical models to take advantage of local models in their range of validity:

- Kiyono's model is applied to dryland forests,
- Chave's models with tree height is applied where tree height has been measured or where local models could be used to estimate tree height,
- Chave's models without height where applied in the other cases.

Local tree height diameter models are presented in the results section.

The R software[4] (R-Core-Team, 2013) was used for data analysis and Quantum GIS[5] software (QGIS-Development-Team, 2014) was used to verify the plots GPS coordinates and verify the spatial analysis results. The R scripts are available upon request. Graphs were made with the "ggplot2" package for R (Wickham and Chang, 2013).

[4] Information and download at: http://www.R-project.org

[5] Information and download at: http://qgis.osgeo.org

3 RESULTS

3.1 Forests and trees characteristics

The total dataset is composed of 88 841 trees measured in 1 755 plots with the support of 30 projects. Most of the plots are located in Community forestry projects (62 %) and in the moist climatic zone (76 %). Only 1% of the plots are located in the wet climatic zone. Five projects measured trees in more than 100 plots (two REDDD conservation projects and three community forestry projects). Eight projects measured trees in less than 20 plots and most of the project considered 30 to 70 plots with an average of 56 plots per project. The results presented in this report are further detailed in a separate annex (Annex 1: Distribution of the plots per climatic zone, project type).

The species names were fully identified by RECOFTC and the FA (for the permanent sampling plots). CI identified close to 80 % of the species in its inventory, WA and WCS less than 50 %. As a consequence, the results presented below (Table 2) are very likely not representative of the top ten families and species of the Cambodian forests but might still be important at country level.

Table 2. Ten most represented tree Families and species in the available forest inventories.

Tree Family	# of trees	%
Dipterocarpaceae	4681	5.27
Guttiferae	1305	1.47
Ebenaceae	929	1.05
Simaroubaceae	430	0.48
Sterculiaceae	415	0.47
Lythraceae	241	0.27
Meliaceae	204	0.23
Melastomataceae	184	0.21
Caesalpiniaceae	152	0.17
Dioscoreaceae	152	0.17
Unknown	52229	58.79
Total	88841	100

Tree genus and species	# of trees	%
Hopea pierrei	3664	4.12
Calophyllum sp.	1079	1.21
Diospyros bejaudii	829	0.93
Calophyllum calaba	750	0.84
Fibraurea tinctoria	669	0.75
Lagerstroemia sp.	592	0.67
Terminalia cambodiana	581	0.65
Irvingia malayana	442	0.5
Sterculia plantanifolia	411	0.46
Shorea vulgaris	400	0.45
Unknown	65641	73.89
Total	88841	100

The biggest tree measured had a DBH of 457 cm. Among the 88 841 trees measured only 432 trees have a DBH bigger than 100 cm (0.5 %) and 9 bigger than 200 cm. Community forestry sites show the highest variability in the DBH distribution among institutions and projects (Figure 2). Some projects have very narrow distributions with low DBH trees (FA and GERES) while others show similar trends to the REDD conservation locations (75 percent quartile around 30-40 cm DBH). Several plots in community forests were most probably measured in degraded forests where very few trees exceed 15 to 20 cm.

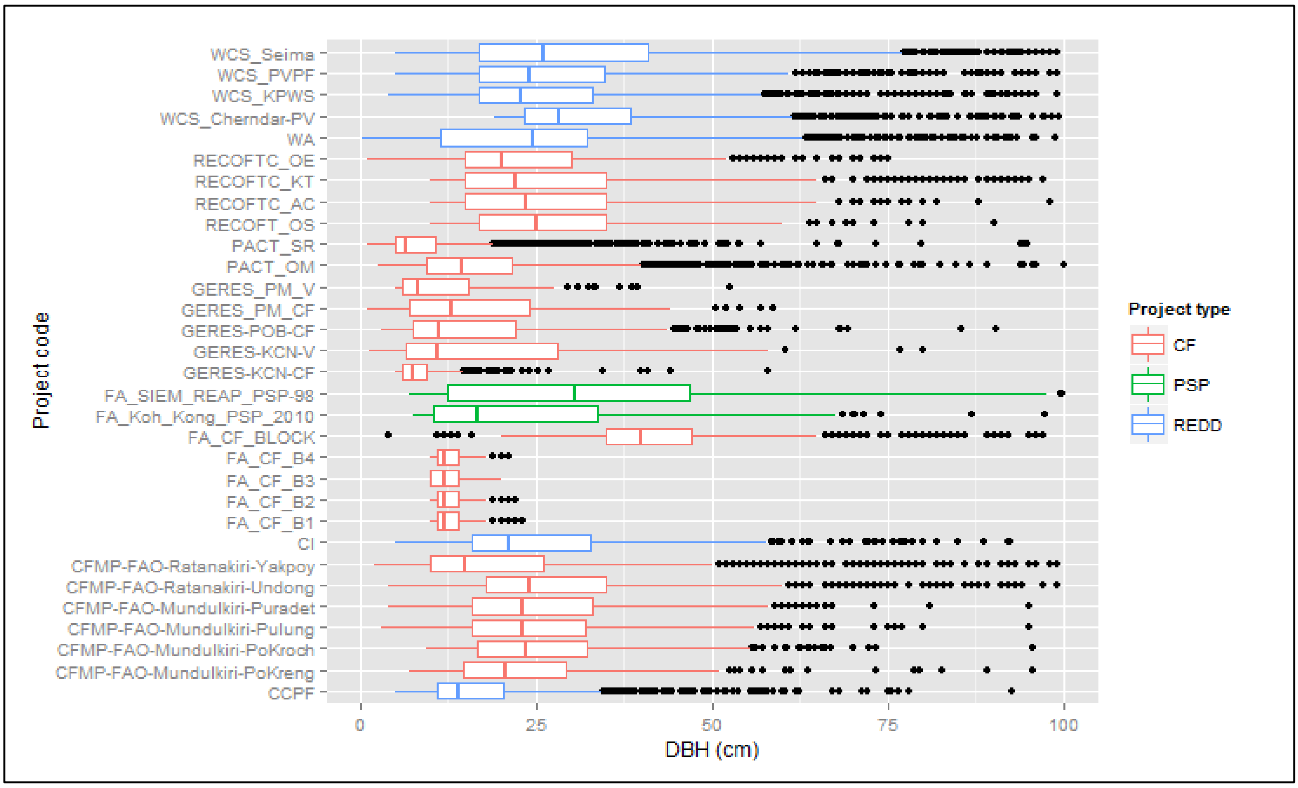

Figure 2: Distribution of trees' DBH per project.

Boxes represent the 25th and 75th percentiles, central bars the medians and the lines propagate the quartiles 1.5 times. Red boxes correspond to projects in community forests, blue boxes on REDD conservation project and green boxes on Permanent sampling plot locations.

3.2 Tree height diameter relationship

3.2.1 Tree height measured in the field

Only three institutions recorded tree height in the field: WA in Cardamom protected area, and FA and RECOFTC in the inventories for Community Forest management plans. Great differences can be observed depending on the condition of the forest. In protected areas the height diameter relations are typical to natural forests whereas in more degraded forests (where most of the community forestry projects were implemented) hardly any relation is visible (Figure 3). In particular, small trees in DBH can be very high (15 cm in diameter for a 20 m height) and very big trees in diameter can have a very small height (DBH > 1 m and H around 10 m). None of the existing models can predict these tree sizes variations and the modelling process can be difficult as most of the models will not converge (parameters cannot be estimated) or will give poor results.

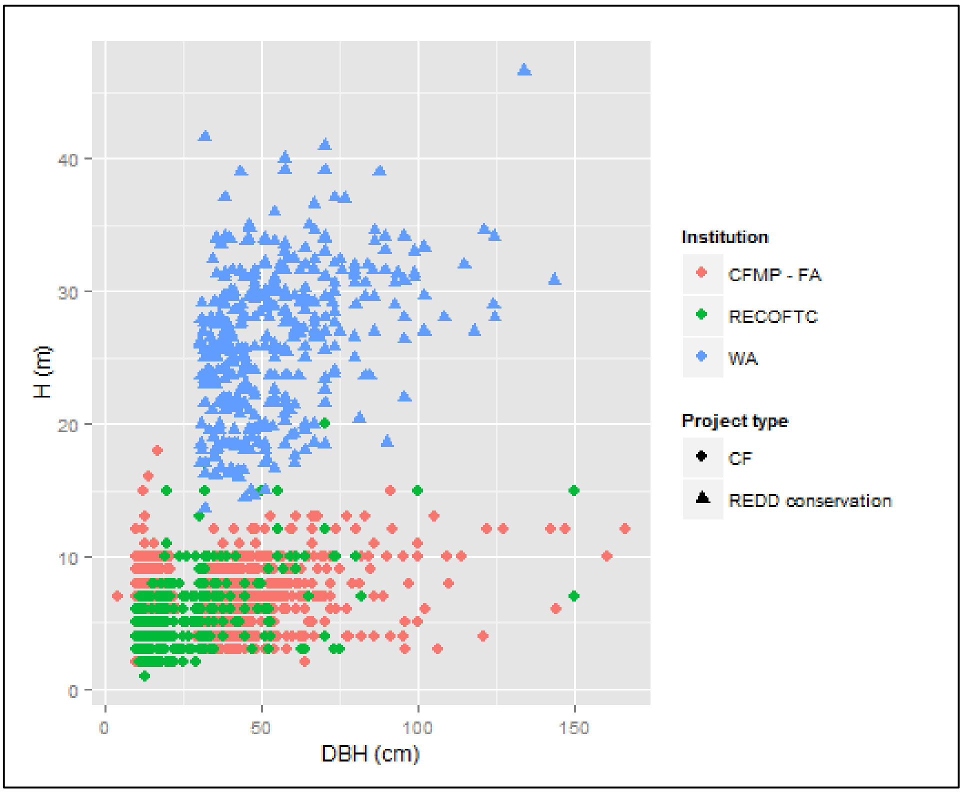

Figure 3: Height diameter relationship of forest inventories from three institutions.

The regional scale model from Feldpausch (Feldpausch et al., 2012) overestimated tree height for WA data and very largely overestimated tree height for the CF projects data. Moreover predicted heights were bigger than 60 meters for trees with 150 cm DBH and more than 100 meters for the biggest trees measured. Therefore the model was not used to predict height. A local model was developed based on WA project data. Among the four types of model tested the power model provided the best results and hence was selected to predict height of supposedly well conserved forests such as locations of REDD conservation projects and permanent sampling plots. The model is:

$$H = 1.3 + 9.303525 \times DBH^{0.24991}$$

For community forestry projects, the same model was applied and the results were divided by 3. No model were converging for the CF data and the bias of this model adaptation to CF trees gave an overall bias of 6.7 %. A detailed analysis of the model development is provided in annex 2.

3.3 Comparison of biomass estimation approaches at tree level

As no model was developed for tree H in community forestry, AGB_04 was calculated as follows:

- AGB_02 (Kiyono's model for PSP and Chave without tree height) was use for PSP data and for CF data for with tree height was not measured.
- Chave model including H was used with local model for tree height for REDD conservation projects and CF where tree height was measured.

And another approach AGB_04bis was calculated with local H-D model adaptation to CF trees. as follows:

- Kiyono's formula for PSP data,
- Chave model including H was used with the local model for tree height for REDD conservation projects,
- Chave model including H was used and tree height was estimated as one third of results from local model for tree height, for CF projects.

To compare approaches, AGB_01 is used as reference as it is the simplest approach, using only DBH as input variable. The differences among approaches can be identified separately for big trees and for trees with a DBH smaller than 100 cm as they represent 99.5 % of the trees measured in the available data and trends and differences among approaches are more visible at this scale. Detailed results are presented in the Annexes of this report.

The main results from this analysis was that the approach AGB_01 (IPCC 2006 model) gave the highest biomass estimates for all trees in almost all conditions. The model of Kyiono gave even higher results for permanent sampling plots and therefore was not selected in the recommended approach.

A conservative estimate of tree AGB for the different conditions in Cambodia would assume that in CF tree height is very low compared to the other projects, probably because CF projects were mostly installed in degraded forests with high human pressure, and use AGB_04bis in this case. AGB_04bis is also suitable for REDD conservation projects in assuming that the locally developed model for tree height better fit the available data. However, using the Kiyono equation results in very high AGB estimates for PSP trees, despite most PSP plots are in the dry climatic zone and given the DBH distribution, they don't seem to be very different from trees in REDD conservation project locations. Using the Chave equation with H estimated from the local model is then found to be a reasonable and conservative approach.

The selected best approach in this study was renamed to AGB_05 and is using the following models:

- **Chave equation including tree height is used for all trees,**
- **Tree height is estimated with the local H-DBH model for trees in REDD conservation and one third of the H estimated with the local model for trees in CF projects.**

3.4 Emission factors calculation

The approach AGB_05 was found conservative and the best approach to assess forest biomass based on the data available. The detailed explanations are provided in annex to this report as well as the results per forest entities i.e. per project.

To develop emission factors, only the plots being simultaneously in the same category for Forest types and Vegetation class (evergreen, semi-evergreen and deciduous forest) were kept, to reduce risks of misclassified plots. As a result 528 plots were used for community forests and 39 in permanent sampling plots and 474 in REDD conservation projects. In total 41% of the 1755 plots were removed. In particular almost half of the CF plots were removed as they were associated to one of the three forest types with one definition but also linked to a different class within another classification system, such as for example 'woodshrub' (no equivalent in the vegetation classification), grassland or built-up area. Many plots in semi-evergreen forest in one classification system were in evergreen or deciduous forest in the other (see in annex for more details).

The plots in community forest sites were separated from the others as their biomass was assessed with a different formula. Still the results were very different from one ecoregion to the other, between provinces and projects. The emission factors are therefore presented for each of the three main forest types, per FAO global ecological zone, province and organization (Table 3). A further separation using the eco-terrestrial zones (more detailed) can be found in annex.

The main results of the aboveground biomass estimates are:

- **The range of plot level AGB and its variability are huge**. The standard deviation of average estimates is never less than half of the average value. This means that in most locations forests plots without much biomass can be found close to very rich ones. The overall range of AGB is from 10 tons/ha to more than 1 000 tons/ha. It reflects, among other things, the importance of big trees, especially when the inventory plots are small (less than one ha). It also implies that to define homogeneous populations within Cambodia's forests, stratification is needed, and strata should be based on human activities to better understand were the degraded forests are.

- **There is more AGB in semi-evergreen forest than in evergreen forest.** Semi-evergreen forest has only been found in few plots in Preah Vihar and Mondolkiri areas. It seems that in Mondolkiri these forests are exceptionally rich, the AGB estimates for semi-evergreen forest should not be applied elsewhere in the country and in particular in degraded forest areas or in lowland forests. Moreover, the forest types were associated from forest maps to plots based on GPS coordinates. It is therefore probable that few plots categorized semi-evergreen are if fact in evergreen forest type. Another reason could be that evergreen forests were more degraded than semi-evergreen ones, as they contain more precious wood that semi-evergreen forests.
- **When two organizations have worked in the same forest type, ecoregion and province, the AGB estimates are similar.** Differences are mainly found in Koh Kong, probably due to different stage of forest condition and in Deciduous forest in Preah Vihar but there are not sufficient plots to make the comparison.

Table 3. Emission factors for the main forest types, FAO global ecological zones and provinces, for plots in REDD conservation projects and PSPs.

Vegetation class (MoE 2007)	FAO ecological zone	Province	# of plots	Aboveground biomass average + sd	Min	Max
Evergreen forests	Tropical dry forest	Preah Vihar	30	257 ± 78	105	423
		Siem Reap	14	277 ± 56	200	413
	Tropical moist deciduous forest	Mondolkiri	80	333 ± 137	78	837
		Preah Vihar	3	287 ± 42	243	328
			10	159 ± 55	69	231
		Siem Reap	1	327	327	327
	Tropical rainforest	Koh Kong	20	359 ± 88	215	539
			57	121 ± 110	11	361
			90	210 ± 72	20	571
Total evergreen forests			305	243 ± 128	11	837
Semi-evergreen forests	Tropical dry forest	Preah Vihar	7	304 ± 179	137	658
	Tropical moist deciduous forest	Mondolkiri	34	416 ± 269	47	1363
		Preah Vihar	8	231 ± 117	64	446
			5	221 ± 70	165	339
Total semi-evergreen forests			54	356 ± 240	47	1363
Deciduous forests	Tropical dry forest	Preah Vihar	9	87 ± 32	52	141
			31	117 ± 55	33	278
		Siem Reap	4	100 ± 45	43	147
	Tropical moist deciduous forest	Kratie	3	197 ± 86	145	297
		Mondolkiri	71	277 ± 201	29	947
		Preah Vihar	13	131 ± 49	82	233
			21	111 ± 40	52	200
	Tropical rainforest	Koh Kong	2	92 ± 118	9	176
Total deciduous forests			154	190 ± 163	9	947

In community forestry projects the average AGB is 50 tons/ha in evergreen and semi-evergreen forest forest, and 30 tons/ha in deciduous forest. Trees in community forestry projects were given a smaller height than PSP and REDD plots, according the tree height measurements and the fact that Community

Forests in the analysis were often established in more degraded areas. The low biomass estimates also correspond to the very low basal areas in CF project compared to the other ones.

4 RECOMMENDATIONS FOR IMPROVING FOREST BIOMASS ESTIMATES

4.1 Forest inventory measurements

4.1.1 Marking difference between tree diameter and circumference measurement

Several forest inventory datasets were reporting DBH measurement while the actual values were circumferences. Some of the results of this study need further analysis of the raw data to ensure the same problem has not occurred. To avoid this issue in the future it is recommended to specify in the numeric datasets and in the field forms what is measured and which tool is used. The use of measurement tapes that provide DBH on one side and circumference on the other side should be avoided. The use of measurement tapes with graduations in cm only is recommended, conversion of circumference to DBH can be calculated afterwards.

4.1.2 Measuring tree height

Given the great influence of tree height estimates in the final AGB estimates, it is recommended to measure tree height systematically in forest inventories. In degraded forest and particularly in CF projects, Tree height could be measured for all trees, whereas in less degraded forest, tree height could be measured every 10 to 15 trees to build local H-DBH models. It is advised to have tree height measured two to four times by different operators and report an average value. Trees with extreme DBH (less than 20 cm and over 2 m) should be measured as well to improve the shape of H-DBH models.

4.1.3 Tree species identification

Very few trees were identified at species level. As species are an important predictor of wood density and wood density is very important for estimating tree biomass, more effort should be dedicated to species identification.

4.1.4 Additional measurements for big trees

Big trees have a very high impact to plot and forest biomass estimates. Measurement of tree height, at least up to the first main branch, and of crown area could improve biomass estimates of these trees, especially given that they are most of the time far away from biomass DBH ranges.

4.1.5 Standard procedures for data entry

The longevity, quality and comparability of forest inventory datasets leave room for improvement. Collecting information on plot size, methodology for field work and location of the forest inventories was extremely difficult, with limited information accessible directly in the datasets, and simple procedure for data entry were mostly not followed. Recommendations to improve the data quality and avoid losing the tremendous work invested and achieved in forest measurement are:

- Simple procedures should be followed to ease use of numeric spreadsheet (no space inside cells, one column per variable, no empty cell),
- Each dataset should contain one sheet with metadata (date of data collection, project or activity reference, link to analytical report, location of the trees),
- Database preferably should follow a nested level structure, with different spreadsheet for: metadata, plot information and tree information,

- Procedure to ensure data quality (double entry, species names check with external lists) are advised and procedures should be specified in the metadata,
- Using special characters and different alphabets may often lead to errors, in particular for the species names. Using codes might reduce entry errors. Species names should also be entered three times: local name in Khmer, local name in English, scientific name.

4.2 Development, selection and use of existing allometric equations

4.2.1 Developing new models for the main ecological zones

None of the available local models was suitable for national scale analysis. These models mainly focused on timber volume and the few biomass models that were developed, were developed with too few trees and too small DBH ranges to be used out of the areas where they were designed. As a consequence, new destructive measurements are highly recommended in Cambodia to test the validity of the approaches selected in this study and develop new models to accurately estimate tree and plot level biomass.

Important efforts are needed in capacity building to develop country level experts on forest biomass and developing new models would be a good opportunity to train key experts to the different stages of biomass modelling, from field work to model fitting, validation and use.

Given the high variability of climatic areas and of forest degradation processes in Cambodia, the influence of these two indicators should be better studied. Several studies only reported if the tree species was Dipterocarpaceae or not. Developing specific models for this family should also be explored to better understand if it has a great influence or not on tree biomass estimates.

4.2.2 Improving Wood density estimates

Recent studies show that wood density is an important predictor of tree biomass (Chave et al., 2005) (Henry et al., 2010) (Gourlet-Fleury et al., 2011) (Chave et al., 2014). Available methodologies and associated cost for measuring it in forest inventories are huge constraints but average wood density at tree species level can be used without creating bias (Fayolle et al., 2013), (Chave et al., 2014). Together with improving species identification in the forest inventories, developing a table of wood density values at species level would significantly improve biomass estimates.

4.2.3 Developing local tree height diameter to be used together with pantropical models

In addition to developing local and national scale biomass allometric models, foresters and scientists should be trained to develop local tree height diameter relationship as high variations have been observed in Cambodia. Pantropical models have been developed in primary forest mainly and might not take into consideration forest degradation and local environmental factors that affect biomass. Therefore biomass models including tree height should be systematically used with tree height estimated from locally developed models.

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ANNEXES TO THE REPORT: FOREST BIOMASS IN CAMBODIA: FROM FIELD PLOT TO NATIONAL ESTIMATES

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Annex 1: Distribution of the plots per climatic zone, project type, forest type, vegetation class and WWF ecoregion

Table 4. Number of plots per project and per climatic zone or project type.

Project Code	Climatic zone			Project type			Total
	DRY	MOIST	WET	CF	PSP	REDD	
CFMP-FAO-Mundulkiri-PoKreng	0	13	0	13	0	0	13
CFMP-FAO-Mundulkiri-PoKroch	0	37	0	37	0	0	37
CFMP-FAO-Mundulkiri-Pulung	0	43	0	43	0	0	43
CFMP-FAO-Mundulkiri-Puradet	0	53	0	53	0	0	53
CFMP-FAO-Ratanakiri-Undong	0	30	0	30	0	0	30
CFMP-FAO-Ratanakiri-Yakpoy	0	41	0	41	0	0	41
CI	0	51	0	0	0	51	51
FA_CF_B1	0	6	0	6	0	0	6
FA_CF_B2	0	6	0	6	0	0	6
FA_CF_B3	0	6	0	6	0	0	6
FA_CF_B4	0	6	0	6	0	0	6
FA_CF_BLOCK	16	0	0	16	0	0	16
FA_Koh_Kong_PSP_2010	0	8	12	0	20	0	20
FA_SIEM_REAP_PSP-98	20	0	0	0	20	0	20
GERES-KCN-CF	21	33	0	54	0	0	54
FFI_CCPF	0	71	0	0	0	71	71
GERES-KCN-V	1	53	0	54	0	0	54
GERES-POB-CF	138	0	0	138	0	0	138
GERES_PM_CF	0	85	0	85	0	0	85
GERES_PM_V	0	19	0	19	0	0	19
PACT_OM	137	3	0	140	0	0	140
PACT_SR	51	0	0	51	0	0	51
RECOFT_OS	0	57	0	57	0	0	57
RECOFTC_AC	0	7	0	7	0	0	7
RECOFTC_KT	0	79	0	79	0	0	79
RECOFTC_OE	0	106	0	106	0	0	106
WA	0	105	0	0	0	105	105
WCS_Cherndar-PV	0	15	0	0	0	15	15
WCS_KPWS	0	57	0	0	0	57	57
WCS_PVPF	0	61	0	0	0	61	61
WCS_Seima	0	308	0	0	0	308	308
Total	384	1 359	12	1 047	40	597	1 755
Total (%)	22	77	1	60	2	38	100

Table 5. Distribution of the inventory plots per project and forest type.

Project Code	Forest Type (MARD map 2010)								Grand Total
	Bamboo	Deciduous forest	Evergreen forest	Non-forest	Other forest	Semi-evergreen forest	Wood shrub dry	Wood shrub evergreen	
CCPF		2	59			10			71
CFMP-FAO-Mundulkiri-PoKreng		5				6		2	13
CFMP-FAO-Mundulkiri-PoKroch		35				2			37
CFMP-FAO-Mundulkiri-Pulung		38				5			43
CFMP-FAO-Mundulkiri-Puradet		47		5		1			53
CFMP-FAO-Ratanakiri-Undong			22	1	5	2			30
CFMP-FAO-Ratanakiri-Yakpoy			15	2	3	21			41
CI		29	3			19			51
FA_CF_B1					6				6
FA_CF_B2				4	2				6
FA_CF_B3				5	1				6
FA_CF_B4				2	4				6
FA_CF_BLOCK		15		1					16
FA_Koh_Kong_PSP_2010			20						20
FA_SIEM_REAP_PSP-98		4	15		1				20
GERES_PM_CF		85							85
GERES_PM_V		14		5					19
GERES-KCN-CF		42		12					54
GERES-KCN-V				50			4		54
GERES-POB-CF		28	110						138
PACT_OM		43	27	35	1	33		1	140
PACT_SR		4	5	9	28	3		2	51
RECOFT_OS		56				1			57
RECOFTC_AC			7						7
RECOFTC_KT			78	1					79
RECOFTC_OE		105	1						106
WA			97	3	1	4			105
WCS_Cherndar-PV			15						15
WCS_KPWS		33	12			12			57
WCS_PVPF		26	24			11			61
WCS_Seima	7	91	133	12	2	60	3		308
Grand Total	**7**	**702**	**643**	**147**	**54**	**190**	**7**	**5**	**1755**

Table 6. Distribution of the inventory plots per project and vegetation class.

Project Code	Vegetation Class								Grand Total
	Built-up / Barren Areas	Deciduous forests	Dryland crops / Paddy	Evergreen / Riparian Forests	Grasslands and Abandoned Fields	Open water	Secondary forest / Swidden	Semi-evergreen forests	
CCPF		4		57	2		8		71
CFMP-FAO-Mundulkiri-PoKreng		5		2	2			4	13
CFMP-FAO-Mundulkiri-PoKroch		24		6	7				37
CFMP-FAO-Mundulkiri-Pulung		27		5	1			10	43
CFMP-FAO-Mundulkiri-Puradet		36		3		1		13	53
CFMP-FAO-Ratanakiri-Undong			1	12	4		10	3	30
CFMP-FAO-Ratanakiri-Yakpoy				28	1		5	7	41
CI		22		8			8	13	51
FA_CF_B1					6				6
FA_CF_B2			1		5				6
FA_CF_B3			2		4				6
FA_CF_B4			3		3				6
FA_CF_BLOCK		4			12				16
FA_Koh_Kong_PSP_2010				20					20
FA_SIEM_REAP_PSP-98		4		16					20
GERES_PM_CF								85	85
GERES_PM_V		2	1				2	14	19
GERES-KCN-CF					54				54
GERES-KCN-V			24		30				54
GERES-POB-CF		38		100					138
PACT_OM	2	67	1	35	4		3	28	140
PACT_SR		4	3	4	6		33	1	51
RECOFT_OS		40		5		1		11	57
RECOFTC_AC				5				2	7
RECOFTC_KT				58	1		20		79
RECOFTC_OE		88		10				8	106
WA				93	1		11		105

WCS_Chern dar-PV				15					15
WCS_KPWS		32		12	5			8	57
WCS_PVPF		27		20	2		1	11	61
WCS_Seima		103		105	5		9	86	308
Grand Total	**2**	**527**	**36**	**619**	**155**	**2**	**110**	**304**	**1755**

Table 7. Distribution of the inventory plots per project and WWF ecoregion.

Project Code	**WWF ecoregion**					**Grand Total**
	Cardomom Mountains moist forests	**Central Indochina dry forests**	**Central Indochina moist forests**	**Da Lat-Phnom Lyr montane forests**	**Tonle Sap-Mekong peat swamp forest**	
CCPF	71					71
CFMP-FAO-Mundulkiri-PoKreng				13		13
CFMP-FAO-Mundulkiri-PoKroch				37		37
CFMP-FAO-Mundulkiri-Pulung				43		43
CFMP-FAO-Mundulkiri-Puradet				53		53
CFMP-FAO-Ratanakiri-Undong			30			30
CFMP-FAO-Ratanakiri-Yakpoy			41			41
CI		24	27			51
FA_CF_B1					6	6
FA_CF_B2					6	6
FA_CF_B3					6	6
FA_CF_B4					6	6
FA_CF_BLOCK		16				16
FA_Koh_Kong_PSP_2010	20					20
FA_SIEM_REAP_PSP-98		5	15			20
GERES_PM_CF	85					85
GERES_PM_V	19					19
GERES-KCN-CF	3	51				54
GERES-KCN-V		54				54
GERES-POB-CF	98	40				138
PACT_OM		52	88			140
PACT_SR		19	32			51
RECOFT_OS		57				57
RECOFTC_AC			7			7
RECOFTC_KT			79			79
RECOFTC_OE		106				106
WA	105					105
WCS_Cherndar-PV		15				15
WCS_KPWS		47	10			57
WCS_PVPF		61				61
WCS_Seima		53	117	138		308
Grand Total	401	600	446	284	24	1755

Annex 2: Details of the local tree height-diameter models

Tree height estimated with a regional model

The model developed by Feldpausch and colleagues overestimates height of the trees located in protected forests and results in very high overestimations of the trees located in community forestry (Figure 4). More importantly as Feldpausch model is not asymptotic it results in unrealistic height for big trees. Forest biomass is mainly stored in the big trees and overestimates of these big trees' height can lead to a non-negligible bias in biomass estimates at plot and at national level. To avoid this risk and given that trees rarely grow over 60 meters in height (Feldpausch et al., 2010), the maximum tree height has been set at this value.

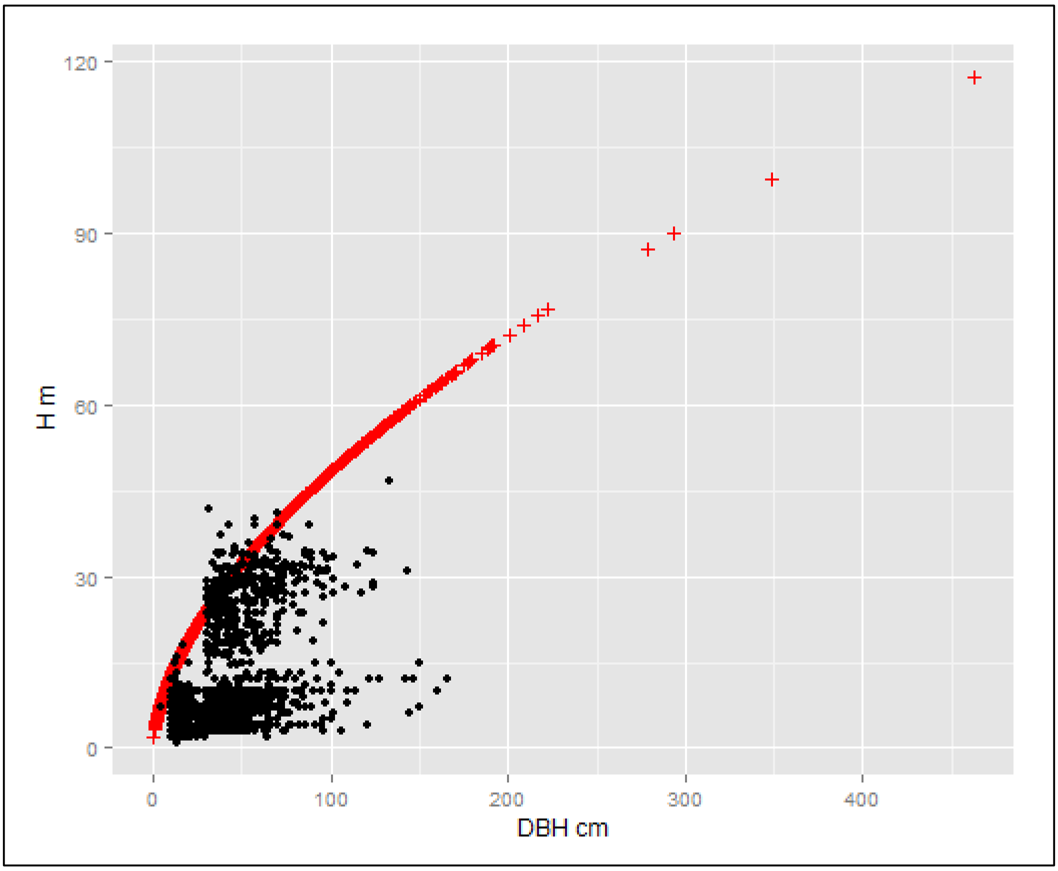


Figure 4: Tree height estimated with Feldpausch model (Feldpausch et al., 2010) for Asia (red crosses) compared to measured tree height (black dots).

Locally developed models

Modelling data from natural forest in protected areas

Given the huge difference between tree height-diameter relationships observed for WA project data compared to the community forestry inventories, local models have been developed. With the dataset of WA, only the Power and Michaelis Menten models converged. Indicators of goodness of the fit were in favor of the Power model (Table 8). Moreover the Michealis Menten model type led to an asymptotic height of 35 m which can be assumed too low for natural forests (Figure 6). So the selected model for natural forests was:

$$H = 1.3 + 9.303525 \times DBH^{0.24991}$$

With DBH in cm and H in m.

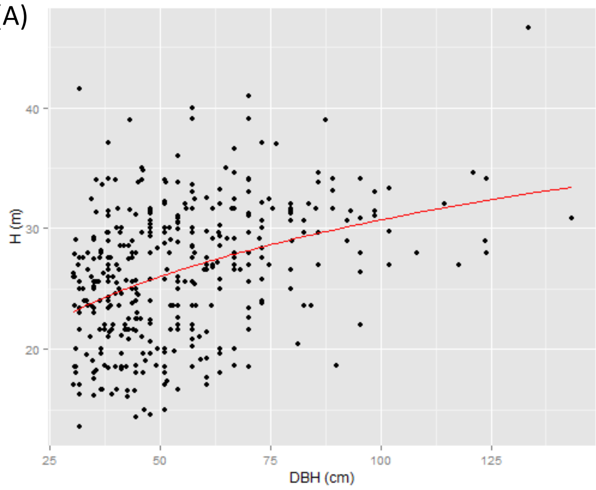
Table 8. Parameters and statistical indicators for tree height-diameter relationship.

Model type	Convergence	a	B	c	RSE	AIC
Power	Yes	9.303525	0.24991		5.145178	2296.743
Prodan	No					
Weibull	No					
Michaelis Mentens	Yes	34.19161	18.47194		5.166057	2299.781
Ratkowsky	No					

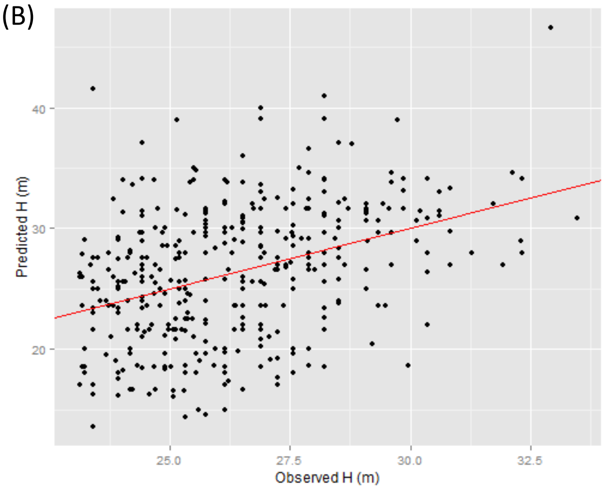
The graphs below show:

- (A) The observed (black dots) and predicted (red line) tree heights against diameters of the WA project forest inventory,
- (B) The predicted values against the observed ones (Black dots) and the line y=x (in red), and
- (C) The residuals of the power model against the predicted values (black dots). The red line represents an automatic fitting model of the variables.

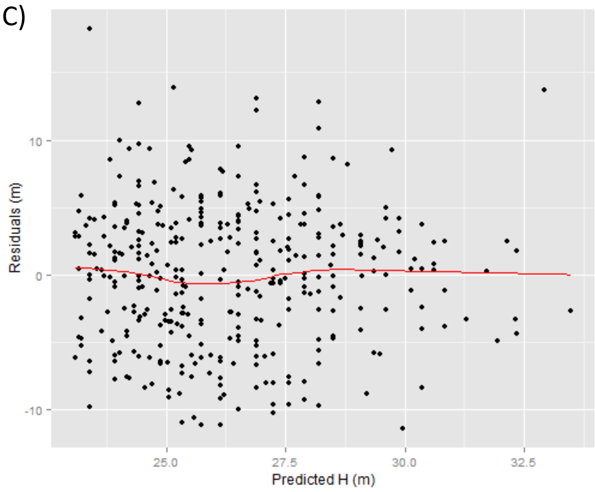
(A)



(B)



(C)



Modelling data from community forestry projects

The tree height and diameter data measured in CF comes from six projects, one in dry and the others in moist climatic zone (Figure 5). Four of the projects supported by FA have very small trees in diameter. This suggests they are located in degraded forest areas. The almost vertical shape of the trees height diameter plot makes it difficult to build models in this case. As per the other projects, the climatic zone could influence tree height diameter relationship, but the other environmental and human influences are probably not equal and developing models based on this modality could give not representative and biased results. The small tree height (less than 20 meters) observed even for big trees in CF suggests that tree height cannot be assessed by the existing models and that even biomass models developed for natural preserved forests might overestimate the biomass here by a factor at least two if tree height is not an input variable.

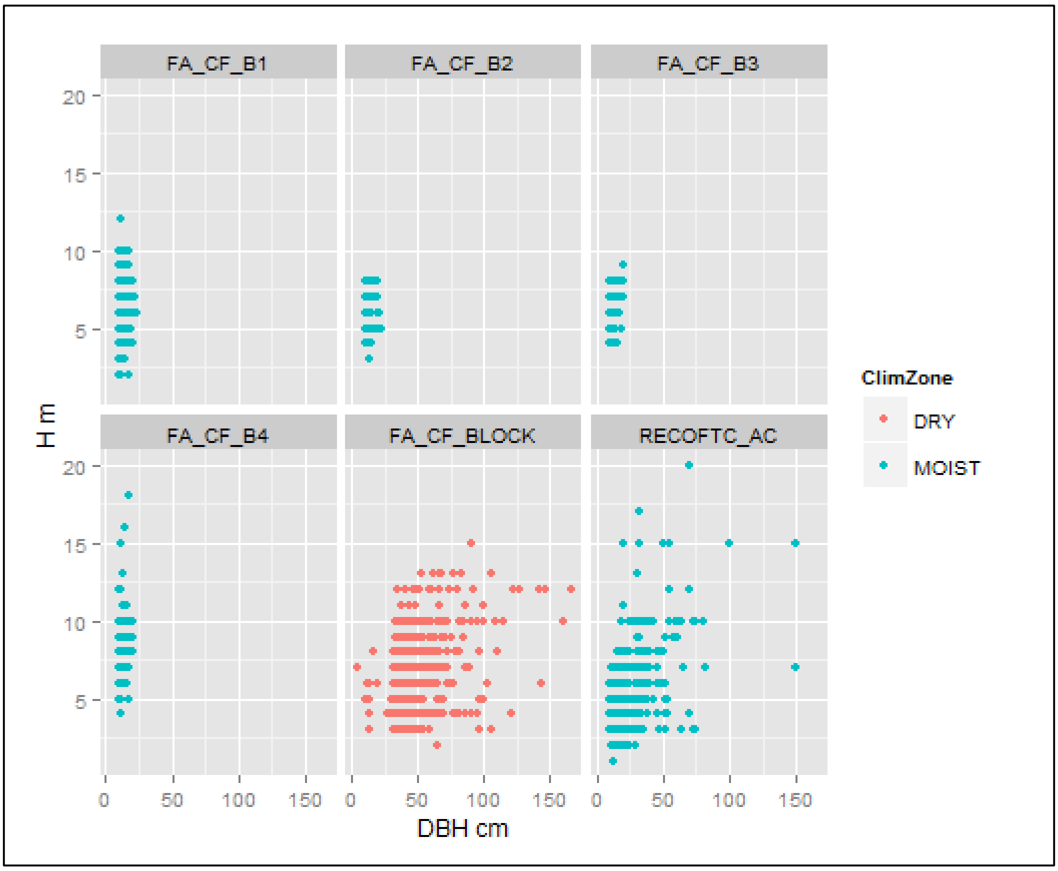


Figure 5: Tree height diameter relationship for six projects in community forestry.

To assess biomass of community forests, models including height are crucial and tree height should be systematically measured. If not, models without tree height that have been developed for not degraded forests might overestimate tree biomass significantly. Given that two datasets report the same low tree height for big trees in community forestry (FA_CF and RECOFTC), a second option for developing AGB_04 (mix of locally developed and pantropical models) was presented (AGB_04bis). In this second option trees from CF will have their height estimated by using the model for less degraded forest (based on data from WA) divided by three (Figure 6). No model converged to predict tree height from it diameter for CF forests and with this factor 3, the adapted model fitted well to the data, corresponded to the maximum tree height in CF compared to the rule of 60 m for natural forest and gave a bias of 6.8 %.

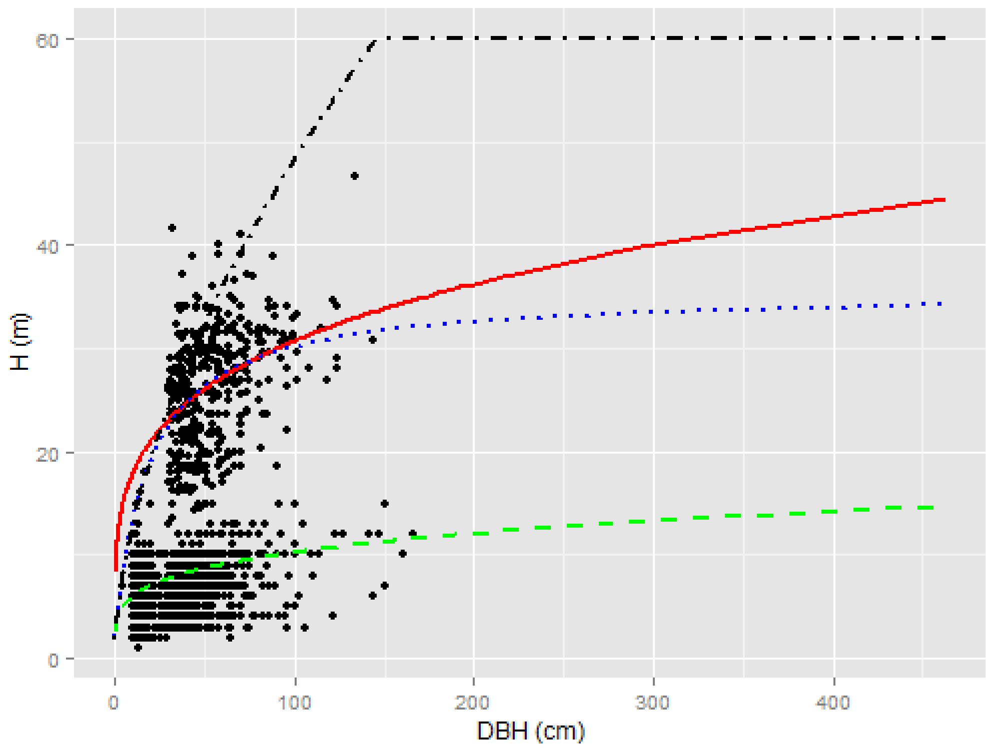


Figure 6: Tree height-diameter models.

Power model is represented with a red line, Michaelis-Menten with a blue dotted line, power model divided by three with a green dashed line, and Feldpausch model for Asia with limit at 60 m height with a black dashed and dotted line. The observed values are represented in black points.

Annex 3: aboveground biomass estimates at tree level and comparison of approaches

Results for AGB_01 and AGB_02

For trees with a DBH under 100 cm, AGB_02 (JICA model selection) gives similar results in PSP and REDD conservation projects for trees that have an average WD (0.4 to 0.6 g/cm^3). But trees in dry climatic zone (mainly CF projects) with a DBH bigger than 30 cm have less than half the AGB compared to approach one. The same range of difference occurs for trees in REDD conservation projects that have a low WD (less than 0.4 g/cm^3). On the contrary, trees in both PSP and REDD conservation projects with a wood density higher than 0.6 have their AGB increased up to 1.6 times compared to AGB_01 (Figure 7).

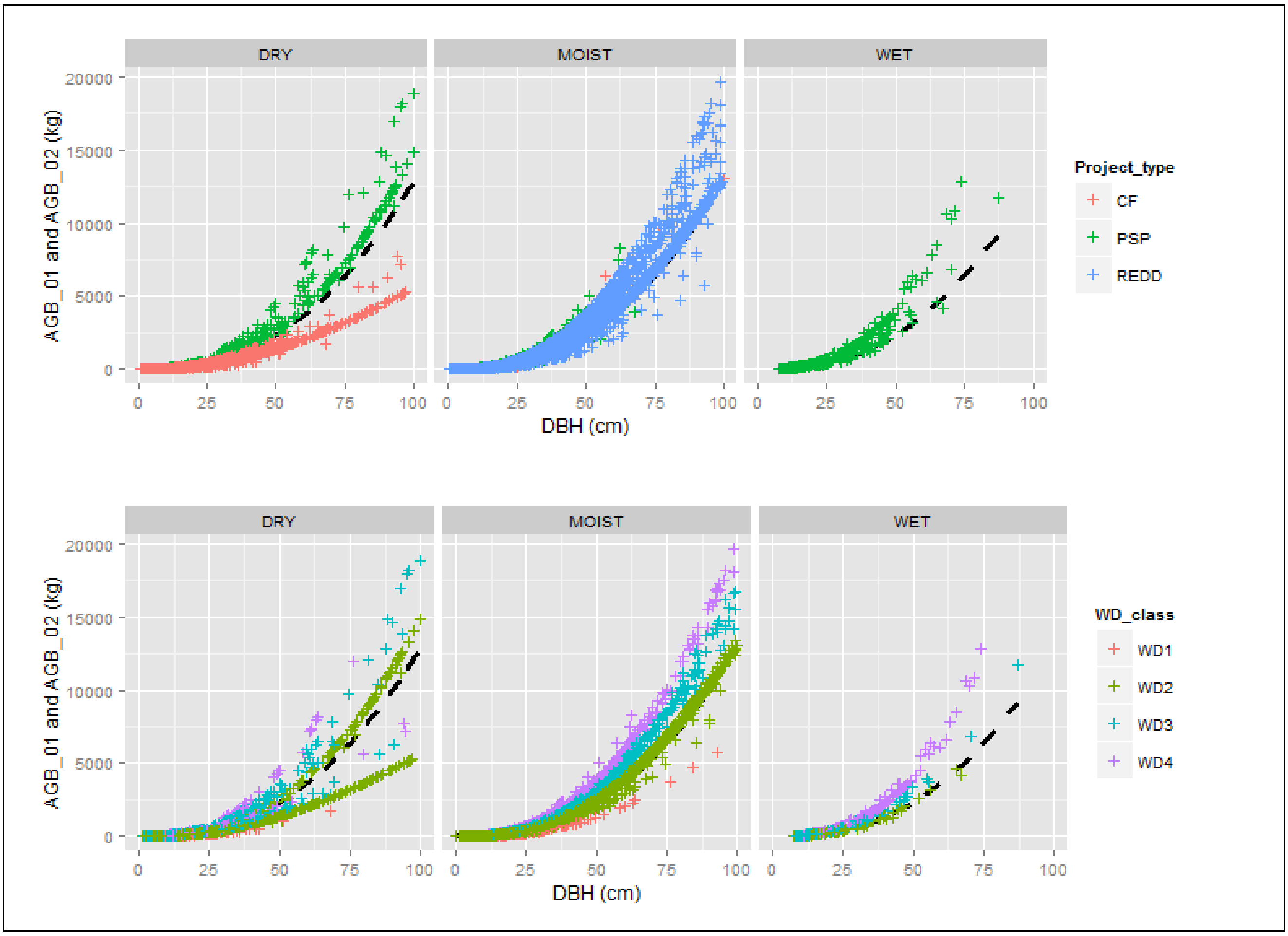


Figure 7: AGB_01 (dashed line) compared to AGB_02 (crosses) for trees under 100 cm DBH.

Each graph represents trees in one climatic zone and colors change with Project types in the above series and with the Wood density classes below (under 0.4, 0.4-0.6, 0.6-0.8 and bigger than 0.8 for WD1 to WD4).

Results for AGB_03

Compared to AGB_02, AGB_03 differs mainly for trees whose H was measured in the field (Figure 8). This approach shows how much models not including H as an input variables overestimate AGB (more than 5 times for tree with a 100 cm DBH in CF and 1.6 times for the same tree in REDD conservation projects). Estimating tree height with regional models leads to similar AGB in PSP data using Chave model (AGB_03) compared to IPCC model (AGB_01). But it is smaller than AGB_02, estimated using Kiyono model.

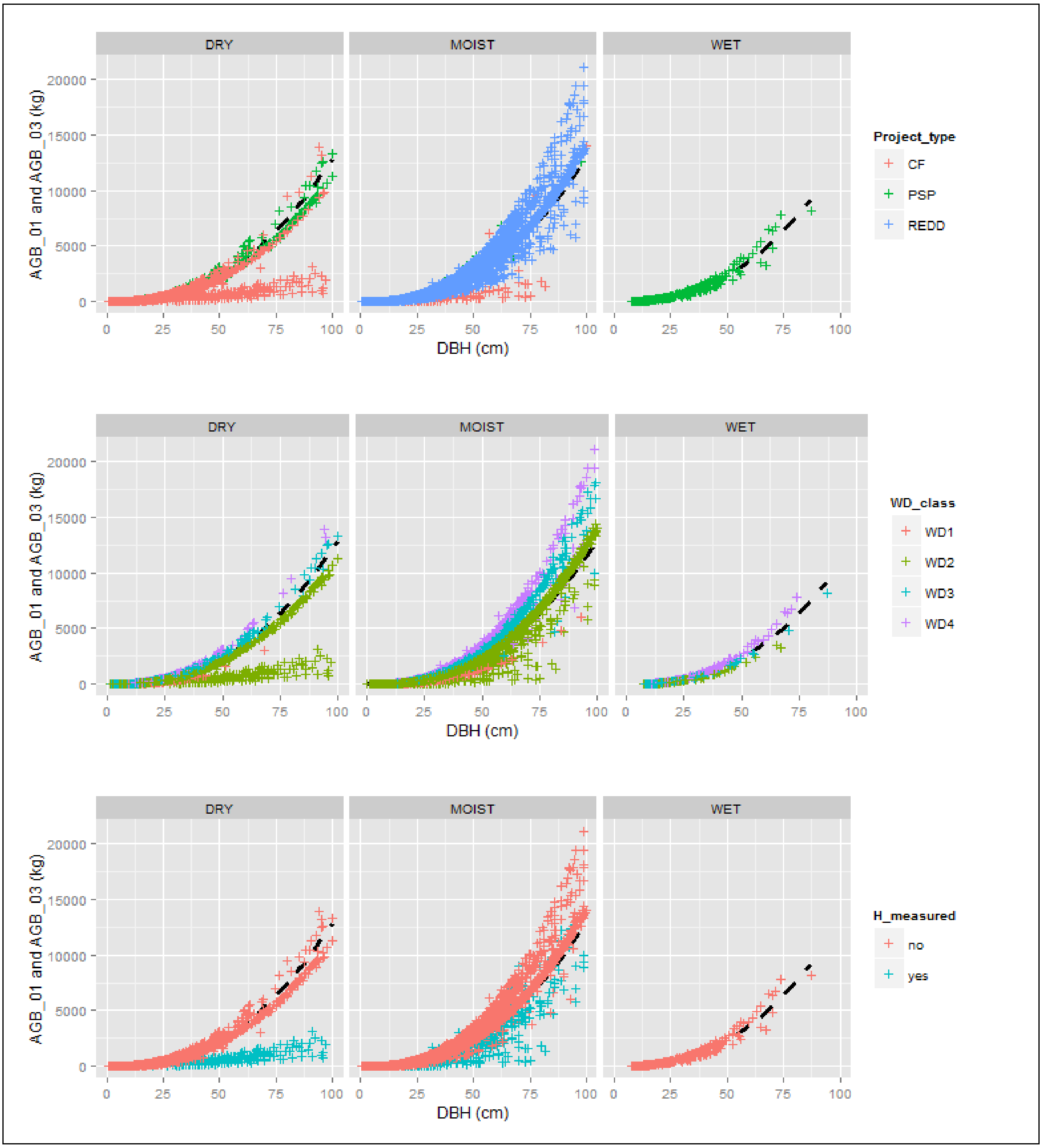


Figure 8: AGB_01 (dashed line) compared to AGB_03 (crosses) for trees under 100 cm DBH.

Each graph in a row represents trees in one climatic zone and colors change with Project types in the above series, with the Wood density classes in the middle series (under 0.4, 0.4-0.6, 0.6-0.8 and bigger than 0.8 for WD1 to WD4), and depend on if tree height was measure or not for the below series.

Results for AGB_04 and AGB_04bis

Compared to AGB_03, AGB_04 is smaller for REDD conservation projects (Figure 9), which is a consequence of the use of the local H-DBH model. As a result AGB of trees with a WD bigger than 0.8 have is similar between AGB_01 and AGB_04. As most of the trees have their WD estimated under 0.8, AGB_04 is smaller than previous approaches for REDD conservation projects. Using Chave model without H gives also better results for CF trees (less difference between trees whose H was measured or not). This shows that using regional H-DBH models is not suitable for all forest conditions. In this case it tends to overestimate AGB (except for trees in PSP plots).

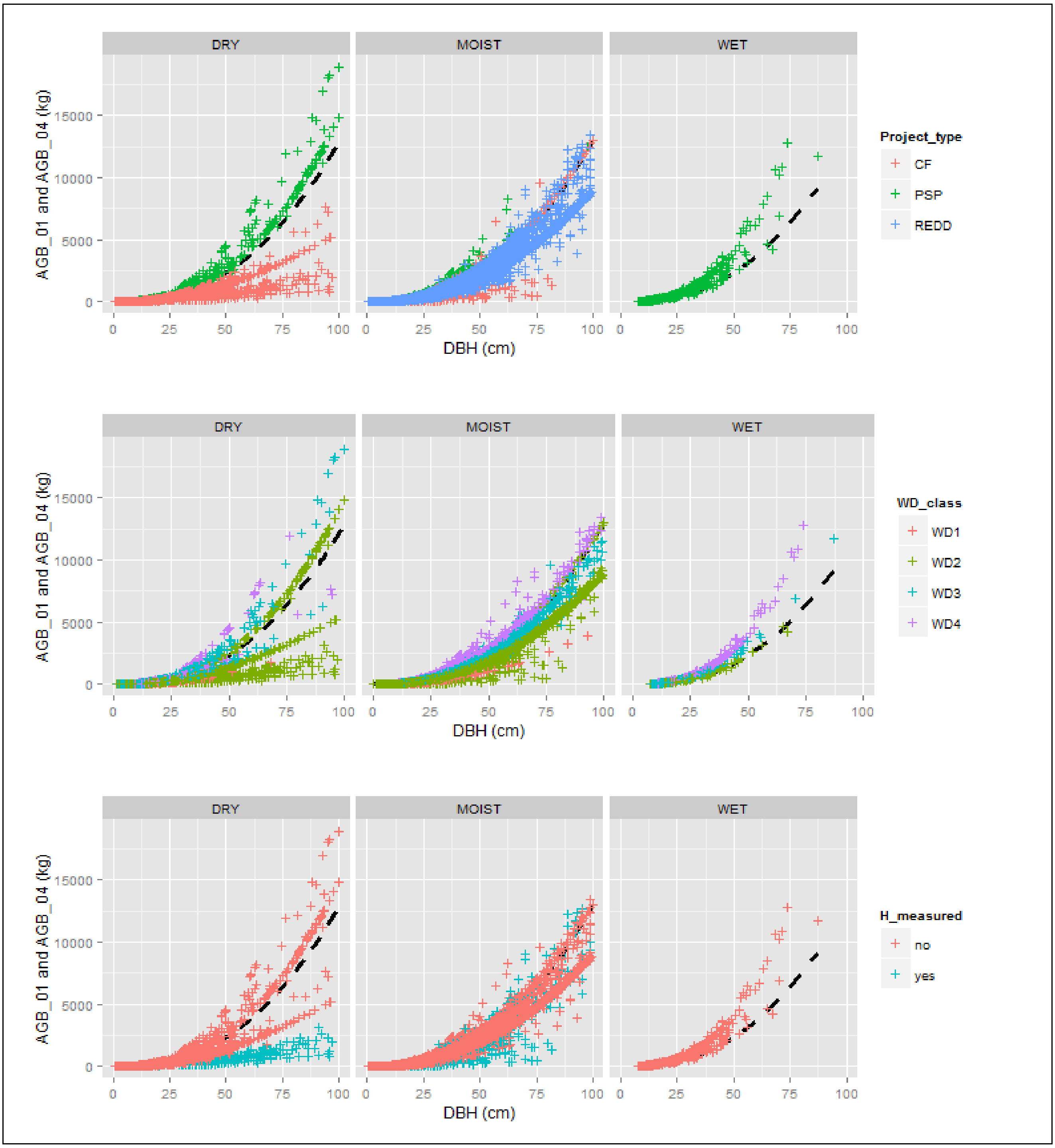


Figure 9: AGB_01 (dashed line) compared to AGB_04 (crosses) for trees under 100 cm DBH.

Each graph in a row represents trees in one climatic zone and colors change with Project types in the above series, with the Wood density classes in the middle series (under 0.4, 0.4-0.6, 0.6-0.8 and bigger than 0.8 for WD1 to WD4), and depend on if tree height was measure or not for the below series.

AGB_04bis gives an estimate of aboveground biomass for CF trees with no H measurement closer to the trees whose H was measured, compared to all the other approaches (Figure 10).

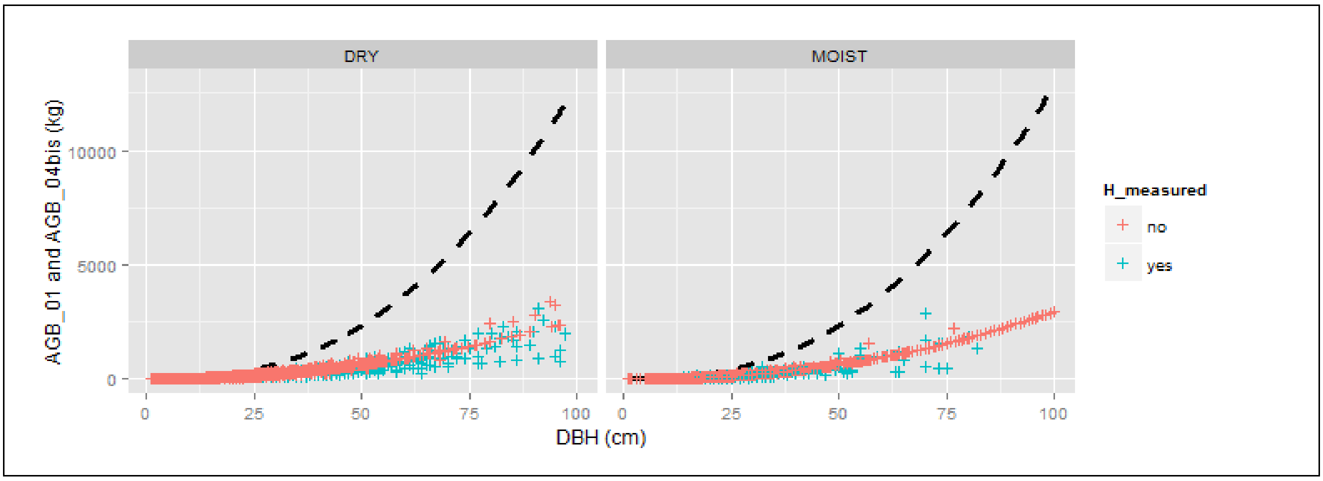


Figure 10: AGB_01 (dashed line) compared to AGB_04bis (crosses) for trees under 100 cm DBH.

Each graph in a row represents trees in one climatic zone and colors depend on if tree height was measure or not.

A new approach: AGB_05

AGB_05 was created with the following characteristics:

- Chave equation including tree height is used for all trees,
- Tree height is estimated with the local H-DBH model for trees in REDD conservation and one third of the H estimated with the local model for trees in CF projects.

The results of this approach are presented in the Figure 11.

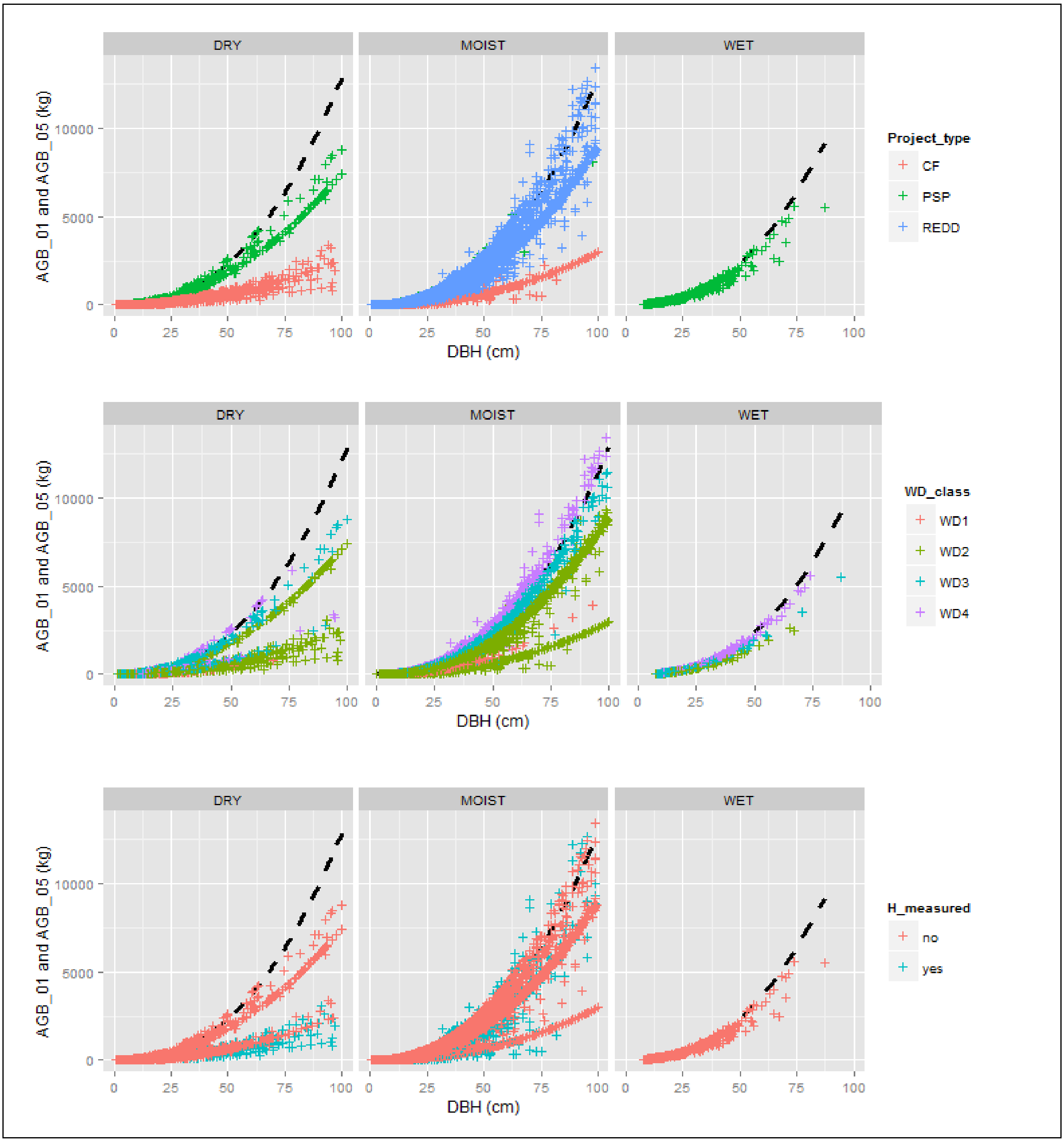


Figure 11: AGB_01 (dashed line) compared to AGB_05 (crosses) for trees under 100 cm DBH.

Each graph in a row represents trees in one climatic zone and colors change with project types in the above series, with the wood density classes in the middle series (under 0.4, 0.4-0.6, 0.6-0.8 and bigger than 0.8 for WD1 to WD4), and depend on if tree height was measure or not for the below series.

Differences among approaches for big trees

All the big trees are estimated out of the models' DBH range (Chave equations have been developed by trees up to 156 cm). All the models tested have a power relation between tree DBH and its AGB so that the big trees AGB estimates are very high. The biggest tree has a diameter of 452 cm and following AGB_05 approaches its AGB is around 3500 tonnes. If this value is realistic, the variation depending on the method is huge: for the same tree AGB is estimated to be 3000 tons following AGB_02, 4500 following AGB_03 and more than 5000 following AGB_01 (Figure 12). Considering that the average AGB_05 of a tree with 100 cm DBH in REDD conservation project is 9 tons. Our biggest tree has the same AGB than around 400 trees with 100 cm DBH.

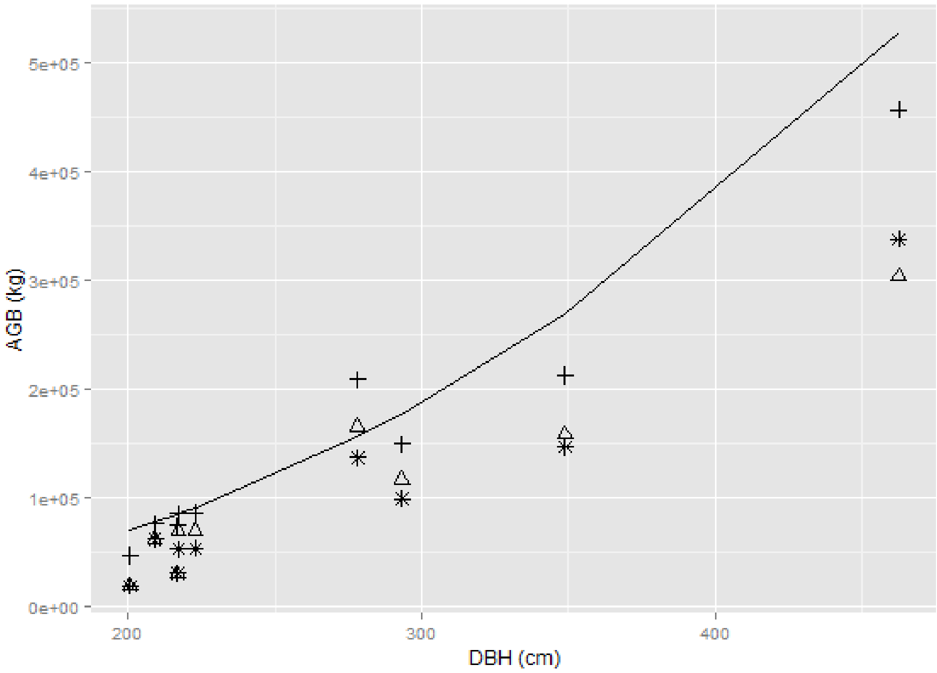


Figure 12: Biomass of trees bigger than 200 cm in DBH estimated following five approaches.

AGB_01 is represented in line, AGB_02 in triangles, AGB_03 in cross, and AGB_04 and AGB_05 in stars.

Annex 4: Comparison of biomass estimates between project types and institutions

Looking at AGB_05 results, the highest biomass averages per ha are found in PSP (426 tons per ha on average) (Table 9). Trees DBH distributions show that PSP trees have bigger DBH and AGB at plot level (Figure 13) than any other project (excluding FA_CF_Block). Even taking into consideration this possible cause, PSP average ABG_05 is still two to three times bigger than in the REDD conservation projects and more information on the forest conditions are necessary to better understand if this is the result of forest conditions or of measurement or data entry errors.

Forest in CF projects have an average biomass content of 29-42 tons per ha (excluding FA_CF where FA_CF_BLOCK increases the average biomass). The three REDD conservation projects have average aboveground biomass of 155 tons per ha for CI, 206 tons per ha for WA, and 155 to 313 for WCS supported projects (depending on the forests).

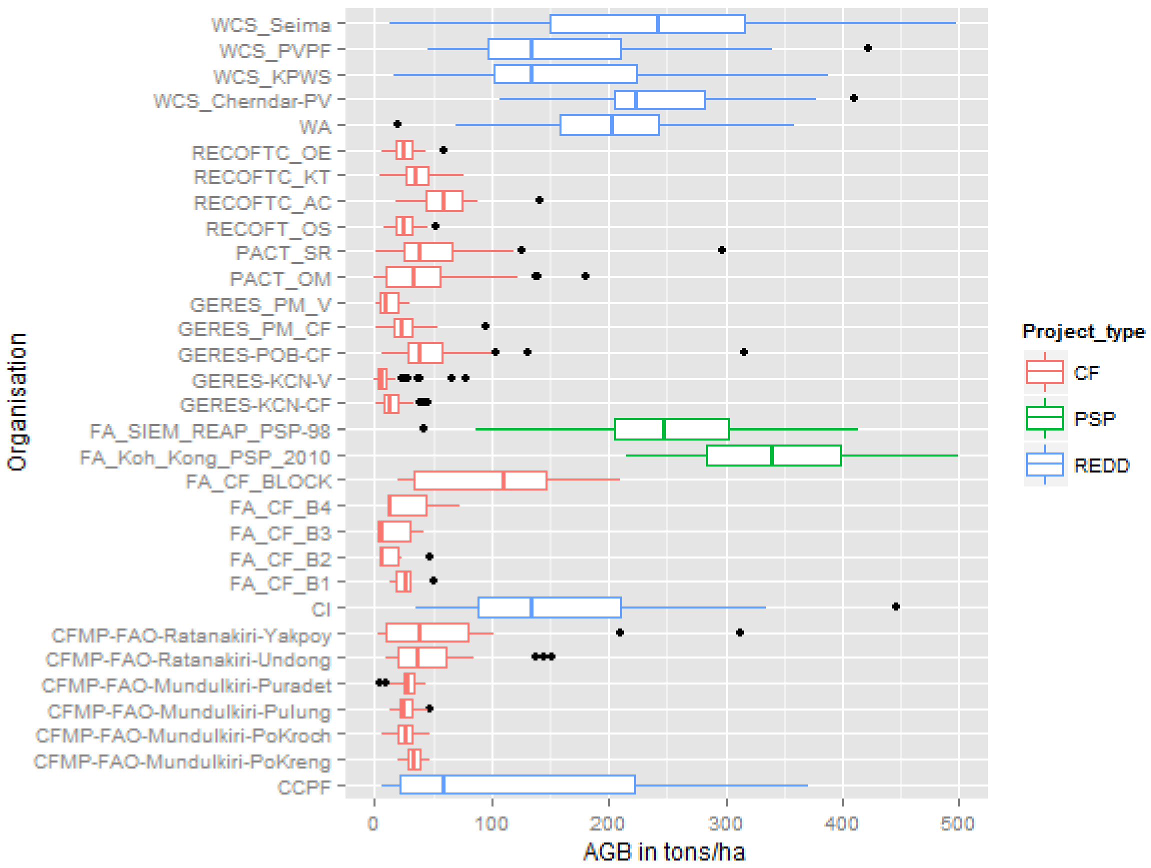


Figure 13: Distribution of AGB_05 per project.

Boxes represent the 25th and 75th percentiles, central bars the medians and the lines propagate the quartiles 1.5 times. Red boxes correspond to projects on community forestry, blue boxes on REDD conservation and green boxes on Permanent sampling plot.

Table 9: Mean basal area (in m2/ha) and aboveground biomass (in tons/ha) per project.

Project and **Organisation** level	Number of plots	Basal area		AGB_01		AGB_02		AGB_03		AGB_05	
		Mean	StdDev	Mean	StdDev	Mean	StdDev	Mean	StdDev	Mean	StdDev
FA_CF_B1	6	12	5	74	27	72	26	27	13	27	13
FA_CF_B2	6	7	7	40	45	39	44	15	17	15	17
FA_CF_B3	6	7	7	41	44	40	43	16	19	16	19
FA_CF_B4	6	9	8	55	50	54	49	30	27	30	27
FA_CF_BLOCK	16	38	20	480	270	262	136	101	61	101	61
CFMP – FA	**40**	**20**	**19**	**224**	**272**	**135**	**138**	**54**	**56**	**53**	**56**
CFMP-FAO-Mundulkiri-PoKreng	13	11	2	110	37	115	37	109	40	33	8
CFMP-FAO-Mundulkiri-PoKroch	37	9	3	87	30	91	31	85	29	27	9
CFMP-FAO-Mundulkiri-Pulung	43	9	3	89	30	93	31	87	31	27	8
CFMP-FAO-Mundulkiri-Puradet	53	10	3	93	29	98	31	91	29	28	8
CFMP-FAO-Ratanakiri-Undong	30	16	11	188	179	194	178	193	192	51	42
CFMP-FAO-Ratanakiri-Yakpoy	41	17	16	197	260	199	249	202	281	53	59
CFMP - FAO	**217**	**12**	**9**	**125**	**141**	**129**	**137**	**125**	**151**	**36**	**33**
CI	**51**	**17**	**9**	**154**	**107**	**175**	**113**	**167**	**111**	**155**	**88**
FA_Koh_Kong_PSP_2010	20	39	9	290	60	430	96	332	81	359	88
FA_SIEM_REAP_PSP-98	20	25	10	286	118	159	60	289	111	241	90
FA	**40**	**32**	**12**	**288**	**93**	**208**	**85**	**311**	**98**	**300**	**106**
FFI	**71**	**13**	**11**	**112**	**115**	**117**	**121**	**125**	**129**	**119**	**109**
GERES_PM_CF	85	8	4	64	41	75	50	71	52	25	13
GERES_PM_V	19	5	3	32	23	35	25	33	23	13	9
GERES-KCN-CF	54	6	4	31	25	31	26	33	26	15	11
GERES-KCN-V	54	4	4	34	55	37	61	35	59	11	15
GERES-POB-CF	138	14	8	110	131	86	59	118	119	46	31
GERES	**350**	**9**	**7**	**71**	**94**	**65**	**57**	**76**	**90**	**29**	**26**
PACT_OM	140	12	10	124	127	81	76	116	112	39	33
PACT_SR	51	15	14	127	200	98	100	138	176	51	46
PACT	**191**	**13**	**11**	**125**	**149**	**86**	**84**	**122**	**132**	**42**	**37**
RECOFT_OS	57	9	3	87	35	91	38	85	36	26	10
RECOFTC_AC	7	22	13	253	150	261	156	174	191	65	40
RECOFTC_KT	79	12	4	126	53	132	55	126	54	36	14
RECOFTC_OE	106	9	3	80	31	84	32	77	30	25	9
RECOFTC	**249**	**10**	**5**	**101**	**56**	**106**	**59**	**98**	**56**	**30**	**15**
WA	**105**	**22**	**6**	**203**	**88**	**231**	**85**	**221**	**93**	**206**	**72**
WCS_Cherndar-PV	15	25	7	314	118	324	116	326	129	245	81
WCS_KPWS	57	19	11	203	156	207	151	206	166	173	112
WCS_PVPF	61	17	8	180	101	187	102	181	106	155	77
WCS_Seima	308	31	17	368	268	402	283	405	305	313	200
WCS	**441**	**27**	**16**	**319**	**247**	**344**	**263**	**346**	**281**	**271**	**187**
General total	**1755**	**17**	**13**	**170**	**187**	**163**	**178**	**176**	**200**	**117**	**148**

Each Project corresponds to one forest area. StdDev represents the standard deviation associated to the given averages. Colors represent the project types: REDD conservation in white, CF in light grey and PSP in dark grey.

Annex 5: Comparison of approaches at forest level

Averages at forest level (project areas correspond to forest entities) show that differences between projects and project types are similar among approaches (AGB_04 and AGB_04bis have been excluded as AGB_05 is more advanced) (Table 9). The most important trends are for CF projects. Assuming the small tree height compared to other projects leads to very small AGB_05 (half to one fourth of AGB_01 for example). AGB_01 gives very high average AGB for one particular case (FA_CF_block) compared to other approaches. It may be a consequence of the high number of trees with a big diameter compare to other forest conditions. Field forms should be checked to ensure that the DBH values in the numeric tables are not in reality circumferences measurement in the field.

All approaches give similar results for REDD conservation projects except for WCS. AGB_02 and AGB_03 give slightly higher results (10 to 20 tons/ha more) than the others (Figure 14), mostly because these approaches do not take into consideration the lower tree heights measured in Cambodia compared to regional H-DBH models. For WCS, the differences among approaches might be the results of the influence of big trees. Forests measured by WCS have more than half of the big trees in the whole dataset (51% of the 432 trees with a DBH bigger than 100 cm). Approach 5 (AGB_05) is conservative here.

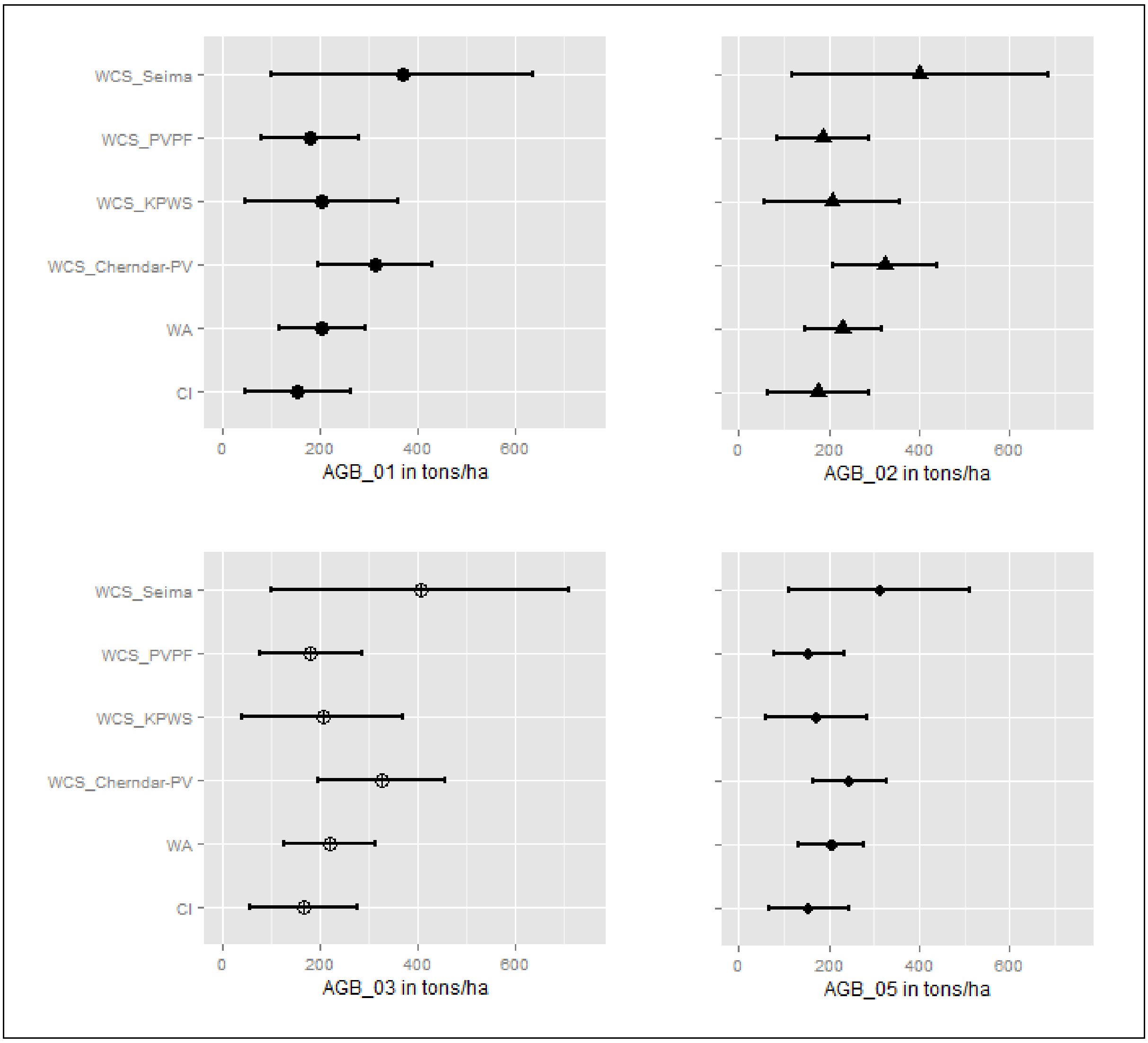


Figure 14: Averages and standard deviation of biomass in REDD conservation projects by four approaches (AGB_01 to AGB_03 and AGB_05).

Use of AGB_05 is recommended as it takes into consideration variability found in tree height among project types and is closer to the H-DBH relations found in Cambodia. Pantropical models might not consider the potential forest degradation that was very probably responsible for differences in H-DBH relations. As a result AGB_05, in using locally developed models, gives more realistic or at least more conservative values.

Annex 6: Number of plots used to develop emission factors for the three main forest types

Project type	Forest type (FA 2010)	Vegetation class (MoE 2007)								Grand Total
		Built-up / Barren Areas	Deciduous forests	Dryland crops / Paddy	Evergreen / Riparian Forests	Grasslands and Abandoned Fields	Open water	Secondary forest / Swidden	Semi-evergreen forests	
Community Forestry	Deciduous forest		**286**		31	61	2	1	136	517
	Evergreen forest		13		**210**	1		30	11	265
	Non-forest	2	29	33	1	51		10	6	132
	Others forest			2	1	20		26	1	50
	Semi-evergreen forest		7		30	1		4	**32**	74
	Woodshrub dry			1		3				4
	Woodshrub evergreen					3		2		5
CF Total		**2**	**335**	**36**	**273**	**140**	**2**	**73**	**186**	**1047**
Permanent sampling plots	Deciduous forest		4							4
	Evergreen forest				**35**					35
	Others forest				1					1
PSP Total			**4**		**36**					**40**
REDD	Bamboo								7	7
	Deciduous forest		150		11	5			15	181
	Evergreen forest		13		**270**	5		13	42	343
	Non-forest		10		2	2		1		15
	Others forest				2	1				3
	Semi-evergreen forest		12		25	2		23	**54**	116
	Woodshrub dry		3							3
REDD Total			**188**		**310**	**15**		**37**	**118**	**668**
Grand Total		**2**	**527**	**36**	**619**	**155**	**2**	**110**	**304**	**1755**

Annex 7 Emission factors for the main forest types (FA 2010), FAO global ecological zones for plots in REDD conservation projects, community forests and PSPs

Forest type (FA 2010)	FAO ecological zone	# of plots	Aboveground biomass average (tons/ha)	StdDev of AGB
Deciduous forest	Tropical dry forest	242	44	45
	Tropical moist deciduous forest	196	136	167
	Tropical rainforest	2	92	118
Deciduous forest Total		**440**	**85**	**125**
Evergreen forest	Tropical dry forest	226	88	94
	Tropical moist deciduous forest	122	254	165
	Tropical rainforest	167	197	114
Evergreen forest Total		**515**	**163**	**139**
Semi-evergreen forest	Tropical dry forest	24	128	148
	Tropical moist deciduous forest	62	287	256
Semi-evergreen forest Total		**86**	**243**	**241**
Grand Total		**1041**	**137**	**152**