Developing Forest carbon stocks estimates for REDD+ Emission and Removal Factors in Thailand

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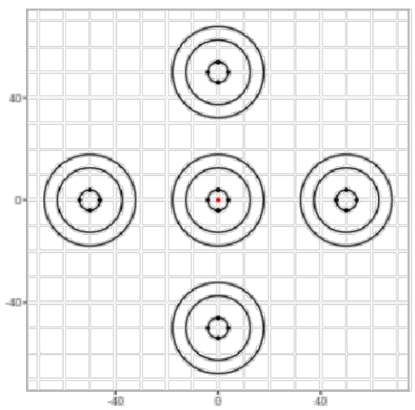

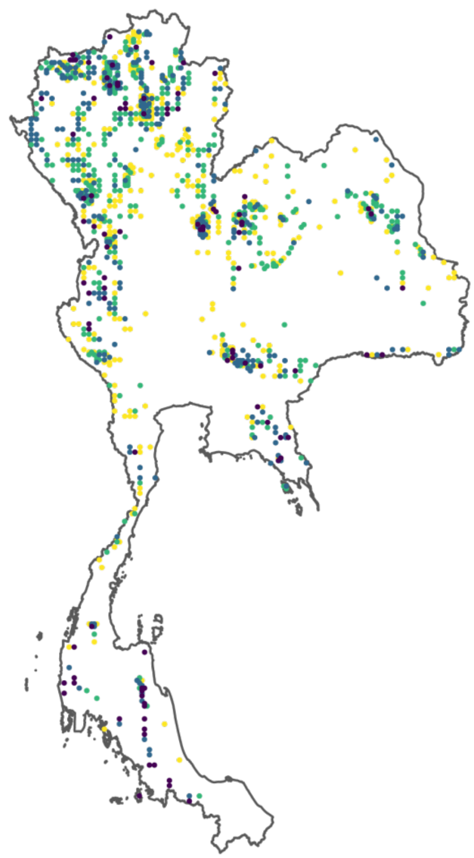

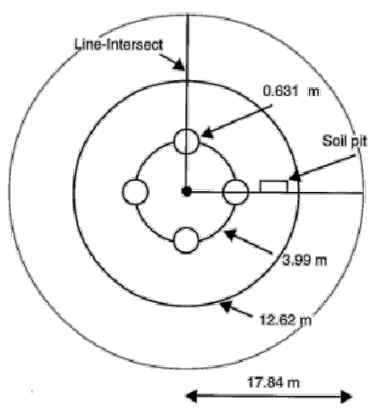

Developing Forest carbon stocks estimates for REDD+ Emission and Removal Factors in Thailand

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Abstract

Context

Thailand received support from the Forest Carbon Partnership Facility to engage in REDD+ and develop its key elements. As part of this package, the Food and Agriculture Organization of the United Nations provided technical support to the Department of National Parks, Wildlife and Plant Conservation to develop Thailand's first Forest Reference (Emission) Levels (FREL/FRL), the benchmark against which future greenhouse gas emissions and removals from the forestry sector would be reported, and Thailand's National Forest Measurement, Monitoring and Reporting System (NFMS/MMR).

Thailand conducted three National Forest Inventories (NFIs) with different sampling intensities and objectives. The first inventory cycle, conducted from 2004 to 2010, was based on a full country sampling with an small emphasis on protected areas. The second cycle was the lowest in terms of intensity and timeframe, with the remeasurements of the plots in protected areas and the 10 km grid only. It was conducted on 2011 and 2012. The third and latest cycle, conducted from 2013 to 2017, kept a small number of the cycle's 1 plot, primarily focusing on protected areas, and was complemented by a large number of plots in a very small 2.5 km grid in a subset of the protected areas.

Objective

This study aimed at estimating forest emission and removal factors to contribute to Thailand first FREL/FRL. Given the differences in sampling design across cycles and that Thailand NFIs did not focus on estimating forest carbon stock at the national level, the study's objectives were to re-analyse the NFI raw data from their archive databases to propose a set of emissions and removal factors for REDD+, which can be applied at the National level to address all forest in Thailand.

Method

The study combined a range of checks and corrections of the raw data, followed by the calculation of trees' aboveground biomass (AGB), and its propagation to plot and forest types. Nationally developed allometric equations were applied to trees' characteristics based on their forest type. As there were not enough plots on mangrove forest, 37 plots from a study conducted by DMCR in 2016-2017 were used to calculate the mangrove carbon stock. Given the importance of protected areas in the sampling designs, the information on protected areas was added to the NFI data based on the plots GPS location.

The NFI cycle 2 and 3 aimed at remeasuring at least partially the forest plots from the cycle 1, but the plot centers were most often not found and the remeasured plots could have been few meters away from their original location. The data could therefore not be used to calculate plot level biomass evolution. Instead averages at forest type level for each cycle were compared.

To account for the differences of sampling intensities across inventory cycles, three approaches were tested to calculate Emission and Removal factors: All plots on the 10 km NFI grid (Approach 1), all the remeasured plots on the 5 and 10 km grids (Approach 2) and all the plots together (Approach 3). With all the approaches, given that not all the plots on the grids were measured both on the cycle 1 and 3, the sampling design was approximated to a stratified random sampling and weighted average were calculated. The basis of the strata were the group of national parks where different sampling intensities were applied. This stratification allows for the fact that protected forests have on average higher biomass/ha than non-protected forests. No error was found in the data but it was too different from all the other plots.

Results

The data quality was overall very good. The species list used for tree species identification was very

complete and no outliers were detected for H and DBH measurements. Less important variables such as timber quality had more errors, but they could be corrected. Only one plot was removed from the analysis because its AGB and basal area were far too high compared to the other plots.

Re-analysing the data confirmed the emphasis on protected areas in the NFI cycle 3 (more than 90 % of the plots), while in the first cycle around half of the plots were measured outside protected areas. The stratified estimators accounted for these differences and all the approaches gave almost the same carbon stock and carbon stock differences between NFI cycle 1 and 3.

All the approaches tested had the same trend: biomass increased from cycle 1 to 3. The trend was very visible for Deciduous forest and more or less clear for evergreen forest depending on the approach chosen. The recommended approach with the 10 km grid only, resulted in evergreen forest aboveground biomass of `130.88 +/- 9 %` and `136.327 +/- 8 %` ton/ha in the cycle 1 and 3 respectively, deciduous forest aboveground biomass of `54.814 +/- 6 %` and `65.465 +/- 7 %` ton/ha and mangrove forest had only one aboveground biomass estimate due to the limited data from a single point in time: `120.779 +/- 18 %`.

Conclusion

The recommended approach aimed at maximizing the number of plots used to calculated carbon stocks while avoiding as many sources of potential bias as possible. Overall the carbon stock increased in the two main forest types, meaning Thailand's forest area remaining forest was accumulating CO_2 from the atmosphere. The approach recommended didn't use all the plots measured, which is fine given that carbon accounting was not a key objective of the inventories at the time. But as a note for future improvement, measuring more plots outside of protected areas and across all land in Thailand would help to better understand if the dynamics are different when forest are under protected status and help reduce the uncertainty in forests remaining forests. Ideally, Thailand could keep measuring plots on the 10 km grid across all forest lands and once this is achieved, intensify the sampling in areas of interest.

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Acronyms and Abbreviations

Acronyms	Description
AGB	Aboveground Biomass, in kg, ton or ton/ha
BGB	Belowground Biomass, in kg, ton or ton/ha
CI (%)	Confidence interval at 95 % expressed in % of the value it is associated with
CRS	Coordinate Reference System
D or DBH	Diameter at Breast Height, in cm
DMCR	Department of Marine and Coastal Resources
DNP	Department of National Parks, Wildlife and Plant Conservation
EFRF	Emission and removal factor
FAO	Food and Agriculture Organization of the United Nations
FCPF	Forest Carbon Partnership Facility
FRL	Forest Reference Emission Levels or Forest Reference Levels for REDD+
GPS	Global Positioning System
GWD	Global Wood Density Database
H	Tree total height in m
ha	Hectare
IPCC	Intergovernmental Panel on Climate Change
NFMS/MMR	National Forest Measurement, Monitoring and Reporting system
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
RFD	Royal Forest Department
RS	Root-to-shoot ratio
WD	Wood Density defined as the ratio of wood dry mass to its fresh volume in g/cm^3

1 Introduction

Estimating forest carbon stock at national level is essential to understand the forest contribution to climate change and a key part of developing countries' efforts to engage in REDD+ and develop Forest Reference (Emission) Levels (FREL/FRL) for REDD+. In Thailand, as part of the FCPF programme, the Food and Agriculture Organization of the United Nations (FAO) provided technical support to the Department of National Parks, Wildlife and Plant Conservation (DNP) to improve forest related greenhouse gas emissions and removals and to develop its first FREL/FRL and NFMS/MMR.

As of 2019, Thailand conducted three National Forest inventories (NFIs) with different objectives. While the first NFI was nationwide, the second and third focused heavily on protected forests, resulting on a different mix of sampling intensities and populations of interest. Because of these differences, not all the plots measured may be usable to calculate unbiased estimations of forest carbon stock at the national level and simple unweighted averages may introduce additional biases complex to account for or avoid.

The data was collected in paper forms and archived in MS Access databases at the DNP and RFD offices, DNP being in charge of protected forests and RFD of the others. Technical support was provided to develop a full chain of data analysis including extracting the data from MS Access databases, harmonizing the different inventories, checking and correcting potential errors, calculating tree aboveground biomass and aggregating carbon stock estimates from trees to plots and forest types at national level.

Since the inventory cycles had different sampling intensities and targeted areas, the objective of this study was to develop and compare several approaches to the data selection and to calculate their influence on emission and removal factors and their uncertainties. This report details the different analysis steps, and present in annex the R scripts and commands used for the calculations.

2 Method

2.1 Description of the National Forest Inventories

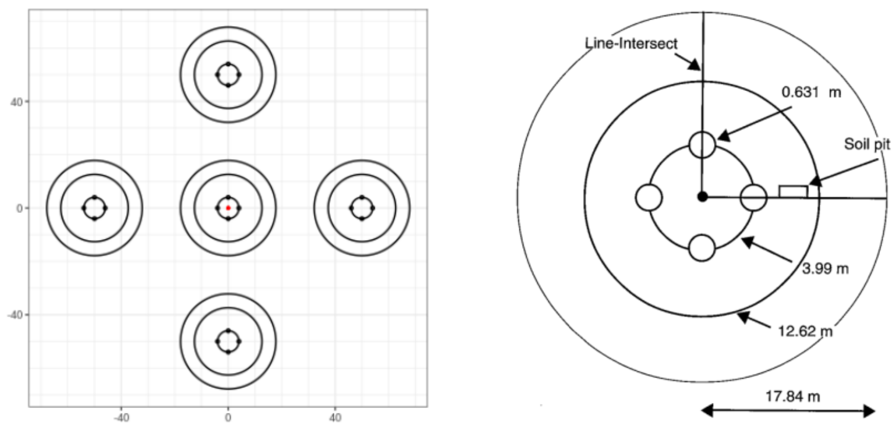
As of 2019, three cycles of national forest inventory (NFI) were completed. The first cycle was carried out from 2003 to 2010, the second cycle in 2011-2012 and the third cycle from 2013 to 2018. The first circle combined a full country coverage with a plot intensity ranging from 20 km spacing outside forests to 10 km inside forest land, plus an emphasis on protected areas where a 5 km grid sampling intensity was added (Table 1). The second cycle repeated the measurements on the 10 km grid only and only in protected areas. The last cycle repeated the 10 km grid, almost exclusively in protected areas by DNP, and around 150 plots outside protected areas were measured by RFD. DNP also measured more than 2000 plots in few targeted protected areas on a 2.5 km grid. In addition to the NFIs, the Department of Marine and Coastal Resources (DMCR) conducted a separate survey of Mangrove forest in 2016-2017 with 37 plots assumed to be randomly located.

Table 1: Overview of the NFI designs.

Attribute	Cycle 1	Cycle 2	Cycle 3	Mangrove
Objective	Estimate forest attributes across all lands	Update the 1st NFI only for protected forests	Update the 2nd NFI with a few plots added back to unprotected forest and an intensification for a few selected protected areas	Survey of mangrove forests
Time period	2003-2010, 2006 as reference	2011-2012	2013-2018, 2014 as ref.	2016-2017
Population of interest	All lands in Thailand	Forest protected areas	Mostly forest protected areas (176 plots intended outside)	All mangroves in Thailand
Sampling grids	20 km outside forest land, 10 and 5 km forest areas, the 10 km grid was systematic while the 5 km doesn't cover all forests.	10 km inside protected areas	10 km outside protected areas (by RFD), a mix of 10, 5 and 2.5 km inside (by DNP). Only few protected areas had the 2.5 km grid applied to them. In practice RFD measured 8 plots inside protected areas, and DNP had a small fraction of their plot falling outside protected area boundaries	Random sampling of 37 plots
PSU design	Cluster of 5 plots	Center plot only	Center plot only	Single plots

As the main objective of the Thailand NFI evolved towards a better understanding of forest in protected areas, only roughly a third of plots were repeatedly measured over time. Even for these plots, the plot centers were only found for around 150 plots. For all the other remeasured plots, they were considered remeasured on paper (same theoretical plot coordinates), but may have shifted few meters from the original center plots. For this reason, plots are not treated as "paired"or permanent plots and carbon stock evolution could not be calculated at the plot level. Averages were only calculated at the forest type level for each NFI separately.

The inventory plots were originally organized in clusters of five plots each, with one center plot and four additional plots 50 m away in each cardinal directions (Figure 1). However from the second cycle onwards, only the center plot was measured. Each plot consisted of circular sub-plots, with a 17.84 m radius circle for measuring trees (corresponding to an area inventoried of 0.1 ha), and other smaller sub-plots designed to record seedling, sapling, bamboo and deadwood. To keep consistency between NFI cycles, only the data measured in the center plots were used for cycle 1.



Data Gathered	*Sampling Method*			
	Plot Type	***Number***	***Radius (m)***	***Total Area (ha)***
Seedling density	Circular	4	0.631	0.0005
Understory vegetation & sapling density	Circular	1	3.99	0.0050
Bamboo and erect rattan length & tree stump volume; site description	Circular	1	12.62	0.0500
Tree attributes; human & natural disturbance; wildlife habitat use	Circular	1	17.84	0.1000
CWD, rattan & climbers volume and length	17.84 m line-intercept	2		

Figure 1: National forest inventory plot design.

At the plot level, the key information recorded was land use, plot GPS coordinates, plot access and reference points, timers and crew composition, and several environmental features such as vegetation cover and several environmental variables. The main trees' characteristics recorded were their location, species, diameter at breast height (DBH), total height (H) measured or estimated, crown size and several indicators of quality.

2.2 Supplementary data on mangroves

The NFIs had very little coverage of mangrove forests with only seven plots in the first cycle (see Table 9 in the result section). It was not enough to get information on this forest type, therefore different data was used from a DMCR study during 2016-2017 in which 37 plots were measured in various locations. At the time of writing this report these plots have not yet been remeasured, hence decay and increment for mangroves in Thailand was unknown. The detailed methodology and the tree level results were not available, only the list of plots, their forest group name and their aboveground biomass content as reported by DMCR (Table 2). From this data the average AGB for Mangrove forest was 120.779 ton/ha and its 95% confidence interval was 18 %.

Table 2: Data available on Mangrove forest.

Plot ID	Forest group name	AGB (ton/ha
1	Trat estuary Mangrove Forest	74.60
2	Laem Ngop Mangrove Forest	158.06
3	Velu estuary Mangrove Forest	104.00
4	Muang Chanthaburi Mangrove Forest	194.86
5	Pakprasae estuary Mangrove Forest	197.36
6	Muang Rayong Mangrove Forest	144.43
7	Bang Pakong estuary Mangrove Forest	32.13
8	Bang Pakong estuary Mangrove Forest	29.72
9	Chaopraya Mangrove Forest	105.23
10	Tha Chin estuary Mangrove Forest	72.81
11	Tha Chin estuary Mangrove Forest	65.93
12	Mae Klong estuary Mangrove Forest	96.40
13	Ban laerm Mangrove Forest	58.17
14	muang phetchaburi Mangrove Forest	83.78
15	Ao prachuap khiri khan Mangrove Forest	45.33
16	Bang saphan Mangrove Forest	29.47
17	Pathiu Mangrove Forest	69.28
18	Ao chum phon Mangrove Forest	79.53
19	Thung tako-Lamae Mangrove Forest	39.76
20	Surat thani Mangrove Forest	189.44
21	Ao Pak phanang Mangrove Forest	99.31
22	Thaleluang Mangrove Forest	130.66
23	Songkhla Lake Mangrove Forest	43.37
24	Chana Mangrove Forest	99.91
25	Pattani Mangrove Forest	270.02
26	Tak Bai-Mai kaen Mangrove Forest	142.53
27	Lam Nam Kra Buri Mangrove Forest	102.49
28	Ranong Mangrove Forest	106.58
29	Ko Ra-Ko Phra Thong Mangrove Forest	53.79
30	Takua pa-Khura buri Mangrove Forest	186.66
31	Thai muang Mangrove Forest	303.76
32	Ao Phangnga Mangrove Forest	147.95
33	Ko lanta Mangrove Forest	125.79
34	Sikao- Mangrove Forest	193.59
35	Trang estuary Mangrove Forest	183.71
36	Thung wa-Pak Bara Mangrove Forest	204.20
37	Cha Bilang-Ko Sarai Mangrove Forest	204.20

2.3 From tree aboveground biomass to forest carbon stock: general approach

Forest carbon stock was calculated in three steps:

1. Aboveground biomass was first calculated at the tree level using Thailand based equations from Ogawa (1965) and Tsutsumi (1983) (See Section 3).
2. Tree biomass was propagated to all the forest plots as the sum of the AGB all the trees in each plot, divided by the plot area (in ha) to get results per hectare then divided by 1000 to convert kg into tons:

$$AGB_{plot} = \frac{\sum AGB_{tree}}{A_{plot}} \times 1000$$

with AGB_{plot} in ton/ha, AGB_{tree} in kg and A_{plot} in ha.

3. In case the NFI sampling design correctly represents all the forests conditions (systematic or random sampling), the AGB values per forest types could be calculated as the average AGB (Equation 1) of all the plots in the targeted forest type. The calculation of the average AGBs and their standard deviation would be straightforward and the confidence interval equation can be found in the IPCC Guidelines (2006) Vol. 1 chapter 3 on uncertainties (Equation 2):

(1)

$$AGB_i = \sum_i \frac{AGB_{tree,i}}{n_{plot,i}}$$

(2)

$$CI_i = \frac{\sigma_i}{\sqrt{n_{plot,i}}} \times 1.96$$

with AGB_i the aboveground biomass, σ_i the standard deviation and $n_{plot,i}$ the number of plots in the of the forest type i.

2.4 Approximation of the sampling design to a stratified random sampling

However, since the different NFIs targeted different populations with different sampling intensities, simple averages could over-represent one population, for example protected areas or the specific areas where the sampling was intensified, over populations where the sampling intensity was reduced, for example non-protected areas. This issue could become a major problem when comparing different time periods, as the differences reflected in the analysis could be the consequence of the differences between the areas inventoried rather than general trends over all forests in Thailand.

To overcome this issue, protected and unprotected forests could be considered as different strata. with this approach, steps 1 and 2 of the general approach remained unchanged (see Section 2.3), but the simple average was only calculated at the strata level and a forth step was added to combine the different strata with weighted averages, in order to account for the differences of sampling intensity between the different cycles. The weights would be the area of the selected forest types in each stratum divided by the total area of all selected forest types. The stratification could be extended to the protected areas where the sampling intensity was intensified with 5 km and 2.5 km grids. The statistical framework and the mathematical formulas for the steps 3 and 4 were taken from Cochran (1977). The sequence of calculations was:

1. Tree AGB (see Section 2.3).
2. Plot AGB (see Section 2.3).
3. simple averages over strata only (Equation 3):

(3)
$$AGB_{i,j} = \sum_{i,j} \frac{AGB_{tree,i,j}}{n_{plot,i,j}}$$

with $AGB_{i,j}$ the Aboveground biomass of the forest type i in the strata j in ton/ha

4. Weighted average of the strata to get the aboveground biomass of the forest type (Equations (4) and (5)):

(4)
$$AGB_i = \sum_j AGB_{i,j} \times \frac{A_{i,j}}{A_i}$$

with: AGB_i the aboveground biomass of the forest type i, $AGB_{i,j}$ the aboveground biomass of the forest type i in the strata j,
$A_{i,j}$ the area of the forest type i in the strata j, and A_i the total area of the forest type i.

(5)
$$CI_i = 1.96 \times \sqrt{\sum_j \frac{A_{i,j}^2}{A_i^2} \times \frac{\sigma_{i,j}^2}{n_{i,j}}}$$

with: $\sigma_{i,j}$ the standard deviation of aboveground biomass in the forest type i and strata j, and $n_{i,j}$ the number of plots in the forest type i and strata j.

2.4.1 Explanation over a schematic example

This approach was presented as example in the Figure 2. In case only the plots on the 10 km grid would be used for the data analysis (top left schema), a simple average could work if all plots were remeasured. But as 2 plots were not remeasured in non protected forest, the simple averages would give a biased estimate for the cycle 3 and therefore a biased comparison of biomass between the cycles 1 and 3.

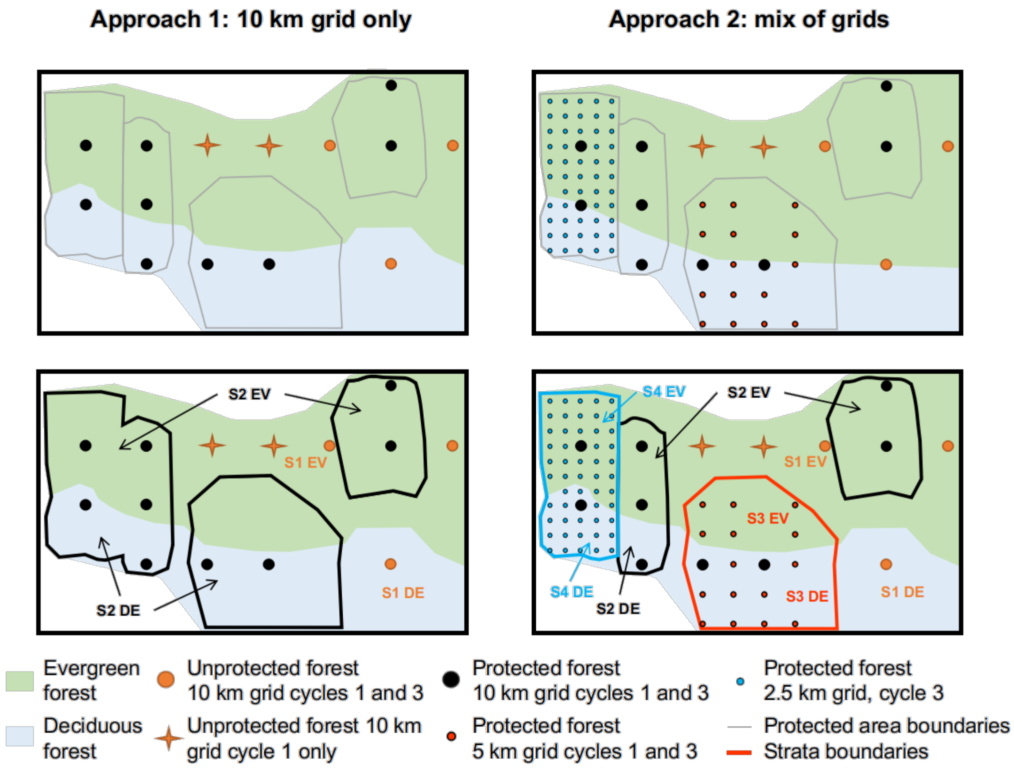


Figure 2: Schematic example of the stratification approach with the 10 km grid only (left side) or with a mix or sampling grids (right side).

To calculate an unbiased estimator, the forest could be divided into 2 strata, S1 for non protected area and S2 for protected areas (bottom left schema). The weighted average of Evergreen forest biomass would then be the average biomass in Evergreen forest in S1 (S1 EV, based on 4 plots in cycle 1 and 2 plots in cycle 3) multiplied by the weight of Evergreen forest in S1 plus the average biomass in Evergreen forest in S2 (S2 EV, based on 9 plots in both cycles) multiplied by the weight of Evergreen Forest in S2 (Equation (6)) and similarly for the aboveground biomass of Deciduous forest.

(6)

$$AGB_{EV} = AGB_{EV,S1} \times \frac{A_{EV,S1}}{A_{EV}} + AGB_{EV,S2} \times \frac{A_{EV,S2}}{A_{EV}}$$

A more complex case would be when in addition to the difference of sampling on the 10 km grid, several protected areas received a sampling intensification with additional plots on 5 and 2.5 km grids (Figure 2, schema top right). In this case the protected areas that received different sampling intensities should be considered as additional strata, leading to four strata with all the sampling grids applied (bottom right schema).

2.4.2 Approaches tested for the data analysis

Three approaches were tested to get the optimal combination of plots, i.e. a good trade-off between simplicity in the approach to avoid unexpected sources of bias and keeping as many plots as possible in the data analysis, given the tremendous efforts it took to collect all this data (Table 3). The schematic examples from the previous section represent two of the approaches tested with the data available. As the second example could still lead to biased estimates due to the complexity of handling a combination of sampling grids and differences between plot measured in the cycle 1 and 3 on the same grid, a slightly simpler intermediate approach was also tested. Only the plots on the 5 and 10 km grids that were remeasured were selected. By using this subset of the plot data, the issues of plot not having been remeasured is taken into consideration. Since the 2.5 km grid was only applied in the Cycle 3, only the plots overlapping the 5 km grid were kept and the number of strata reduced to 3.

It should also be noted that according to the ITTO project report for the NFI Cycle 1, around 12% of the plots in Tropical Evergreen Forest could not be measured. No corrections were made to compensate this lack of data, and as Tropical Evergreen Forest is the highest carbon stock forest type, the overall carbon stock is considered conservative

Table 3: Approaches to deal with the complex mix of sampling intensities and plot selection in the NFI cycle 1 and 3.

Approach	Approach 1	Approach 2	Approach 3
Data selected	all plots on the 10 km grid	Plots on the 10 and 5 km grids that were measured both in the NFI cycle 1 and 3	All the plots
Number of strata	2	3	4
Strata definition	Strata 1: all the protected areas, Strata 2: non-protected areas	Strata 1: Protected areas where the 5 km gird sampling intensification was implemented, Strata 2: Other protected areas (where only the original 10 km grid was applied), Strata 3: non-protected areas	Strata 1: Protected areas where the 2.5 km gird sampling intensification was implemented, Strata 2: Other protected areas where the 2.5 km grid sampling intensification was implemented, Strata 3: Other protected areas (where only the original 10 km grid was applied), Strata 4: non-protected areas
Areas (x1000 ha)	S1: 9849, S2: 6110	S1: 2197, S2: 7652, S3: 6110	S1: 2336, S2: 7093, S3: 733, S4: 6110

In the approaches 2 and 3, the protected areas of the different strata were selected by their names. This list of protected areas in each strata was placed in Annex.

2.5 Belowground biomass and carbon stock

Belowground biomass was calculated at the forest type level with root-to-shoot (RS) ratios from the IPCC guidelines: 0.37 and 0.2 for Evergreen and Deciduous forest respectively (IPCC, 2006, Vol. 4, Table 4.4) and 0.49 for Mangroves (IPCC, 2013, table 4.5). The biomass was then converted to carbon stock (Cstock) with the carbon fraction (CF) of 0.47 (IPCC, 2006, Vol. 4, Table 4.3) and with the ratio of atomic masses of carbon and CO_2: 44/12 (Equation 7). The IPCC based carbon fraction was validated by a study from AFPnet (http://www.apfnet-kuff.com), during which around 30 key species had their CF measured via increment borer core sampling. The CF ranged from 45.43 to 49.66%.

(7)

$$Cstock(tCO_2/ha) = AGB \times (1 + RS) \times CF \times \frac{44}{12}$$

The confidence interval of the aboveground biomass in percent was assigned to the carbon stock in CO_2, as uncertainties in percentage are kept unchanged when multiplying by constant values.

2.6 Emission and removal factors

the emission and removal factors for forest remaining forest (EFRF, in tCO_2/ha/yr) were calculated as the difference between the carbon stock of the NFI cycle 1 and 3 divided by the time period between the two inventories, resulting in positive values when the stock decreased (emissions) and negative values when the stock increased (removals) (Equation 8). The confidence interval (CI) associated to the difference between carbon stocks was based on the propagation of error approach in IPCC guidelines 2006, with the following formulas (Equation 9):

(8)

$$EFRF = \frac{Cstock_i - Cstock_j}{period}$$

(9)

$$CI = 1.96 \times \sqrt{\frac{\sigma_i^2}{n_{plot_i}} + \frac{\sigma_j^2}{n_{plot_j}}}$$

with σ_* the standard deviation of the carbon stock and n_{plot*} the number of plots measured during the NFI cycle *.

2.7 Workflow

The data analysis was carried out in a series of R scripts targeting a specific group of data checks, corrections and calculations:

- Conversion MS Access to CSV:

  1. Converting the data from MS Access database to individual CSV tables for each database.

- Preparing plot data:

  2. Loading the plot table of all the databases simultaneously and concatenating into a simple table.
  3. Removing plot duplicates when different databases hosted the same plot measured during the same NFI cycle.
  4. Converting plot ID from GPS coordinates based on the CRS Indian75 to the CRS WGS 84 using a table of equivalence.
  5. Converting remaining plot ID from GPS coordinates based on the CRS Indian75 to the CRS WGS 84 using GIS based transformation of CRS.
  6. Converting all the GPS coordinates (not plot ID) from to WGS84 UTM48 to WGS84 UTM47 to have all the plots available under one CRS.
  7. Loading and preparing shapefiles for administrative boundaries and protected areas in R.
  8. Assigning province, region and protected areas name and type to each plot based on GIS and visual interpretation for plots falling outside the country boundaries (the country shapefile may not be completely accurate).
  9. Correcting protected areas duplicates due to bad geometries (some areas overlapped resulting in plot being duplicated).
  10. Adding NFI grid spacing from 'tblCluster' to plot.
  11. Adding land use name from 'tblLanduse' to plot.
  12. Correcting inventory year.
  13. Developing maps to show plot features spatially.

- Preparing tree data:

  14. Loading the tree table from all the databases simultaneously and concatenating into a single table.
  15. Removing tree duplicates (cf. 03).
  16. Checking and correcting DBH and H (No outlier found).
  17. Adding tree species and family name based on 'tblPlant' and 'tblPlantFamily' concatenated from Cycle 1 and 3 to include all species codes.
  18. Adding tree wood density from the Global Wood Density database based on species and genus.
  19. Calculating AGB from Chave and Thai equations.

- Aggregating from tree to plot data:

  20. Calculating the sum of the tree AGB per ha for each plot.
  21. Detecting and correcting/removing outliers at plot level.

- Aggregating plot to forest type based on two classifications:

22. Adding land use change to plot data.
23. Developing a function to calculate simple and weighted average based on different stratification approaches.
24. Preparing the stratifications with spatial data.
25. Developing a function to calculate the EFRF.
26. Calculating the EFRF for Approach 1: 10 km grid and 2 strata.
27. Calculating the EFRF for Approach 2: remeasured plots on 5 and 10 km grids (3 strata).
28. Calculating the EFRF for Approach 3: all plots (4 strata).
29. Functions to develop tree crown mapping.

2.8 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), `sf` (Pebesma, 2020); for visualizations: `ggplot2` (Wickham et al., 2020), `ggthemr` (Tobin, 2020), `ggpubr` (Kassambara, 2020); and for reporting: `knitr` (Xie, 2020b, 2015), `bookdown` (Xie, 2020a), `tmap` (Tennekes, 2020) and `webshot` (Chang, 2019). The package `Hmisc` (Harrell Jr et al., 2020) together with mdbtools were used to convert the MS Access data to CSV files. NFI plot visualization was also carried out with QGIS.

3 Selecting allometric equations to estimate tree aboveground biomass

Forest carbon stocks assessments are usually the results of tree biomass estimates propagated to forest inventory plots and then to forests. At the tree level, allometric equations are used to calculate diffcult to measure tree characteristics (such as biomass) from easy-to-measure ones like tree diameter or height (Picard et al., 2012). The choice of the allometric equation have a major impact on the quality of the tree, plot and forest biomass estimates, and using the wrong equations could lead to to large errors and bias on the final biomass estimates (Henry et al., 2010; Picard et al., 2015).

In Thailand, tree aboveground biomass allometric equations were developed in the sixties (Ogawa et al., 1965) and eighties (Tsutsumi et al., 1983). The development of allometric equations for natural forest stopped shortly after, due to a nationwide logging ban on natural forest in 1989. Since then studies on forest biomass focused on timber plantations (Ounban et al., 2016; Warner et al., 2016) or used either the above equations (Terakunpisut, 2007; Chaiyo et al., 2012) or pan-tropical allometric equations (Jha et al., 2020).

The nationally developed equations could be seen as old, potentially outdated and even presenting a risk of bias given that very few indicators of the model performance were presented in the articles. An alternative could be to use the more recent pan-tropical equation from Chave et al. (2014) which could be seen as more robust given the range of trees and locations included in their study. The Chave equation could also present a risk of bias given that the closest site in Southeast Asia were Cambodia and Indonesia.

At first both Chave and the Thailand based equations were applied to the NFI data. Then to help deciding between the two approaches, a small study was implemented in 2019. It consisted of the semi-destructive measurement of 60 trees in one Tropical Evergreen Forest and two Mixed Deciduous Forest sites, in order to generate a data set of approximate tree biomass for testing the accuracy of the equations (Section 3.3).

3.1 Presentation of the equations

The equations from Thailand were developed to estimate the biomass of different forest types: Ogawa (1965) in tropical evergreen Forest (Equation 1) and mixed deciduous forest (Equation 2), and Tsutsumi (1983) in hill and dry evergreen forest (Equation 3):

(1)

$$AGB = TC + \frac{1}{\frac{18.0}{TC} + 0.025}$$

with $TC = 0.0396 \times (DBH^2 \times H)^{0.9326} + 0.006002 \times (DBH^2 \times H)^{1.027}$

This equation was developed based on two sites in Khao Chong Forest Reserve, far South Thailand, where 74 trees were felled, with a DBH range from 4.5 cm to 100 cm (approx.) and max tree height of 46.1 m.

(2)

$$AGB = TC + \frac{1}{\frac{28.0}{TC} + 0.025}$$

with $TC = 0.0396 \times (DBH^2 \times H)^{0.9326} + 0.003487 \times (DBH^2 \times H)^{1.027}$

This equation was developed based on three sites in Ping Kong Forest Reserve, Northwest Thailand, where 45 trees were felled, with a DBH range of 4.5 cm to 100 cm (approx.) and max tree height of 36 m. The three sites covered a range of deciduous forest conditions.

(3)

$$AGB = 0.0509 \times (DBH^2 \times H)^{0.919} + 0.00893 \times (DBH^2 \times H)^{0.977} + 0.0140 \times (DBH^2 \times H)^{0.669}$$

This equation was developed based on one site in Nam Phrom Area, in mixed forest conditions between dry evergreen and deciduous forest. 60 trees were felled with a DBH range from 4.5 to 84.5 cm.

The equation from Tsutsumi was also applied to Pine, Swamp and Beach forests.

These equations were reported without any indicator of performance such as standard error, only R-squared was reported for Tsutsumi model. They were ccompared to the equation from Chave et al. (2014), applicable to all forest types and based on tree DBH (in cm), H (in m) and WD (in g/cm3) (Equation 4):

(4)

$$AGB = 0.0673 \times (DBH^2 \times H \times WD)^{0.976}$$

Tree wood density was not recorded as part of the NFI but could be estimated based on the tree species. More precisely, Wood density (WD) was assigned to each tree based on species or 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. If the tree species matched a record in the GWD it was assigned the species' average wood density. If the species did not match but the genus did, the genius level average wood density was assigned. if neither species nor genus matched, a default value of 0.57 g/cm^3 was assigned. The default value was based on a wood density average for Tropical Asia in Reyes et al. (1992).

3.2 Application of the allometric equations to the NFI data

Thanks to the low number of unknown species in the NFI data, most trees had their wood density estimated at the species level (Table 4) and only 13 % of the trees had to rely on the regional default WD value. Neither the species list used for the NFI nor the Global WD database had their species name cross-checked with a Taxonomic Name Resolution Service. With these corrections the number of trees with default WD could be slightly further reduced, but these first results were already outstanding.

Table 4: Number of trees from all grids with the different wood density levels assigned: species, genus or default WD value for Southeast Asia.

Forest type	NFI cycle	Default WD	Genus WD	Species WD
Cycle 1	DNP	26346	75070	90693
Cycle 2	DNP	5862	19803	22864
Cycle 3	DNP	24497	92548	92598
Cycle 3	RFD	1007	4348	4723
Total	Total	57712	191769	210878

Tree aboveground biomass was calculated for each key forest type in Evergreen and Deciduous forest with Thai equations. All the other land uses not related to Evergreen, Deciduous or Mangrove forest were given a AGB value of 0 to be conservative. If additional forest types were to be added in the future to the FREL/FRL, they could be added at this stage of the data analysis. For all trees, the pan-tropical model of Chave was used to have a second value of AGB. The equation from Chave et al. 2014 gave higher AGB values in general, especially in the small to mid-range trees (Figure 3). These general findings should be nuanced by the results using tree wood densities where trees with large DBH and H add AGB values in the higher and lower part of the AGB values.

The Thai models were based on DBH and H. The Tropical evergreen model (EV) had the highest AGB values for a given surrogate of volume, followed by the model from Tsutsumi for Hill and Dry Evergreen forest and the model for Deciduous forest (DD) had the lowest AGB.

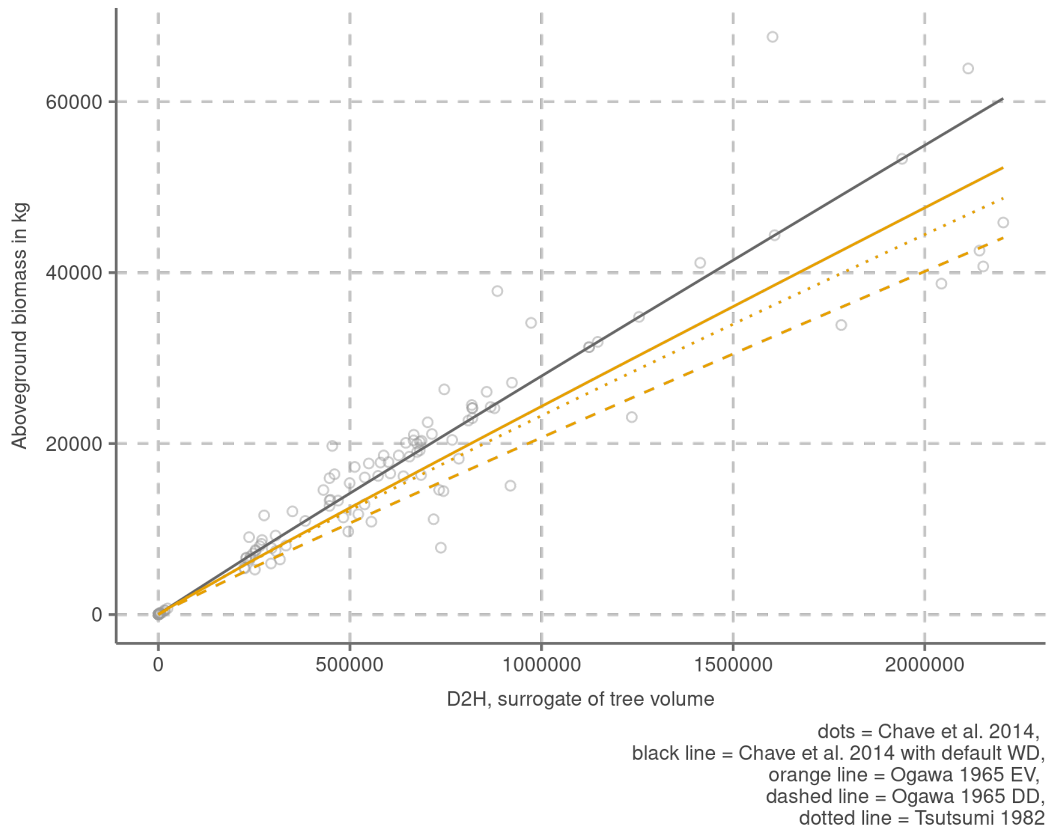


Figure 3: Tree aboveground biomass against tree surrogate of volume D^2H, for a random sample of trees along the values of D^2H.

3.3 Validation of the allometric equations

During the small study implemented in 2019, 60 trees had their biomass measured with a semi-destructive method. The stem and the main branches had their volume measured and 3 branches were cut and had both their volume and their mass measured, separating the main branches from the smaller branches and the leaves. Aliquots were selected from the sampled branches to calculate the tree wood density and fresh to dry mass ratio (See Appendix A).

Chave and the Thailand based equations were applied to these 60 trees and compared to the observed biomass. Overall, Chave's equation overestimated the biomass while the Thailand based equations underestimated the tree biomass (Table 5). The equations for evergreen forest had the best performance, closely followed by Chave's equation and the equation for Mixed Deciduous Forest had the worst overall performance. Surprisingly Chave's equation performed the worst in the Tropical Evergreen Forest and best in one of the Mixed Deciduous Forest.

Table 5: Bias of the Chave and Thailand based allometric equations in percent.

Nat. park	Chave 14	Ogawa 65 trop.	Ogawa 65 dec.	Tsut. 82
KK	21.5	-4.8	-17.9	-5.3
TSL	7.2	-22.7	-33.0	-22.1
PP	17.8	-13.2	-24.7	-12.4
Total	15.5	-13.6	-25.2	-13.3

Given that there was not a clear winner from the study and that the results could not be compared to the models' performance, the Thailand based equations were selected to calculate national level carbon stock. One possible explanation for the Mixed Deciduous Forest model not performing well was that even in Mixed Deciduous Forest, the sites selected were very similar to Evergreen Forest as the team focused on sites with big trees, to cover the range of tree DBH reported in the NFI data.

4 Data cleaning and preparation

4.1 Preparation of the plot data

4.1.1 Removing plot duplicates

From the first version of the data received in 2019 to the latest corrected version from April 2020, a number of harmonization and corrections procedures were applied. In the first version of the data, inventory plots were scattered in 12 MS Access databases, in particular 3 databases for cycle 1, containing duplicates of the inventory plots. In the latest version, inventory plots were grouped per NFI cycle with one database for each cycle and another database for the plots measured by RFD during cycle 3. One plot was measured both by DNP and RFD and in this case the measurements from DNP were kept. Cycle 1 had the highest number of plots measured in the 10 km grid as it was a wall-to-wall NFI whereas during cycle 2 and 3 there was only a partial remeasurement of the plots on the 10 km grid (Table 6). The number of plots measured in the 2.5 and the 5 km grids were similar but these plots targeted different protected areas, i.e different populations, they could increase the chances of producing biased estimates at the national level. The location of the plots in the 2.5 and 5 km grids should be checked carefully to ensure that when comparing time periods, the carbon stocks still reflect similar forest conditions and not different locations.

Table 6: Number of plots recorded per inventory cycle, institution and NFI sampling grid.

NFI cycle	Institution	2.5 km	5 km	10 km
Cycle 1	DNP	0	3093	2435
Cycle 2	DNP	0	8	888
Cycle 3	DNP	2639	646	636
Cycle 3	RFD	0	8	168

4.1.2 Harmonizing plot data

All cycle 1 plots apart for the center plots were disregarded to maintain consistency between inventories. The plot IDs were composed by the UTM zone, longitude and latitude of the theoretical plot location (from the planning stage). Since the NFI cycles 1 and 2 used Indian 75 as coordinate reference system and cycle 3 used WGS 84, the plot IDs differed between inventory cycles for the same plots. All the plots from the cycles 1 and 2 had their plot map coordinates re-projected to WGS 84 and their plot IDs updated to have the same IDs as in cycle 3 (Table 7).

Table 7: Example of 5 plots that were coded differently in the NFI cycles 1 and 2 compared to cycle 3.

Old plot ID	New plot ID	Old longitude	Old latitude	New longitude	New latitude	Cycle 1	Cycle 2	Cycle 3
477651761C	477646671761304C	765000	1761000	764667	1761304	1	1	1
475251681C	475246661681304C	525000	1681000	524666	1681304	1	1	1
474651906C	474646661906304C	465000	1906000	464666	1906304	1	0	1
474700936C	474696660936300C	470000	936000	469666	936300	1	0	1
475351236C	475346661236302C	535000	1236000	534666	1236302	1	0	1

4.1.3 Adding region, protected areas' type and name from shapefiles

The land use type information was collected at plot level. The province and NFI grid were known at the planning stage and stored in the cluster tables. However no information on protected area was recorded in the data. Since protected areas played an important role in the plot location and distribution, the information was added from the shapefile. Region was also added to visually check the plot distribution at a smaller scale than country level. The majority of the plots were measured inside protected areas (Table 8). These plots were a combination of the 10 km grid and all the plots measured in the 2.5 and 5 km grids. While more than a thousand plots were located outside protected areas in the first NFI cycle, they were only a couple of hundred in the cycle 3. A large number of the plots located outside protected areas were non forest plots and/or had no trees. Non forest plots were removed from the analysis at a later stage.

Table 8: Number of forest plots measured inside and outside protected areas.

	Non-protected area			Protected area			
NFI grid	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3	Total
10	506	326	154	679	458	572	2695
5	743	1	25	1541	6	538	2854
2.5	0	0	51	0	0	2249	2300
Total	1249	327	230	2220	464	3359	7849

4.1.4 Number of plots measured in the different forest types

The original NFI plot data contained 42 land use types. For the FREL/FRL, the study aggregated forest types and focused on 3 key forest types. First, Evergreen forest, composed of Tropical, Hill and Dry Evergreen forests, plus Pine, Peat Swamp, Fresh Water Swamp and Beach forests. Second, Deciduous forest, composed of Mixed Deciduous and Dry Dipterocarp forest. Dry Dipterocarp and Mixed Deciduous forests were grouped as they were negligible differences between their carbon stocks. The other forest types were grouped into evergreen to match the Activity Data for which all forests not identified as Deciduous or Mangrove were categorized as Evergreen. For the third forest type, mangrove, the NFI plot data included only 7 plots in Cycle 1, so instead mangrove AGB was estimated using the DMCR study (37 plots). All the other land uses were considered non forest, they included plantations, disturbed forest (which was assumed to be below the forest definition thresholds), agricultural land, water bodies and build-up areas.

On the 10 km grid, the number of plots per forest type was relatively constant across NFI cycles in protected areas, but dropped down considerably outside protected areas (Table 9). On the 5 km grid, the number of plots was distributed mainly in protected areas, especially in Evergreen forest, and more equally distributed between protected and non-protected areas in Deciduous forest. This seemed to reflect well the areas of forest protected with 77 % of Evergreen forests and 54 % of Deciduous forests being under a protection status. The 5 km grid was only implemented in cycle 1, and replaced by the 2.5 km grid in cycle 3. The 2.5 km grid was quasi-exclusively implemented in protected areas.

Table 9: Number of plots per forest type, NFI cycle and protection status.

NFI grid	LU code	LU	Non-protected area Cycle 1	Non-protected area Cycle 2	Non-protected area Cycle 3	Protected area Cycle 1	Protected area Cycle 2	Protected area Cycle 3
10	111	Tropical Evergreen Forest	11	11	4	54	43	37
	112	Dry Evergreen Forest	45	33	22	175	104	138
	113	Hill Evergreen Forest	27	17	5	33	21	45
	114	Pine Forest	3	3	2	1	1	3
	115	Peat Swamp Forest	2	1	1	1	1	2
	116	Mangrove Forest	1	0	0	0	0	0
	117	Fresh water Swamp Forest	1	0	1	1	0	0
	121	Mixed Deciduous Forest	265	170	70	308	209	258
	122	Dry Dipterocarp Forest	151	91	49	106	79	89
5	111	Tropical Evergreen Forest	28	0	4	151	0	59
	112	Dry Evergreen Forest	41	0	1	254	0	99
	113	Hill Evergreen Forest	49	0	5	93	0	53
	114	Pine Forest	10	0	0	6	0	2
	115	Peat Swamp Forest	0	0	1	4	0	0
	116	Mangrove Forest	0	0	0	6	0	0
	117	Fresh water Swamp Forest	1	0	0	1	0	0
	118	Beach Forest	1	0	0	0	0	0
	121	Mixed Deciduous Forest	390	1	12	733	5	258
	122	Dry Dipterocarp Forest	223	0	2	293	1	67
	111	Tropical Evergreen Forest	0	0	1	0	0	223

Table 9: Number of plots per forest type, NFI cycle and protection status. *(continued)*

NFI grid	LU code	LU	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3
2.5	112	Dry Evergreen Forest	0	0	6	0	0	449
	113	Hill Evergreen Forest	0	0	5	0	0	212
	114	Pine Forest	0	0	0	0	0	9
	121	Mixed Deciduous Forest	0	0	36	0	0	1039
	122	Dry Dipterocarp Forest	0	0	3	0	0	317

4.1.5 Plot location

As the distribution of the inventory plots across the country could generate bias given that plots were measured in different areas in cycle 1 and 3, plots were mapped with "remeasured plots" (A) and plots measured only one time (B) side by side (Figure 4). The main observation was that combining the 5 and 10 km girds, a decent amount of plots were remeasured, even if they were not at the exact same location. The Figure B revealed that the difference of sampling intensity and the emphasis on protected areas in the NFI cycle 3 led to a large number of plots from cycle 1 not being revisited. The cycle 3 concentrated the efforts in a number of national parks instead. With such a disparity in plot distribution, it was hard to understand if the areas targeted in the cycle 3 could represent the country conditions as well as the cycle 1 and to what extent using all the inventory plots could lead to biased carbon stock estimates if different grid densities were not considered.

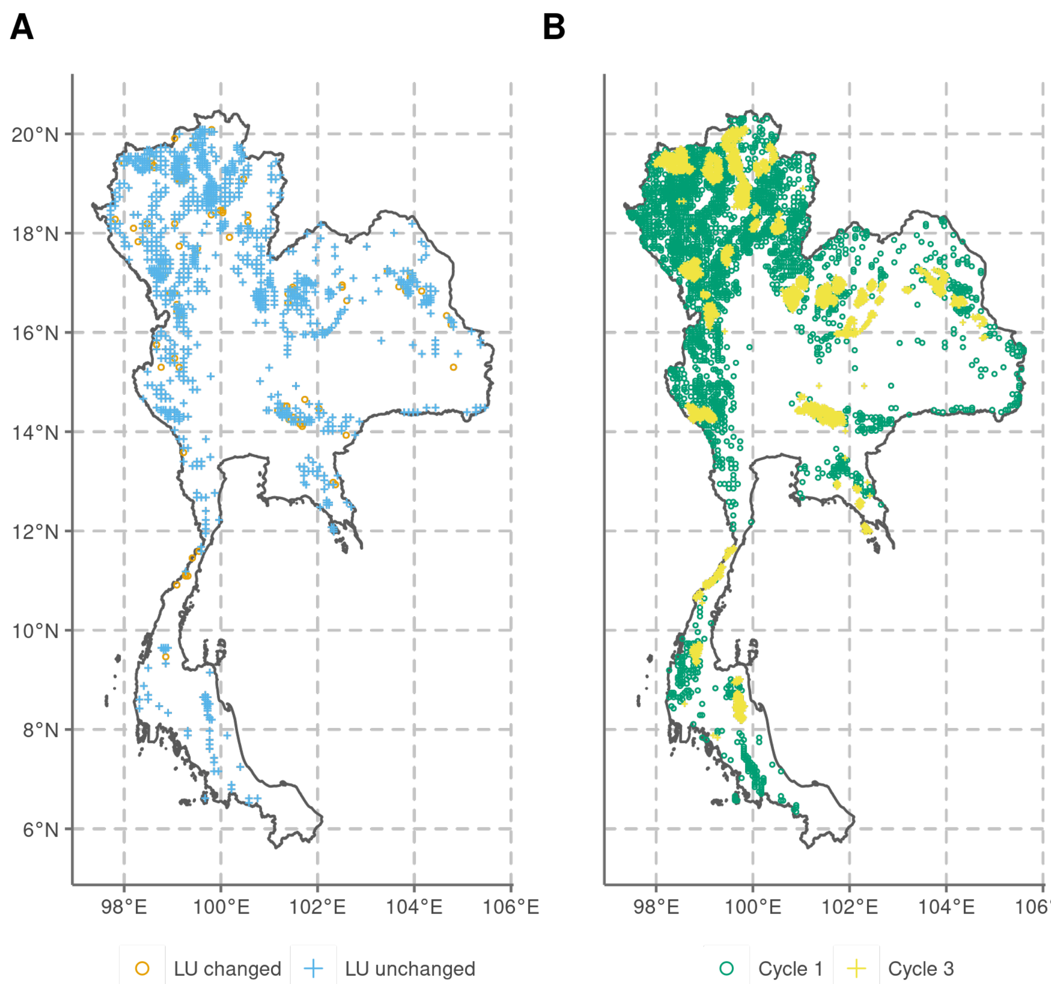


Figure 4: Plot location, remeasured plots (A) and plots measured only one time (B). Plots from all grid densities are shown.

4.2 Preparation of the tree data

4.2.1 Removing pseudotrees and dead trees

Similarly to the plot data, the tree data was extracted from MS Access databases and concatenated into one table. When duplicated plots were found (previous version of the data) the associated trees were also removed. A few trees had also duplicated IDs for different trees (species, DBH, H) and were also removed. In the latest version of the data no duplicates were found (Table 10). Other data removed were pseudotrees, i.e. plants recorded in the NFI but not considered as trees, and dead trees. Fallen trees were kept in the data when alive as their information was recorded normally.

Table 10: Number of trees measured after data cleaning process.

NFI cycle	Institution	Initial	Without Pseudotrees	Without Duplicates	Without Dead Trees	Without missing DBH or H
Cycle 1	DNP	220752	217070	217070	209914	209914
Cycle 2	DNP	50697	50659	50659	49536	49536
Cycle 3	DNP	221453	221277	221277	215047	215047
Cycle 3	RFD	10964	10905	10905	10570	10570
Total	Total	503866	499911	499911	485067	485067

4.2.2 Tree diameter and height

Dead trees had the same range of DBH and H as the trees alive, with more dead trees having a smaller height for the same DBH as the live ones (Figure 5. Several live trees had very low height relatively to their diameter. These trees were most likely broken but since there was no information on their health condition they were all kept in the data. Another way to check tree DBH and H was to display the number of logs and the timber quality with the tree H-DBH scatter plots (Figure 6. Inconsistencies were found in the data with trees with low height having a large number of logs and trees with incorrect timber quality codes (around 300 trees concerned originally, 60 after corrections). Without additional information on these trees, they were kept unchanged in the data. In a future work, a height diameter relationship could be developed and used to estimate the height of trees for which the measurement could have been incorrectly reported.

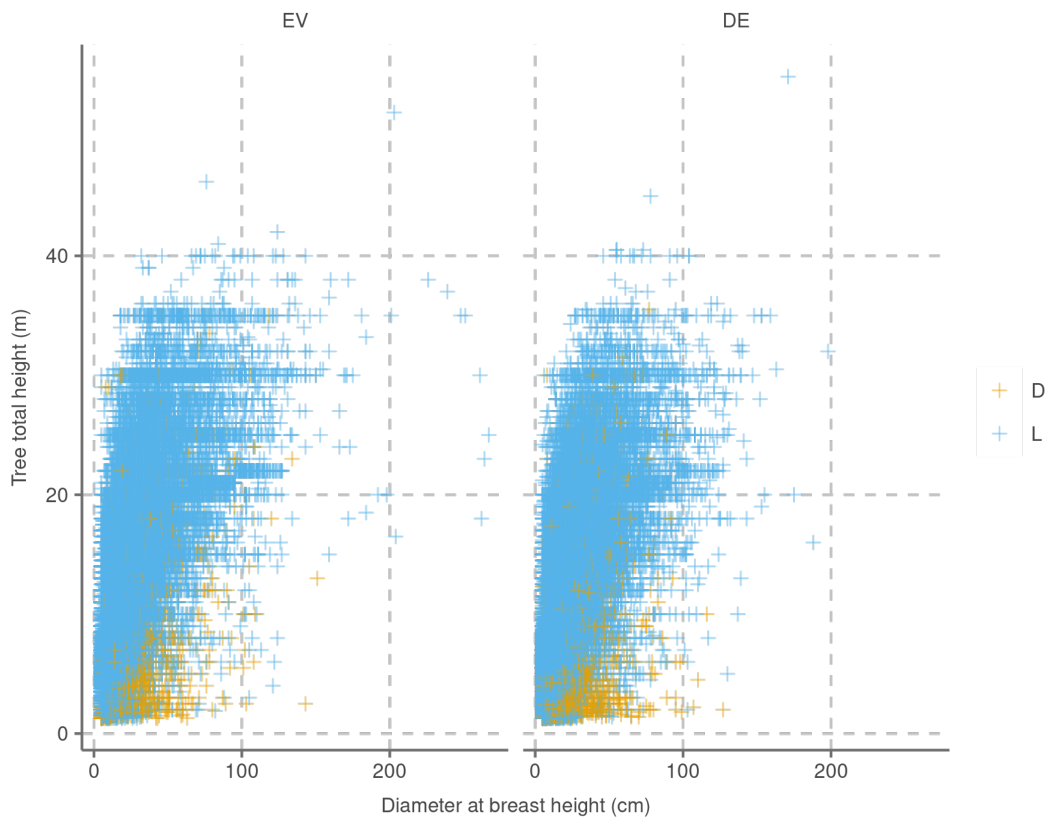


Figure 5: Tree height against diameter at breast height for dead (D) and live (L) trees.

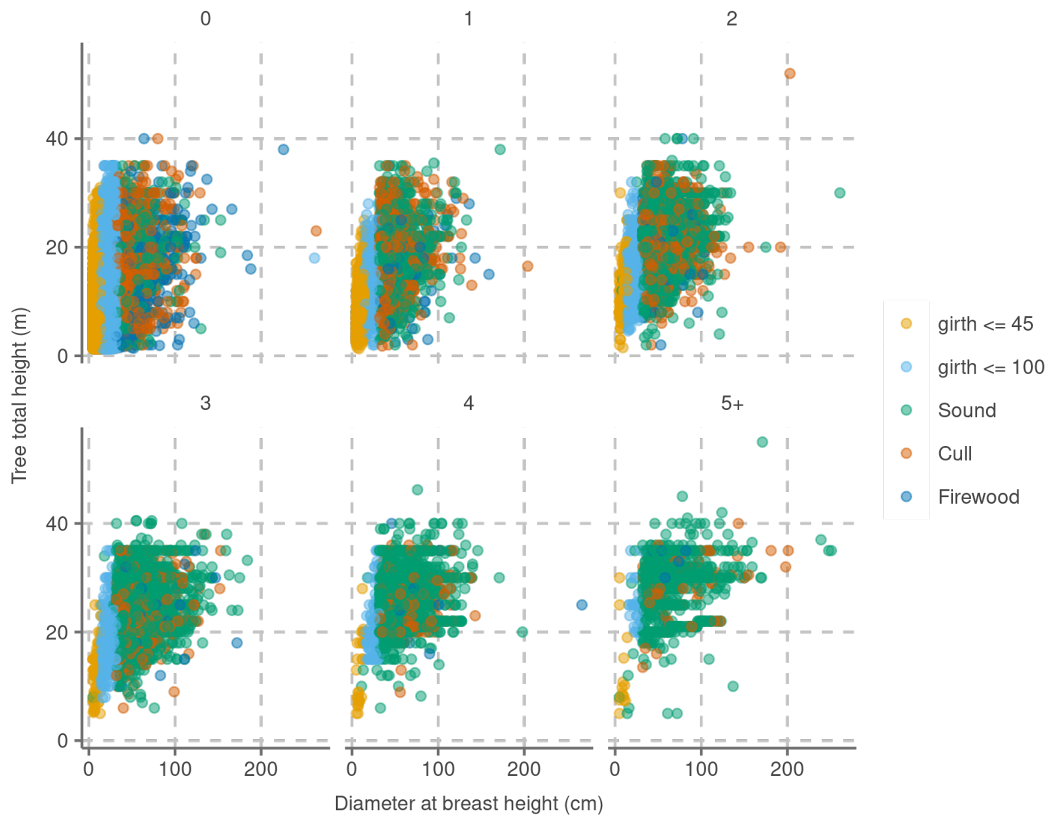


Figure 6: Tree height against diameter at breast height per timber quality and number of logs estimated.

4.2.3 Tree species

The overall percentage of unknown tree species was 5 %, which is very low for a full scale NFI. The species lists combining the cycle 1 and 3 (as some species code changed) had almost 1500 entries. The most represented species was *Shorea siamensis* closely followed by *Shorea obtusa* (Table 11). These two species were predominantly measured in Dry Dipterocarp Forests, while the rest of the top 10 species were measured in different forest types.

Table 11: Ten most frequent species and their distribution in Evergreen (EV) or Deciduous forest (DE).

Species name	Evergreen forest	Deciduous forest
Aporosa villosa	180	570
Canarium subulatum	59	733
Croton persimilis	68	766
Dipterocarpus obtusifolius	33	1459
Dipterocarpus tuberculatus	17	1596
Pterocarpus macrocarpus	62	1158
Shorea obtusa	94	4010
Shorea siamensis	25	3044
Streblus ilicifolius	844	64
Xylia xylocarpa var. xylocarpa	15	1649

4.3 Preparation of the dataset for analysis

4.3.1 Basal area and aboveground biomass at plot level

AGB was calculated at the tree level (See section 3), then propagated to plot level. From the initial number of plots around 1500 plots didn't have trees, mostly in non-forest land uses. If they belonged to Evergreen, Deciduous forest or their affiliated classes they were kept in the data. All the plots measured in land uses that were not affiliated to Evergreen or Deciduous forest were considered non-forest and removed (Table 12). Only one outlier was found at plot level (Figure 7) and its data was removed as well.

Table 12: Evolution of the number of inventory plots during the data cleaning process.

Plot characteristics				Data cleaning process					
Institution	NFI cycle	Protection status	NFI grid	Initial	EV and DE	No outlier	Approach 1	Approach 2	Approach 3
DNP	Cycle 1	NPA	10	1473	505	505	505	144	505
			5	1283	743	743	0	12	743
		PA	10	962	679	679	679	528	679
			5	1810	1535	1534	0	376	1534
	Cycle 2	NPA	10	396	326	0	0	0	0
			5	2	1	0	0	0	0
		PA	10	492	458	0	0	0	0
			5	6	6	0	0	0	0
	Cycle 3	NPA	10	22	20	20	20	17	20
			5	24	17	17	0	8	17
			2.5	78	51	51	0	0	51
		PA	10	614	556	556	556	512	556
			5	622	538	538	0	376	538
			2.5	2561	2249	2249	0	0	2249
RFD		NPA	10	152	134	134	134	127	134
			5	8	8	8	0	4	8
		PA	10	16	16	16	16	16	16
Total	Total	Total	Total	10521	7842	7050	1910	2120	7050

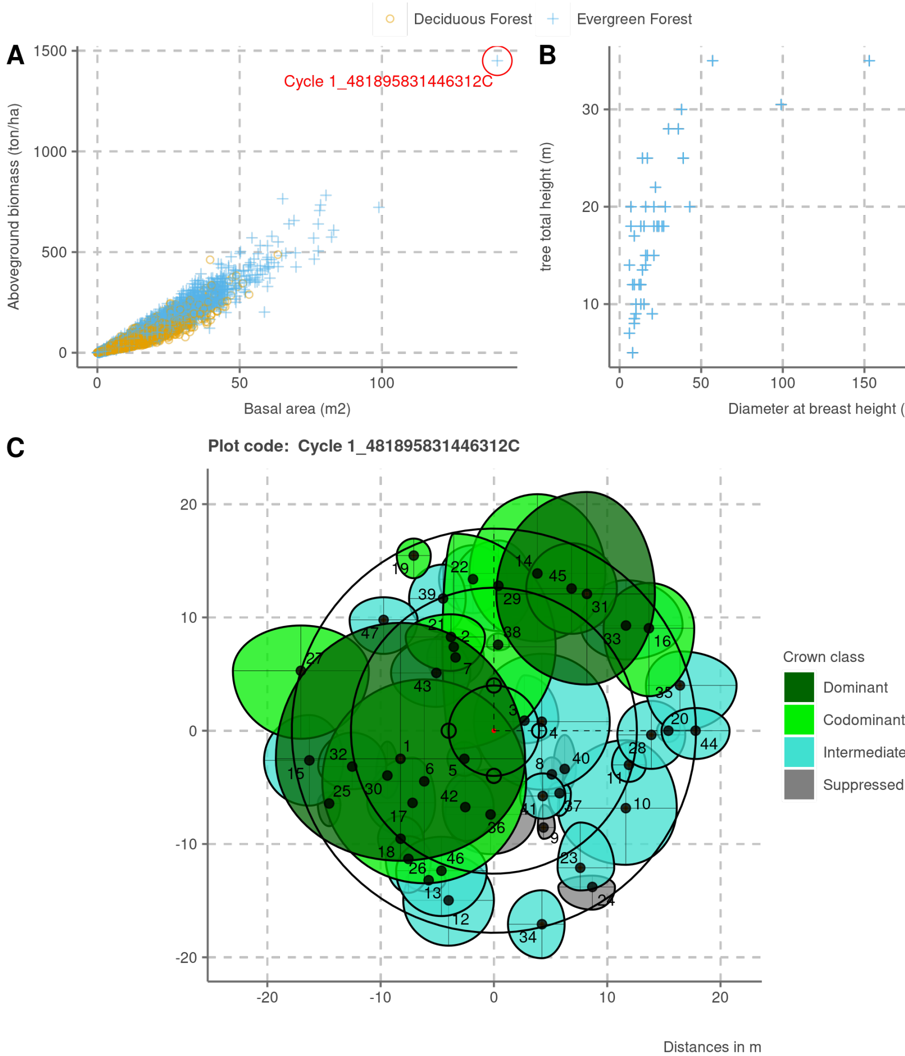


Figure 7: plot aboveground biomass against basal area (A) with outlier in red and tree H against DBH of the outlier plot (B).

After removing this plot and the plots from the Cycle 2, as it was not used in the FREL/FRL calculations, the plots kept for the data analysis ranged from 1910 plots if only based on the 10 km grid (Approach 1) to 7050 with all the plots (Approach 3).

No outlier was detected at the tree level, but the graph of plots' AGB against their basal area showed one plot with exceptional basal area and AGB (Figure 7 A). The tree DBHs and Hs were checked to understand how this plot's AGB and BA could be so high. It didn't show any potential error, just both a high number of small and big trees (Figure 7 B). The Figure 7 (C) confirmed the plot had a high tree density. This plot was still removed from the final data.

4.3.2 Plot location

To better understand the location of the plots following the different approaches and grids a dynamic map (Figure 8) was embedded in the HTML version of the report. All the different grids and the remeasured plots were activable as layers to the dynamic map and ESRI Satellite images could be displayed in the background. In the PDF and MS Word versions only a screenshot could be displayed.

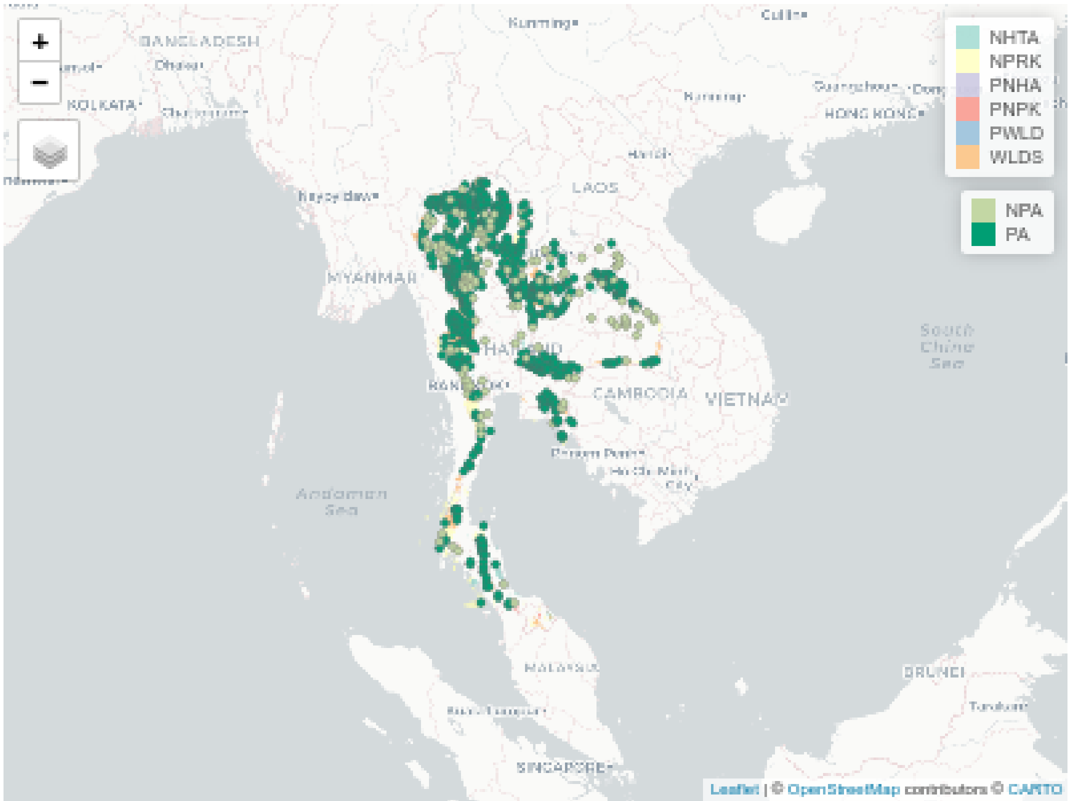


Figure 8: Dynamic map with plot locations.

4.3.3 Choice of the reference year for the different NFI cycles

To calculate the emission and removal factors the time period was estimated by looking at the median year of each NFI cycle, the year 2006 for the cycle 1 and the year 2014 for the cycle 3 (Table 13). The time period between the two inventories was considered to be 8 years. The emission and removal factor could therefore be calculated as the difference between the carbon stock from cycle 1 and cycle 3 divided by 8 to be expressed in ton biomass or tCO_2 per year.

Table 13: Plot measurement per year to assign a reference year for each cycle.

NFI cycle	Inventory year	N. plots	Cum. sum plots	Total N. plots (perc.)
Cycle 1	2000	1	1	0
Cycle 1	2002	17	18	0
Cycle 1	2003	99	117	2
Cycle 1	2004	1017	1134	21
Cycle 1	2005	1477	2611	47
Cycle 1	2006	1145	3756	68
Cycle 1	2007	507	4263	77
Cycle 1	2008	460	4723	85
Cycle 1	2009	265	4988	90
Cycle 1	2010	536	5524	100
Cycle 1	2011	4	5528	100
Cycle 3	2012	120	120	3
Cycle 3	2013	1084	1204	29
Cycle 3	2014	1088	2292	56
Cycle 3	2015	717	3009	73
Cycle 3	2016	440	3449	84
Cycle 3	2017	564	4013	98
Cycle 3	2018	84	4097	100

4.3.4 Carbon stock of the different detailed forest types

To further demonstrate how close the carbon stocks from Mixed Deciduous and Dry Diptercoarp forest were, they were calculated separately inside and outside protected areas and for cycles 1 and 3 (Figure 9). The graph also showed differences in carbon stock between the Evergreen forest sub-classes. One key observation was that Tropical Evergreen Forest had much higher biomass than other Evergreen Forests and as around 12% of the plots in the richer forest types could not be measured due to security reasons, the overall Carbon stock estimates could be considered conservative. Minor forest types, such as Beach, Swamp and Pine forest had a wide range of aboveground biomass but played a very minor role in the overall Evergreen Forest AGB due to the low number of plots measured, reflecting the small area covered by these types.

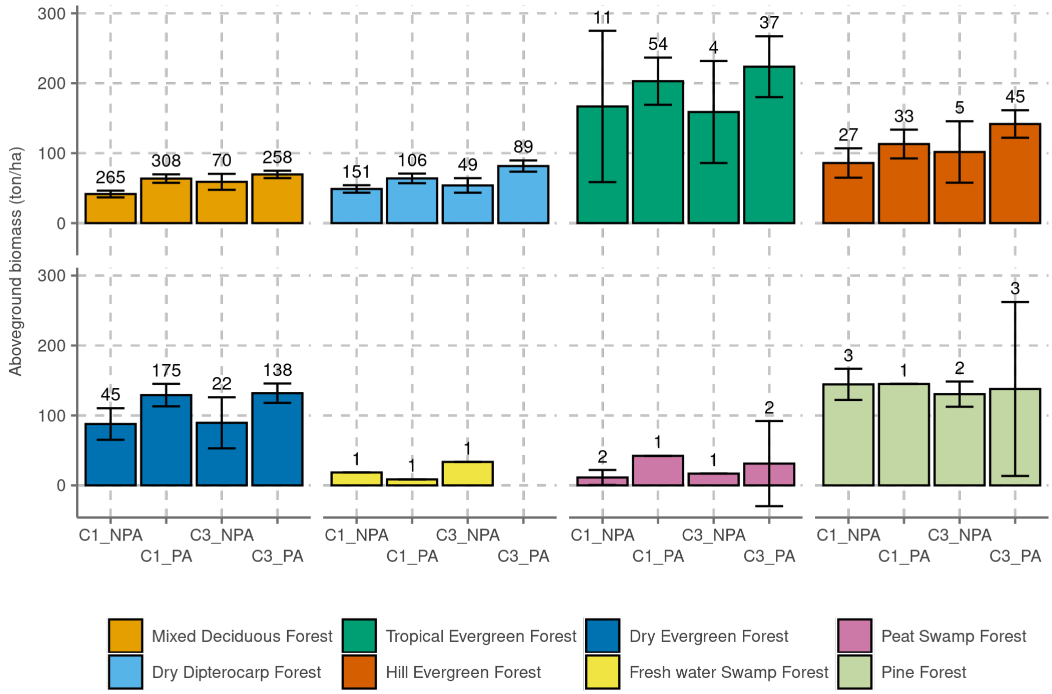


Figure 9: Detailed aboveground biomass for all forest types related to Deciduous and Evergreen Forest (10 km grid). The number of plots for each category is displayed above the bars.

5 Emission and removal factors with approach 1: plots on the 10 km grid

5.1 Plot location (Approach 1)

This approach was based on all the plots on the 10 km grid, split into 2 strata: Protected Areas (PA) and Non-Protected Areas (NPA). This subset of the data had much less plots measured outside protected areas in the cycle 3 than in the cycle 1 (Figure 10).

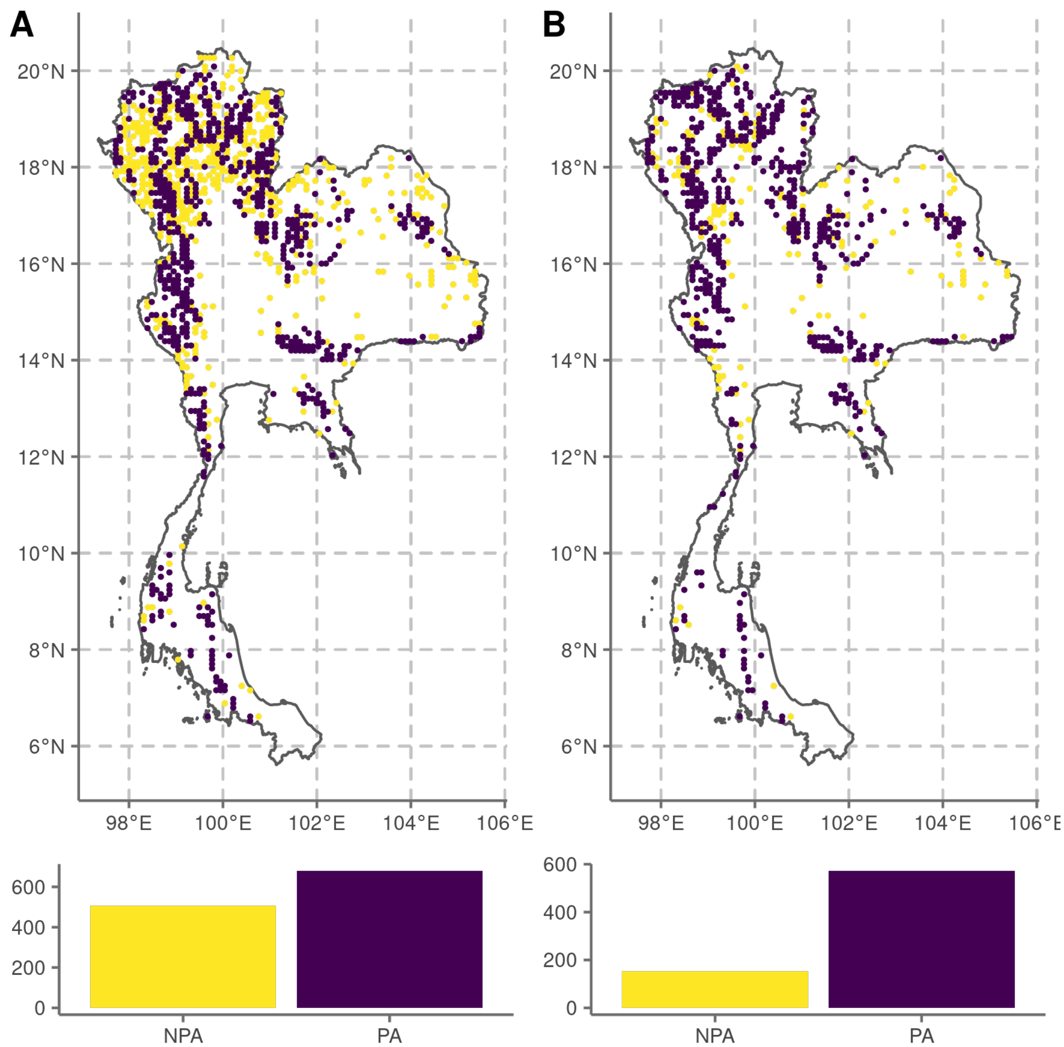


Figure 10: Nationwide distribution of the plots in Approach 1, cycle 1 (A) and cycle 3 (B), with the number of plots per strata

5.2 Aboveground biomass (Approach 1)

In addition to having less plots measured in the cycle 3, non-protected areas had also a lower biomass content than protected areas, especially in Evergreen forest (Figure 11 and Table 14). The number of plots was lower in the cycle 3, but the difference didn't translate in a large difference between simple average and weighted average. The weighted average was kept as it was more robust.

Table 14: Aboveground biomass per forest type for the different strata in t/ha (Approach 1).

NFI cycle	Forest type	Strata	N. plots	AGB (t/ha)	CI (perc.)	weight
Cycle 1	EV	NPA	89	96.397	20	0.234
Cycle 1	EV	PA	265	141.414	10	0.766
Cycle 1	DE	NPA	416	44.238	8	0.458
Cycle 1	DE	PA	414	63.751	8	0.542
Cycle 3	EV	NPA	35	97.822	27	0.234
Cycle 3	EV	PA	225	148.089	9	0.766
Cycle 3	DE	NPA	119	56.912	14	0.458
Cycle 3	DE	PA	347	72.693	6	0.542

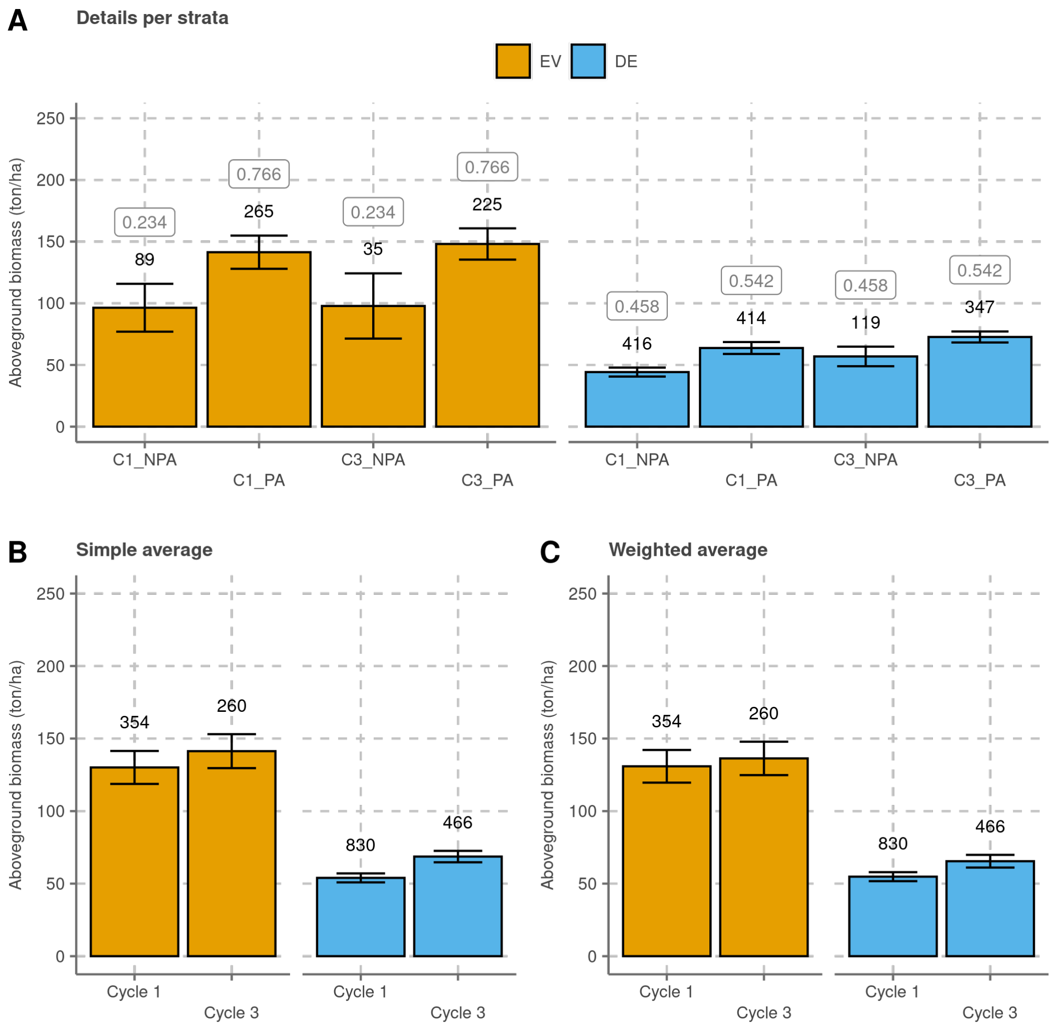


Figure 11: Aboveground biomass per forest type calculations for approach 1. Simple average per strata (A), simple average of all plots (B) and weighted average of the strata (C). The strata weights are represented in grey and number of plots in black.

5.3 Carbon stock (Approach 1)

The weighted average was calculated across strata to generate carbon stock estimates for Evergreen and Deciduous forests (Table 15). The confidence intervals for Evergreen and Deciduous forests were very low, however the carbon stock differences between cycle 1 and 3 were also small, meaning the emission and removal factors, may end up with large confidence intervals.

Table 15: Carbon stock per forest type in t/ha with their half confidence interval (Approach 1).

NFI cycle	Forest type	N. plots	AGB (t/ha)	StDev. AGB	CI (perc.)	BGB (t/ha)	Cstock (tC/ha)	Cstock in tCO_2/ha
Cycle 1	EV	354	130.880	108.105	9	48.426	84.274	309.005
Cycle 1	DE	830	54.814	45.605	6	10.963	30.915	113.355
Cycle 1	MG	37	120.779	68.614	18	59.182	84.582	310.134
Cycle 3	EV	260	136.327	94.714	8	50.441	87.781	321.864
Cycle 3	DE	466	65.465	48.144	7	13.093	36.922	135.381
Cycle 3	MG	37	120.779	68.614	18	59.182	84.582	310.134

5.4 Emission and Removal factors (Approach 1)

The emission and removal factor tables were prepared for AGB in t/ha, CO_2 in tCO_2/ha/yr and the confidence intervals in percent (Tables 16, 17 and 18). The key result was the clear trend of increasing carbon stock in forest remaining unchanged, with -5.447 and -10.651 ton biomass/ha increase over the 8 year period in Evergreen and Deciduous forest respectively. The confidence interval was rather small for Deciduous forest but quite large for Evergreen forest were the trend was less clear.

Table 16: Emission and removal factors in tAGB/ha for Approach 1.

		Cycle 3			
		EV	DE	MG	NF
Cycle 1	EV	-5.447	65.415	10.101	130.880
	DE	-81.513	-10.651	-65.965	54.814
	MG	-15.548	55.314	0.000	120.779
	NF	-136.327	-65.465	-120.779	0.000

Table 17: Emission and removal factors in tCO_2/ha/yr for Approach 1.

		Cycle 3			
		EV	DE	MG	NF
Cycle 1	EV	-1.607	21.703	-0.141	38.626
	DE	-26.064	-2.753	-24.597	14.169
	MG	-1.466	21.844	0.000	38.767
	NF	-40.233	-16.923	-38.767	0.000

Table 18: Half confidence interval of the emission and removal factors in percent for Approach 1.

		Cycle 3			
		EV	DE	MG	NF
Cycle 1	EV	296	18	246	9
	DE	15	50	34	6
	MG	160	41	Inf	18
	NF	8	7	18	NaN

6 Emission and removal factors with Approach 2: remeasured plots on the 5 and 10 km grids

6.1 Plot location (Approach 2)

This approach was based on all the plots on the 5 and 10 km grids that were measured both in cycle 1 and 3. The objective was to compare the same sampling and location to reduce the risk of bias further than stratifying. The forest land was split into 3 strata: Protected Areas were the 5 km grid was applied (PA05), The other protected areas where only the 10 km grid was applied (PA) and Non-Protected Areas (NPA). As only remeasured plot were selected, no discrepancies were found in the plot location between cycle 1 and 3 (Figure 12).

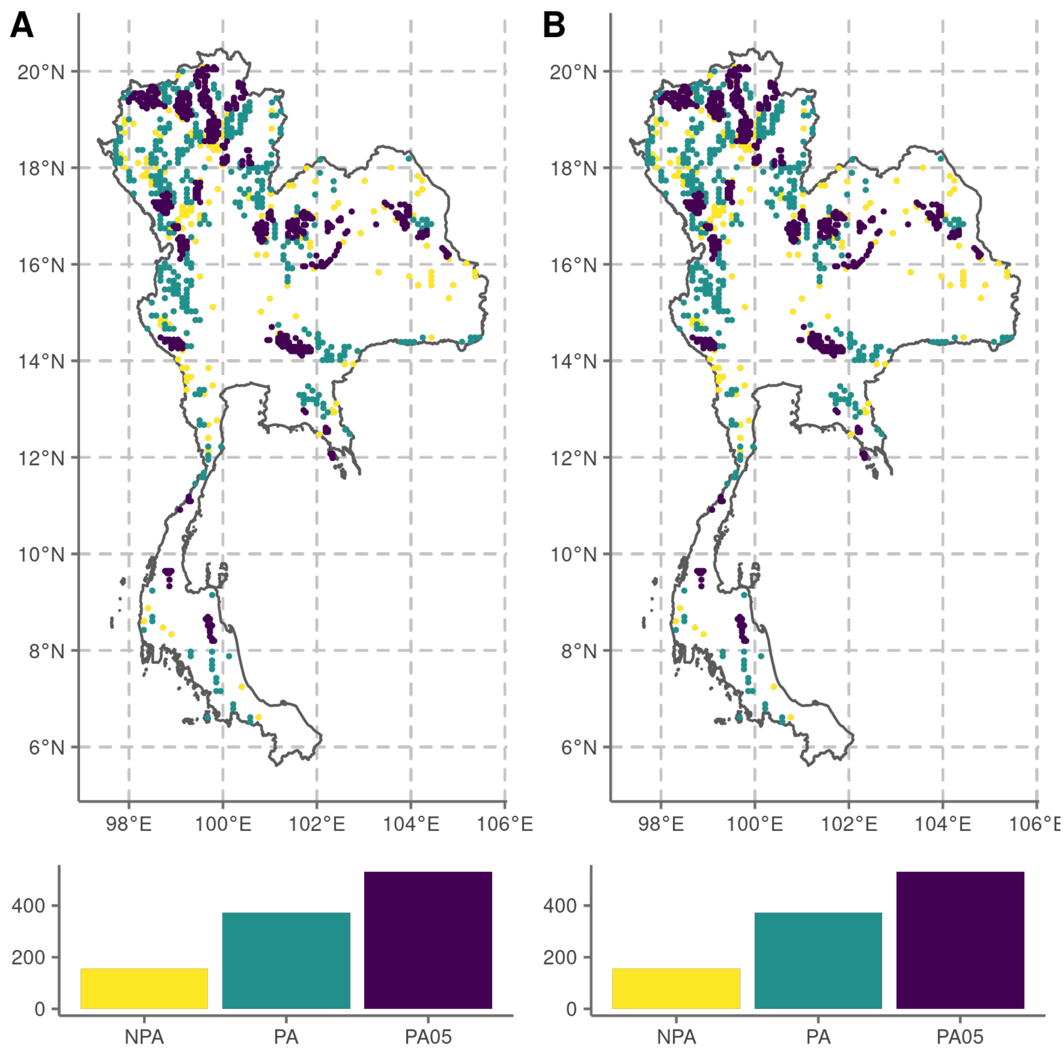


Figure 12: Nationwide distribution of the plots in Approach 2, cycle 1 (A) and cycle 3 (B), with the number of plots per strata

6.2 Aboveground biomass (Approach 2)

When looking at the aboveground biomass per strata, the same conclusions as with Approach 1 could be drawn: The non-protected areas had less biomass that the protected one and the two protected area strata had very similar numbers (Figure 13 and Table 19). With this approach the weighted average again did not translate in a large difference between simple average and weighted average. The weighted average was kept as it was more robust.

Table 19: Aboveground biomass per forest type for the different strata in t/ha (Approach 2).

NFI cycle	Forest type	Strata	N. plots	AGB (t/ha)	CI (perc.)	weight
Cycle 1	EV	NPA	26	113.034	25	0.234
Cycle 1	EV	PA	141	143.491	13	0.616
Cycle 1	EV	PA05	158	144.614	12	0.151
Cycle 1	DE	NPA	130	46.806	15	0.458
Cycle 1	DE	PA	232	62.376	10	0.411
Cycle 1	DE	PA05	373	68.522	8	0.131
Cycle 3	EV	NPA	33	112.694	23	0.234
Cycle 3	EV	PA	149	154.649	10	0.616
Cycle 3	EV	PA05	176	142.836	10	0.151
Cycle 3	DE	NPA	123	57.035	14	0.458
Cycle 3	DE	PA	224	75.193	7	0.411
Cycle 3	DE	PA05	355	74.633	7	0.131

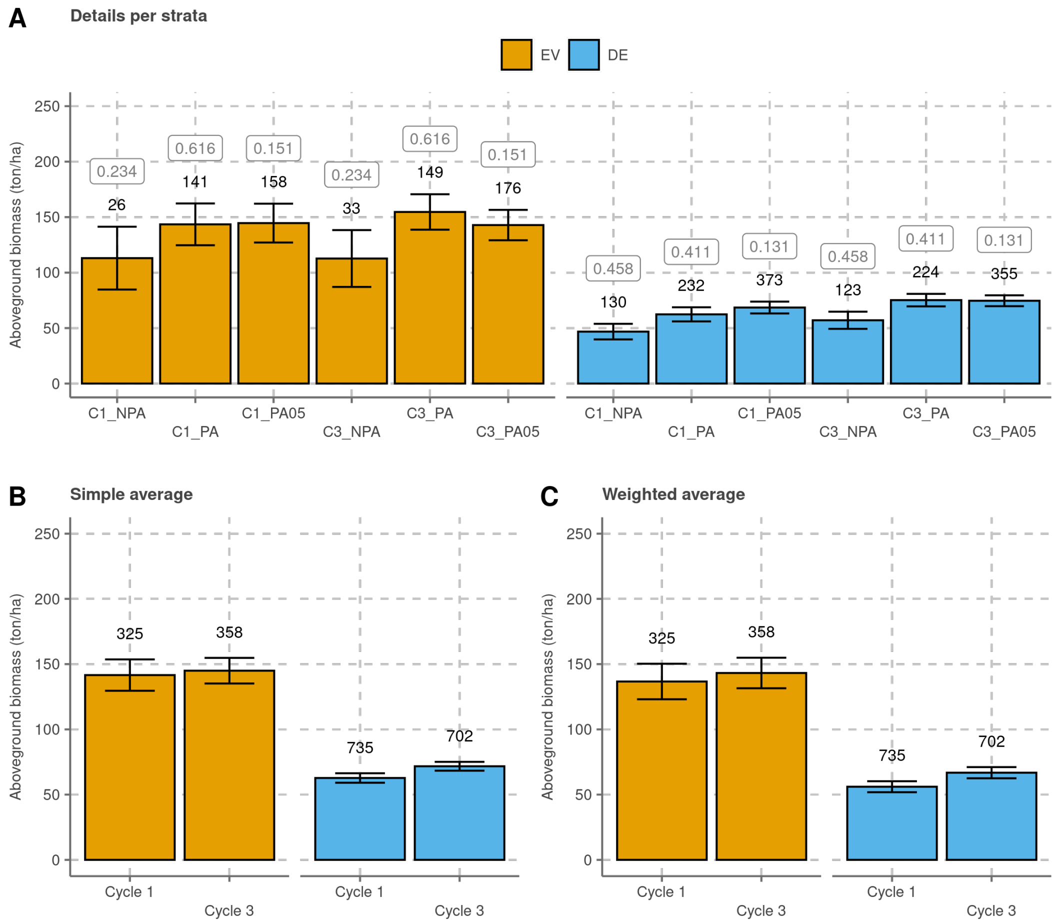


Figure 13: Aboveground biomass per forest type calculations for approach 2. Simple average per strata (A), simple average of all plots (B) and weighted average of the strata (C). The strata weights are represented in grey and number of plots in black.

6.3 Carbon stock (Approach 2)

The weighted average was calculated across strata to generate carbon stock estimates for Evergreen and Deciduous forests (Table 20). The confidence intervals for Evergreen and Deciduous forests were again very low, however the carbon stock differences between cycle 1 and 3 were also small, meaning the emission and removal factors, may end up with large confidence intervals. Surprisingly this approach had slightly worse confidence intervals compared to Approach 1, despite have a few more plots.

Table 20: Carbon stock per forest type in t/ha with their half confidence interval (Approach 2).

NFI cycle	Forest type	N. plots	AGB (t/ha)	StDev. AGB	CI (perc.)	BGB (t/ha)	Cstock (tC/ha)	Cstock in tCO_2/ha
Cycle 1	EV	325	136.677	125.211	10	50.570	88.006	322.689
Cycle 1	DE	735	56.050	58.182	8	11.210	31.612	115.911
Cycle 1	MG	37	120.779	68.614	18	59.182	84.582	310.134
Cycle 3	EV	358	143.202	112.980	8	52.985	92.208	338.096
Cycle 3	DE	702	66.803	57.879	6	13.361	37.677	138.149
Cycle 3	MG	37	120.779	68.614	18	59.182	84.582	310.134

6.4 Emission and Removal factors (Approach 2)

The emission and removal factor tables were prepared for AGB in t/ha, CO_2 in tCO_2/ha/yr and the confidence intervals in percent (Tables 21, 22 and 23). Approach 2 had slightly more removals in Evergreen forest and slightly less in Deciduous forest. It was the opposite for the confidence interval but to a very small extent. The complexity of this approach did not result in any significant difference with the Approach 1.

Table 21: Emission and removal factors in tAGB/ha for Approach 2.

		Cycle 3			
		EV	DE	MG	NF
Cycle 1	EV	-6.525	69.874	15.898	136.677
	DE	-87.152	-10.753	-64.729	56.050
	MG	-22.423	53.976	0.000	120.779
	NF	-143.202	-66.803	-120.779	0.000

Table 22: Emission and removal factors in tCO_2/ha/yr for Approach 2.

		Cycle 3			
		EV	DE	MG	NF
Cycle 1	EV	-1.926	23.068	1.569	40.336
	DE	-27.773	-2.780	-24.278	14.489
	MG	-3.495	21.498	0.000	38.767
	NF	-42.262	-17.269	-38.767	0.000

Table 23: Half confidence interval of the emission and removal factors in percent for Approach 2.

		Cycle 3			
		EV	DE	MG	NF
Cycle 1	EV	275	20	163	10
	DE	14	56	35	8
	MG	112	42	Inf	18
	NF	8	6	18	NaN

7 Emission and removal factors with Approach 3: all plots from all grids

7.1 Plot location (Approach 3)

This approach was based on all the plots. The objective was to use all the plots measured to take advantage of the large amount of data collected. To account for the different population sampled at different intensities, the forest land was split into 4 strata: Protected Areas were the 2.5 km grid was applied during cycle 3 (PA25), the other protected areas were the 5 km grid was aplied (PA05), the rest of the protected areas where only the 10 km grid was applied (PA) and Non-Protected Areas (NPA). With this approach there were clear discrepancies in the number of plots measured outside protected areas and the plots measured on the 2.5 km grid only partially covered the plots from the 5 km grid (Figure 14).

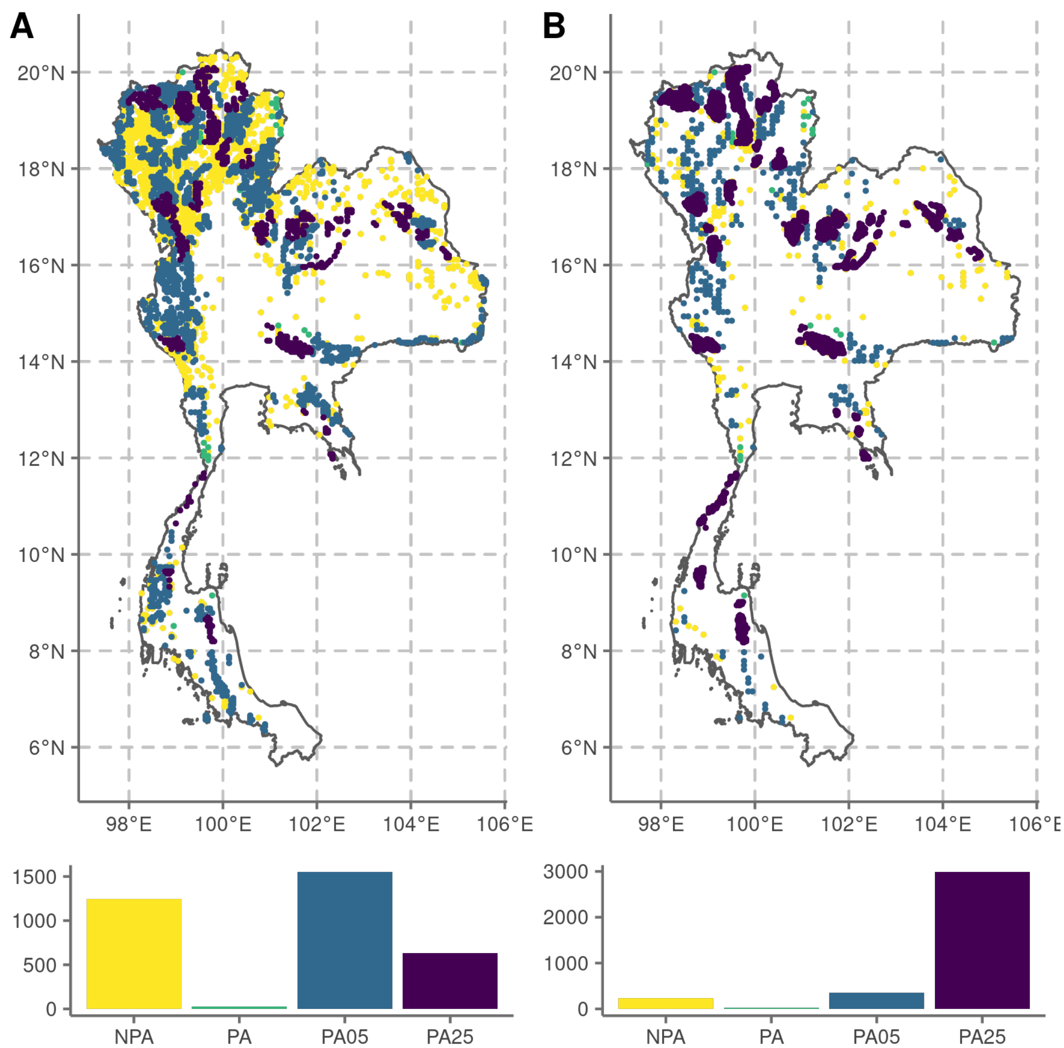


Figure 14: Nationwide distribution of the plots in Approach 3, cycle 1 (A) and cycle 3 (B), with the number of plots per strata

7.2 Aboveground biomass (Approach 3)

This approach also showed that the non-protected areas had less biomass that the protected ones, but by stratifying protected areas further, the number of plot left in the PA10 strata was small, resulting in unstable AGB values with large confidence intervals (Figure 15 and Table 24). Despite the large discrepancies between strata, the simple average biomass was only a little bit different than the weighted average. The weighted average was kept as it was more robust.

Table 24: Aboveground biomass per forest type for the different strata (Approach 3).

NFI cycle	Forest type	Strata	N. plots	AGB (t/ha)	CI (perc.)	weight
Cycle 1	EV	NPA	219	108.626	11	0.234
Cycle 1	EV	PA	17	108.884	34	0.055
Cycle 1	EV	PA05	577	149.492	6	0.551
Cycle 1	EV	PA25	179	142.807	11	0.160
Cycle 1	DE	NPA	1029	47.484	5	0.458
Cycle 1	DE	PA	10	31.639	46	0.035
Cycle 1	DE	PA05	974	68.412	5	0.372
Cycle 1	DE	PA25	456	65.131	7	0.135
Cycle 3	EV	NPA	58	97.663	19	0.234
Cycle 3	EV	PA	13	142.751	39	0.055
Cycle 3	EV	PA05	135	155.170	11	0.551
Cycle 3	EV	PA25	1183	143.730	4	0.160
Cycle 3	DE	NPA	172	53.553	11	0.458
Cycle 3	DE	PA	8	61.975	37	0.035
Cycle 3	DE	PA05	216	75.734	8	0.372
Cycle 3	DE	PA25	1804	74.672	3	0.135

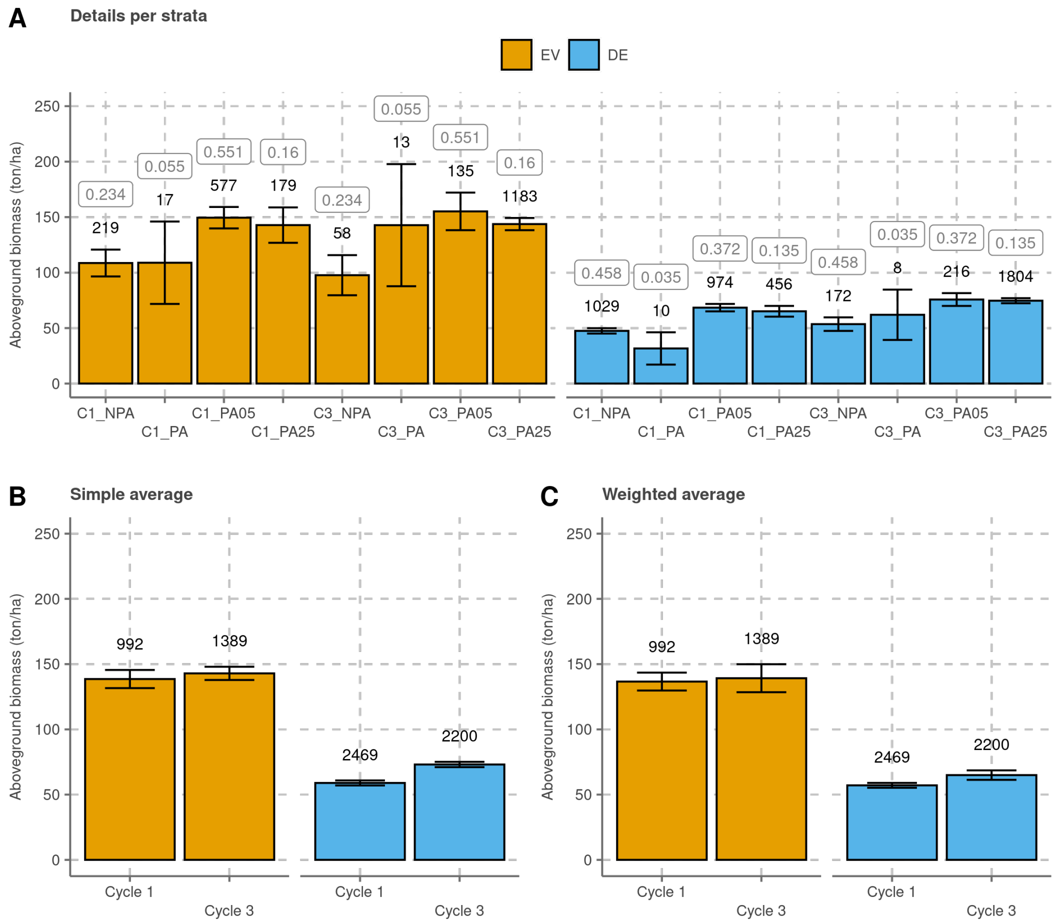


Figure 15: Aboveground biomass per forest type calculations for approach 3. Simple average per strata (A), simple average of all plots (B) and weighted average of the strata (C). The strata weights are represented in grey and number of plots in black.

7.3 Carbon stock (Approach 3)

The weighted average was calculated across strata to generate carbon stock estimates for Evergreen and Deciduous forests (Table 25). The confidence intervals for Evergreen and Deciduous forests were the lowest of all three approaches, but so were the differences in carbon stock between cycle 1 and 3. Overall the carbon stock were very similar for the three approaches and the simplest approach, approach 1, would be the best option.

Table 25: Carbon stock per forest type in t/ha with their half confidence interval (Approach 3).

NFI cycle	Forest type	N. plots	AGB (t/ha)	StDev. AGB	CI (perc.)	BGB (t/ha)	Cstock (tC/ha)	Cstock in tCO_2/ha
Cycle 1	EV	992	136.626	110.245	5	50.552	87.974	322.571
Cycle 1	DE	2469	57.097	47.347	3	11.419	32.203	118.078
Cycle 1	MG	37	120.779	68.614	18	59.182	84.582	310.134
Cycle 3	EV	1389	139.200	203.881	8	51.504	89.631	328.647
Cycle 3	DE	2200	64.950	86.855	6	12.990	36.632	134.317
Cycle 3	MG	37	120.779	68.614	18	59.182	84.582	310.134

7.4 Emission and Removal factors (Approach 3)

The emission and removal factor tables were prepared for AGB in t/ha, CO_2 in tCO_2/ha/yr and the confidence intervals in percent (Tables 26, 27 and 28). The Approach 3 had the lowest removal factor for evergreen forest, and it had the highest confidence interval (in percent), and a comparable removal factor for stable deciduous forest and its confidence interval.

Table 26: Emission and removal factors in tAGB/ha for Approach 3.

		Cycle 3			
		EV	DE	MG	NF
Cycle 1	EV	-2.574	71.676	15.847	136.626
	DE	-82.103	-7.853	-63.682	57.097
	MG	-18.421	55.829	0.000	120.779
	NF	-139.200	-64.950	-120.779	0.000

Table 27: Emission and removal factors in tCO_2/ha/yr for Approach 3.

		Cycle 3			
		EV	DE	MG	NF
Cycle 1	EV	-0.759	23.532	1.555	40.321
	DE	-26.321	-2.030	-24.007	14.760
	MG	-2.314	21.977	0.000	38.767
	NF	-41.081	-16.790	-38.767	0.000

Table 28: Half confidence interval of the emission and removal factors in percent for Approach 3.

		Cycle 3			
		EV	DE	MG	NF
Cycle 1	EV	495	11	146	5
	DE	13	52	35	3
	MG	133	40	Inf	18
	NF	8	6	18	NaN

Conclusion and recommendations

Given that the three approaches tested had very similar results, the simplest approach, Approach 1, was recommended. The differences between the number of plots measured were accounted for with the stratification and the weighted averages, and at the same time adding complexity by stratifying protected areas further was avoided.

Thailand has collected a very large number of tree and plot data over the past 15 years. The first national forest inventory was designed to collect information on a wide range of forest conditions with full country coverage. The other inventories repeated measurements only in a portion of the first inventory's plots. The last inventory completed the portion of the former NFI plots with a large number of plots collected in a 2.5 km grid to give very good details in several protected areas. The differences between NFI sampling designs led to recommending using only a small part of all measured plots, the plot measured on the 10 km grid, to ensure that the emission factors reflected all forest lands in Thailand, and were related to on-the-ground changes and not artificially created by the differences in plot location or sample populations.

The Carbon stock increased between the NFI cycle and 3 leading to Thailand's stable forests being a sink of greenhouse gas over the reference period. The trend was clear in Deciduous forest, but less so in Evergreen forest, resulting in high uncertainties around the emission and removal factors. It could be noted as a potential future improvement to monitor separately forest inside and outside protected areas in the activity data and increase the number of plots measured outside protected areas, especially in evergreen forest, to better understand if the dynamics are different. A key recommendation would be to ensure that all forest plots from the NFI cycle 1 are measured across the complete national 10 km grid in every new cycle to ensure nationally consistent coverage. Finally, mangrove forests are a key ecosystem in Thailand but were not well covered by the NFI and only few other studies targeted this forest type. This could also be noted as an area for future improvement.

A Annex: Summary of the study to validate Aboveground biomass allometric equations

A.1 Background

As a part of Thailand engagement on REDD+, the country revised its national forest inventories to improve its forest carbon stock estimates. One key aspect of estimating forest carbon stock was the choice of allometric equations to calculate tree aboveground biomass from easy-to-measure tree characteristics such as tree diameter, height or wood density, which was estimated from tree species.

Tree aboveground biomass allometric equations were developed in Thailand in the sixties (Ogawa et al., 1965) and eighties (Tsutsumi et al., 1983). As the most common method to measure tree biomass involved felling the trees to measure their weight (Picard et al., 2012) and a nationwide logging ban on natural forest in 1989, no further scientific studies aimed at developing allometric equations for natural forests. Recent studies focused on timber plantations (Ounban et al., 2016; Warner et al., 2016) or used either the above equations (Terakunpisut, 2007; Chaiyo et al., 2012) or pan-tropical allometric equations (Jha et al., 2020).

In case the whole aboveground trees could not be fell or measured, terrestrial Lidar seemed promising (Momo Takoudjou et al., 2018), but if the technology was not available, semi-destructive measurements were also used to overcome technical, legal or cultural barriers preventing from felling the trees or weighing all the compartments (Picard et al., 2012).

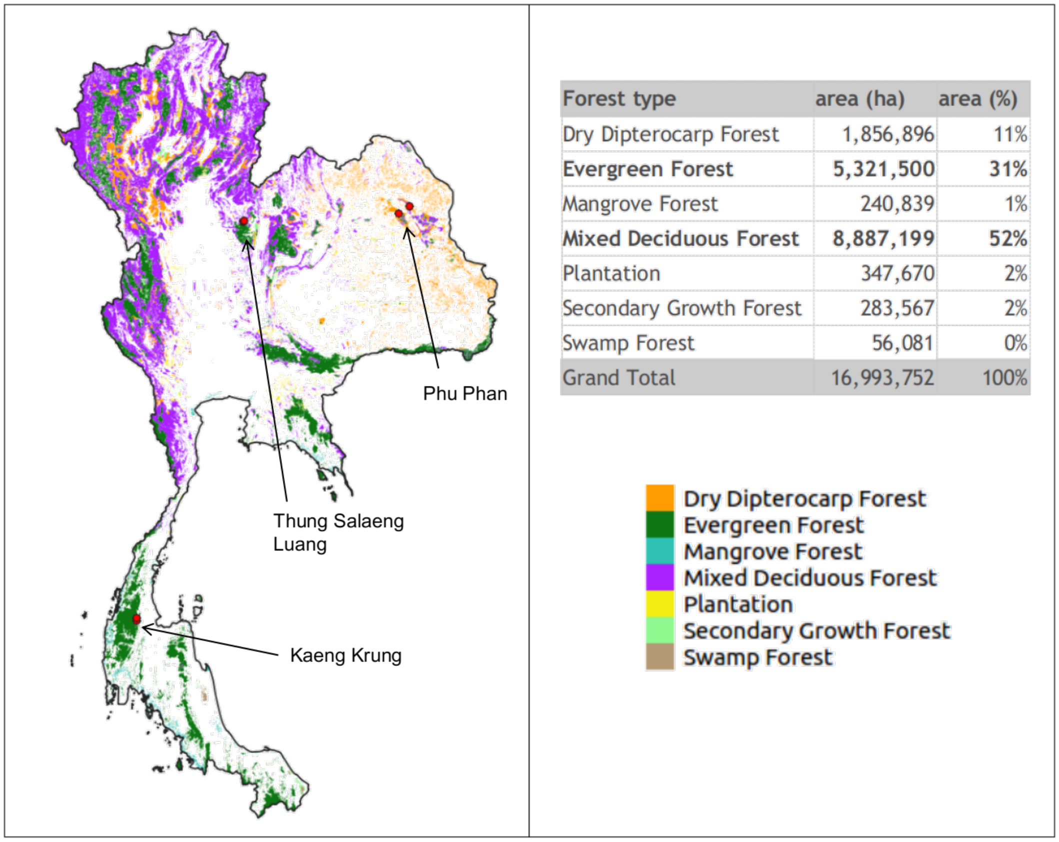
These methods could be used to develop new equations or, if the number of trees measured was too small, to validate existing equations. In Thailand, since the most used equations were very old and their quality was difficult to assess due to the lack of information reported, validating these equations and comparing them to the latest pan-tropical model (Chave et al., 2014) was critical to ensure the quality of the forest carbon stocks at national level.

A.2 Method

The method for selecting the trees, measuring them in the field and laboratory and calculating the their aboveground biomass was taken from Picard et al. (2012), in particular the section on semi-destructive measurements.

A.2.1 Site selection

The study focused on the two main forest types in Thailand, Mixed deciduous and Evergreen forest, covering 83 % of the country's forests combined (Figure 16). The study targeted 20 trees per site in three sites, selected using the country's NFI data. One site was located in the Tropical evergreen forest in Southern Thailand and two sites in Mixed Deciduous Forest, one in Central Thailand and one in Eastern Thailand. NFI plots were selected when they had tree recorded with diameter bigger than one meter and located in national parks, where the Department of National Parks, Wildlife and Plant Conservation could provide logistical support. Accessibility was also a key factor and the three locations were finally selected to cover a wide range of forest conditions, with pure tropical evergreen forest in Kaeng Krung (KK), proximity to Evergreen forest in Thung Salaeng Luang (TSL) and proximity to Dry Dipterocarp forest in Phu Phan (PP).



Forest type	area (ha)	area (%)
Dry Dipterocarp Forest	1,856,896	11%
Evergreen Forest	**5,321,500**	**31%**
Mangrove Forest	240,839	1%
Mixed Deciduous Forest	**8,887,199**	**52%**
Plantation	347,670	2%
Secondary Growth Forest	283,567	2%
Swamp Forest	56,081	0%
Grand Total	16,993,752	100%

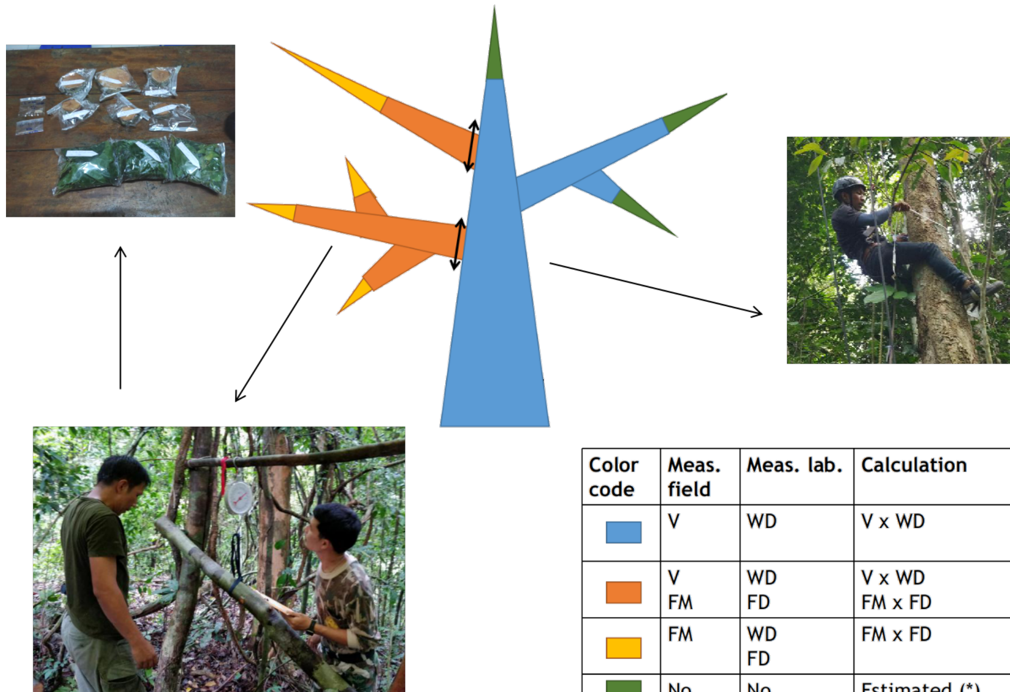
Figure 16: Site location and area of the main forest types in Thailand.

A.2.2 Tree selection

The tree selection followed a uniform distribution of two trees per diameter class on each site, with a slight emphasis on big trees (classes 60-70, 70-80, 80-90 and 90+ cm diameter) for which one additional tree was selected per class. This selection aimed at capturing as much as possible the increased biomass variability for big trees. The key element for selecting trees to be fell on site was their diameter. If enough trees could be found for each diameter class, the trees were selected first from the main species and then other species to maintain a good diversity. The team followed the expert judgement of the park staff for finding accessible sites with big trees and of the climbing team leader to ensure the trees selected were safe to climb on and measure.

A.2.3 Tree measurement in the field

As tree felling was not allowed due to the logging ban, only two to three main branches were cut and weighted (fresh weight W in kg) for each tree. The stem and the other branches had only their volume (V in m^3) measured in the field. Due to the limited resources available for the study, the all standing parts could not be measured, especially for the big trees, so the team stopped the measurement when tree parts reached one fifth of the tree diameter at breast height. The weight of each part that had a diameter smaller DBH/5 was estimated as the average of the same part from the fell branches. For example, in the Figure 17, the fresh mass of each green tree part was estimated as the average of the four yellow tree parts, including branches and leaves. A team of professional tree climbers performed the diameter measurements, assessed if the preselected branches were healthy and fell the selected branches.



Color code	Meas. field	Meas. lab.	Calculation
(blue)	V	WD	V x WD
(orange)	V FM	WD FD	V x WD FM x FD
(yellow)	FM	WD FD	FM x FD
(green)	No	No	Estimated (*)
(*) Average dry mass of felled small branches and leaves			

Figure 17: Volume and biomass measurements on the selected tree

Regarding the volume measurements, the stem had its girth measured every meter from 1 meter up to the point where the stem diameter was equal to DBH/5. The branches were measured from their insertion point to the stem or their branch of origin to the next branch insertion point or to the point where their diameter was equal to DBH/5. The volume of each segment, stem or branch, was then calculated with the truncated cone volume formula (Equation (1)).

(1)

$$V_f = L \times \frac{\pi}{3} \times (r_1^2 + r_1 \times r_2 + r_2^2)$$

with V_f the fresh volume in m^3,r_1 and r_2 the radius of the two extremity of the log and L its length, all in meter. Each radius was calculated from its girth g with the Equation (2):

(2)

$$g = \frac{r}{\pi \times 2 \times 100}$$

with g in cm and r in meter.

The main branches 2, 4 and 6 of each tree, counted from the ground, were fell. If the branches was partly or completely dead or broken, the next branch was selected. After felling, the branches were separated between, big branches if their diameter was bigger than DBH/5, their leaves (shortcut name big leaf), small branches if their diameter was less than DBH/5 and their leaves (shortcut name small leaf). All these four compartments were cut in pieces not exceeding a few kg and weighted with a hanging scale. The compartment fresh biomass was calculated as the sum of its parts' weight (Equation (3)).

(3)

$$W_{f,c} = \sum_i w_{f,c_i}$$

with $W_{f,c}$ the fresh mass of a compartment c and w_{f,c_i} the weight of one of its part i, all in kg.

A.2.4 Laboratory measurements

Aliquots were taken from each of the four compartments to measure the trees' wood density (Equation (4)) and fresh-to-dry ratio (Equation (5)).

(4)

$$WD_i = \frac{w_{d,i}}{V_{f,i}}$$

with WD_i the wood density of the aliquot i in g/cm^3, $w_{d,i}$ its dry weight in g and $V_{f,i}$ its fresh volume in cm^3.

(5)

$$FD_i = B_i/W_i$$

with FD_i the fresh-to-dry ratio, unitless, B_i and W_i the dry and fresh mass respectively, in g.

The biomass, i.e dry mass, B of the standing tree parts was calculated as sum of the volume measurements multiplied by the average wood density of the big branches for stem and big branches, and small branches otherwise (Equation (6)).

(6)

$$B = 1000 \times (\sum_i V_{f,st,i} \times WD_{bb} + \sum_j V_{f,bb,j} \times WD_{bb} + \sum_k V_{f,sb,j} \times WD_{sb})$$

with B the biomass in kg, $V_{f,st,i}$, $V_{f,bb,j}$ and $V_{f,sb,k}$ the fresh volume of the stem segment i, big branch segment i and small branch k in m^3, WD_* the wood density of the compartment $*$ in g/cm^3.

The biomass of the fell branches was calculated as the sum of fresh masses multiplied by the average fresh-to-dry ratio of their compartment (Equation (7)).

(7)

$$B = \sum_i W_{bb,i} \times FD_{bb} + \sum_j W_{sb,j} \times FD_{sb} + \sum_k W_{lf,k} \times FD_{lf}$$

with $W_{bb,i}$, $W_{sb,j}$ and $W_{lf,k}$ the fresh mass of the big branch i the small branch j and the leaf k respectively, in kg, and FD_* the fresh-to-dry ratio of the compartment $*$.

A.3 Results and discussion

The trees measured had their diameter ranging from 5.1 to 124 and their height from 6.8 to 45 (Table 29). They belonged to 35 species with a dominance of *Parashorea stellata*, *Xylia xylocarpa*, *Pterocarus macrocarpus* and *Lagerstroemia duperreana* in the big trees (Figure 18 A). All the trees had their aboveground biomass coming mostly from their stem, and the contribution of big and small branches varied greatly between trees. *Parashorea stellata* had a large contribution of small branches over big ones to their overall biomass, whereas other species such as *Xylia xylocarpa* had the opposite.

Table 29: Measured tree characteristics.

ID	Park	Species	DBH	H	WD
1	KK	Sterculia scaphigera	35.00	20.0	0.89
2	KK	Aglaia elliptica	12.70	15.0	0.53
3	KK	Parashorea stellata	90.00	40.0	0.73
4	KK	Xerospermum noronhianum	12.60	16.7	0.83
5	KK	Pterospermum lanceifolium	32.20	27.0	0.57
6	KK	Adinandra integerrina	65.41	32.0	0.67
7	KK	Nephelium meliiferum	42.00	32.0	0.89
8	KK	Xerospermum noronhianum	28.40	17.0	0.91
9	KK	Alseodaphne obovata	45.90	27.0	0.60
10	KK	Parashorea stellata	107.00	42.0	0.63
11	KK	Parashorea stellata	60.20	38.0	0.60
12	KK	Parashorea stellata	67.40	43.0	0.61
13	KK	Heritiera javanica	37.20	33.0	0.58
14	KK	Aglaia aspers	45.00	27.0	0.77
15	KK	Brownlowia helferiana	47.70	26.0	0.46
16	KK	Parashorea stellata	124.00	45.0	0.65
17	KK	Aglaia erythrosperma	66.30	34.0	0.76
18	KK	Alphonsea elliptica	50.30	33.0	0.67
19	KK	Parashorea stellata	71.60	40.0	0.65
20	KK	Brownlowia helferiana	57.90	27.0	0.48
21	PP	Pterocarpus macrocarpus	70.00	28.0	0.69
22	PP	Erythrina subumbrans	57.00	24.0	0.36
23	PP	Lagerstroemia duperreana	72.00	26.0	0.66
24	PP	Millettia leucantha var. buteoides	76.00	28.0	0.73
25	PP	Sindora siamensis var. siamensis	44.00	23.0	0.68
26	PP	Terminalia nigrovenulosa	57.00	29.0	0.76
27	PP	Lagerstroemia duperreana	93.00	23.0	0.58
28	PP	Cratoxylum formosum subsp. pruniflorum	30.00	24.0	0.65
29	PP	Rothmannia wittii	16.00	15.0	0.69
30	PP	Symplocos macrophylla	34.00	15.0	0.61
31	PP	Hymenodictyon orixense	12.00	15.0	0.48
32	PP	Cratoxylum formosum subsp. pruniflorum	63.00	28.0	0.59

Table 29: Measured tree characteristics. *(continued)*

ID	Park	Species	DBH	H	WD
33	PP	Dialium cochinchinense	44.00	21.0	0.85
34	PP	Canarium subulatum	60.40	24.0	0.53
35	PP	Adina dissimilis	26.00	22.0	0.64
36	PP	Dialium cochinchinense	33.00	26.0	0.85
37	PP	Xylia xylocarpa	66.00	34.0	0.90
38	PP	Xylia xylocarpa	89.00	29.0	0.92
39	PP	Adina dissimilis	84.00	38.0	0.62
40	PP	Pterocarpus macrocarpus	77.00	38.0	0.61
41	TSL	Spondias pinnata	70.20	29.0	0.39
42	TSL	Mangifera pentandra	27.00	17.0	0.60
43	TSL	Pterocarpus macrocarpus	60.40	28.0	0.75
44	TSL	Lagerstroemia duperreana	76.40	29.0	0.66
45	TSL	Lagerstroemia duperreana	76.00	25.0	0.65
46	TSL	Terminalia belliraca	38.50	27.0	0.59
47	TSL	Xylia xylocarpa	79.50	29.0	0.90
48	TSL	Terminalia nigrovenulosa	52.00	29.0	0.69
49	TSL	Hymenodictyon orixense	16.00	12.0	0.45
50	TSL	Vitex pinnata	45.00	23.0	0.72
51	TSL	Pterocarpus macrocarpus	66.00	28.0	0.74
52	TSL	Pterocarpus macrocarpus	87.00	25.0	0.78
53	TSL	Microcos paniculate	5.10	6.8	0.46
54	TSL	Carallia brachata	61.00	23.0	0.63
55	TSL	Hopea odorata	105.00	36.0	0.82
56	TSL	Lagerstroemia duperreana	37.20	24.0	0.64
57	TSL	Dipterocarpus turbinatus	55.00	29.0	0.67
58	TSL	Terminalia nigrovenulosa	28.00	27.0	0.59
59	TSL	Mangifera pentandra	57.00	22.0	0.65
60	TSL	Xylia xylocarpa	41.00	28.0	0.84

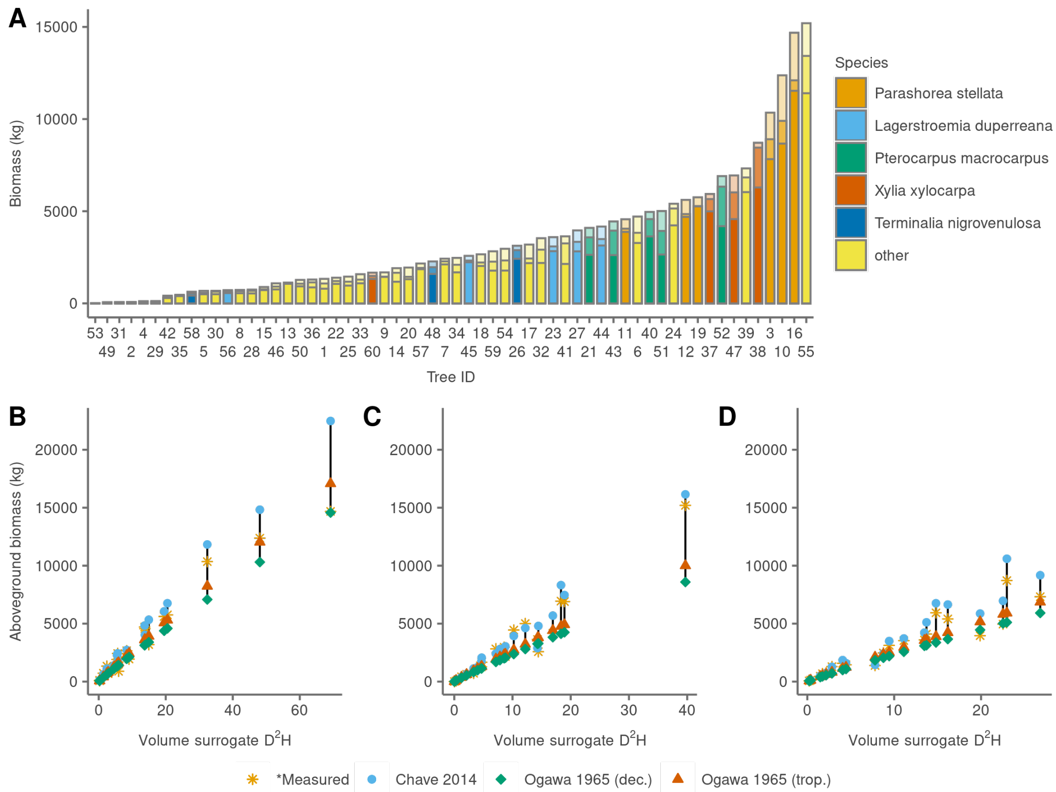


Figure 18: Measured tree compartments' biomass (stem, big branches, small branches plus leaves) (A), Measured and estimated tree aboveground biomass in Kaeng Krung (B), Thung Salaeng Luang (C) and Phu Phan (D) national parks.

Chave equation systematically overestimated tree biomass, while the Thai equations underestimated it most of the time (Figure 18 B, C, D). This was very obvious in KK and PP national parks whereas in the TSL Chave equation was closer to the measurements than the others. The equation from Ogawa for Deciduous forest, largely underestimated tree biomass even in Mixed Deciduous forests.

This was reflected in the bias calculations (Table 30), where Ogawa (dec.) and Chave had the worst overall bias. The overall bias of Chave equation was still close to the best equations, but mainly due to the one very big tree in TSL park, for which the estimated biomass was very close to the measurement. The Evergreen forest equations from Ogawa (trop.) and Tsutsumi had the lowest bias overall. They performed very well in tropical evergreen forest, the forest type these equations was design for, but surprisingly also performed better than Ogawa (dec.) in Mixed Deciduous forest.

After consultation with DNP experts, the team interpreted these results as a consequence of putting an emphasis on big trees, which led to selecting sites in conditions very close to Evergreen forest, even if the forest type of the larger area was Mixed Deciduous. There was not a clear winner of this study. The Thai equations seemed to reflect well the increased biomass from Deciduous (Ogawa dec.) to Dry and Hill Evergreen (Tsutsumi) and to Tropical Evergreen (Ogawa trop.) forests. These equations could still greatly underestimate the biomass of dense woods, where the Chave equation would perform better as wood density was an input variable of the model. Following this study it was recommended to continue using the Thai equation as they were very popular in Thailand and did not perform worse than more recent pan-tropical models.

Table 30: Bias of the Chave and Thailand based allometric equations in percent.

National park	Chave 2014	Ogawa 1965 trop.	Ogawa 1965 dec.	Tsutsumi 1982
KK	21.5	-4.8	-17.9	-5.3
TSL	7.2	-22.7	-33.0	-22.1
PP	17.8	-13.2	-24.7	-12.4
Total	15.5	-13.6	-25.2	-13.3

A.4 Conclusion

Forest carbon stock is commonly estimated with forest inventory measurements and allometric equations to convert easy-to-measure tree characteristics to tree, plot level and forest level biomass. The choice of allometric equations has a very large impact on the robustness of the carbon stock estimates as equations that are used outside the tree diameter range or biomes can lead to highly biased carbon stock estimates.

Since felling trees, even for research purpose, was banned by law in Thailand, the natural forest carbon stocks were based on a series of allometric equations developed in the sixties and eighties. Very little information was available on these equations and they were quite old, meaning using them could lead to significant bias.

Sixty trees had their aboveground biomass measured with a combination of semi-destructive measurements and laboratory analysis of the stem and branches fresh-to-dry mass ratio and wood density. As a result, the equations from Ogawa (1965) and Tsutsumi (1983) had a bias from5 to 33 % depending on the forest condition. The equation developed for Deciduous forest did not perform well but the site selected were essentially Evergreen forest. In these conditions, the Thai equations seemed to reflect well the forest conditions in Thailand and did not perform worse than more recent pan-tropical equations. Given that they were very popular in Thailand and that their did relatively well in the validation process, these equations were recommended to calculate the forest carbon stocks in Thailand.

B List of protected areas placed in the different strata

The list of protected areas was:

- Approach 1, strata 1: Buntharik - Yot Mon, Chae Son, Chaloem Rattanakosin, Chaloemphrakiat Thai Prachan, Chiang Dao, Doi Inthanon, Doi Khun Tan, Doi Luang, Doi Pha Chang, Doi Pha hom pok, Doi Pha Klong, Doi Pha Maung, DOI PHRA BATH, DOI PHU KA, Doi Phu Nang, Doi Su Thep - Pui, Doi Wiang La, Doi Wiang Pha, Dong Yai, Erawan, Had Noppharat Thara-Mhukho PP, Hat Khanom - Muko Thale Tai, Haui Nam Dang, Huai Khakhakeng, Huai Sala, Huai Thap Than - Huai Samran, Kaeng Chet Khwae, Kaeng Krachan, Kaeng Krung, Kaeng Tana, kangkoy, Khao Ang Runai, Khao Banthat, Khao Chamao - Khao Wong, Khao Khiao - Khao Chomphu, Khao Khit chakut, Khao Kho, Khao Laem, Khao Lak - Lam Ru, Khao Lampi - Hat Thai Mueang, Khao Luang, Khao Nam Khang, Khao Nan, Khao Noi - Khao Pradu, Khao Phanom Bencha, Khao Phra Wihan, Khao Phu Luang, Khao Pra Chon Daen, Khao Pu - Khao Ya, Khao Sam Roi Yot, Khao Sanam Phriang, Khao Sip Ha Chan, Khao Sok, Khao Yai, Khao Yai - Khao Napha Tang - Khao Ta Phrom, Khao-Pra Bang-Kram, Khlong Khruo Wai Chalerm Prakiet, Khlong Lan, Khlong Nakha, Khlong Phanom, Khlong Phraya, Khlong Saeng, Khlong Tron, Khlong Wang Chao, Khlong Yan, Khoao Soi Daow, khosok, Khuean Sinakharin, Khun Chae, Khun Khan, Khun Nan, Khun Pga Wo, Khun Sathan, Kra Thun, kuanmayaimon, KUIBURI, Lam Klong Ngu, Lam Nam Kok, Lam Nam Nan, Lam Nam Nan Fang Khwa, Lan Sang, Lum nan pai, Mae Charim, Mae Lao - Mae Sae, Mae Moei, Mae Nam Phachi, Mae Ngao, Mae Ping, Mae Puem, Mae Takhrai, Mae Tho, Mae Tuen, Mae Wa, Mae Wang, Mae Wang (Doi Chong), MAE WONG, Mae Yom, Mae Yuam Fang Khwa, Maeyom, Mai Klaipen Hin, Mu Ko Chang, Muko Li Bong, Muko Ranong, Na Yung - Nam Som, Nam Nao, Nam Pat, Nam Phong, Nam Tok Chet Sao Noi, Namtok Chat Trakan, Namtok Huai Yang, Namtok Mae Surin, Namtok NgaoNamtok Ngao, Namtok Pha Charoen, Namtok Phlio, Namtok Sam Lan, Namtok Si Khit, Namtok Yong, Namtokklongkeaw, Nantha Buri, Nong Thung Thong, Omkoi, Op Khan, Op Luang, Pa Hin Ngam, Pang Sida, Pha Phueng, Pha Taem, PhaDeang, Phanom Dong Rak Phanom Dong Rak, Phu Chong Na Yoi, Phu Hin Rong Kla, Phu Kao - Phu Phan Kham, Phu Khat, Phu Khiao, Phu Kho - Phu Kratae, Phu Kradueng, Phu Laen Kha, PHU LANG KA, Phu Luang, Phu Miang - Phu Thong, Phu Pa Ya, Phu Pha Lek, Phu Phan Yon, Phu Ruea, Phu Sa Dok Bua, Phu Sang, Phu Si Than, Phu Soi Daow, Phu Suan Sai, Phu Toei, Phu Wiang, Phu Wua, Phupha Daeng, Phuphaman, Phuphan, Prince Chumphon (North), Prince Chumphon (South), Ramkhamhaeng, Sai Yok, Saithong, Salak Phra, Salawin, Samoeng, San Ka La Khiri, San Pan Daen, Si Lan Na, Si Nan, Si Phang - nga, Si Satchanalai, Sub Lung Ka, Ta Phraya, Taboh - Huai Yai, Tai Rom Yen, Taksin Maharat, Tarutao, Tat Mok, Tat Ton, Thale Ban, Thale Noi, Thale Sap, Tham Chao Ram, Tham Lawa - Tham Daowadueng, Tham Pha Nam Thip, Tham Pha Thai, Tham Pla - Namtok Pha Suea, Tham Pra Thun, Tham Sa Koen, Thap Lan, Thong Pha Phoom, Thung Raya - Na Sak, Thung Salaeng Luang, Thung Yai Naresuan, Ton Nga Chang, Ton Pariwat, Um Phang, Unnamed park 25, Unnamed park 26, Unnamed park 27, Unnamed park 28, Unnamed park 29, Unnamed park 30, Unnamed park 34, Unnamed park 35, Uthayan Somdet Phra Sinakharin, Weang Lor, Wiang Kosai, Yot Dom

- Approach 2, strata 1: Doi Luang, Doi Pha Klong, Erawan, Haui Nam Dang, Kaeng Krung, kangkoy, Khao Chamao - Khao Wong, Khao Luang, Khao Yai, Khlong Wang Chao, Khun Sathan, Lam Nam Kok, Lan Sang, Lum nan pai, Mae Tuen, Mu Ko Chang, Nam Nao, Nam Phong, Namtok Phlio, Namtok Sam Lan, Namtok Yong, Phu Hin Rong Kla, Phu Kao - Phu Phan Kham, Phu Kho - Phu Kratae, Phu Kradueng, Phu Laen Kha, Phu Pha Lek, Phu Sa Dok Bua, Phu Sang, Phu Si Than, Phu Wiang, Phupha Daeng, Phuphan, Prince Chumphon (North), Sai Yok, Si Lan Na, Si Satchanalai, Tat Ton, Tham Chao Ram, Tham Pha Thai, Thung Salaeng Luang, Unnamed park 28, Weang Lor
- Approach 2, strata 2: Angkepnam Bang Phra, Angkepnam Huai Chon Khe Mak, Angkepnam Huai Talat, Angkepnam Sanambin, Ao Manao - Khao Tanyong, Ao Phangnga, Ao Siam, Bang Lang, Bo Lo, Budo - Su - Ngai - Padi, Bueng Borapet, Bueng Chawak, Bueng Ke Ring Ka Wia - Nong Namsap, Bueng Khong Long, Buntharik - Yot Mon, Cha-am, Chae Son, Chaloem Phra Kiet Somdej Phrathep Rattana Rachasuda, Chaloem Rattanakosin, Chaloemphrakiat Thai Prachan, Chiang Dao, Doi Inthanon, Doi Khun Tan, Doi Pha Chang, Doi Pha hom pok, Doi Pha Maung, DOI PHRA BATH, DOI PHU KA, Doi Phu Nang, Doi Su Thep, Doi Su Thep - Pui, Doi Wiang La, Doi Wiang Pha, Dong Yai, Du Nalam Phan, Ha La - Ba La, Had Noppharat Thara-Mhukho PP, Hat Chao Mai, Hat Khanom - Muko Thale Tai, Hat Wanakon, Huai Khakhakeng, Huai Sala, Huai Thap Than - Huai Samran, Kaeng Chet Khwae, Kaeng Krachan, Kaeng Tana, Khao Ang Runai, Khao Banthat, Khao Chi On, Khao Erawan, Khao Khiao - Khao Chomphu, Khao Khit chakut, Khao Kho, Khao Kradong, Khao Krapuk - Khao Tao Mo, Khao Laem, Khao Laem Ya - Mu Ko Samet, Khao Lak - Lam Ru, Khao Lampi - Hat Thai Mueang, Khao Nam Khang, Khao Nam Phrai, Khao Nan, Khao Noi - Khao Pradu, Khao Pa Chang - Laem Khan, Khao Phaeng Ma, Khao Phanom Bencha, Khao Phra Thaeo, Khao Phra Wihan, Khao Phu Luang, Khao Pra Chon Daen, Khao Prathap Chang, Khao Pu - Khao Ya, Khao Reng, Khao Sam Roi Yot, Khao Sanam Phriang, Khao Sip Ha Chan, Khao Sok, Khao Som Phot, Khao Tha Phet, Khao Yai - Khao Napha Tang - Khao Ta Phrom, Khao-Pra Bang-Kram, Khlong Khruo Wai Chalerm Prakiet, Khlong Lam Chan, Khlong Lan, Khlong Nakha, Khlong Phanom, Khlong Phraya, Khlong Saeng, Khlong Tron, Khlong Yan, Khoao Soi Daow, khosok, Khuean Pa Sak Chon Sit, Khuean Sinakharin, Khun Chae, Khun Khan, Khun Nan, Khun Pga Wo, Khung Kraben, Kra Thun, kuanmayaimon, KUIBURI, Laem Son, Laem Talumphuk, Lam Klong Ngu, Lam Nam Kra Buri, Lam Nam Nan, Lam Nam Nan Fang Khwa, Lam Nangrong, Lam Pao, Mae Charim, Mae Lao - Mae Sae, Mae Moei, Mae Nam Phachi, Mae Ngao, Mae Ping, Mae Puem, Mae Takhrai, Mae Tho, Mae Wa, Mae Wang, Mae Wang (Doi Chong), MAE WONG, Mae Yom, Mae Yuam Fang Khwa, Maeyom, Mai Klaipen Hin, Mu Ko Chumphon, Mu Ko Lanta, Mu Ko Similan, Mukdahan, Muko Ang Thong, Muko Li Bong, Muko Phetra, Muko Ranong, Muko Surin, Na Yung - Nam Som, Nam Pat, Nam Tok Chet Sao Noi, Namtok Chat Trakan, Namtok Huai Yang, Namtok Mae Surin, Namtok NgaoNamtok Ngao, Namtok Pha Charoen, Namtok Saikhao, Namtok Si Khit, Namtok Si Po, Namtokklongkeaw, Nantha Buri, Nong Han Kumphawapi, Nong Hua Khu, Nong Namkhao, Nong Plak Phraya - Khao Ra Ya Bang Sa, Nong Thung Thong, Nong Waeng, NONGBONGKAY, Omkoi, Op Khan, Op Luang, Pa Hin Ngam, Pa Krat, Pa Phru, Pa Rang Kai, Pang Sida, Pha Phueng, Pha Taem, PhaDeang, Phan Thai

Norasing, Phanom Dong Rak   Phanom Dong Rak, Phru Khangkhao, Phu Chong Na Yoi, Phu Khat, Phu Khiao, PHU LANG KA, Phu Luang, Phu Miang - Phu Thong, Phu Pa Ya, Phu Phan Yon, Phu Ruea, Phu Soi Daow, Phu Suan Sai, Phu Toei, Phu Wua, Phuphaman, Prince Chumphon (South), Ramkhamhaeng, Saithong, Salak Phra, Salawin, Samoeng, San Ka La Khiri, San Pan Daen, Si Nan, Si Phang - nga, Sirinat, Sub Lung Ka, Ta Phraya, Taboh - Huai Yai, Tai Rom Yen, Taksin Maharat, Tarutao, Tat Mok, Thale Ban, Thale Luang, Thale Noi, Thale Sap, Tham Khangkhao - Khao Chong Phran, Tham Lawa - Tham Daowadueng, Tham Pha Nam Thip, Tham Pha Tha Phon, Tham Pla - Namtok Pha Suea, Tham Pra Thun, Tham Sa Koen, Than Sadet - Kho Pha - ngan, Than Bok Khorani, Thap Lan, Thap Phayalo, Thong Pha Phoom, Thong Pha Phum, Thung Raya - Na Sak, Thung Thale, Thung Yai Naresuan, Ton Nga Chang, Ton Pariwat, Um Phang, Unnamed park 1, Unnamed park 10, Unnamed park 11, Unnamed park 12, Unnamed park 13, Unnamed park 14, Unnamed park 15, Unnamed park 16, Unnamed park 17, Unnamed park 18, Unnamed park 19, Unnamed park 2, Unnamed park 20, Unnamed park 21, Unnamed park 22, Unnamed park 23, Unnamed park 24, Unnamed park 25, Unnamed park 26, Unnamed park 27, Unnamed park 29, Unnamed park 3, Unnamed park 30, Unnamed park 31, Unnamed park 32, Unnamed park 33, Unnamed park 34, Unnamed park 35, Unnamed park 36, Unnamed park 37, Unnamed park 38, Unnamed park 39, Unnamed park 4, Unnamed park 40, Unnamed park 41, Unnamed park 5, Unnamed park 6, Unnamed park 7, Unnamed park 8, Unnamed park 9, Uthayan Somdet Phra Sinakharin, Wat Phai Lom - Wat Amphu Wara Ram, Wat Tan En, Wat Tham Rakhang - Khao Phra Non, Watrat Sattha Ka Ya Ram, Wiang Kosai, Yot Dom

- Approach 3, strata 1: Doi Luang, Doi Pha Klong, Erawan, Haui Nam Dang, Kaeng Krung, kangkoy, Khao Chamao - Khao Wong, Khao Khit chakut, Khao Luang, Khao Yai, Khlong Wang Chao, Khun Sathan, Lam Nam Kok, Lan Sang, Lum nan pai, Mae Tuen, Mai Klaipen Hin, Mu Ko Chang, Nam Nao, Nam Phong, Namtok Huai Yang, Namtok Phlio, Namtok Sam Lan, Namtok Si Khit, Namtok Yong, Phu Hin Rong Kla, Phu Kao - Phu Phan Kham, Phu Kho - Phu Kratae, Phu Kradueng, Phu Laen Kha, Phu Pha Lek, Phu Sa Dok Bua, Phu Sang, Phu Si Than, Phu Wiang, Phupha Daeng, Phuphan, Prince Chumphon (North), Prince Chumphon (South), Sai Yok, Si Lan Na, Si Satchanalai, Tat Ton, Tham Chao Ram, Tham Pha Thai, Thung Salaeng Luang, Unnamed park 28, Unnamed park 30, Unnamed park 34, Weang Lor

- Approach 3, strata 2: Buntharik - Yot Mon, Chae Son, Chaloem Rattanakosin, Chaloemphrakiat Thai Prachan, Chiang Dao, Doi Inthanon, Doi Khun Tan, Doi Pha Chang, Doi Pha Maung, Doi Phu Nang, Doi Su Thep - Pui, Doi Wiang La, Doi Wiang Pha, Dong Yai, Had Noppharat Thara-Mhukho PP, Huai Khakhakeng, Huai Sala, Huai Thap Than - Huai Samran, Kaeng Chet Khwae, Kaeng Krachan, Kaeng Tana, Khao Ang Runai, Khao Banthat, Khao Khiao - Khao Chomphu, Khao Kho, Khao Laem, Khao Lak - Lam Ru, Khao Lampi - Hat Thai Mueang, Khao Nam Khang, Khao Nan, Khao Noi - Khao Pradu, Khao Phanom Bencha, Khao Phra Wihan, Khao Pra Chon Daen, Khao Pu - Khao Ya, Khao Sam Roi Yot, Khao Sanam Phriang, Khao Sip Ha Chan, Khao Sok, Khao-Pra Bang-Kram, Khlong Khruo Wai Chalerm Prakiet, Khlong Lan, Khlong Nakha, Khlong Phanom, Khlong Saeng, Khlong Tron, Khlong Yan, Khoao Soi Daow, khosok, Khuean Sinakharin, Khun Chae, Khun Khan, Khun Nan, Khun Pga Wo, Kra Thun, kuanmayaimon, Lam Klong Ngu, Lam Nam Nan, Lam

Nam Nan Fang Khwa, Mae Charim, Mae Lao - Mae Sae, Mae Moei, Mae Nam Phachi, Mae Ngao, Mae Ping, Mae Puem, Mae Takhrai, Mae Tho, Mae Wa, Mae Wang, Mae Wang (Doi Chong), MAE WONG, Mae Yom, Mae Yuam Fang Khwa, Maeyom, Muko Li Bong, Muko Ranong, Na Yung - Nam Som, Nam Pat, Namtok Chat Trakan, Namtok Mae Surin, Namtok NgaoNamtok Ngao, Namtok Pha Charoen, Namtokklongkeaw, Nantha Buri, Nong Thung Thong, Omkoi, Op Khan, Op Luang, Pa Hin Ngam, Pang Sida, Pha Phueng, Pha Taem, PhaDeang, Phanom Dong Rak Phanom Dong Rak, Phu Chong Na Yoi, Phu Khat, Phu Khiao, PHU LANG KA, Phu Luang, Phu Miang - Phu Thong, Phu Pa Ya, Phu Phan Yon, Phu Ruea, Phu Soi Daow, Phu Suan Sai, Phu Toei, Phu Wua, Phuphaman, Ramkhamhaeng, Saithong, Salak Phra, Salawin, Samoeng, San Ka La Khiri, San Pan Daen, Si Nan, Si Phang - nga, Sub Lung Ka, Ta Phraya, Taboh - Huai Yai, Tai Rom Yen, Taksin Maharat, Tarutao, Tat Mok, Thale Ban, Thale Noi, Thale Sap, Tham Lawa - Tham Daowadueng, Tham Pha Nam Thip, Tham Pla - Namtok Pha Suea, Tham Pra Thun, Tham Sa Koen, Thap Lan, Thong Pha Phoom, Thung Raya - Na Sak, Thung Yai Naresuan, Ton Nga Chang, Ton Pariwat, Um Phang, Unnamed park 26, Unnamed park 27, Unnamed park 29, Unnamed park 35, Uthayan Somdet Phra Sinakharin, Wiang Kosai

- Approach 3, strata 3: Angkepnam Bang Phra, Ao Manao - Khao Tanyong, Ao Phangnga, Ao Siam, Bang Lang, Bo Lo, Budo - Su - Ngai - Padi, Bueng Borapet, Bueng Ke Ring Ka Wia - Nong Namsap, Bueng Khong Long, Cha-am, Chaloem Phra Kiet Somdej Phrathep Rattana Rachasuda, Doi Pha hom pok, DOI PHRA BATH, DOI PHU KA, Doi Su Thep, Du Nalam Phan, Ha La - Ba La, Hat Chao Mai, Hat Khanom - Muko Thale Tai, Hat Wanakon, Khao Chi On, Khao Erawan, Khao Kradong, Khao Krapuk - Khao Tao Mo, Khao Laem Ya - Mu Ko Samet, Khao Nam Phrai, Khao Pa Chang - Laem Khan, Khao Phaeng Ma, Khao Phra Thaeo, Khao Phu Luang, Khao Prathap Chang, Khao Reng, Khao Som Phot, Khao Yai - Khao Napha Tang - Khao Ta Phrom, Khlong Phraya, Khung Kraben, KUIBURI, Laem Son, Laem Talumphuk, Lam Nam Kra Buri, Lam Nangrong, Lam Pao, Mu Ko Chumphon, Mu Ko Lanta, Mu Ko Similan, Mukdahan, Muko Ang Thong, Muko Phetra, Muko Surin, Nam Tok Chet Sao Noi, Namtok Saikhao, Namtok Si Po, Nong Plak Phraya - Khao Ra Ya Bang Sa, NONGBONGKAY, Pa Krat, Pa Phru, Phan Thai Norasing, Sirinat, Thale Luang, Tham Pha Tha Phon, Than Sadet - Kho Pha - ngan, Than Bok Khorani, Thap Phayalo, Thong Pha Phum, Thung Thale, Unnamed park 10, Unnamed park 11, Unnamed park 12, Unnamed park 13, Unnamed park 14, Unnamed park 15, Unnamed park 16, Unnamed park 17, Unnamed park 18, Unnamed park 19, Unnamed park 2, Unnamed park 20, Unnamed park 21, Unnamed park 23, Unnamed park 24, Unnamed park 25, Unnamed park 3, Unnamed park 31, Unnamed park 32, Unnamed park 33, Unnamed park 36, Unnamed park 37, Unnamed park 38, Unnamed park 39, Unnamed park 4, Unnamed park 41, Unnamed park 5, Unnamed park 6, Unnamed park 7, Unnamed park 8, Unnamed park 9, Yot Dom

C Annex : R setup

C.1 Recommended online materials

The following list contains further reading recommendations to better understand how the R packages mentionned in the section 2.8 contributed to the data analysis and reporting:

- General advice and use of tidyverse in R for Data Science: https://r4ds.had.co.nz/
- Overview of the sf package for geospatial data in R: https://www.r-spatial.org/r/2018/10/25/ggplot2-sf.html
- Advanced use of sf in Geocomputation with R: https://bookdown.org/robinlovelace/geocompr/
- Plots improvements with ggpubr: http://www.sthda.com/english/articles/24-ggpubr-publication-ready-plots/
- How to use cttobin's ggthemr: https://github.com/cttobin/ggthemr
- Everything about bookdown in Authoring Books and Technical Documents with R Markdown: https://bookdown.org/yihui/bookdown/
- Dynamic maps in html documents with the tmap package: https://cran.r-project.org/web/packages/tmap/vignettes/tmap-getstarted.html
- Using git version control with R and RStudio: https://happygitwithr.com/

C.2 Structure of the data folder

The analysis files were organised in one main folder containing everything. The main folder was divided in subfolder and files as follows:

- Subfolders:
  - _bookdown_files: contains the figures generated by R for pdf and html reports,
  - data: contains all the data,
  - images: contains the images used in the report,
  - Report: contains the report in pdf and docx format,
  - Report-Cstock-*: contains the report in gitbook (html) format,
  - results: contains the results of the analysis, mostly plots saved as images and tables,
  - Rscripts: contain the R scripts used for the data analysis
  - .git: folder generated by git for version control
  - .Rproj.user: is an R project feature
- Files:
  - .gitignore: place to specify what file and folder that should be ignored by Git, important to avoid having sensitive data sync with Github,
  - .Rhistory: R file,
  - _bookdown.yml: YAML header for bookdwon, section dealing with folder and report name,
  - _output.yml: YAML header for bookdown, section dealing with formats and options for building the report,

- Index.Rmd: First section of the report, contains YAML header, R chunk options, Cover page, Disclaimer page, Abstract and table of content.
- all the Rmd files: Report and annexes,
- packages.bib: auto-generated bibliography with references for R and R packages,
- page-break.lua: custom script for pandoc to apply Tex "\newpage" to .doc files,
- papers.bib: bibliography,
- preamble.tex: custom functions for pdf output,
- README.md: description of the repository for Github,
- ref-empty.docx: reference document for docx output styles,
- style.css: custom styles for html output,
- Thailand-EF-update-2020.R: Main R script,
- Thailand-EF-update-2020.Rproj: R project file, mostly deals with the relative pathing to the analysis subfolders.

The main R script (`Thailand-EF-update-2020.R`) was placed in the main project folder. It contained two user defined variables and sourced the other R scripts, each focusing on one element of the workflow described in section 2.7. The two user defined variables were: `assign_plot_style` to determine whether to use color or greyscale for figures; and `assign-data` to determine with version of the data to use, the original version shared in February 2019 or the revised version shared in March 2020.

The first script called was `00-Starter.R` had four purposes: (1) Load additional R packages with the function `library()`, (2) define plot style with a colorblind friendly palette (Figure 19) using `define_palette()` or the default greyscale palette from `ggthemr()`, (3) set the path to the data and results in the computer and create the necessary folders and (4) load custom functions developed for the analysis.

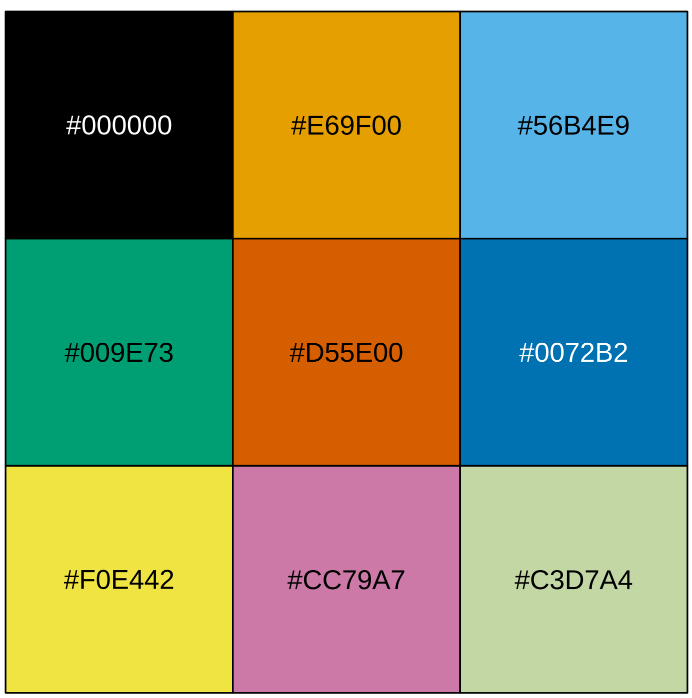


Figure 19: Custom color palette for figures in the document

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