Updated Forest carbon stocks for REDD+ Emission and Removal Factors in Cambodia

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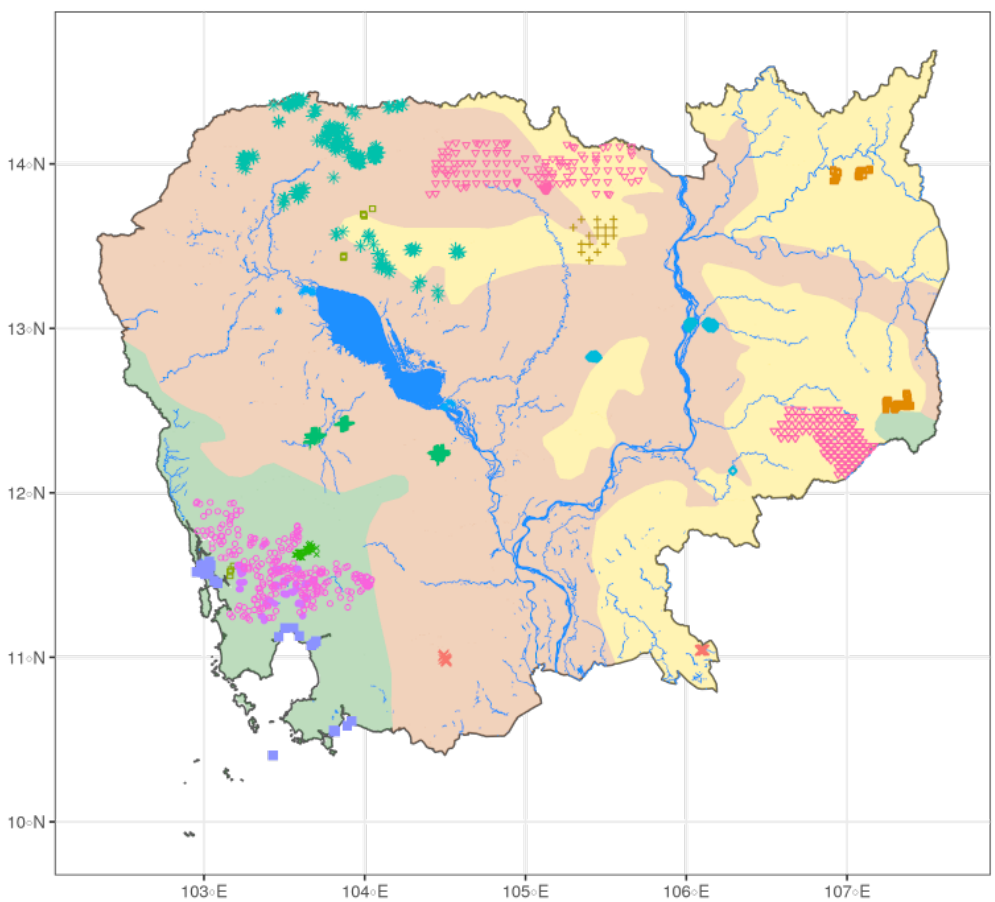

Updated Forest carbon stocks for REDD+ Emission and Removal Factors in Cambodia

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We finally thank the Food and Agriculture Organization of the United Nations (FAO) team of the Technical Cooperation Project to design Cambodia's first multi-purpose National Forest Inventory and the UNREDD Programme in undertaking the first assessment and UNDP and FCPF for providing the resources to update the assessment.

Abstract

Context
Accurately understanding the contribution of Cambodian forests to Greenhouse Gas emissions and removals requires good quality estimates of their carbon stock. While unbiased estimates are better provided by a national scale forest inventory, such initiative has not been implemented yet in Cambodia. As an alternative most project based forest inventory data was collected by the government and in 2014 a first set of forest carbon stocks were calculated and used for the country's first REDD+ forest reference (emission) levels submission.

Objective
The objective of this study was to update the 2014 forest carbon stock estimates with the inclusion of new data, increasing the quality of the emission factors for forest types already covered and including field based estimates for flooded forest and mangroves.

Method
The data for all the inventories was harmonized with a common set of correction rules, map-based forest classes, allometric equations for aboveground biomass, and conversion factors such as root-to-shoot ratios and carbon fraction. A new height-diameter relationship was developed in this study thanks to the new data collected since the 2014 study.

Results
The overall dataset included 2100 plots collected by 14 projects from 1998 to 2017, covering the main forest types of Cambodia: evergreen, semi-evergreen, deciduous, flooded and mangrove forests. Around 10 % of the trees had both tree diameter and height recorded. Data from different projects in Community Forestry exhibited a different tree height-diameter trend than that of the other forests and were isolated in another forest type class named 'community land', with much lower tree heights than the other forest types for equivalent diameter. The final carbon stocks were presented with and without the data from one sub-project, because it targeted very high value forests and could lead to overestimating semi-evergreen but also to a lesser extent evergreen and deciduous forests. Without that sub-project the carbon stocks above and below ground ranged from 114.66 tCO_2/ha in community land to 341.7 tCO_2/ha in semi-evergreen forest (evergreen carbon stock being a few ton lower), with a combined carbon stock for evergreen, semi-evergreen and deciduous forest of 281.12 tCO_2/ha.

Conclusion
Thanks to the addition of three new datasets to the data available for the 2014 study, field based carbon stocks were developed for flooded and mangrove forests, and all other forest types had improved carbon stock estimates with a better H-D model and updated IPCC root-to-shoot ratios. The inclusion of the high value forests carbon stock remained to be decided but most importantly, only a full scale national forest inventory could help to understand the contribution of the different forest conditions and provide unbiased carbon stock estimates. In the meantime, this study presents the most comprehensive analysis of existing data to calculate forest carbon stocks in Cambodia.

Contents

List of Tables

List of Figures

Acronyms and Abbreviations

Acronyms	Description
AGB	Aboveground Biomass, in kg ton or ton/ha
BGB	Belowground Biomass, in kg ton or ton/ha
CF	Community forest
CI	Conservation International
CI (%)	Confidence Interval at 95 % expressed in % of the value it is associated with
CRS	Coordinbate Reference System
D or DBH	Diameter at Breast Height, in cm
FA	Forest Administration of the Royal Government of Cambodia
FAO	Food and Agriculture Organization of the United Nations
FCPF	Forest Carbon Partnership Facility
FFI	Fauna and Flora International
FiA	Fisheries Administration of the Royal Government of Cambodia
FRL	Forest Reference Emission Levels or Forest Reference Levels for REDD+
GDANCP	General Department of Administration for Nature Conservation and Protection of the Royal Government of Cambodia
GERES	Groupe Energies Renouvelables et Solidarités
GPS	Global Positioning System
GWD	Global Wood Density Database
H	Tree total height in m
ha	Hectare
RECOFTC	The Center for People and Forests
REDD+	The mechanism for Reducing emissions from deforestation and forest degradation 'plus' the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries
RUA	Royal University of Agriculture
UNDP	United Nations Development Programme
UNREDD	United Nations REDD+ programme
USFS	United States Forest Service
USAID	United States Agency for International Development
WA	Wildlife Alliance
WCS	Wildlife Conservation Society
WD	Wood Density defined as the ratio of wood dry mass to its fresh volume in g/cm^3

1 Introduction

To estimate the contribution of Cambodian forests to Greenhouse Gas emissions and removals, a set of forest carbon stocks was developed in 2014 using project based forest inventories. The method and results were described in the first Forest Reference (Emission) Levels submission of Cambodia and in the 2014 UNREDD report: Forest biomass in Cambodia: from field plot to national estimates (Sola et al., 2014).

The results of the 2014 study showed differences among forest types, which were due to forest characteristics such as number of trees per ha, tree diameter and height, species composition, but also in part due to the use of different forest inventory methodologies (15 different methodologies had been applied), and to another degree to the management regime. A full scale national forest inventory (NFI) will address aspects related to the inconsistencies between plot design, recording and analysis, as well as potential bias introduced by project-based forest inventories established mostly in conservation sites and community forests, thereby not reflecting the full variability of forest in Cambodia.

Also, none of the local allometric equations were found suitable for estimating tree biomass from the diameter and height parameters. The most reliable and conservative estimates came from a combination of locally developed tree height diameter relationships together with pan tropical models. Several recommendations were provided to improve forest inventory datasets, allometric equations and forest biomass estimates in Cambodia.

The present study builds on the 2014 study and addresses some of the recommendations: increasing the range of forests covered in Cambodia, in particular including forest assessment in mangrove and flooded forest; utilizing new country specific multi-species allometric equations developed in Cambodia for upland (semi-evergreen and deciduous) and flooded forest; and improving the locally developed tree height-diameter model with additional data. Other key aspects of improvement won't be addressed until data from full national forest inventory becomes available.

2 Method

2.1 Description of the data

The detailed description of the project based inventories collected can be found in the first Forest Reference (Emission) Levels submission of Cambodia and in the 2014 UNREDD report "Forest biomass in Cambodia: from field plot to national estimates" (Sola et al., 2014). The data was collected by the Royal Government of Cambodia (RGC) in partnership with different institutions and analysed in support of designing a country appropriate National Forest Inventory and providing first estimates of forest biomass across the country.

Additional data used to refine the emission factors were:

- **WA-2017**, a set of data collected in the Cardamoms in 2017, across evergreen, semi-evergreen and deciduous natural forests. The tree data was collected in 15 m radius circular plots.
- **USFS-2015-M**, data collected on mangrove forests between 2014 and 2015, following the SWAMP protocol. Trees with DBH bigger than 70 cm were collected in a 50 x 50 meter square plots while smaller trees were collected in 5 circular plots of 7 m radius each.
- **RUA-2015**, flooded forest data collected around the Tonle Sap following the design for national forest inventory subplot system: small trees were collected in 10m squares (5 cm +), medium trees in 15 x 30 m rectangle (15 cm +) and large trees (30 cm +) in the larger plot with 30 x 50 m dimensions (Kim et al., 2019a).
- **USFS-2016-F**, another dataset collected in the Tonle Sap flooded forests. This inventory focused on the North side of the lake. Tree were measured in 11 m radius circular plots. The report mentioned plots were composed by 6 circles forming a gradient perpendicular from the lake front, but the data showed that each circle was considered as a one plot.

2.2 Data harmonization

The data harmonization process consisted of: selecting relevant information from project files, adding information on forest type (based on maps) and wood density (WD – based on tree species), and estimating tree height (H) and aboveground biomass (AGB) with a common set of allometric equations.

2.2.1 Key information from project data

The key information gathered from project files was:

- Plot information:
  - project,
  - plot ID,
  - plot size,
  - subplot size and tree diameter thresholds,

- forest type,
- plot GPS coordinates.

- Tree information:
  - tree ID,
  - Diameter at breast height (DBH),
  - tree total height (H) (if measured),
  - tree species,
  - tree health status.

Forked trees were considered multiple trees, one per stem, if the fork is below 1.3 m. The number of trees reported could be slightly higher than the reality as most data files didn't have a specific identifier for forked tree stems. In particular in the WA-2017 data, the files used for calculations had some of the trees with forks (ex: plot CM04 tree 19) removed if no stem had a DBH bigger than 10 cm. Other forked trees were duplicated to one stem equal to one tree.

2.2.2 Adding forest type and wood density

The land uses or forest types were most often not reported in the data or inconsistent across data sets. To harmonize the forest types, they were retrieved from maps using plot GPS coordinates. The 2007 vegetation map from MoE (MoE2007) and the forest cover 2016 map developed for REDD+ (FC2016) were used to identify forest types at the plot level. They are referred to as **forest type** when based on MoE2007, **forest type 'fc'** when based on FC2016 and **forest type 'mix'** when based on FC2016 for recent data (collected during or after 2013) and MoE2007 for older data.

Flooded forest and mangrove data where labelled as such in all three forest type classifications, even if the maps classes were different as the records could ascertain these classes.

Wood density was added to the tree level data based on species and genus averages from the Global Wood Density Database (GWD) (Chave et al., 2009; Zanne et al., 2009). The data from Southeast Asia and Southeast Asia Tropical were selected and averages calculated for each species and genus. Wood density for each tree was based on species if available in the GWD, genus if species was not available, or a default value of 0.57 g/cm^3 if both species and genus were unknown, not recorded or not in the data. The default value was based on a wood density average for Tropical Asia in Reyes et al. (1992).

2.2.3 Allometric equations

When not recorded in the field, tree height was estimated using forest type based allometric equations, developed with the other available data on tree H and DBH (see section 2.4).

Aboveground biomass was estimated with different allometric equations for different forest types or species for mangrove (Table 1). The equation from Chave et al. (2014) was applied to evergreen forest, the equation developed in Cambodia for upland forest (Kim et al., 2019b) was used for semi-evergreen and deciduous forest, as well as community land and non-forest. The equation developed in Cambodia for flooded forest (Kim et al., 2019a) was applied to flooded forest data and species specific equations were applied to mangrove forest, based on the SWAMP protocol (Kauffman and Donato, 2012) and the report from USFS on the methodology to calculate mangrove carbon stock in Cambodia.

Table 1: Aboveground biomass allometric equations.

Forest type	Equation
Evergreen	AGB = 0.0673 * (DBH^2 * H * WD)^ 0.976
Semi-evergreen	AGB = 0.0607 * DBH^2.2692 * H^0.5122 * WD^0.3183
Deciduous	AGB = 0.0607 * DBH^2.2692 * H^0.5122 * WD^0.3183
Community land	AGB = 0.0607 * DBH^2.2692 * H^0.5122 * WD^0.3183
Non forest	AGB = 0.0607 * DBH^2.2692 * H^0.5122 * WD^0.3183
Flooded forest	AGB = 3238.2787 * (1 - exp(-0.00000837 * (DBH^2 * H)))
Mangrove	
- Avicennia alba	AGB = 0.1848 * DBH^2.3524
- Avicennia marina	AGB = 0.1848 * DBH^2.3524
- Bruguiera cylindrica	AGB = 0.0754 * WD * DBH^2.505 + 0.0679 * DBH^1.4914
- Bruguiera gymnorhiza	AGB = 0.0754 * WD * DBH^2.505 + 0.0679 * DBH^1.4914
- Rhizophora apiculata	AGB = 0.043 * DBH^2.63
- Rhizophora mucronata	AGB = 0.043 * DBH^2.63
- Rhizophora sp.	AGB = 0.043 * DBH^2.63
- Sonneratia alba	AGB = 0.3814 * WD * DBH^2.101 + 10^(-1.1679 + 1.4914 * log10(DBH))
- Sonneratia ovata	AGB = 0.3814 * WD * DBH^2.101 + 10^(-1.1679 + 1.4914 * log10(DBH))
- Xylocarpus granatum	AGB = 0.3814 * WD * DBH^2.101 + 10^(-1.1679 + 1.4914 * log10(DBH))
- Xylocarpus moluccensis	AGB = 0.3814 * WD * DBH^2.101 + 10^(-1.1679 + 1.4914 * log10(DBH))
- Other mangrove species	AGB = 0.251 * WD * DBH^2.46

2.3 Outlier detection and data correction

Outlier detection and corrections were applied to plot GPS coordinates, tree DBH, H and species. GPS coordinates were particularly important to assign plots an harmonized forest type classification. Most data didn't specify the coordinate reference system used (WGS 1984 or Indian 60) and many typos were found in the different inventories. The corrections were mostly manual, outlier plots were identified through mapping and corrected based on plot ID and neighbour plots from the same project. The CRS couldn't be retrieved for all the data and Indian 60 UTM 48N was assumed for all the FRL data. For the data added in 2019, WGS84 UTM 48N was assumed when not specified. The difference between WGS 84 and Indian 60 could have resulted in plots being more than a hundred meters away from their location. This part of the analysis was performed with QGIS and R with the package `sf` (Pebesma, 2020).

Tree DBH and H were corrected using a boxplot representing tree diameters variability per inventory and H-DBH scatter plots. Very big trees with no information on species or tree height were removed (DBH > 5 m). Similarly, trees higher than 60 m had their height measurement removed.

Tree species were corrected automatically with the Taxonomic Name Resolution Service (TNRS) with the R package `BIOMASS` (Réjou-Méchain et al., 2020).

2.4 Developing tree height-diameter allometric equations

Allometric equations for tree aboveground biomass were found in the literature (see section 2.2). Tree height diameter relationships were developed with the tree data collected, using maximum likelihood non-linear models with mixed effect. The analysis was performed with the R packages `nlme` (Pinheiro et al., 2020) and `lmfor` (Mehtatalo and Kansanen, 2020). The data was split randomly into 2/3 of the trees per forest type 'mix' and per DBH class for developing the model and the remaining 1/3 for validation. The model forms tested were Weibull (1), Gomperz (2) and Meyer (3):

- Weibull:

(1) `H = 1.3 + a * (1 - exp(-b * DBH^c))`

- Gomperz:

(2) `H = 1.3 + a * exp(-b * exp(-c * DBH))`

- Meyer:

(3) `H = 1.3 + a * (1 - exp(-b * DBH))`

The effect of the three forest type classifications were tested as random effect on the models' parameter `a`. The random effect was first applied to all two or three parameters but models didn't converge easily and had at least one parameter with low significance (p-value > 0.01).

The best models were selected based on: parameter significance (p-value), Akaike Information Criterion (AIC) (Akaike, 1974) and visual checks of the models' fitted values and residuals behaviour (Picard et al., 2012). The selected models were then validated with the smaller dataset and compared to the 2014 UNREDD study and Feldspauch (2011) model for Asia. The bias formula was calculated, with a formula (4) taken from Chave et al. (2005).

(4) `Bias = mean((prediction - observation) / observation) * 100`

2.5 From tree aboveground biomass to plot level and forest type carbon stock

Trees' aboveground biomass was summed to plot level and converted to ton per hectare, then simple averages were calculated per forest type and project or sub-project to identify potential outliers. Sub-projects carbon stock estimates could be removed if their carbon stock was too different from other projects in the same forest types. As a wide range of plot shapes and sizes was used across inventories, the estimates could be corrected for plot size differences by using a ratio estimator (Cochran, 1977). However given that most projects covered different areas, a simple average was used. Using a ratio estimator would also give more weight to large plots, but the project inventories based on large plots did not necessarily reflect better country forest conditions than other projects.

A 95 % confidence interval was calculated with the forest type average aboveground biomass, based on the formula (5), with `sd` the standard deviation associated to the averages and `n_plot` the number of plots per class considered.

(5) `ci = sd / sqrt(n_plot) * 1.96`

The carbon stocks were finally calculated as the sum of aboveground and belowground biomass multiplied by conversion factors (6):

(6) `Cstock ($CO_2$) = AGB * (1 + RS) * 0.47 * 44/12`

With `RS` the root-to-shoot ratio, 0.47 the carbon fraction (IPCC 2006) and 44/12 the atomic mass conversion from carbon to CO2. Different root-to-shoot ratio were applied to the different forest types: 0.49 for mangrove (IPCC 2013), 0.37 for evergreen forest (IPCC 2006) and 0.2 for all other types (IPCC 2006).

2.6 Data analysis and reporting

The data analysis and reporting were performed with `R` (R Core Team, 2019) and `Rstudio` (RStudio Team, 2015). In addition to the packages already mentioned the following packages were used for data analysis: `tidyverse` (Wickham, 2019), for visualizations `ggplot2` (Wickham et al., 2020), `ggthemr`, `gridExtra`, `tmap`, `leaflet`, `magick`, `webshot` and for reporting `knitr` (Xie, 2020b, 2015), and `bookdown` (Xie, 2020a). Plot visualisation was also carried out with QGIS.

3 Results

3.1 Harmonizing historical inventories

All the project based inventories were collected between 1998 and 2017 and the number of plots established per project ranged from 10 to more than 300 (Table 2). Main characteristics or modifications of the data from the three new datasets were:

1. WA-2017 - Koh Kong:

- All trees with DBH < 10 cm were removed as they were classified as shrub.
- All standing and lying dead trees were removed.
- All trees recorded outside the plot boundaries (tree distance > 15 m) were removed.

2. USFS-2015 - Mangrove:

- Corrected a number of discrepancies and typos in species codes (UNKNOWN, UNKW, AV, AVSP, etc.).
- Harmonized unknown species (XYGA and XYGY change to XYGR, all unknown coded UNKN),
- A number of species identified in the data were not reported in the list of mangrove species wood densities and allometric equations and could not be identified, ex: Acrostichum (re-coded ACSP, removed as palm tree), ACAU (Acrostichum aureum?), ACSP, BRKI, CLIN, CO, ESERH, HITI, NYFR, NYPA, Pheonix (PHSP), PHPA, etc.
- In the data the wood density of the unknown species was calculated as the average of the same subplot known species wood density (ex. if there are 4 known species, the unknown species' wood density will be the average of 4 wood densities). For the national level data analysis unknown species have a default wood density from Reyes et al. (1992) for Tropical Asia: 0.57 g/cm^3.

3. RUA-2015 - Tonle Sap:

- All trees measured outside their DBH based subplot were removed.

4. USFS-2016 - Tonle Sap:

- Dead trees and lianas were removed.
- the report related to this forest inventory mentioned 6 circular sub-plots with 11 m radius to be considered one plot but the data showed only one subplot per plot.
- The plot locations were recorded with a mix of WGS 84 UTM 48 (in meter) and WGS 84 degrees decimals or degrees minutes seconds.
- Note: As the data was received in a later stage of the data analysis it was not used to develop tree H-D relationships. It was used however to calculate the bias of the model for this data.

Table 2: Number of trees and plots measured in the different projects.

Project	Year (approx)	Plot size (m^2)	Number of plots	Number of trees
FA	1998	2500.00	20	545
WCS	2004	5000.00	15	1465
PACT	2009	2500.00	201	14045
WCS	2009	1256.64	308	7819
FA	2010	2500.00	20	1268
WA	2010	10000.00	105	20657
FFI	2011	615.75	71	1476
RECOFTC	2011	5000.00	249	10564
WCS	2011	3769.91	118	7096
CFMP - FA	2012	2500.00	40	2717
CFMP - FAO	2012	5000.00	218	16485
GERES	2012	600.00	349	3648
CI	2013	1256.64	51	1056
RUA-2015	2015	1500.00	18	325
USFS-2015-M	2015	2500.00	48	6206
USFS-2016-F	2016	380.00	33	1206
WA-2017	2017	707.00	247	7837

If all the projects put together represent a decent coverage of the country the inventories were scattered over almost 20 years.

3.2 Outlier detection and corrections

3.2.1 GPS coordinates

A number of mangrove plots had no GPS coordinates or typos: `USFS-2015-M_4`, `USFS-2015-M_SHV1`, `USFS-2015-M_6`, `USFS-2015-M_KK01A`, `USFS-2015-M_KK08`, `USFS-2015-M_KK12`, `USFS-2015-M_KK13`, `USFS-2015-M_KK14`, `USFS-2015-M_KK15`, `USFS-2015-M_KK16`, `USFS-2015-M_KK19`, `USFS-2015-M_KK3`, `USFS-2015-M_KK4A`, `USFS-2015-M_RN33`, `USFS-2015-M_RN36`, `USFS-2015-M_SA22`, `USFS-2015-M_SA23`, `USFS-2015-M_SA25`, `USFS-2015-M_SA27`, `USFS-2015-M_SA31`, `USFS-2015-M_SA32`.

GPS coordinates for missing plots were replaced by: plot 5 coordinates for plot 6, average coordinates of plots in KK, SA and RN locations.

For FRL data, plot coordinates were corrected based on a preliminary analysis by Lauri Vesa in 2013 as part of the Cambodia's NFI design undertaking, plus several manual corrections to remove different GPS coordinates given to the same plots or due to typos:

```
x_corr = case_when(plot_id2 == "WA_230"                    ~ 335801,
                   plot_id2 == "WA_3"                      ~ 331660,
```

```
                    plot_id2 == "CFMP - FA_Trapaing Saray_1" ~ 618409,
                    plot_id2 == "RECOFTC_07"                 ~ 610386,
                    project == "CFMP-FAO-Ratanakiri-Yakpoy" & x == 27302 ~ 727302,
                    plot_id2 == "CFMP - FAO_OBRV 25"         ~ 706748,
                    plot_id2 == "CFMP - FAO_Tokor13"         ~ 749725,
                    TRUE ~ x_corr),
y_corr = case_when(plot_id2 == "WA_21"               ~ 1276101,
                    project == "CFMP-FAO-Ratanakiri-Yakpoy" & y == 116154 ~ 1541161,
                    plot_id2 == "CFMP - FAO_Bora40"  ~ 1541116,
                    plot_id2 == "CFMP - FAO_OBRV 25" ~ 1544818,
                    plot_id2 == "CFMP - FAO_Tokor13" ~ 1383208,
                    plot_id2 == "CFMP - FAO_OPTT3"   ~ 1394322,
                    TRUE ~ y_corr))
```

The plot distribution showed that all the main areas of Cambodia had plots measured, with a higher concentration in few key areas such as the Cardamoms, and Mondolkiri (Figures 1, 2 and 3).

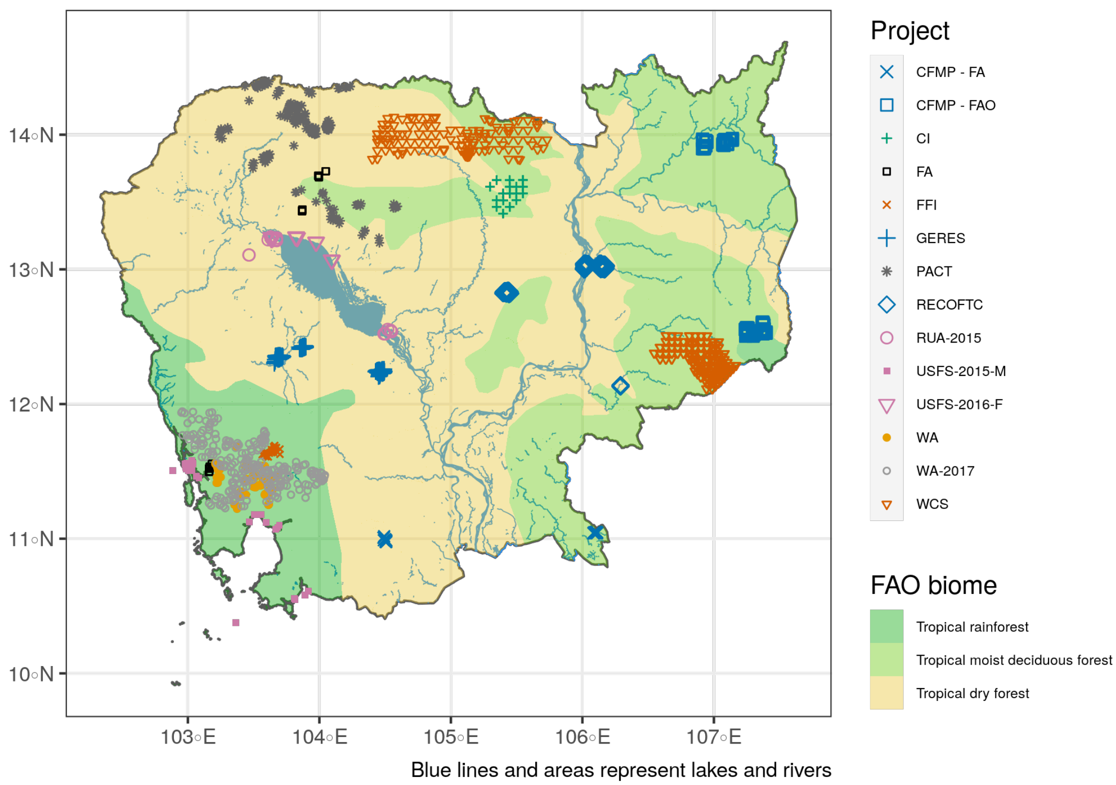

Figure 1: Plot locations with FAO biome.

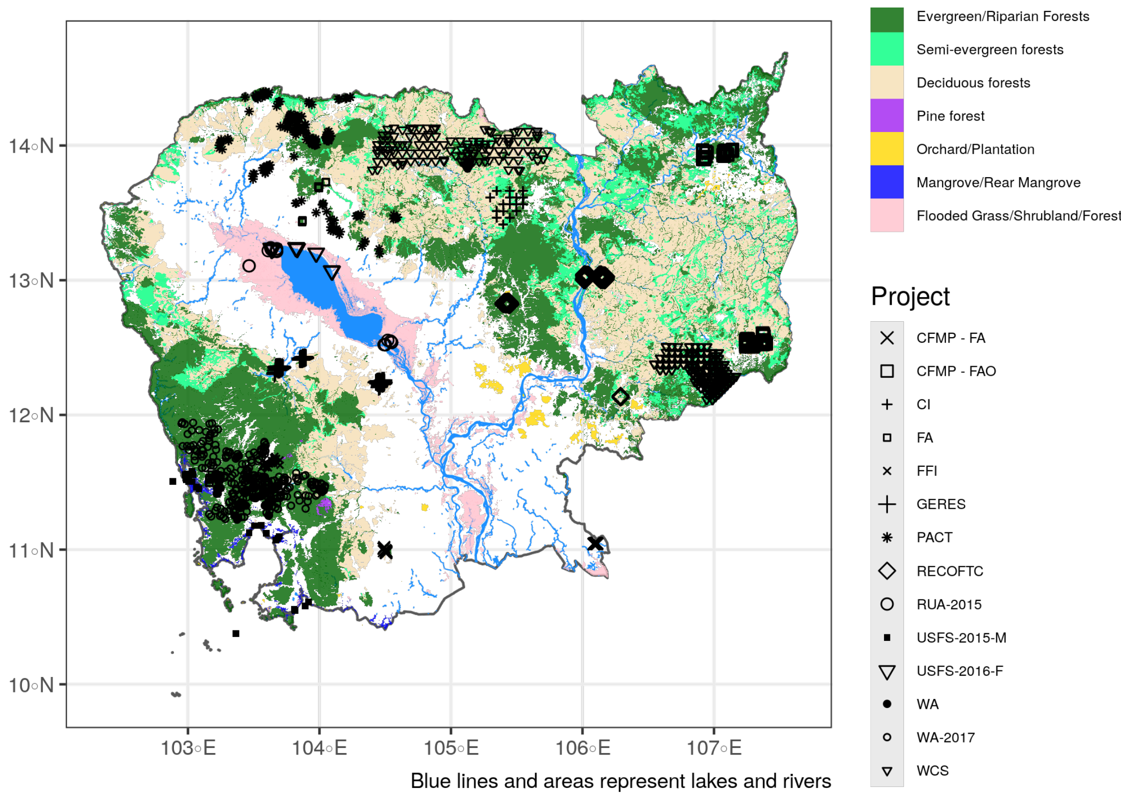

Figure 2: Plot locations with MoE2007 map.

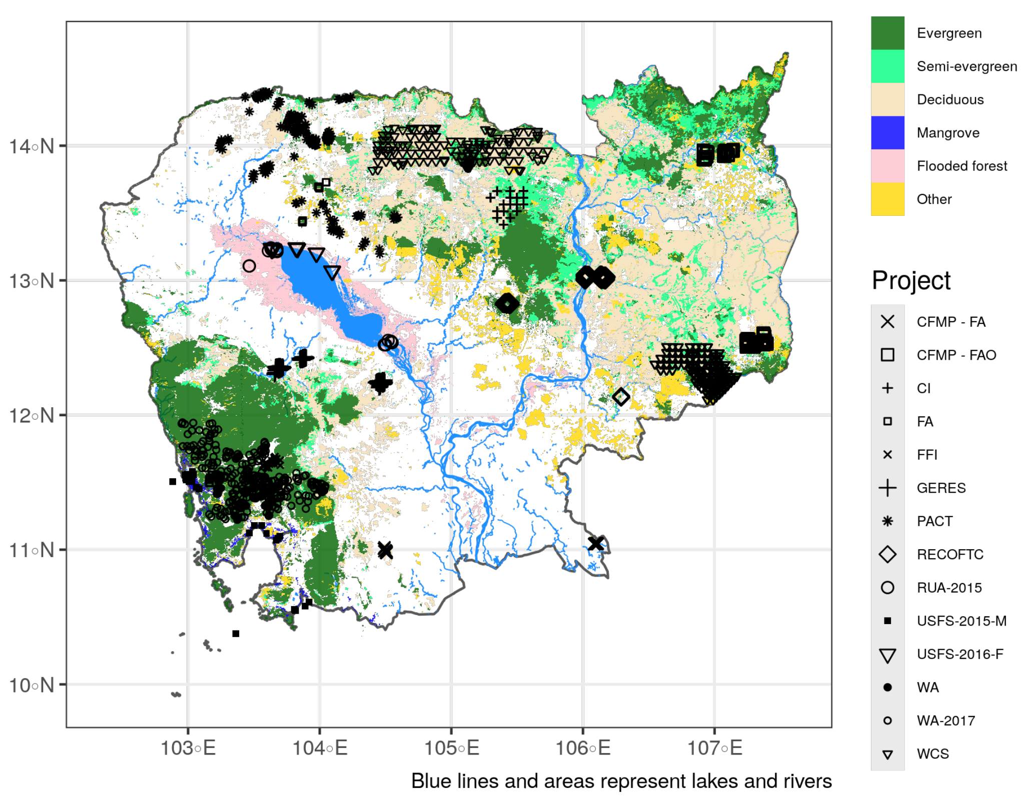

Figure 3: Plot locations with FC2016 map.

3.2.2 Tree diameter at breast height

Several plots from the FRL data had trees bigger than 5 m diameter. These trees were removed from the analysis as their diameter could be typos and recording them as big trees could largely overestimate the carbon stock of their forest type. Thirteen plots had such trees: CFMP - FAO_KN14, CFMP - FAO_Bora38, CFMP - FAO_KN22, CFMP - FAO_KN23, CFMP - FAO_KN23, CFMP - FAO_ST28, CFMP - FAO_ST31, CFMP - FAO_ST31, CFMP - FAO_ST31, CFMP - FAO_TP10.

WA had a number of trees larger than 2 m diameter, but these trees were kept as there was no evidence they were typos. All other projects / forest types had similar diameter distribution except CFMP-FA (Figure 4).

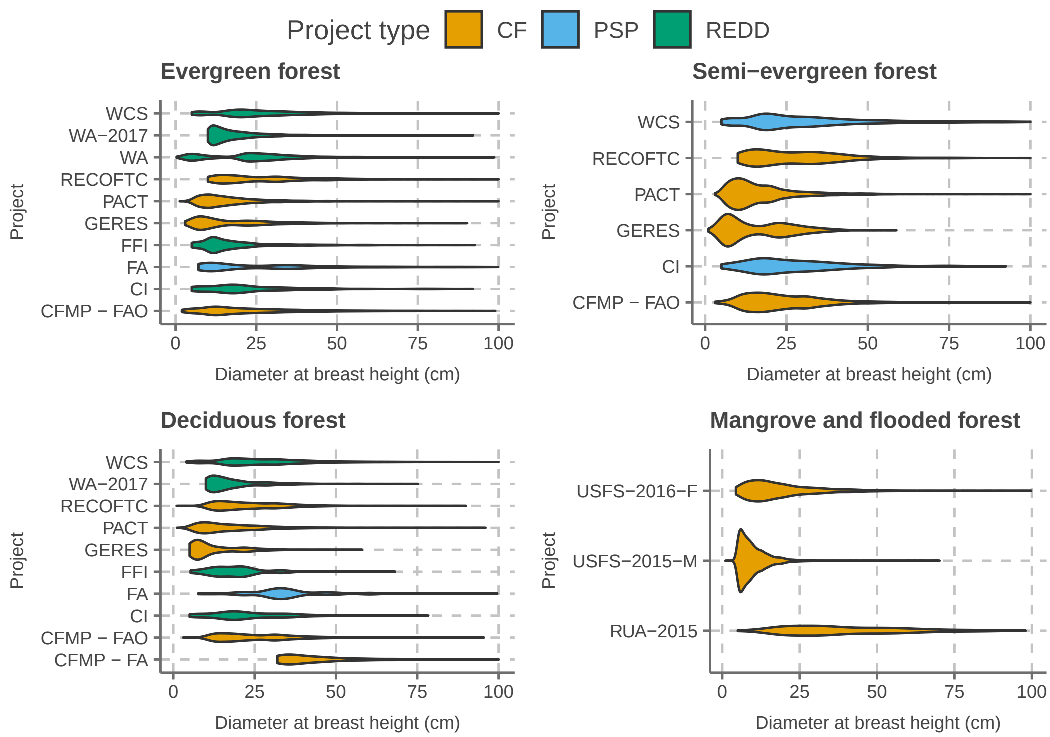

Figure 4: Tree diameter distribution per forest type and project.

3.2.3 Tree height

Out of 102577 trees measured, 13299 had height measurements after outlier correction. Several trees had height above 100 m and could be corrected, all other trees with a top higher than 55 m and no obvious comma misplaced were removed.

From the tree H-DBH visualisation, a different relationship between tree height and diameter could be observed in Community Forestry (CF) projects compared to others projects (Figure 5). In community forestry projects, trees had very small height at a given diameter compared to the other projects. Height measurements or estimations could be biased, or CF forests could be in early stage of recovery and had marks of past degradation. The forest classifications **forest**

type, **forest type 'fc'** and **forest type 'mix'** were updated with a separate class regrouping community forestry data across different type of forest into one category: Community land.

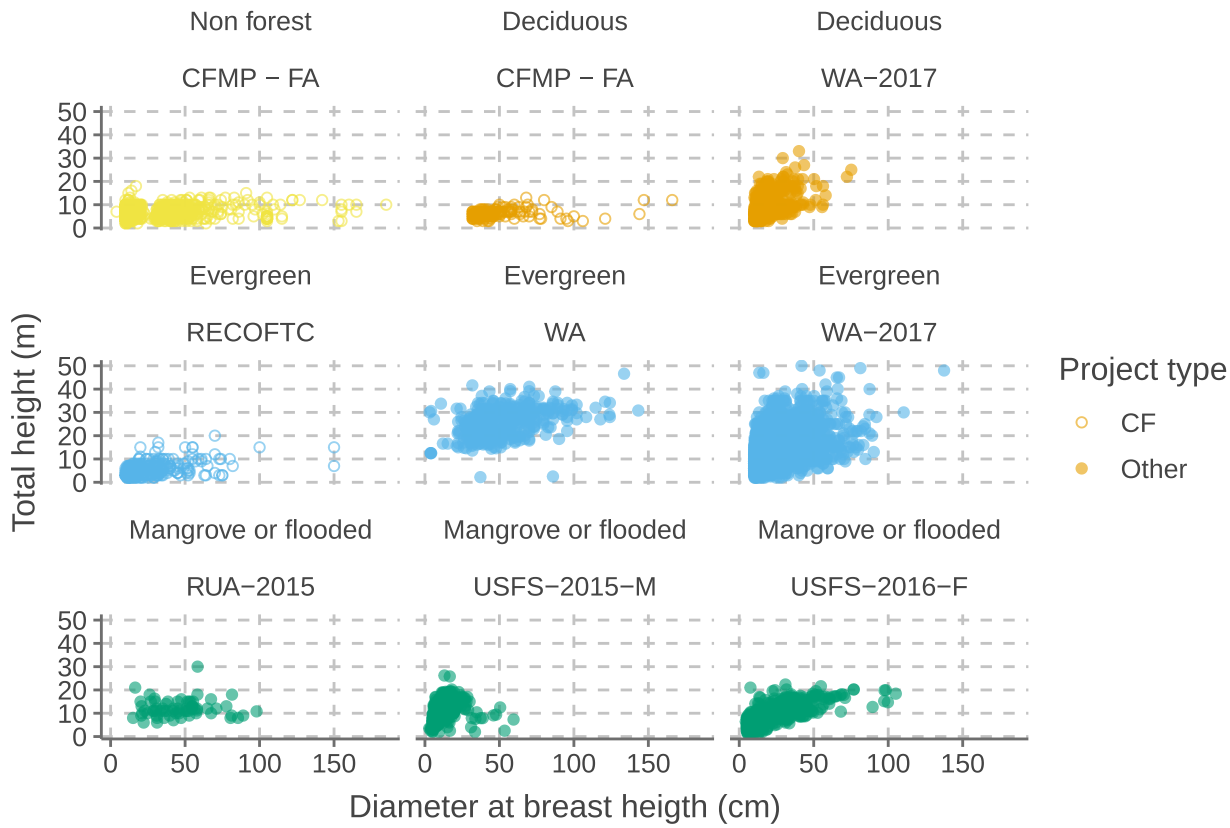

Figure 5: Tree H against DBH per forest and project type.

3.2.4 Tree species names

Unknown species were recorded differently among inventories and were harmonized to "Unknown" when both Genus and Species were missing. After several runs of the TNRS, the species list changed from `522` species to `450` with 107 automatic corrections, 20 manual ones, and around 50 manual corrections not implemented due to lack of time (wrong name kept unchanged). After the corrections, there were still `75688` trees with no species identification or species name that could not be corrected.

The top 10 most recorded species (regardless of plot size) were (Table 3):

Table 3: Trees species sorted by number of records.

Species name	Number of trees
Hopea pierrei	3691
Rhizophora apiculata	2938
Calophyllum sp.	1079
Diospyros bejaudii	916
Calophyllum calaba	750
Lagerstroemia sp.	749
Fibraurea tinctoria	669
Terminalia cambodiana	581
Lumnitzera littorea	478
Irvingia malayana	462

3.2.5 Tree wood density

From the `102577` trees measured, `15527` trees had wood density at species level and `9451` at genus level, the rest were given the 0.57 g/cm^3 default value for tropical Asia (Reyes et al., 1992).

3.3 Tree height-diameter allometric equations

3.3.1 Models used in the FRL data

In the FRL data tree height was estimated when not recorded, based on the data project type:

- Permanent sample plots had no tree height recorded and height was estimated using Feldpausch et al. (2011) tree height-diameter equation for Asia:
  - `H =  exp(1.2156 + 0.5782 * log(DBH))` and if `H >= 60, H = 60`
- REDD/Conservation projects had tree height measurements for part of the trees. A local equation was developed with these measurements and applied to trees with missing height:
  - `H = 1.3 + 9.303525 * DBH^0.24991`
- Community Forestry had tree height records for part of the trees. Tree height in these projects was very low compared to REDD/conservation for similar DBH measurements, the height in CF projects was roughly one third of REDD/Conservation projects. this ratio was applied to the REDD/Conservation tree height estimates:
  - `H = (1.3 + 9.303525 * DBH^0.24991) / 3`

3.3.2 Developing new H-D relationship

With the addition of USFS, WA and RUA project data to the study, many tree height measurements were added and new tree height diameter equations could be developed. The data was split from 12094 trees with both DBH and H into one set of 8059 trees for model development and 4035 trees for validation, following a random sampling of 2/3 of the trees per diameter class and forest type 'mix' class. The forest type class was updated to separate the trees in community forestry from the others in order to take into consideration their unique H-D relationship.

The best model form was Weibull and the selected random effect was forest type 'mix'. Gomperz model had lower AIC (Table 4) but both Gomperz and Meyer models reached tree height asymptote too low with maximum tree height around 15-25 m (Figures 6, 7 and 8). Forest type 'mix' was selected over the forest types based only on MoE2007 or FC2016, which seemed logical as in the 'mix' approach, map based forest types were applied to inventories close to their year of production.

Table 4: Local tree H-D models comparison.

Model form	Random effect	AIC	max p-value
Weibull	None	48315	0
Weibull	Forest type	46280	0
Weibull	Forest type 'fc'	46284	0
Weibull	Forest type 'mix'	46256	0
Gomperz	None	48252	0
Gomperz	Forest type	46260	0
Gomperz	Forest type 'fc'	46262	0
Gomperz	Forest type 'mix'	46232	0
Meyer	None	48239	0
Meyer	Forest type	46311	0
Meyer	Forest type 'fc'	46317	0
Meyer	Forest type 'mix'	46288	0

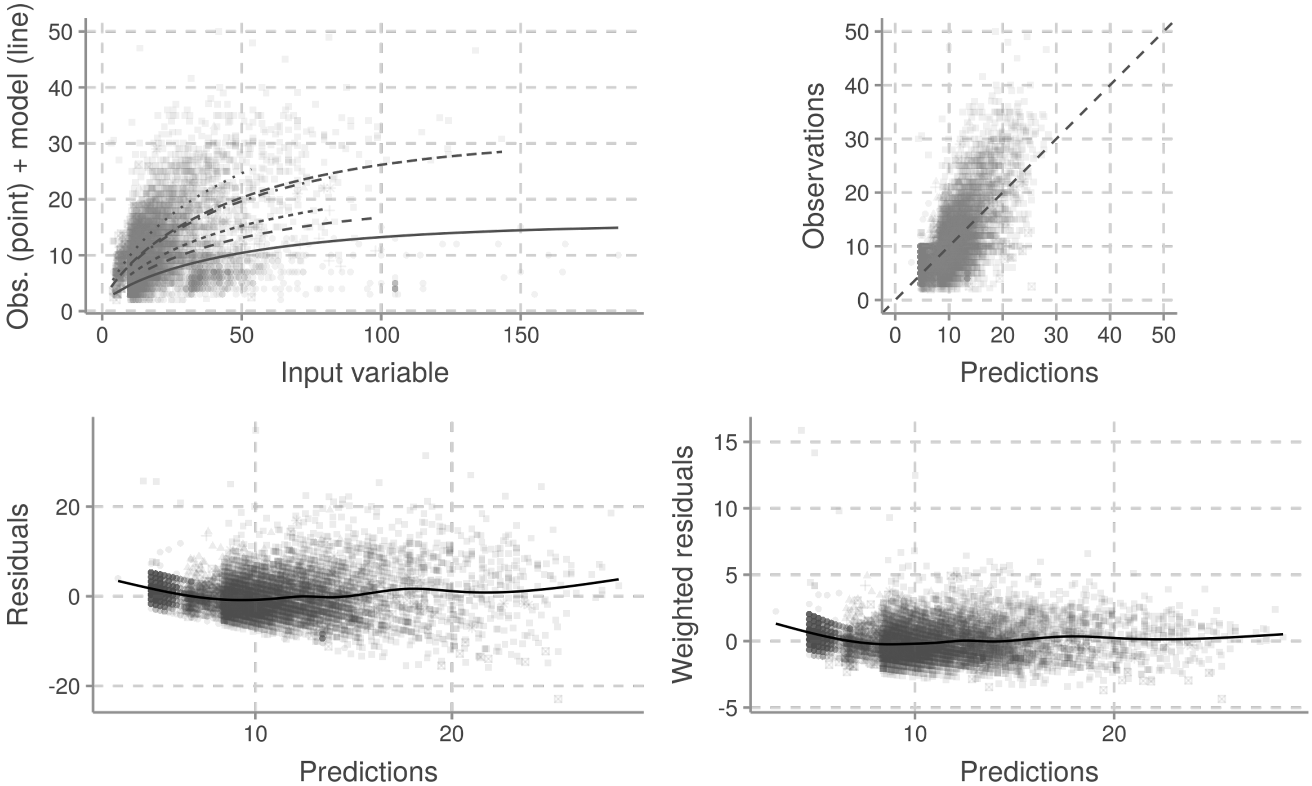

Figure 6: Weibull model visual checks.

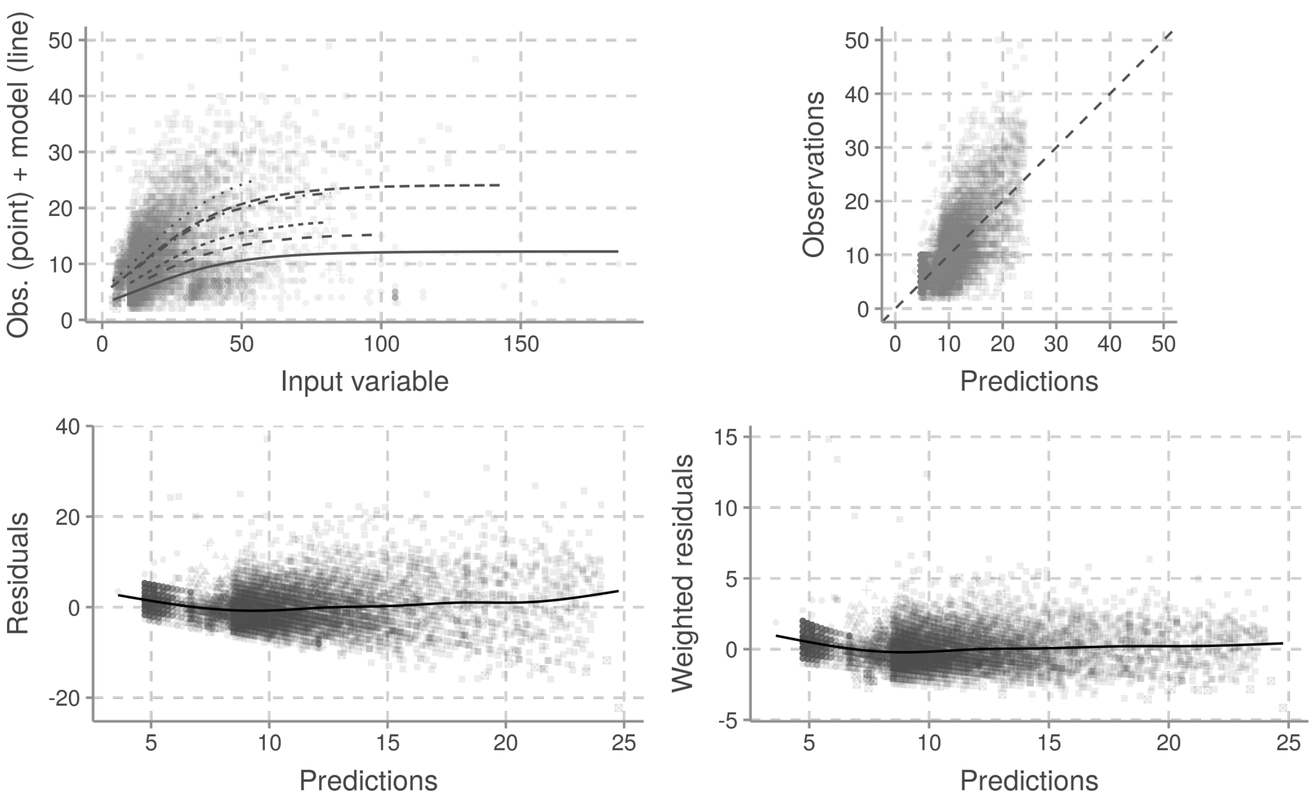

Figure 7: Gomperz model visual checks.

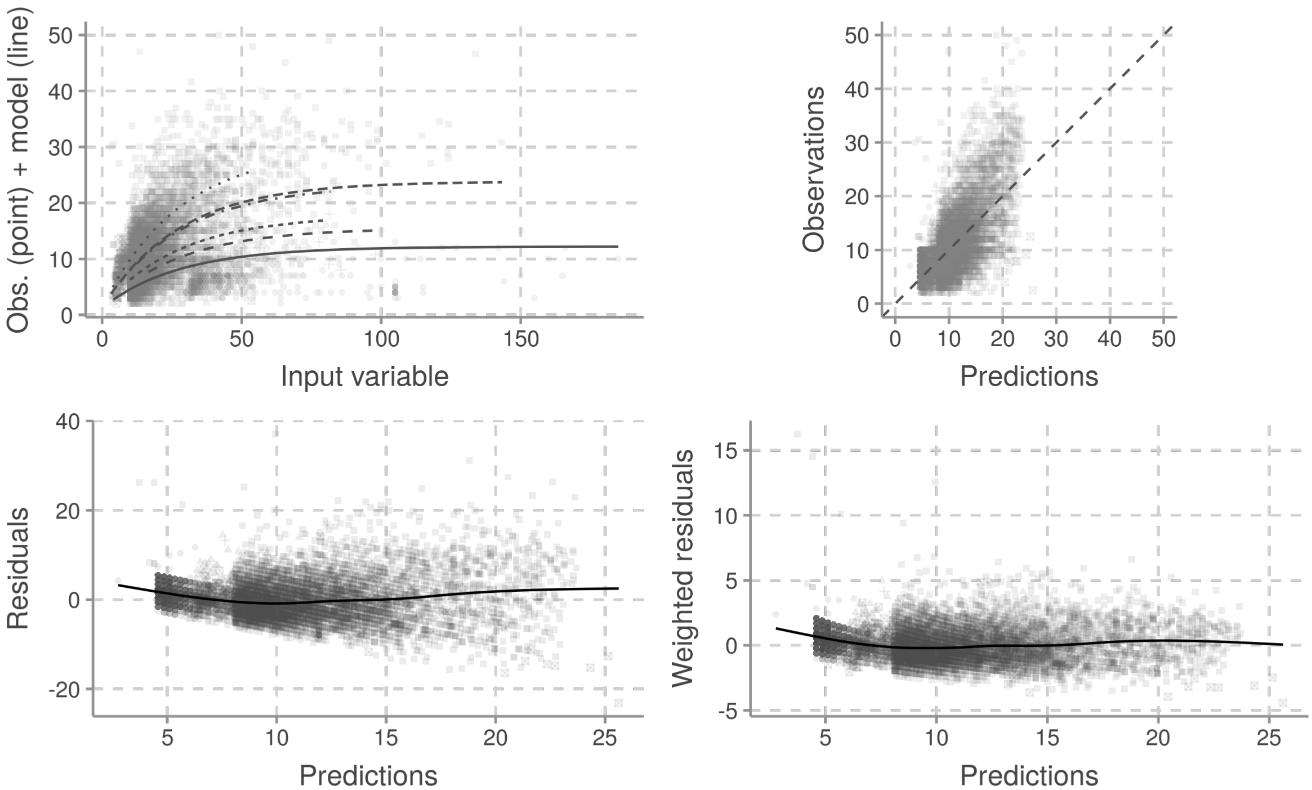

Figure 8: Meyer model visual checks.

As a result one model was developed with a different parameter ‘a’ for each forest type (Table 5).

Table 5: Selected tree H-D models with parameters per forest type ’mix’.

Forest type ’mix’	Model
Community land	H = 1.3 + 14.3706 * (1 - exp(-0.0407 * DBH^0.8198))
Deciduous	H = 1.3 + 21.986 * (1 - exp(-0.0407 * DBH^0.8198))
Evergreen	H = 1.3 + 29.9423 * (1 - exp(-0.0407 * DBH^0.8198))
Flooded forest	H = 1.3 + 18.6158 * (1 - exp(-0.0407 * DBH^0.8198))
Mangrove	H = 1.3 + 36.8175 * (1 - exp(-0.0407 * DBH^0.8198))
Semi-evergreen	H = 1.3 + 29.0446 * (1 - exp(-0.0407 * DBH^0.8198))

3.3.3 Local model validation

The local model had very good performance, considering the variability of forest conditions covered with the inventory pots. It had 17 % bias overall and less than 20 % bias in all forest type classes (Table 6). The model for flooded forest was also tested on the dataset from the project ‘USFS-2016-F’. The bias was `16.902353`.

Table 6: Bias of the local H-D models.

Forest type 'mix'	Bias (%)
Community land	16
Evergreen	18
Flooded forest	8
Mangrove	12
Deciduous	15
Semi-evergreen	17
Overall	17

3.4 Plot and forest type Carbon stock

3.4.1 Results at plot level

When looking at plot AGB per project (Figure 9), several plots have very high AGB in Community land, which could be due to typos in DBH records, tree girth recorded as DBH or a wrong plot size associated to the records during the harmonization process. The high basal area AGB for community land all come from CFMP-FA project.

The highest plot AGB were found in semi-evergreen forest, more particularly in a WCS project. While in evergreen and deciduous forests, the impact of WCS high values was reduced by the quantity of plots from other projects, in semi-evergreen forest the overall AGB was very much impacted by this project. One of WCS sub-project focused on very high value forests and the results were still within the range of high carbon forests, but their representativity of national semi-evergreen forest could be questioned and this sub-project could be removed from the final forest carbon stocks if it is overestimating the carbon stock at country level.

Regarding flooded forest, the inventory from USFS gave much higher biomass values than the inventory from RUA and the representativity of both inventories and thier respective impact on country level forest carbon stock needs to be furhter investigated (see next section).

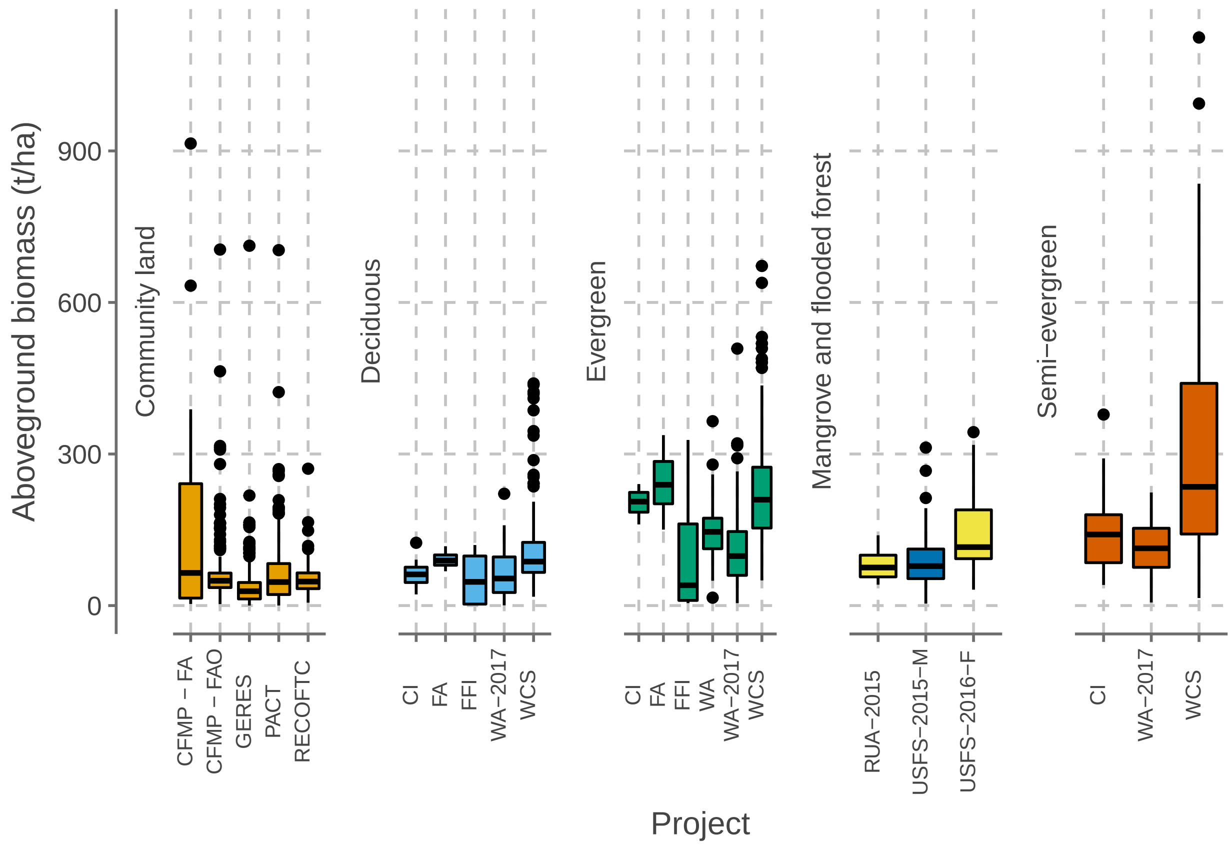

Figure 9: Plot AGB per project.

A dynamic map was embedded in the HTML version of the report. In this visualization the plot with represented with color based on project or AGB classes and FAO biomes or ESRI Satellite images could be displayed in the background. The different layers could be managed with the 'layer' button. In the PDF and MS Word versions only a screenshot could be displayed.

3.4.2 Forest carbon stock estimates

To better understand the impact of the unlikely high carbon stock projects, plot AGB was displayed together with the sub-project average AGB (Figures 10 and 11). The high AGB in CFMP-FA was only found in two sub-projects and both were removed from the final estimates.

Regarding WCS, only the sub-project WCS_Seima contained very high AGB. The raw data was cross-checked and no error was found, plus the results were still within the range of high carbon forests. The estimates for this sub-project were also consistent with the project's findings and the reason why the carbon stock was so high was most probably that the project targeted very high value forests. However keeping this sub-project's data in the final carbon stock estimates could lead to overestimating semi-evergreen carbon stock, as most of Cambodian semi-evergreen forests may not be as rich as forests found in WCS inventory location.

Regarding flooded forest the overall AGB with both inventories was 123.95 ton biomass per ha, 79.73 and 148.06 for RUA and USFS respectively. The flooded forest value for USFS was comparable to evergreen forest, which would seem overestimating the AGB if used for the whole flooded forest. Similarly to WCS Seima, USFS targeted very rich forests and using these values at national level could overestimate the carbon stock of flooded forest in general.

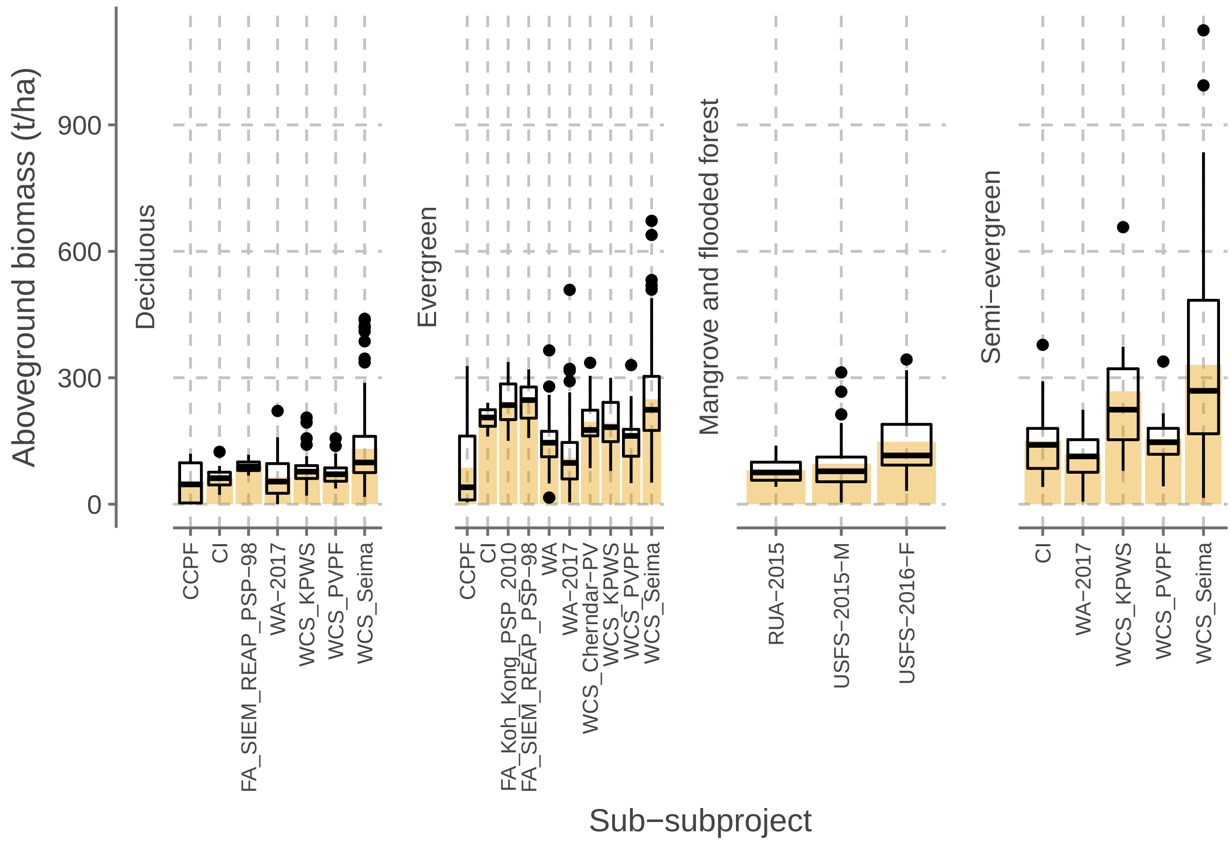

Figure 10: Plot AGB distribution and sub-project averages.

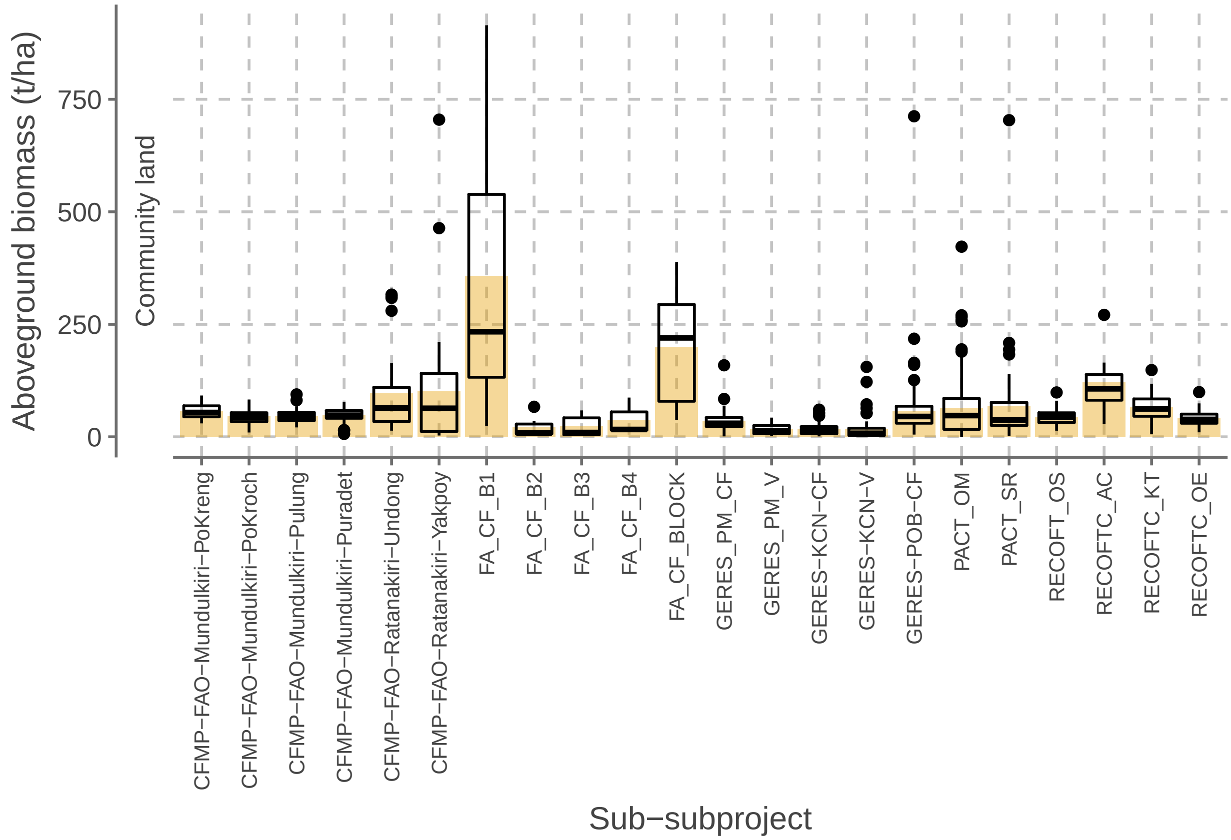

Figure 11: Plot AGB distribution and sub-project averages in Community land.

The resulting AGB, belowground biomass (BGB) and final carbon stock estimates were calculated both with (Table 7) and without both WCS_Seima sub-project and USFS-2016-F project (Table 8). In the FRL carbon stocks, WCS_Seima was kept in the data. The updated carbon stocks including WCS_Seima, therefore consistent with the FRL, were slightly higher for all the forest types. For Evergreen and Mangrove forest, AGB was actually smaller but the overall carbon was higher due to the change of root-to-shoot ratios. Without the Seima data the carbon stocks of semi-evergreen, deciduous and evergreen forests lost around 150, 30 and 15 tons of CO_2 per hectare respectively.

Since removing Seima data mostly impacted semi-evergreen forests and their carbon stock may decrease when a national level forest inventory will be implemented, the estimates without Seima data would be recommended over the data with Seima plots. Historical GHG emissions and removals could be recalculated when the country develop an updated Forest Reference (Emissions) Levels document to take correct the inconsistencies due to the very high overall carbon stock of semi-evergreen forest in the first FRL.

Surprisingly, the default forest carbon stock, calculated with plots from mainland forests (evergreen, deciduous and semi-evergreen) and **not** including Seima and USFS flooded forest data, was still similar to the FRL: 281.39 ton CO_2 per ha in the FRL vs `281.12` in the updated calculations). With Seima data in, the default carbon stock increased to `352.43` ton CO_2 per ha. This could be explained by the smaller number of plots in semi-evergreen forest compared to evergreen and the increase in carbon stocks in all forest types when Seima data in included.

The confidence intervals (CI %) are expressed in % of the AGB but applicable to biomass, carbon and CO_2 as CI in % are constant when the value they are associated with is multiplied by a constant.

Table 7: Carbon stock estimates per forest type ’mix’ (t/ha).

Forest type ’mix’	Number of plots	AGB	BGB	Total Biomass	Total Carbon	Total CO_2	CI (percent)
Community land	1045	55.44	11.09	66.53	31.27	114.66	8
Deciduous	235	97.02	19.40	116.43	54.72	200.64	10
Evergreen	551	155.20	57.42	212.62	99.93	366.41	5
Flooded forest	51	123.95	24.79	148.73	69.91	256.32	17
Mangrove	48	95.25	46.67	141.92	66.70	244.57	19
Semi-evergreen	135	270.60	54.12	324.72	152.62	559.59	13
Total EV, SE, DD	921	157.27	47.24	204.51	96.12	352.43	5

Table 8: Carbon stock estimates per forest type ’mix’ (t/ha) without Seima and USFS-F.

Forest type ’mix’	Number of plots	AGB	BGB	Total Biomass	Total Carbon	Total CO_2	CI (percent)
Community land	1045	55.44	11.09	66.53	31.27	114.66	8
Deciduous	132	70.87	14.17	85.04	39.97	146.55	10
Evergreen	446	133.12	49.26	182.38	85.72	314.30	5
Flooded forest	18	79.73	15.94	95.67	44.97	164.88	17
Mangrove	48	95.25	46.67	141.92	66.70	244.57	19
Semi-evergreen	49	165.23	33.05	198.28	93.19	341.70	19
Total EV, SE, DD	627	122.52	40.60	163.13	76.67	281.12	5

3.4.3 Usability of community land carbon stock

In the FRL data analysis, all plots in Community Forestry land were removed as this class could not be mapped accurately nor merged with forest types as they would bring all the forest types’ carbon stock to a very low level. In the carbon stock update, this class was kept separated from other forests and a carbon stock was calculated for it. It could be applied to specific areas, maybe based on province if there is a strong correlation.

Looking at the number of plots per forest type and province (12), several provinces had only community forestry plots. Community forestry carbon stocks could be applied to these provinces if there is a consensus among experts that most forests in these provinces were previously degraded and in a recovery process. Recent Community Forestry data would also be useful to better understand and account for the recovery process in these forests.

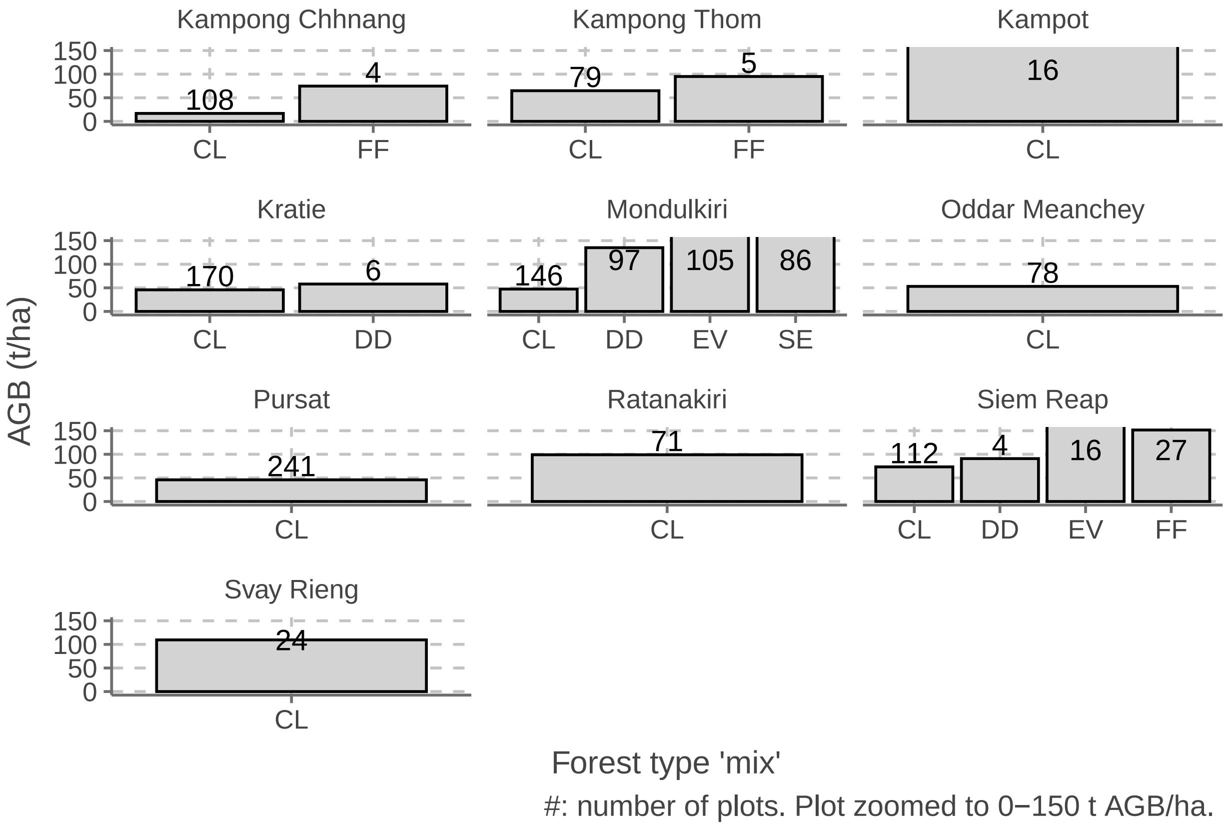

Figure 12: Average AGB per forest type at the province level.

4 Conclusion

With the addition of three datasets and the work done in country to develop AGB models for Cambodian forests, new forest carbon stocks were developed, with new estimates for flooded forest and mangroves based on in-country field measurements rather than literature, and updated estimates for mainland forests, including improved H-D models.

The carbon stocks developed represent the most comprehensive estimates at the time of the publication given the data available. Thanks to all the projects implemented and the government efforts to collect the data, most forest conditions were captured. However some of the estimates could be biased, as project sites could be over represented over less studied locations. A full scale national forest inventory would give a better understanding of the projects representativeness and overcome the potential bias issues due to sampling methods and project based inventory locations.

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