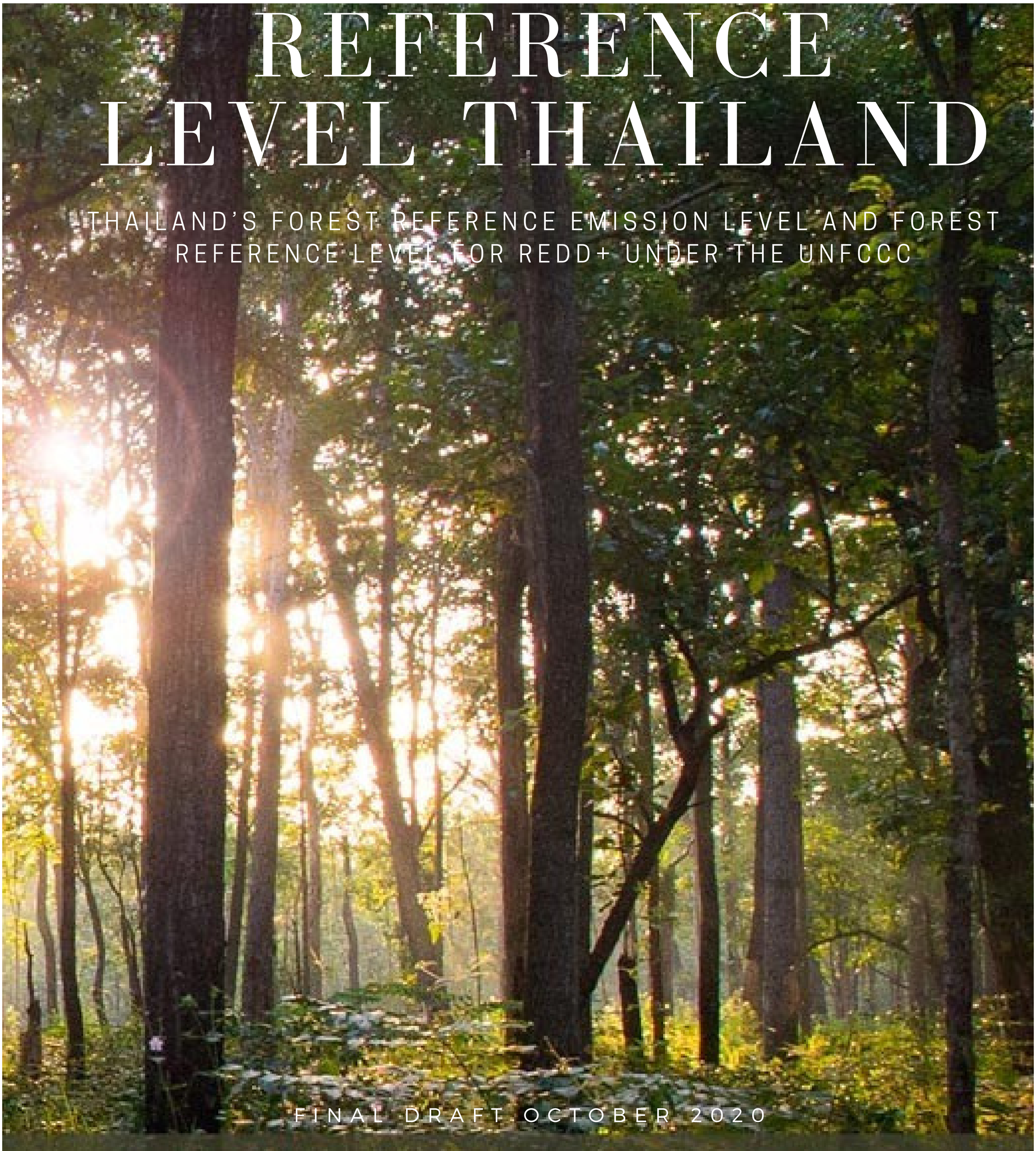
FOREST REFERENCE EMISSION LEVEL AND FOREST REFERENCE LEVEL THAILAND

THAILAND'S FOREST REFERENCE EMISSION LEVEL AND FOREST REFERENCE LEVEL FOR REDD+ UNDER THE UNFCCC



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Acronyms

AD	Activity Data
AGB	Above Ground Biomass
BAU	Business as Usual
BGB	Below Ground Biomass
BUR	Biennial Update Reports
CCCO	Climate Change Convention Officer
CCMP	Climate Change Master Plan
CCNS	Climate Change Negotiation Sub-Committee
CCTS	Climate Change Technical Sub-Committee
CDM	Clean Development Mechanism
CH_4	Methane
CI	Confidence Interval
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
COP	Conference of the Parties
DIO	Department of International Organizations
DNA	Designated National Authority
DNP	Department of National Parks, Wildlife and Plant Conservation
EF	Emission Factor
FAO	Food and Agriculture Organization of the United Nations
FREL	Forest Reference Emission Level
FRL	Forest Reference Level
$GgCO_2eq$	Giga grams of Carbon dioxide equivalent
GHG	Greenhouse gases
GIS	Geographic Information System
GISTDA	Geo-Informatics and Space Technology Development Agency
GoT	Government of Thailand
GPG	Good Practice Guidance
INDC	Intended Nationally Determined Contribution

IPCC	Intergovernmental Panel on Climate Change
LDD	Land Development Department
LULUCF	Land Use, Land Use Change and Forestry
MONRE	Ministry of Natural Resources and Environment
NC	National Communication
NCPC	National Climate Change Policy Committee
NDA	National Designated Authority
NDC	Nationally Determined Contributions
NFI	National Forest Inventory
NO_2	Nitrogen dioxide
ONEP	Office of Natural Resources and Environmental Policy and Planning
QA	Quality Assurance
QC	Quality Control
REDD+	The acronym "REDD+" is used under the UNFCCC negotiations to refer to developing country Party mitigation actions in the forest sector by undertaking the following activities, as deemed appropriate by each Party and in accordance with their respective capabilities and national circumstances: a) Reducing emissions from deforestation; b) Reducing emissions from forest degradation; c) Conservation of forest carbon stocks; d) Sustainable management of forests; e) Enhancement of forest carbon stocks
REDD+ TF	REDD+ Taskforce
RFD	Royal Forest Department
SOC	Soil Organic Carbon
SNC	Thailand's Second National Communication
TA	Technical Assistance
TACCC	Transparent, Accurate, Complete, Consistent and Comparable
TNC	Thailand's Third National Communication
tCO_2e	Tons of Carbon dioxide equivalent
UNFCCC	United Nations Framework Convention on Climate Change

PROPOSED FOREST REFERENCE LEVEL

Assessed Emission and Removal estimates

According to Thailand's Forest Reference Emission Level (FREL) presented in this submission, annual Greenhouse Gas (GHG) emissions from the forestry sector were estimated as 15,326,056 tCO_2e with a 95% Confidence Interval (CI) of +/- 39%. Thailand's Forest Reference Level (FRL) estimates annual GHG removals from the forestry sector as -31,511,649 tCO_2e with a CI of +/- 74%. The assessed FREL and FRL are based on historic average emissions and removals over the 10-year period of 2006-2016. The emissions and removals, divided between three REDD+ activities (Deforestation, Degradation and Enhancement) are presented in the table below:

Table 1 Thailand's FREL and FRL 2006-16[1]

		E/R over reference period (tCO_2e)	Average annual E/R (tCO_2e)	95% Confidence Interval (%)
Deforestation (Forest – Non-Forest)		153,260,563	15,326,056	39
Enhancement (Non-Forest - Forest)		-26,314,503	-2,631,450	90
Degradation (Forest - Forest)	Net Change (Forest - Forest)[2]	-288,801,988	-28,880,199	80
Enhancement (Forest - Forest)				
FREL (Total Emissions)			15,326,056	39
FRL (Total Removals)			-31,511,649	74

[1] The FREL includes activities which reduce emissions. The scope of the FREL includes reduced emissions from deforestation and/or forest degradation. The FRL includes activities which increase removals. The scope of the FRL includes enhancement of forest carbon stocks. In this first FREL and FRL submission Net change is reported for forest remaining forest

[2] A stock difference approach has been used to assess the net removals or emissions from forest remaining forest. Since Thailand's forest have accumulated on average more biomass than what was lost over the reference period, the resulting net change is removals

Purpose of submission

Thailand voluntarily presents this FREL and FRL as part of the country's commitment to the United Nations Framework Convention on Climate Change (UNFCCC). This is in response to the invitation extended by the Conference of the Parties (COP) under decision 12/CP.17 paragraphs 9 and 11. In doing so, Thailand adheres to the Convention's objective to stabilize of GHG concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system including implementation on related measures on forest sector to promote Reducing Emissions from Deforestation and forest Degradation, conserved, sustainable management of forests, and the enhancement of forest carbon stock (REDD+).

This submission would support the Thailand's GreenHouse Gas Inventory and Nationally Determined Contribution (NDC) to the Paris Agreement. Currently Thailand has not yet determined the target on forest sector for GHG mitigation. However, Thailand has national strateqic plan in increasing forest cover up to 40% through local community participation particularly in headwater and mangrove forests. Besides of enhancing adaptive capacities of related ecosystems which is one of Thailand's prioritized adaptation efforts, this would also result in enhanced removals of GHGs through forest-related actions.

As per decision 12/CP.17 paragraph 7 of the COP, the FREL and FRL function as the baselines against which the country's implementation of REDD+ activities can be compared. Thailand's FREL and FRL cover the national scale across 6 regions of the country. A step-wise approach has been applied that will allow for improvements in future submissions when methods and new information available.

Consistency of submission

This document and its annexes were prepared in accordance with the modalities and guidelines established in decision 12/CP.17 Section II, the Annex to this decision, and following the Guidelines for National Greenhouse Gas Inventories by the Intergovernmental Panel on Climate Change (IPCC, 2006). The submission presents all the information and methods in a transparent, complete and precise manner following the principles of TACCC[3]. Methodological elements, such as the definition of forest used by Thailand for the purpose of REDD+ activities, are described in the chapter on FREL and FRL methodological elements and choices, and data and methods used, such as to assess the emissions and removals and establish the FREL and FRL, are described in the chapter on FREL and FRL construction.

In comparison, both the third, and most recent, National Communication (NC) (TNC, 2018) and Biennial Update Report (BUR2, 2017) show a trend of increased net removals for the LULUCF sector in Thailand. In 2005, when rubber plantations were included in the calculation for the initial NC, the results showed an increase of CO_2 removals compared to other communications. Since 2000, LULUCF activities have contributed to Thailand's net GHG removals from the atmosphere.

Methodologies applied in the Thailand's National GHG Inventory for the 2018 TNC were based on the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 1997) and the uncertainty analysis of the activity data and emission factors was undertaken according to the Good Practice Guidance (GPG) for LULUCF (IPCC, 2003). Forest carbon pools were classified into 5 categories including living above-ground biomass (AGB), living below-ground biomass (BGB), dead wood, litter and soil organic carbon (SOC) (IPCC, 1997). However only the AGB and BGB pools were taken into account for this FREL and FRL.

Appropriate methodology tiers, either with or without change of forest land to other land use were chosen according to the GPG for LULUCF (IPCC, 2003). Thailand adopted multiple tiers in the national GHG inventory for the LULUCF sector. Activity Data (AD) were obtained from the interpretation of satellite imagery and statistical reports from relevant agencies. Tier 2 Emission Factors (EFs) were adopted for most activities using country-specific data from local publications; IPCC defaults were applied as Tier 1 EFs when appropriate. This was mostly for estimation of non-CO_2 emissions.

[3] Transparency. Accuracy. Completeness. Comparability. Consistency

For Changes in Forest and Other Woody Biomass Stocks, the annual increment in biomass, wood density and carbon fraction of dry matter for EFs estimation were obtained from local publications that were reported in the Guideline of the Potential Tree Species Used for Promoting under Clean Development Mechanism by Faculty of Forestry (1997). Reviewing more recent research with regard to large areas and tree samples showed that the average annual biomass increment decreased. Therefore, the EFs used in the recent communication were lower than those used in previous submissions.

For Forest and Grassland Conversion, the AGB by forest type before conversion, and carbon fraction of dry matter by forest type, were obtained from local publications. Fractions of biomass burned on-site and off-site by forest type and fraction of biomass left to decay by forest type were country-specific data, which was obtained from a literature review and by expert judgment.

For Abandonment of Managed Lands, the supporting data for estimating Tier 2 EFs, the data were the annual rates of AGB growth for land abandoned in the last twenty years and land abandoned between 20 and 100 years ago classified by forest type. These were country-specific data.

NATIONAL CONTEXT

Policies & Legislation

One of the threats facing Thailand's forests is illegal logging. To reduce deforestation, several actions have been taken such as improving forest law enforcement, declaring national conserved forests, rehabilitating degraded forests, and promoting community forest management. The Government of Thailand (GoT) imposed a nationwide logging ban by emergency decree in January 1989. Implementation has reduced the deforestation rate.

To prepare itself to cope with the threat of climate change and contribute to efforts of climate change mitigation, Thailand has introduced various policies and plans incorporating climate change into the forest sector.

Key national policies relating to climate change in the forest sector include :

- Raise awareness and public participation on climate change in forest sector: This is in line with the National Strategy (2018 – 2037) in the key of "The National Strategy on Eco Friendly Development and Growth", and the Thailand Climate Change Master Plan (2015-2050) in the article of "Capacity Building on the Climate Change Management".
- Promote greenhouse gases mitigation activities based on sustainable development principles, in particular in relation to the SDG13 on Climate Action which to take urgent action to combat climate change and its impacts.
- Support research and development on climate adaptation and mitigation in forestry sector: This is in line with the Thailand Climate Change Master Plan (2015-2050) in the article of "Capacity Building on the Climate Change Management" which included the development of research and data for enhancing efficiency on climate change management.
- Build capacity for climate change adaptation and reducing vulnerability and risks of climate impact in forestry sector: This is in line with the Thailand Climate Change Master Plan (2015-2050) in the article of "Capacity Building on the Climate Change Management" which included the development of mechanism to support the climate change implementation.
- Capacity Building of relevant institutions and staff, and establishing framework for coordination and integration systems: This is in line with the Thailand Climate Change Master Plan (2015-2050) in the article of "Capacity Building on the

Climate Change Management" which included arising awareness and enhancing efficiency climate change management

- Enhance the resilience of ecosystems to sustain environmental services for Thai livelihoods: This is in line with the present National Forest Policy of Thailand (2019).
- Introduce, and perhaps at appropriate timing, impose the tax measure used for sustainable forest management tools: This is in line with the Thailand Climate Change Master Plan (2015-2050) in the article of "Capacity Building on the Climate Change Management" which included establishment of mechanism to support growth base on low carbon.
- Forest conservation and restoration with monasteries in forest areas as well as the training for monks and priests: This is in line with the National Strategy (2018 – 2037) in the key of "The National Strategy on Eco Friendly Development and Growth" and Thailand Climate Change Master Plan (2015 - 2050) in the article of "Capacity Building on the Climate Change Management"
- Harmony between Forest, People, and all Living things, including Trees and Wildlife: This is in line with the National Strategy (2018 – 2037) in the key of "The National Strategy on Eco Friendly Development and Growth".

Thailand has also put strong emphasis on international cooperation on climate change in the forest sector including :

- Promoting international cooperation related to climate change adaptation and mitigation, in particular with key major international players such as the UNFCCC, and all related United Nations Agencies, major donor countries and multilateral development banks.
- Promote effective community forestry activities as a model for climate change mitigation and adaptation, through international frameworks – UNFCCC, ASEAN, bilateral or multilateral agreements
- Obtain financial support from developed countries or international organizations; initiate projects on climate change mitigation and adaptation in the forest sector, to ensure sustainability of projects currently funded from Global Environment Facility (GEF), the Forest Carbon Partnership Facility (FCPF), and Technical Assistance from Asian Development Bank (ADB)
- Promote experience sharing in the region, with countries that have similar context to Thailand regarding climate change mitigation and adaptation in the forest sector, starting with neighboring countries and existing regional platforms such as ASEAN Senior Officials on Forestry (ASOF).

Institutional setting

The Department of National Parks, Wildlife and Plant Conservation (DNP) and the Royal Forest Department (RFD) are the two leading authorities for the forest sector in Thailand. DNP is the national focal point for REDD+. The Department's main mandate is responsibility for all National Parks within Thailand, and for related conservation work within the National Parks. RFD is in charge of National Reserve Forest (NRF) and national forest policy. Most of Thailand's national forest lawas had been established under RFD before the department was split, in 2000, into RFD, DNP and DMCR.

The National Secretariat for Climate Change is within the Office of Natural Resources and Environment Policy and Planning (ONEP), within the same ministry (MoNRE). ONEP has the role of the National Designated Authority (NDA) of Thailand under the UNFCCC. On matters relating to REDD+, DNP and ONEP collaborate closely with each other, and act in coordination, both at national and international levels. Collaboration and involvement from RFD is key for REDD+ matters, in light of RFD's position as the responsible agency for forest policy and legislation.
In addition to these three agencies (DNP, RFD, and ONEP), several other agencies in Thailand possess mandates related to REDD+, including:

- Faculty of Forestry, Kasetsart University
- Land Development Department (LDD)
- Geo-Informatics and Space Technology Development Agency (Public Organization - GISTDA)
- Department of Marine and Coastal Resources (DMCR), overseeing all mangrove areas
- Forestry Industry Organization (FIO)
- Thailand Greenhouse Gas Management Organization (Public Organization - TGO)
- Ministry of Interior responsible for provincial administration
- Municipalities and local governments

These agencies are attached to various Ministries, and belong to all levels of the country's administration, from national, regional to local levels. The mandates of these agencies are guided by the main functions of the Ministries in which they are located. Some have already incorporated the concept of REDD+, climate change or forestry management into their objectives and reflected these issues in budgets and planning, while some have yet to develop this perspective.

DNP has made recent progress in reaching out to regional administrative levels by instituting regional REDD+ centres in order to better support the development of REDD+ strategy in the country. The main purpose of the regional centers is to provide links between authorities and local people on the issues of forest and climate change. The centers were established first to oversee the reduction of GHG emissions from forests within Thailand, and to increase the forest carbon stock within the country. Currently, 9 regional REDD+ centers have been established in the following provinces: Chanthaburi (eastern); Kanchanaburi (western); Phatthalung (southern); Sakon Nakorn (northeastern); Loei (northeastern); Phitsanulok (central); Phrae (northern); Tak (northern); Chiangmai (northern).

Thailand established the National Committee on Climate Change Policy (NCCC) chaired by the Prime Minister or The Deputy Prime Minister and the members which are from both public and private sectors. Under the NCCC, Five sub-committees in charge of the technical, negotiation and coordination on issues related to climate change were established, namely 1) Sub-Committee on Climate Change Policy and Planning Integration 2) Sub-Committee on Climate Change Knowledge and Database 3) Sub-Committee on Climate Change Negotiation and International Cooperation 4) Sub-Committee on Action for Climate Empowerments and Public Relations 5) Sub-Committee on Climate Change Law (Figure 1). It is envisaged that this CC structure will contribute to the effective implementation of REDD+ readiness.

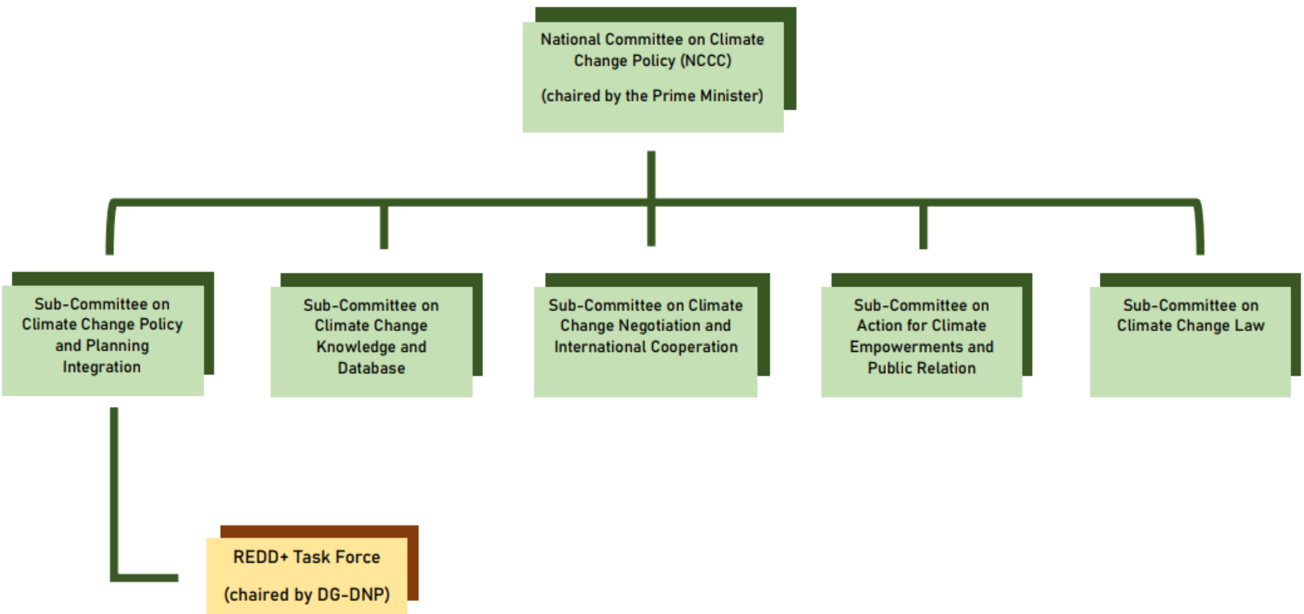


Figure 1 Organization chart of policy decision-making body related to climate change in Thailand

In 2010, GoT decided to participate in the REDD+ partnership and established the REDD+ Taskforce (TF) as an inter-ministerial and multi-sectoral committee. Although few activities related to REDD+ have been carried out in Thailand, however, the Climate Change Master Plan (CCMP) expects that the REDD+ mechanism would be the potential mechanism for the country to promote forest conservation and enhancement of carbon stock in the forest sector which is one of the major strategies in climate change mitigation. Capacity building on REDD+ including development of FREL and FRL, forest inventory, study on land use change, measuring of carbon stock by local community and dissemination of information are suggested as the activities in CCMP. The need for a multi-sectoral approach to REDD+ implementation as the drivers of deforestation and forest degradation often lie outside the forestry sector is recognized by the GOT.

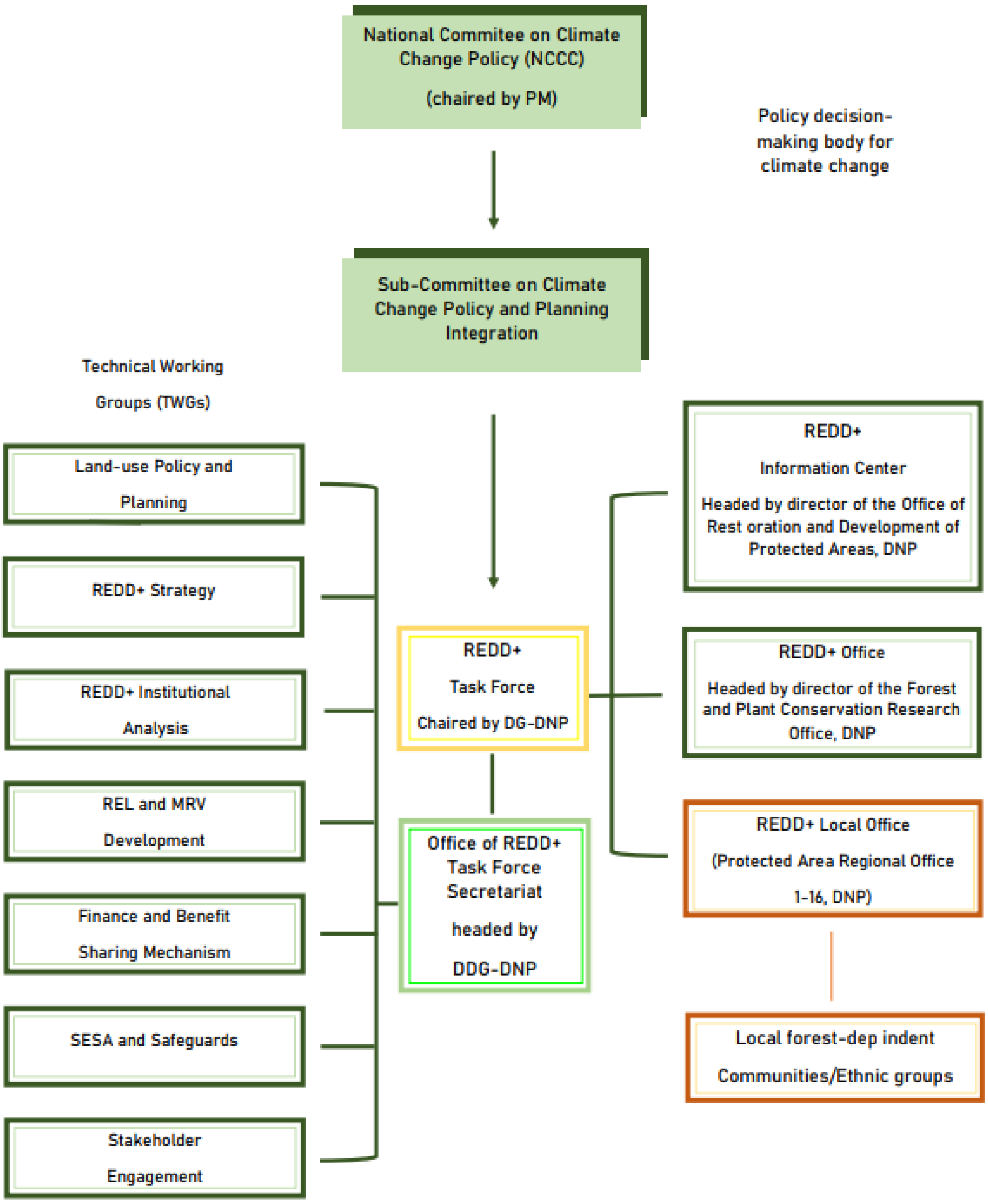


Figure 2 Organization chart of policy decision-making body related to climate change in Thailand and REDD+

The REDD+ TF in Thailand is currently chaired by DG of the Department of National Parks, Wildlife and Plant Conservation (DNP) and includes representatives from key agencies related to the drivers for deforestation and forest degradation. One of its main roles would be to facilitate, coordinate and spearhead the process by bringing together relevant stakeholders to engage in decision-making and action and these sectors may be impacted by REDD+ implementation.

Regarding international coordination, ONEP, in its capacity as the NDA of the country, is responsible for the overall GHG reporting, through the National Communications, Biennial Update Reports (BURs) and future Biennial Transparency Reports (BTRs), to the UNFCCC. The National Forest Monitoring System (NFMS), Measurement, Monitoring and Reporting (MMR) for REDD+, and the FREL and FRL are all under the responsibility of DNP. However, all decisions made regarding any International Forum will have to undergo Cabinet Approval, and in some cases, the approval from Parliament must also be obtained.

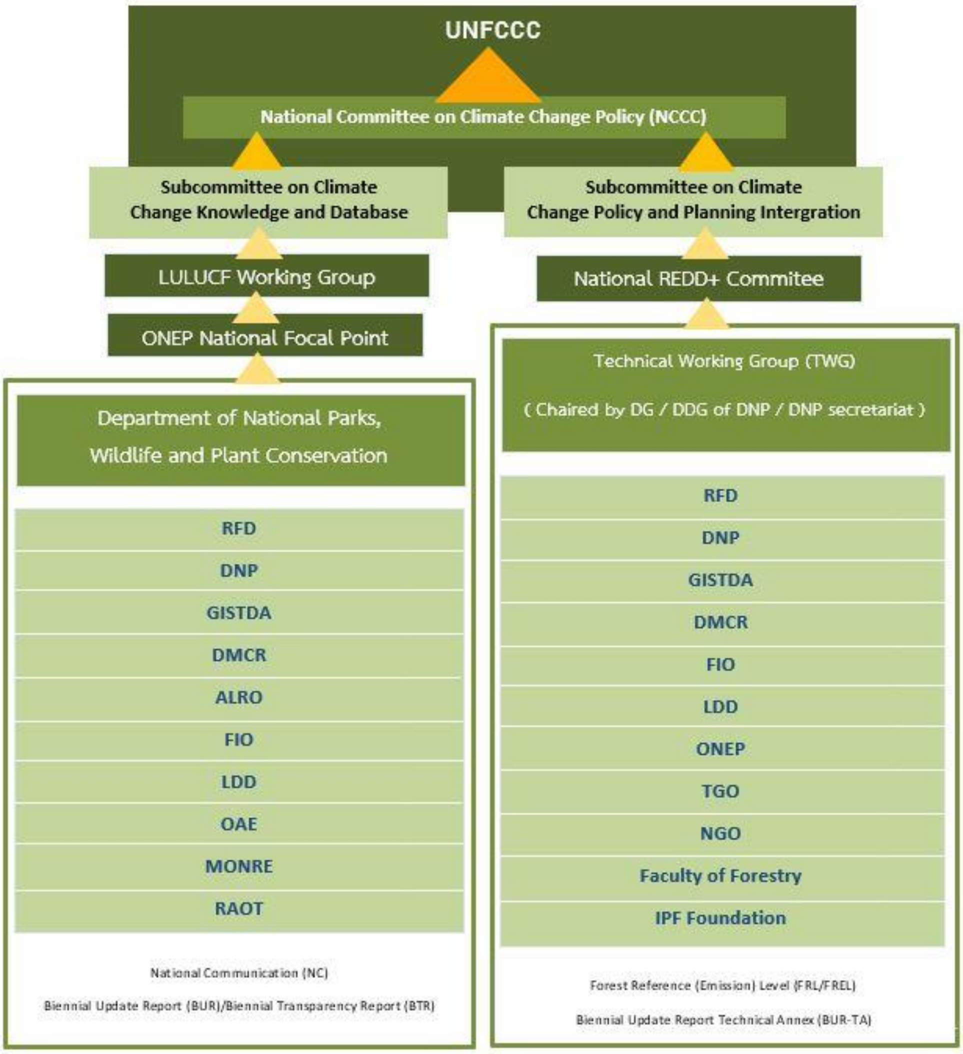


Figure 3 Diagram: REDD+ institutional setting

Thailand's Forest sector

Thailand has a total land area of approximately 51.3 million hectares. As of 2015, 47% of the nation's total land area (or 24 million hectares) was zoned as agricultural land. Non-agricultural land and forested land accounted for 21% and 32% of the total area, respectively. Slash-and-burn farming, shifting cultivation, land resettlement, and dam and road construction have encroached on forest areas. In 1973, the total forest area of Thailand covered over 43% of the country but the proportion of forest area declined to 25.28% in 1998. In 2000 as a result of changes in the scale and method of calculation, establishing a new benchmark for this category of land use, area estimates chnaged. RFD's current estimate in 2018 of forest area is roughly 102 million Rai (Thai national units for land area), equivalent to 16.4 million hectares (RFD, 2019). The forest area in Thailand has been recorded by RFD as relatively stable since 2014, accounting for 31.62% in 2014, 31.60% in 2015, 31.58% in 2016, 31.62% in 2017, and 31.68% in 2018. At sub-national level, 36 provinces out of 77 have less than 20% of total area under forest cover, 23 provinces have forest cover of 20-40%, 7 have 40-60%, and 7 provinces have over 60% of forest cover. These latter 7 provinces are Chiangmai, Nan, Phrae, Lampang, Mae Hong Son, Tak and Kanchanaburi, which are all located in the North and the West of the country. (sources: Royal Forest Department website http://www.forest.go.th/land, accessed March 2019)

Thailand divides forest land into three different management classes:

- Conservation Forests are managed by DNP and consist of National Parks, Wildlife Sanctuaries and other conserved forest classifications which historically were not subjected to active forest management practices. In the context of REDD+ these forests may be subjected to a variety of human activities which result in deforestation or forest degradation.
- National Reserve Forests are managed by RFD and consist of forest lands which historically were subjected to active forest management activities. However, under current law, all forests in Thailand are excluded from timber harvest. In the context of REDD+, National Reserve Forests may be subjected to a variety of human activities which result in deforestation or forest degradation.
- Mangrove forests are managed by the Department of Marine and Coastal Resources (DMCR).

Conserved Forests account for approximately 64% of the total forest area in Thailand. Reserved Forests account for approximately 34% and the remaining 2% are mangrove forests.

Evergreen forest

Evergreen forest is subdivided into tropical evergreen forest, pine forest, mangrove forest and beach forest.

- Tropical evergreen forest is found all over the moist part of the country. This type of forest is also subdivided into tropical rainforest, semi-evergreen forest and hill evergreen forest.
  - *Tropical rain forest* is characterized by very rich flora and very dense undergrowth. This type of forest is commonly found in the Southern and the Eastern regions where rainfall is above 2,000 mm. It is also found along rivers and/or in valleys in other parts of the country. The predominant species (the top storey species) are, for example, *Dipterocarpus spp*, *Hopea spp*, *Lagerstroemia spp*, and *Shorea spp*, whereas the lower storey species are bamboos, palms and rattans.
  - *Semi-evergreen forest* is scattered all over the country where the rainfall is between 1,000- 2,000 mm. The predominant species are *Dipterocarpus spp*, *Hopea spp*, *Diospyros spp*, *Afzelia spp*, *Terminalia spp*, and *Artocarpus spp*. The main undergrowth species consist of bamboo and rattan.
  - *Hill evergreen forest* is found in the highlands (above 1,000 metres above sea level) where the climatic condition is humid subtropical. The presence of mosses and lichens on trees and rocks is the indicator of this forest type. The predominant species are oaks (*Quercus spp*), chestnuts (*Castanopsis spp*) and *Lithocarpus spp*.
- Pine forest has two species of tropical pines, *Pinus merkusii* locally called Son Song Bi (the two needle pine) and *P. kesiya* locally called Son Dam Bi (the three-needle pine). *P. merkusii* where the soil is poor, lateritic and podzolic. Otherwise *P. kesiya*.
- Mangrove forests occur along the coastal areas of the Eastern, Central and Southern regions. The mangrove forest is scattered along the estuaries of rivers and seashores where the soil is muddy and influenced by the tide. The predominant species are *Rhizophora* spp, *Xylocarpus* spp, *Avicennia* spp, *Bruguiers* spp, and *Nypa* spp.
- Beach forests occur along the sandy coastal plains especially in the eastern coast of the Southern region. The main species in this type of forest are *Diospyros* spp, *Croton* spp, *Lagerstroemia* spp and *Casuarina* spp.

Deciduous forest

Deciduous forest is characterized by the presence of deciduous tree species and is commonly found throughout the country. It is broadly subdivided according to the species composition into mixed deciduous forest (with and without teak) and dry dipterocarp forest.

- Mixed deciduous forest is commercially among the most valuable forests of Thailand. In the Northern Region, this type of forest is called teak forest with *Tectona grandis, Xylia kerrii, Pterocarpus marcrocarpus, Afzelia xylocarpus* and *Dalbergia* spp (rose wood) as dominant/common species.
- Dry dipterocarp forest is commonly found in the dry area (rainfall below 1,000 mm) with sandy or gravelly lateritic fertile soils. The predominant species are mainly *Dipterocarpaceae* such as *Dipterocarpus tuberculatus, D. obtusifolius, Shorea obtusa, S.siamensis* with the presence of *Dalbergia spp*, *Lagerstroemia spp*, *Terminalia spp* and other species.

For the purposes of this FREL and FRL, it was initially proposed to divide Deciduous forest into the two sub-classifications. However, no significant difference in EF was detected between these sub-classifications based on the results of field exercises described in the section on Emission and Removal Factors below. It was therefore proposed to consider Deciduous forests as a single class for the purposes of this FREL and FRL. With the exception of Mangrove forest, which is a very distinct ecosystem with high significance in terms of forest carbon stocks, all Tropical Evergreen forest sub-classifications were considered as a single category. Thailand's forests are therefore classified in three (3) forest types for the purposes of this FREL and FRL: Deciduous, Evergreen and Mangrove forest (See FREL and FRL methodological elements and choices – Forest Definition).

National Circumstances under period ofreview for FRL development

Severe deforestation took place in Thailand during the 1970s and 1980s in particular. Since then, the Thai government has imposed many interventions to prevent further deforestation of the country. Factors contributing to deforestation in Thailand include fuel wood gathering, traditional shifting agriculture, government resettlement programs, and development projects. More recently, plantations of cash crops have replaced significant areas of forest.

Some key underlying factors contributing to the loss of forest areas in Thailand are:

1) Population growth. Most significant in the northeast region of Thailand, the most populated region of the country, with the least productive soils for agriculture. As population increased, much forest land was cleared to plant crops to increase food production.
2) High economic value of timber. Several species native to Thailand are in high demand for construction, furniture etc, in particular for teak, and have historically been logged and sold legally and on the black market. Illegal logging is unlikely to disappear completely from Thailand.
3) Land ownership and Land rights. The inability of many Thai citizens to secure property has resulted in their turning forests into their living and working areas.
4) Uncertain agriculture policy. Fluctuating prices for agricultural products, sometimes influenced by central policy, combined with variations in land policy and weak land rights have led to many farmers encroaching regularly on forest land to expand cropping areas whenever financially viable or necessary.

Various preventive measures were introduced from 1989 onwards to stop deforestation and illegal logging, with the aim of increasing the area of forest land. In addition, Thailand promoted various reforestation measures, and as a result, from the early 2000s, the area of forest land in Thailand has remained relatively stable at about 30%. The period from 2006-2016, identified as the reference period for FREL and FRL development for Thailand, has seen the government and all sectors working hard together to preserve the country’s forest land. No major forest losses have been identified from 2006, and Thailand expects to accelerate interventions to preserve and expand forest areas in the decades to come.

FREL AND FRL METHODOLOGICAL ELEMENTS AND CHOICES

Scale and REDD+ Activities

The FREL and FRL encompass Thailand's Nation. The national scale is chosen to include considerations such as institutional mandates, with the responsibility of the forest under three institutions, linkages to different REDD+ activities in different settings, and due consideration of linkages to national policies to implement REDD+ and the NDC.

Applying the national scale is possible due to the establishment of the Measurement, Monitoring and Reporting (MMR) of the National Forest Monitoring System (NFMS), availability of data and capacities of national institutions.

The FREL and FRL include three REDD+ activities: deforestation, forest degradation and enhancement of forest carbon stocks (afforestation/reforestation).

Deforestation: Forest areas where tree canopy cover has been reduced to below 10% by the drivers are defined as deforestation. The forest areas converted for settlement and agricultural purposes are also considered as deforestation.

Degradation: Forest areas with a canopy cover equal to, or above, 10 % but in which canopy cover has been reduced but remained forest land, were considered as degraded forest. In practice Degradation was defined when forest type changed from a higher carbon stock forest type to a lower carbon stock forest type, or when a stable forest type had its carbon stock decreased.

Enhancement: Enhancement of forest carbon stocks is divided into two categories for the purposes of this FRL. Reforestation/afforestation (non-forest land converted to forest land), and Restoration (enhancement of forest carbon stocks in forest remaining as forest) are both included in the calculation of GHG removals for this FRL. In the case of restoration, it was associated with stable forests where the carbon stock increased or forests changing from a lower carbon stock forest type to a higher forest carbon stock.

No separate calculation has been considered for GHG emissions or removals due to conservation of forest carbon stocks and sustainable management. However, the impacts of these two 'REDD+ activities' are considered to be covered by the measurement of emissions due to deforestation and forest degradation and by the measurement of removals due to forest carbon stock enhancement.

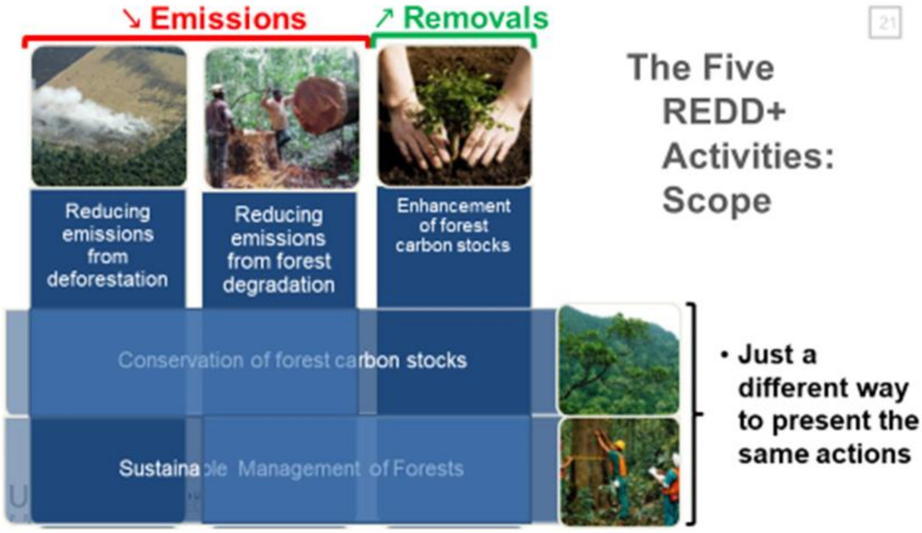


Figure 4 The five REDD+ activities

Forest Definition

The current definition of the RFD is used as the basis for the definition of forest used by Thailand for the purpose of REDD+ activities, however in due consideration of the accurate estimation of emission and removals, areas of grassland and bedrock areas, which were considered as forest in prior data, have been omitted from the forest definition for the purposes of the FREL and FRL. Also, tree crops and plantations of exotic species, for instance Rubber, Eucalyptus and Oil Palm, are excluded from the definition of forest for the purpose of the FREL and FRL. Teak forests are considered part of the natural forest complex, including areas which have been reforested, subject to enrichment planting or assisted natural regeneration.

Forest definition thresholds:

- Minimum area: 0.5 Ha
- Crown cover: minimum 10%
- Height: Not defined (in practice 2m)

This includes areas of forest both inside and outside of areas under the management of RFD, DNP and DMCR.

Forests are classified in three (3) forest types: Deciduous, Evergreen and Mangrove forest. Per hectare the highest carbon content can be found in the Evergreen forest area, however in terms of forest area change, the largest changes occur in the Deciduous forests (see FREL and FRL AD and EF sections). The Deciduous forest type is also the most important in terms of contributor to livelihoods

Carbon pools and GHG considered

Out of five carbon pools as described per IPCC guidelines, two pools, AGB and BGB, are included for this FREL and FRL, which is consistent with the LULUCF section in the national GHG inventory, and believed to be conservative, while limited information exists on the litter, deadwood, and SOC pools. Information on these pools is considered an area of future improvement for the FREL and FRL (see section on improvement).

The only GHG included in Thailand's FREL and FRL is CO_2, since emissions of other GHGs from land use and land use change are considered to be minor (peatland areas are very small and isolated, areas affected by forest fire are relatively limited and in decline on an annual basis[4]), and while limited information exists on these gases their exclusion from the FREL and FRL is considered a conservative approach. Thailand intends to monitor and explore inclusion of other gases in its future submissions.

Reference Period and Construction Method

Thailand chose the period from 2006 to 2016 as the historical reference period for FREL and FRL construction. Thailand believes this period to provide a good approximation of deforestation, forest degradation and enhancement rates. This time period also allows for comparison of available data, with both remote sensing data and NFI data available at the start and end point of the reference period. A historical average construction method is applied (see section FREL and FRL construction).

[4] Data in the in FRA Thailand country report 2015 from the Forest Fire Control Division, National Park, Wildlife and Plant Conservation Department show a gradual decline of forest area burned per year in Thailand to less than 10.000 Ha

FREL AND FRL CONSTRUCTION

Typically, the removal and emission estimates are based on a combination of EFs, or tCO_2e emitted or removed from the atmosphere per hectare of land use change, and AD, which estimates the number of hectares of land use change by type of change over the reference period. The land use change is divided into categories of deforestation, forest degradation, or enhancement. Since a historical average construction method is applied, the average emissions and removals over the reference period are used to predict the expected (and compare the actual) levels of emissions and removals over the results period.

Activity Data

According to the revised IPCC Guidelines for National Greenhouse Gas Inventories, AD are defined as data on the magnitude of human activity resulting in emissions or removals taking place during a given period. The emissions include human activities resulting from forest loss through deforestation and from forest degradation while the removals include forest gain or enhancement of canopy cover. In this report the AD has been developed by estimating the extent of forest change measured as area estimates of forest under three major forest types: Evergreen, Mixed Deciduous, and Mangroves and non-forest during 2006 – 2016. The areas under forest cover include both natural and secondary forests. The amount of deforestation (forest loss) and enhancement (forest gain) have been estimated using maps produced for establishing a FREL and FRL because existing maps do not qualify the revised forest definition that excludes grassland and bare rock. The AD is estimated using a sample-based approach on top of a stratified map produced from the 2006 and 2016 maps showing Forest and Non-Forest areas (Forest/Non-Forest maps). The datasets used to generate a forest mask which leads to AD are listed in Table 2.

Table 2 Various datasets were used to produce maps and accuracy assessment

Data Type	2006	2016	Note
Satellite Data	Landsat TM 4,5 & 7 cloud free best pixel mosaic	Landsat TM 8, cloud free best pixel mosaic	All data are corrected for atmosphere and for bidirectional reflectance
Auxiliary Data	-Forest data from MOAC 2003 for Land Develop Department, -Image from Google earth	- Forest layer from Forestry Technical unit - Image from Google earth	
Validation (Reference) Data	High spatial resolution aerial imagery from Google Earth, Bing map, and Google Earth Engine (Landsat)	High spatial resolution imagery from Google Earth and Earth Engine (Landsat and Sentinel 2)	The validation work was performed through an independent sample assessment procedure using Collect Earth System

Forest Change Assessment

Digital change detection of land cover and forest changes using satellite imagery can be performed by applying several techniques, including post-classification comparison and temporal image differencing between two images in a time series (Jensen, 1996; Lunetta and Elvidge, 1981, Coppin et al., 2004). Post-classification is one of the most commonly used techniques, which is based on overlaying coincident thematic maps from different periods to identify change (Tewksebury et al. 2015). Thailand decided to use post-classification because of high confidence in the forest mask from two thematic maps prepared for 2006 and 2016 in the context of this project. The REDD+ activities deforestation and enhancement of forest carbon stocks were mapped using national-scale remote sensing data for Thailand, whereas forest degradation was not mapped; instead emissions were calculated using NFI data from two cycles

Forests are managed by three departments in Thailand; the Department of National Parks, Wildlife and Plant Conservation (DNP), the Royal Forest Department (RFD), and the Department for Marine and Coastal Resources (DMCR), which work independently. Therefore, data generated are not always consistent and it was decided to produce new spatial data using an updated forest definition and with a nationally consistent approach for time one (2006) and time two (2016).

Given the extent of the country's geographical boundary, the whole country was divided into six tiles or blocks in order to manage for processing. Then Landsat's best pixel mosaic was created using SEPAL for the years 2006 and 2016. The satellite data from Landsat 4-5 & 7 were combined to get the best pixel mosaic over the Area Of Interest (AOI) for 2006 whereas for 2016 only Landsat 8 and Sentinel-2 data were used. The forest area was visually interpreted and the extent was manually digitized by using the various datasets; satellite images of Landsat, high-resolution images from Google Earth, and auxiliary data sets from the DNP over the forest area (see Figure 3 for details, images a-e).

As a starting point, the existing forest mask layer for 2016 from DNP (layer A) was used as a basis and was overlaid on the Landsat image of 2016 (Layer B), Then both layers were visually interpreted and areas with missing or overestimated forest were reshaped based on the updated forest definition in the context of this FREL and FRL submission. When the 2016 forest mask was completed, it was overlaid on the best pixel mosaic from Landsat for the year 2006 and was edited to create the 2006 forest layer. The Non-Forest layer for both years was generated by using the difference tool in ArcMap[5], where the forest layer of the respective year was subtracted from the national boundary shapefile. The last vector data of both years was rasterized to facilitate analysis with a resolution of 10 m^2.

[5] https://desktop.arcgis.com/en/arcmap/latest/extensions/production-mapping/creating-a-difference-polygon.htm#:~:text=The%20Production%20Difference%20Polygon%20construction%20tool%20is%20similar%20to%20the,polygons%20from%20the%20same%20layer.&text=Load%20data%20in%20the%20map%20if%20necessary.

Figure 5: Picture (a) shows the tiling at national scale for work distribution. In (b) the yellow arrow points towards the base layer of forest mask 2016 from DNP, which was overlaid on the Landsat data from 2006. The blue arrow indicates a green dotted line which was used to digitize areas which appeared as forest on the Landsat 2006 image, but were not included in the 2016 forest mask. Picture (c) shows the high-resolution image from Google Earth used to validate the forest cover in the concerned area for 2016 and Picture (d) shows the overlaid image with the forest mask corrected to include this area. Picture (e) is the final F/NF map showing both 2006 and 2016 forest cover mask overlaid on 2016 Landsat data.

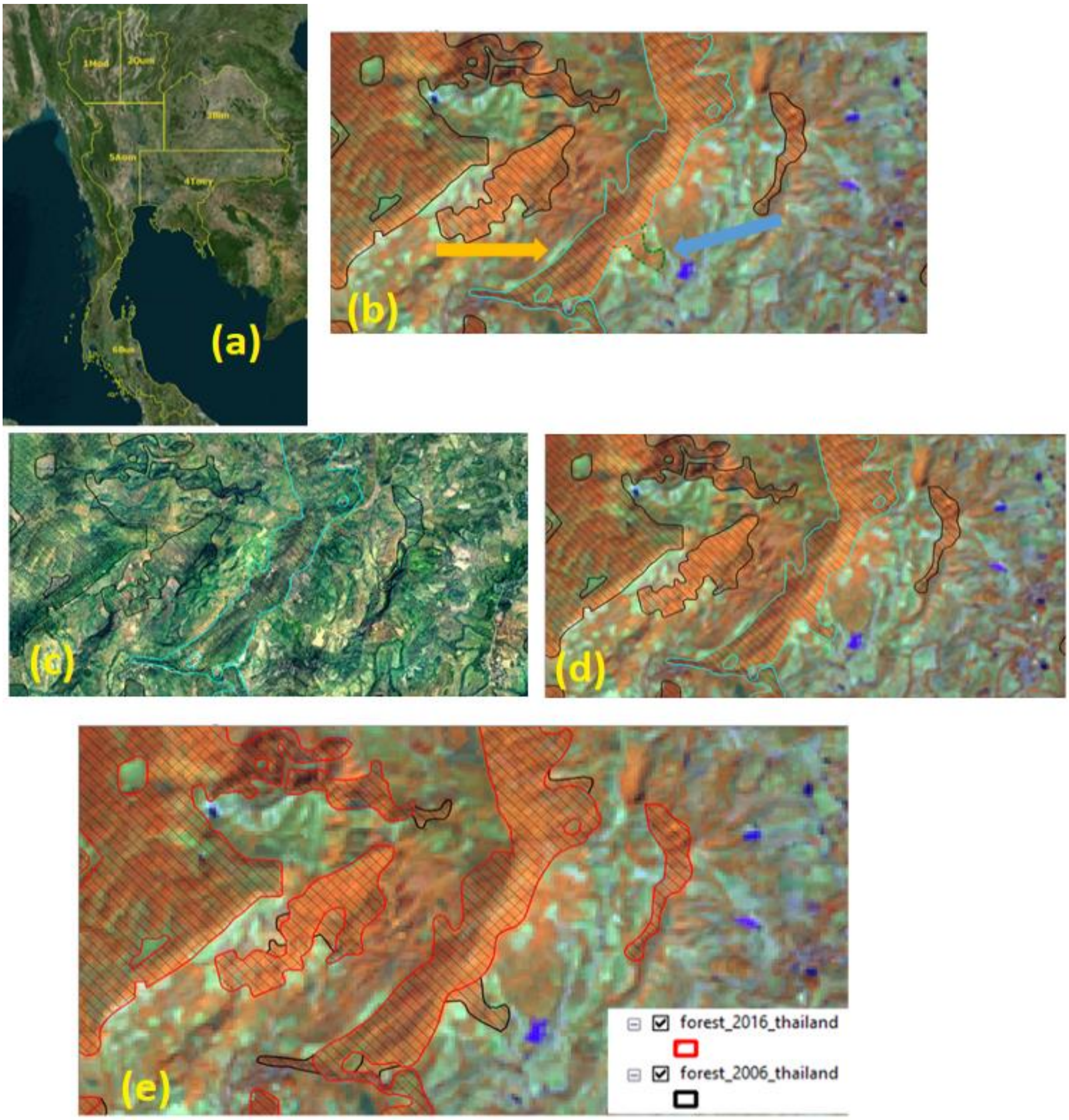


Figure 5 Forest mask development steps

Thus, forest mask maps of 2006 and 2016 were overlaid to detect changes in forest canopy over the reference period, according to the workflow shown in figure 6. The Final map covered ten classes; one Stable Non-Forest (i.e. non-forest land at both 2006 and 2016), and Stable Forest, Forest loss, and Forest gain according to the three forest types: mangrove, evergreen, and deciduous forest. In order to avoid potential errors such as polygons shaped like slivers as a result of post-classification, a sieving tool was applied to remove those potential errors and 'noise' and to adapt the map to a Minimum Mapping Unit (MMU) of 0.5 hectares as per forest definition.

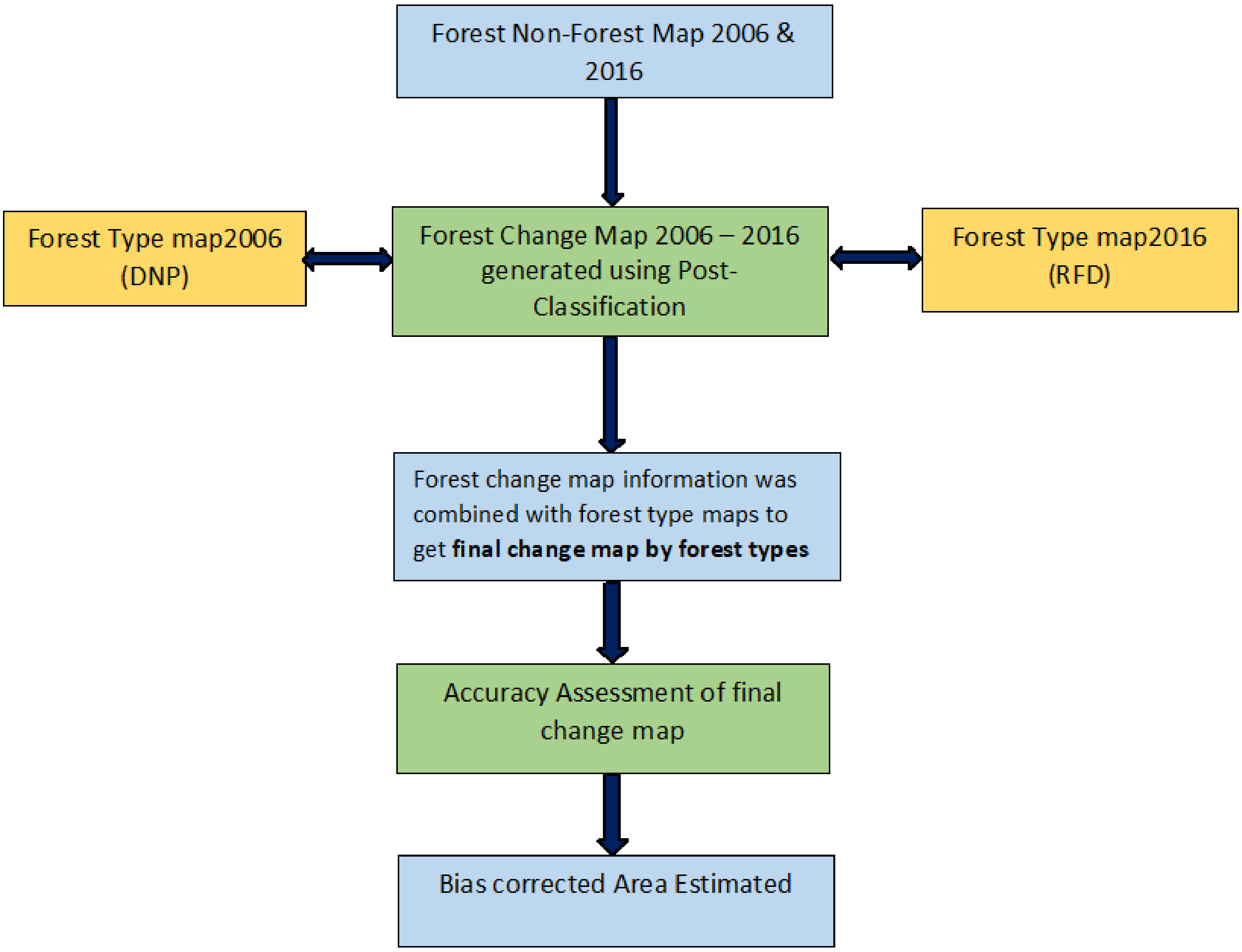


Figure 6 workflow of forest change map and stratified area estimate analysis. Intermediate products and processing are depicted in green, supporting products in light orange and final products in blue color.

Map Accuracy Assessment

Any map produced using remote sensing data is subject to classification errors from various sources, such as quality of images, poor training data, and interpreter errors. Classification errors are unavoidable and the calculation of those errors determines the quality of any map (McRoberts, 2011). Map accuracy assessment is the process used to quantify the errors in any given map and to estimate the areas with uncertainties by following IPCC good practice guidelines. Therefore it is common practice that map data is compared with reference data which is considered of higher accuracy, in order to calculate the uncertainty in map classes and confidence intervals

The final map was therefore assessed for accuracy following the methodology of "Good practices for estimating area and assessing the accuracy of land change" by Olofsson et al. (2014) and "Map Accuracy Assessment and Area Estimation – A Practical Guide" (FAO 2016). The detailed methodology is explained in the Annex II Activity Data.

The sampling design refers to the methods used to select the locations at which the reference data are obtained, in this case, the methods through which the 2,118 samples were derived from the strata map of 2006-2018 using SEPAL's Stratified Area Estimator – Design tool. The tool allows the user to define the minimum sample size for classes, which in this case was 50, following the Cochran (1977) formula (Equation 1) to reduce uncertainty in area estimates and to reduce standard error of the change (Olofsson et al., 2014).

Equation 1

$$n = \frac{(\sum W_i S_i)^2}{[S(\hat{O})]^2 + \left(\frac{1}{N}\right)\sum W_i S_i^2} \approx \left(\frac{\sum W_i S_i}{S(\hat{O})}\right)^2$$

Where: $N = number\ of\ units\ in\ the\ region\ of\ interest$

$S(\hat{O})\ is\ the\ standard\ error\ of\ the\ estimates\ over\ all\ accuracy\ that\ we\ would\ like\ to\ achieve,$

$W_i = mapped\ proportion\ of\ area\ of\ class\ i,$

$S_i = standard\ deviation\ of\ stratum\ i, S_i = \sqrt{U_i(1 - U_i)}$

The initial stratification for sample assessment to derive Stratified Area Estimates (SAEs) for the reference period 2006 to 2010 was done using a forest change map with four classes namely Non-Forest (NF), forest stable, loss, and gain. At the end of the first round of reference data collection and analysis, when results were compiled by forest type, a few classes had insufficient samples to derive meaningful SAE. Thus the decision was taken to intensify the sample assessment. Thailand aimed to report the FREL and FRL based on forest categories and has calculated Emission Factors (EFs) according to three major forest types. The Activity Data (AD) was adapted accordingly to ensure coverage of the three major forest types and their changes. A sample enhancement was performed by combining change map information with forest type map information from the years 2006 and 2016. The 2006 map used was produced as part of the FAO-supported component of the FCPF project that facilitated the development of this FREL and FRL, and the forest type map from the Royal Forest Department (RFD) for the year 2016 was used to categorize the classes of stable forest, gain and loss according to forest layers. Figure 6 shows three maps and a zoomed view of the final map with target classes for intensification. The final strata layers are explained in table 3. Sample intensification was only done in Evergreen loss, Evergreen gain, Mangrove loss, mangrove gain, and mangrove stable forest strata with an additional 50 samples per strata. The sample distribution is illustrated in tables 6 and 7 of Annex II.3. The 2006 forest type map used for this purpose was a draft version but it was sufficiently accurate to identify target forest classes for sample intensification, and did not affect the overall forest change classes. The processing was done in R studio with code developed by FAO and can be accessed by the link in the footnote[6].

[6] https://drive.google.com/file/d/1xbeI_7SyvORi0_CQ429l_c0oqIFPtPkS/view?usp=sharing

Table 3 Final Change map (2006- 2016) class's information

Forest Non Forest Map	Forest Type Map	Forest Type Change Map
Non Forest stable	Non Forest stable	Non- Forest stable
Forest	**Deciduous Forest (DF)**	**Deciduous forest stable**
		Deciduous forest loss
		Deciduous forest gain
	Evergreen Forest (EG)	Evergreen forest stable
		Evergreen forest loss
		Evergreen forest gain
	Mangrove forest (MG)	Mangrove forest stable
		Mangrove forest loss
		Mangrove forest gain

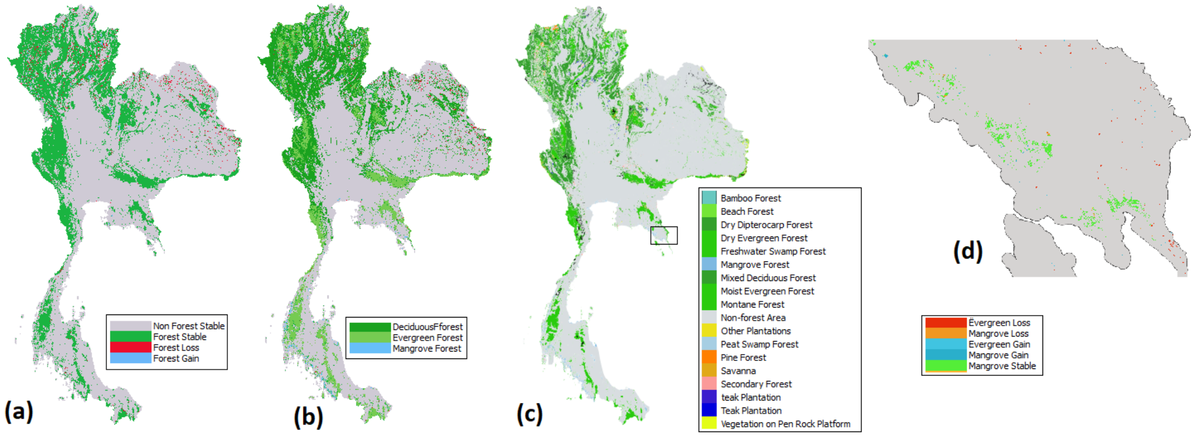


Figure 7 (a) Forest change map (2006-2016) (b) Forest type 2006 by DNP (c) Forest type map of 2016 from Royal Forest department (d) Zoomed in view of map created for sample intensification using a ,b and c map together with a focus to mangrove and evergreen class intensification only (in order to ensure sample intensification for target classes)

The main objective of the accuracy assessment of the change map was to quantify the error in the map and calculate uncertainty around the AD (area estimates). A number of parameters were considered for data collection and, based on the objectives of the assessment, a customized survey was developed using FAO's Open Foris Collect tool.

Reference data were collected using a customized survey tool of FAO's Open Foris package, Collect Earth, that works with Google Earth and Google Earth Engine (GEE) data. An example is illustrated in figure 8 with high resolution Google Earth imagery in the background, the yellow sample plot is ~0.5 ha, and each yellow dot inside the plot area represents two percent of the total sample unit area. For any sample to qualify as a forest it should have five dots falling entirely within the forest area, to comply with the 10% cover threshold of the forest definition.

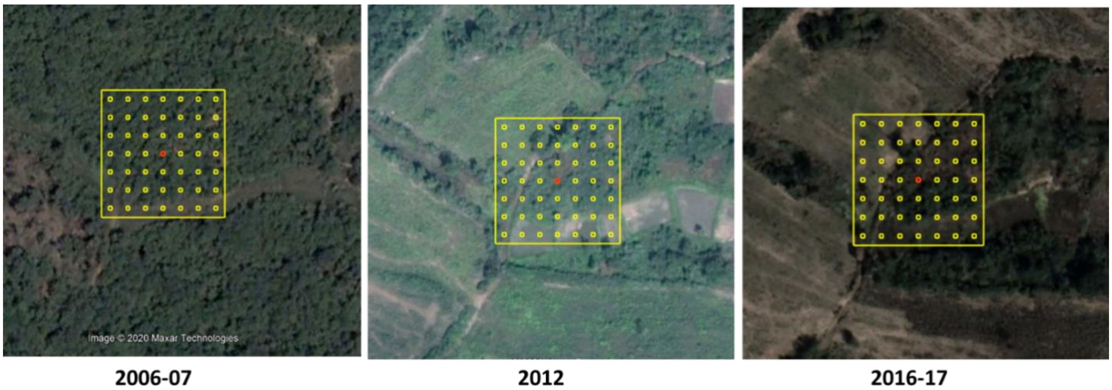


Figure 8 Example of reference data (Google Earth Archive)

Results of Activity Data

The results are displayed in the form of a confusion/Error matrix that is created in tabulation format against map and reference classes. The Error matrix gives information on agreement, omission, and commission across all classes. Table 4 shows the final activity data matrix, as highlighted in the table, light blue color cells show the agreement of map and reference data per class, whereas the first row is showing omissions of forest loss, gain and stable canopy cover based in the non-forest category and the first column indicates commission error for each class in non-forest category. In total, only two samples from the reference data were excluded because of false confidence. In the same manner, the error matrix of the area estimate (table 5) was created to better understand the weightage associated with omissions in stable classes which are directly linked to confidence intervals of each class as explained by Olofsson et.al. 2020.

The light orange heightened cells in both tables indicate the areas of omission in stable classes and high weight samples in terms of hectares. In Table 4 EG (Evergreen forest) loss in the stable Forest and Non-forest cell is highlighted with light orange color, meaning that in the map data these points are classified as non-forest areas whereas reference data says that both samples were forest in 2006 and were observed as the loss over the reference period. Olofsson et.al. 2020 says a reference observation is the most accurate and provides information on true land surface conditions.

Therefore these points are considered as an omission of evergreen forest loss in the non-forest stable category. When it is compared with table 5 where the weighted area is calculated for all classes, these two samples of omission in EG loss represent an area of 74,530 ha, which is almost three times bigger than the correctly estimated area of evergreen forest loss (20,641 ha). Such omission errors result in higher confidence intervals (CI). The total stratified area estimate (SAE) for each class is given in the last row of the table as the sum of figures in each column. Olofsson et.al. 2020 advises that omissions in the stable classes are results of classification error and insufficient sampling or lack of proportional sampling design in the stable classes are most likely generating high CI. When omissions occur in the stable classes that are occupying a large proportion of the map area, the weightage associated with those omissions is also high which increases the CI of rare classes (change classes) which occupy comparatively small areas on the map. Therefore, reducing omission errors in a stable class can reduce the CI for the change classes.

Tables 6 and 7 display the forest change transition with stratified area estimates in hectare and CI in percentage, highlighting deforestation in red, and enhancement of forest carbon stocks in green.

Table 4 Error Matrix of the accuracy assessment results

class	Non Forest	DF stable	DF loss	DF gain	EG Stable	EG loss	EG gain	MG Stable	MG loss	MG gain
Non Forest	913	29	5	0	10	2	0	0	4	1
DF stable	2	223	2	0	3	0	0	0	0	0
DF loss	66	37	99	0	7	10	0	0	1	0
DF gain	43	73	2	58	8	0	6	0	0	3
EG Stable	8	31	1	2	158	1	0	0	0	0
EG loss	12	7	10	0	16	18	0	2	5	0
EG gain	3	13	0	9	41	0	21	0	0	0
MG Stable	1	0	0	0	2	0	0	55	1	0
MG loss	7	0	0	0	0	0	0	6	24	0
MG gain	8	0	0	0	0	0	0	19	0	28

Table 5 Stratified area Estimates and confidence interval of error matrix

class name	Non Forest	DF stable	DF loss	DF gain	EG Stable	EG loss	EG gain	MG Stable	MG loss	MG gain
Non Forest	34,022,947	1,080,685	186,325	0	372,650	74,530	0	0	149,060	37,265
DF stable	77,979	8,694,631	77,979	0	116,968	0	0	0	0	0
DF loss	199,746	111,979	299,619	0	21,185	30,265	0	0	3,026	0
DF gain	22,555	38,291	1,049	30,423	4,196	0	3,147	0	0	1,574
EG Stable	270,357	1,047,632	33,795	67,589	5,339,542	33,795	0	0	0	0
EG loss	13,761	8,027	11,467	0	18,348	20,641	0	2,293	5,734	0
EG gain	888	3,849	0	2,664	12,138	0	6,217	0	0	0
MG Stable	3,613	0	0	0	7,225	0	0	198,693	3,613	0
MG loss	137	0	0	0	0	0	0	117	470	0
MG gain	237	0	0	0	0	0	0	563	0	830
SAE	34,612,219	10,985,093	610,234	100,677	5,892,252	159,230	9,364	201,668	161,902	39,669

Table 6 Stratified Area estimates for forest change transition

SAE (ha)	2016			
2006	Evergreen Forest	Deciduous Forest	Mangrove Forest	Non-Forest
Evergreen Forest	5,892,252			159,230
Deciduous Forest		10,985,093		610,234
Mangrove Forest			201,668	161,902
Non-Forest	9,364	100,677	39,669	34,804,971

Table 7 Confidence Interval of forest change transition

CI (%)	2016			
2006	Evergreen Forest	Deciduous Forest	Mangrove Forest	Non-Forest
Evergreen Forest	8%			78%
Deciduous Forest		5%		35%
Mangrove Forest			7%	90%
Non-Forest	36%	93%	184%	2%

Deforestation

Enhancement of carbon stocks (gain)

Because of the high CI around forest type change classes, aggregated results were also checked by classes including non-forest, stable forest, loss, and gain, and results are presented in Annex II in more detail. The aggregated results show CI for forest loss results is 30% whereas for forest gain it is 77%. The overall CI for stable classes remains low at 2 and 3 percent for non-forest and stable forest categories respectively.

The final results reported in the FREL and FRL are based on AD by forest types and EF data which is calculated by forest type. The results show that evergreen forest loss and deciduous forest loss were probably not captured correctly, because of the difficulty in correctly identifying the forest type. However, the high CI for mangrove loss estimates probably arose from inaccuracies in the mapped data. The five omissions of EG loss class falling in the mangrove loss category means that those areas were misclassified as EG forest whereas according to reference data those samples fall inside mangrove forest.

Emission and Removal Factors

Available forest inventory data

2003-2010: First National Forest Inventory (cycle 1): This inventory was conducted with support from the International Tropical Timber Organization (ITTO), to help design, train and implement a forest inventory across all land in Thailand. The method is documented in the ITTO report PD 195/03 Rev.2 'Sampling design, plots establishment, and estimation methods for Thailand's national forest resources monitoring information system'

The inventory was conducted in two phases:

> 2003-04: A national 20x20km grid was used to establish Primary Sample Units (PSUs) across all lands. In each PSU falling in forest land a cluster of 5 plots was measured, collecting the typical forest mensuration measurements.
>
> 2005-2010: The second phase of the inventory consisted of an additional set of PSUs established at 10x10km and 5x5km spacing in forest land which were measured for the same set of variables.

Though the inventory was conducted over 7 years, more than half of the plots on the 10x10 km grid were measured by the end of 2005, therefore carbon stock estimates calculated from this inventory are considered for the year 2005.

2011-2012: Partial repeat of the National Forest Inventory (cycle 2). This measurement covered the same PSUs as established in 2005 for the first NFI cycle with the 10x10km grid. The 20x20km grid was not sampled. This repeat only collected data from the center subplot of each PSU. The data from this inventory were not used to construct the FREL/FRL as there was no intermediate activity data in the middle of the reference period.

2013-2018: National Forest Inventory with intensification in coserved areas (cycle 3).

The inventory was conducted following two designs:

DNP conducted sampling across all conserved forests in Thailand at a sample intensity of 10x10km, followed by an inventory of forests in conserved areas on a 2.5 x 2.5 km grid. Many of the PSUs were re-measurements of the original PSUs established in 2004-2005; however due to errors in GPS use in 2004-2005 approximately 20% of the original PSUs could not be relocated or re-measured, so new PSUs were established. Only a small percentage of the plots were exactly relocated, the majority of the plots had similar GPS coordinates but the exact centers of the plots were not found. The sampling only collected data from the center subplot.

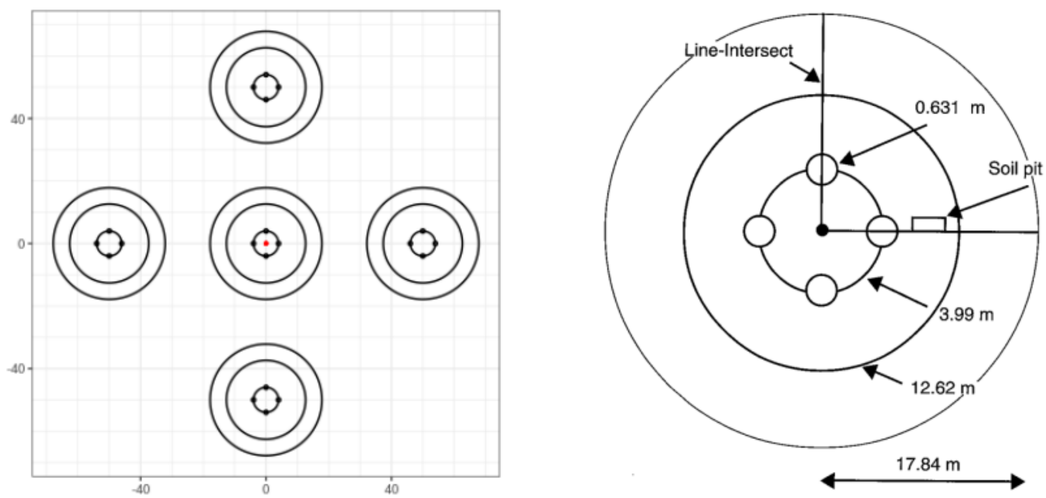
In 2018 RFD conducted sampling across all reserved forest in Thailand and measured several plots from the 10x10 km sampling grid, including the original 20x20km grid established in 2004. The sampling only collected data from the center subplot.

The cycle was implemented from 2013 to 2018 but by the end of 2017 half of the plots on the 10x10 km grid had been measured and 2017 was therefore considered the reference year for this cycle.

The NFIs had only seven plots in Mangrove forest and only in the first cycle. It was not enough to get information on this forest type, therefore additional 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 re-measured, hence decay and increment for mangroves in Thailand was unknown.

From this data the average AGB for Mangrove forest was 120.779 ton/ha and its confidence interval was 18 %. More information on the Mangrove carbon stock calculations can be found with DMCR.

All the NFIs followed the same plot design with nested circular subplots, the largest of 0.1 ha area. However, during cycle 1 five plots were measured to constitute the PSU, while in cycle 2 and 3 only the center plot was measured.



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 9 Plot design the National Forest Inventory

Table 8 Summary of the NFIs and the mangrove study.

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	2005	2011-2012	2017	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) (**).	Random sampling of 37 plots
PSU design	Cluster of 5 plots	Center plot only	Center plot only	Single plots

(*) In practice RFD measured 8 plots inside conserved areas, and DNP had a small fraction of their plot falling outside conserved area boundaries.

(**) Only few conserved areas had the 2.5 km grid applied to them.

Method for emission and removal factors calculation

From the description of the NFI data the following methodological choices were made:

1. Use only the center plots from cycle 1 to keep consistency with cycle 2 and 3.
2. The cycle 2 data was not used as there was no activity data from around 2010. The annualized differences between the cycle 1 and 3 were assumed to reflect well the changes during the FREL and FRL period.
3. As most plots were not relocated exactly, carbon stock differences could not be calculated at the plot level but were instead the results of averages at the forest type level, following a gain-loss approach.
4. All forest types were grouped to Deciduous forest and Evergreen forest to align with the Activity Data. Deciduous forest was composed of Mixed Deciduous and Dry Dipterocarp forest, Evergreen forest was composed by Tropical Evergreen, Hill Evergreen, Dry Evergreen, Freshwater Swamp, Peat Swamp, Pine and Beach forest, noting that the 4 last forest types were marginal both in area and number of plots measured.
5. The approach chosen to calculate the carbon stock was to keep only the plots measured on the 10 km grid in cycle 1 and 3 and use a stratified random sampling approach to account for different sample intensities (most plots outside conserved areas not being remeasured in cycle 3). Two strata were defined, one for Conserved Areas (CA) and one for Reserved Areas (RA).

The calculation process was (see Annex on EF for more details on methods):

1. Data preparation and cleansing:

   All the raw data were stored in multiple MS Access databases, with sometimes plot data duplicated in several databases. The storage was improved to one database per NFI cycle. The data quality was very good, no outliers were found in tree measurements, the species list was very complete with a very good level of species identification, and only one outlier was found at plot level. The outlier plot's AGB was still realistic but much higher than all the other plots and this plot was not used for the final analysis.

2. **Calculation of AGB at tree level with Thailand based allometric equations:**
   The Thailand based equations were developed in 1965 and 1983. They could seem old and the studies presenting them didn't include exhaustive indicators of performance, but these models were still very popular in Thailand and only pan-tropical equations could be used as alternatives.

   To help validating these equations, 60 trees had their biomass measured with a semi-destructive method and both the Thai equations and the pan-tropical model from Chave et al 2014 were applied to the measurements. The study concluded that both models had acceptable performances and the Thai equations were selected.

Table 9 Allometric equations used for tree aboveground biomass calculation.

Tropical Evergreen forest (Ogawa 1965 trop.):

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

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

Mixed Deciduous forest (Ogawa 1965 md.):

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

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

Hill and dry evergreen forest (Tsutsumi 1983) (*):

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

(*) Tsutsumi was also applied to Pine, Swamp and Beach forests.

Table 10 Bias of the Chave and Thailand based allometric equations in percent, based on a study of 60 trees (see Annex).

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

3. Pro gation to plot level:

   Tree AGB was summed to plot level and converted from kg to ton/ha.

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

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

4. Aggregation to forest type level:
   The aggregation from plot to forest types followed the method for stratified random sampling from Cochran 1997 and was done in two steps:

   a. Simple averages and standard deviations were calculated for the two main forest types with all the plots inside each forest type and strata (CAs and RAs).
   b. A weighted average was calculated between strata to account for the difference of sampling intensity inside each stratum:

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

   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.

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

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.

5. Carbon stock calculations:
   Carbon stock was calculated from the AGB with root-to-shoot ratios (RS) from the IPCC guidelines, a carbon fraction of 0.47 (from the IPCC guidelines 2006), and the ratio of the CO2 and C atomic masses:

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

Table 11 Root-to-Shoot Ratios.

Forest type	RS	Source
Evergreen	0.37	IPCC 2006, Vol. 4, Table 4.4.
Deciduous	0.2	
Mangrove	0.49	IPCC 2013, table 4.5

6. Emission and removal factors:
   The emission and removal factors (EFRF, in tCO2/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 (11 years), resulting in positive values when the stock decreased (emissions) and negative values when the stock increased (removals). The confidence interval (CI) associated to the difference between carbon stocks was calculated as follows (IPCC guidelines 2006):

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

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

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

Emission and removal factors calculations

The average biomass per strata showed less biomass in reserved areas than in conserved areas, especially for evergreen forest, and a general increase of biomass between cycle 1 and 3. The confidence intervals are relatively small, expect for reserved evergreen forests where few plots only were measured, particularly in the cycle 3.

Table 12 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	RA	89	96.397	20	0.234
Cycle 1	EV	CA	265	141.414	10	0.766
Cycle 1	DE	RA	416	44.238	8	0.458
Cycle 1	DE	CA	414	63.751	8	0.542
Cycle 3	EV	RA	35	97.822	27	0.234
Cycle 3	EV	CA	225	148.089	9	0.766
Cycle 3	DE	RA	119	56.912	14	0.458
Cycle 3	DE	CA	347	72.693	6	0.542

(*) EV : Evergreen , DE : Deciduous , MG : Mangrove (**) RA : Reserved Areas , CA : Conserved Areas

With the stratified approach, the smaller number of plots in reserved areas was accounted for and resulted in lower increase between cycle 1 and 3, both in Evergreen and Deciduous forest.

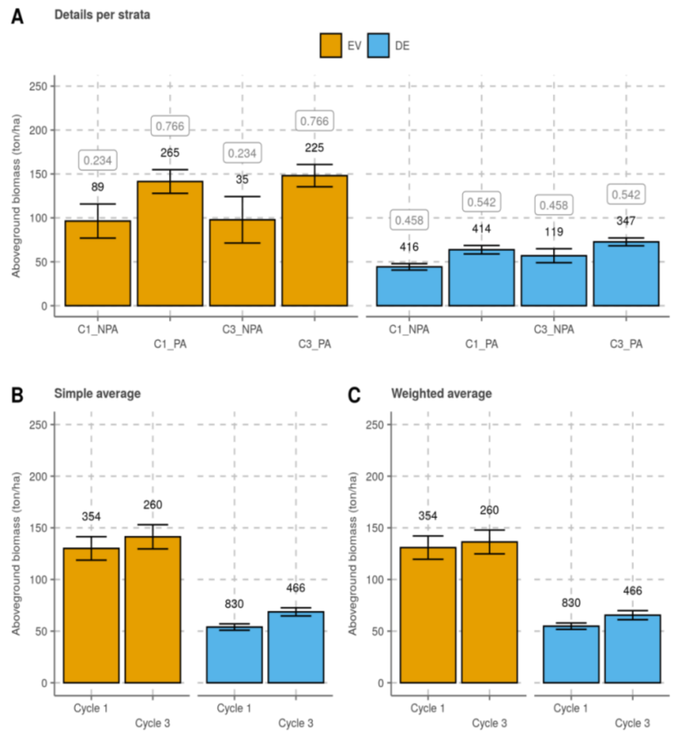


Figure 10 Aboveground biomass per forest type calculations for approach 1. Simple average per strata (A), simple average of all plots (B) and weighted average of the strata (C). The strata weights are represented in grey and a number of plots in black.

The final carbon stocks in cycle 1 and 3 were 309 +/- 9% to 322 +/- 8% tCO2/ha in Evergreen forest and 113 +/- 6% to 135 +/- 7% in Deciduous forest, resulting in removals of 1.2 and 2 tCO2/ha/year during the reference period, for Evergreen and Deciduous forest, respectively.

Table 13 Carbon stock per forest type in t/ha with their half confidence interval.

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[7]	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

[7] DMCR study during 2016-2017 of plots 37 plots is used for both cycles

Table 14 Emission and removal factors in tAGB/ha.

EFRF (tAGB/ha)		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 15 Emission and removal factors in $tCO_2/ha/yr$.

EFRF (tCO_2/ha/year)		Cycle 3			
		EV	DE	MG	NF
Cycle 1	EV	-1.169	15.784	-0.103	28.091
	DE	-18.955	-2.002	-17.889	10.305
	MG	-1.066	15.887	0	28.194
	NF	-29.26	-12.307	-28.194	0

Table 16 Half confidence interval of the emission and removal factors in percent.

CI EFRF (%)		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

(*) EV : Evergreen , DE : Deciduous , MG : Mangrove , NF : Non-Forest

ASSESSMENT OF EMISSIONS AND REMOVALS AND UNCERTAINTY

Method for calculating the emissions and removals

Following the IPCC 2006 Guidelines, the Emissions and Removals (ER) were calculated for each land use change category as the product of the Activity Data and Emission and Removal Factors:

$$\mathrm{ER}_{i,j} = AD_{i,j} \times EFRF_{i,j} \times RP$$

With AD and EFRF the activity data (in ha) and the emission and removal factor (in tCO2e/ha/yr) are associated with the change from the forest type i in 2006 to the forest type j in 2016, and RP the reference period.

The Emissions and Removals per REDD+ activity were calculated as the sum of the Emissions/Removals from the land use changes associated with the REDD+ activities. The FREL and FRL were then the sum of Emissions from Deforestation and Degradation and the sum of Removals from Forest restoration and Reforestation, respectively.

Their uncertainty was propagated with the formula for the sum and product of uncertainties in the IPCC 2006 guidelines Vol. 1 Chapter 3:

$$U_{\mathrm{ER}_{i,j}} = \sqrt{{U_{AD_{i,j}}}^2 + {U_{EFRF_{i,j}}}^2}$$

$$U_{FREL} = \frac{\sqrt{(U_{DF} \times ER_{DF})^2 + (U_{DG} \times ER_{DG})^2}}{|FREL|}$$

$$U_{FRL} = \frac{\sqrt{(U_{RF} \times ER_{RF})^2 + (U_{RE} \times ER_{RE})^2}}{|FRL|}$$

With: U the percentage uncertainty, ER the Emission/Removal, DF deforestation, DG forest degradation, RF afforestation/reforestation, and RE restoration.

Emissions and Removals per land use change category

According to the activity data, forests did not change from one forest type to another. As there was no change of land use inside forest areas and the emission and removal factors for stable forest were all removed, i.e. increase of carbon stock, no forest degradation was reported. Forest degradation very likely occurred in Forest land however according to the NFI data there was as much or even more removals on average, leading to stable forests being a net sink of CO_2 during the reference period. The increase in carbon stock in Deciduous Forest is very clear, however in Evergreen forest it is very small and with a very large Uncertainty.

Table 17 Emissions and Removal (tCO_2e) over reference period

EFRF (tCO_2e/ha/year)		2016			
		EV	DE	MG	NF
2006	EV	-1.169	15.784	-0.103	28.091
	DE	-18.955	-2.002	-17.889	10.305
	MG	-1.066	15.887	0	28.194
	NF	-29.26	-12.307	-28.194	0

AD (ha) over 10 years		2016			
		EV	DE	MG	NF
2006	EV	5,892,252			159,230
	DE		10,985,093		610,234
	MG			201,668	161,902
	NF	9,364	100,677	39,669	34,804,971

ER (tCO_2e) over 10 years		2016			
		EV	DE	MG	NF
2006	EV	-68,880,426	-	-	44,729,299
	DE	-	-219,921,562	-	62,884,614
	MG	-	-	-	45,646,650
	NF	-2,739,906	-12,390,318	-11,184,278	-

(*) EV : Evergreen , DE : Deciduous , MG : Mangrove , NF : Non-Forest

Table 18 Emission and Removals Uncertainties in Percent over reference period

CI (%)		Cycle 3			
		EV	DE	MG	NF
Cycle 1	EV	296	18	246	75
	DE	15	50	34	36
	MG	160	41	7	92
	NF	37	93	185	2

(*) EV : Evergreen , DE : Deciduous , MG : Mangrove , NF : Non- Forest

Table 19 Emission and Removals: Sum of total over reference period and annual estimates with assessed uncertainties

		E/R over reference period (tCO_2e)	Average annual E/R (tCO_2e)	95% Confidence Interval (%)
Deforestation (Forest – Non-Forest)		153,260,563	15,326,056	39
Enhancement (Non-Forest - Forest)		-26,314,503	-2,631,450	90
Degradation (Forest - Forest)	Net Change (Forest - Forest)	**-288,801,988**	**-28,880,199**	**80**
Enhancement (Forest - Forest)				
FREL (Total Emissions)			**15,326,056**	**39**
FRL (Total Removals)			**-31,511,649**	**74**

Confidence Interval (CI) propagation according to IPCC 2006 guidance for uncertainties

PLAN OF FUTURE FREL AND FRL IMPROVEMENT

In the development of the FREL and FRL, and the underlying National Forest Monitoring system (NFMS/MMR), a step-wise approach has been applied that will allow for improvements in future submissions as methods improve and new information becomes available. The following areas are considered areas of future improvement:

- NFI coverage

The Carbon stock increase between the NFI cycles 1 and 3 means that stable forests have become a sink of GHGs over the past 10 years. The trend was clear in Deciduous forest, but less so in Evergreen forest, resulting in high uncertainties around the emission and removal factors. A potential future improvement to the FREL and FRL could be to distinguish AD between forests inside and outside conserved areas, and increase the number of plots measured outside conserved areas, especially in evergreen forest, to better understand if the dynamics are different. A base 10 km grid that covers all land (forest and non-forest) would be the best way to track change at the national level in the future, whereas the grid could be intensified in certain areas of interest. Finally, mangrove forests are a key ecosystem in Thailand but were not well covered by the NFI and only a few other studies targeted this forest type. This is also a potential area of future improvement.

- Diversifying carbon pools

Out of five carbon pools as described per IPCC guidelines, only two pools (AGB and BGB) are included in this FREL and FRL, which is consistent with LULUCF section in the national GHG inventory, and believed to be conservative while limited information exist on the litter, deadwood, and SOC pools. Information on these pools is considered an area of future improvement.

- **Inclusion of non-CO_2 GHGs**

Only CO_2 is included in this FREL and FRL because Thailand's emissions of other GHGs from land use and land use change are considered to be minor, and their exclusion is considered a conservative approach while limited information exists. Thailand intends to monitor and explore inclusion of other gasses in its future submissions.

- **Activity Data**

The overall result of accuracy assessment is satisfactory for the aggregated classes but the confidence intervals around forest type change classes are high. Most of the omission of evergreen loss was in deciduous forest category and vice versa which is indicating that probably the forest type is miss classified in the map used to assign forest types or the reference data need careful review for forest type interpretation.

The future areas of improvement which Thailand would like to consider include improvement of forest monitoring methods by using direct supervised change detection or time series analysis such as with the tools Break for Additive Seasonal and Trend (BFAST) or Continuous Change Detection and Classification (CCDC).

Another area of improvement to consider is to use a stratified random sample design with a proportional sample allocation and a multi interpreter approach for reference data collection to calculate the interpretation bias and interpretation error.

The highest CI is observed around gain classes, which is tricky to capture and a map with more accurate information can improve the estimates of the forest gain layer. In the current analysis most of the gains in map data were actually observed as a stable class, therefore improvement of the mapping of forest enhancement is considered an area of future improvement.

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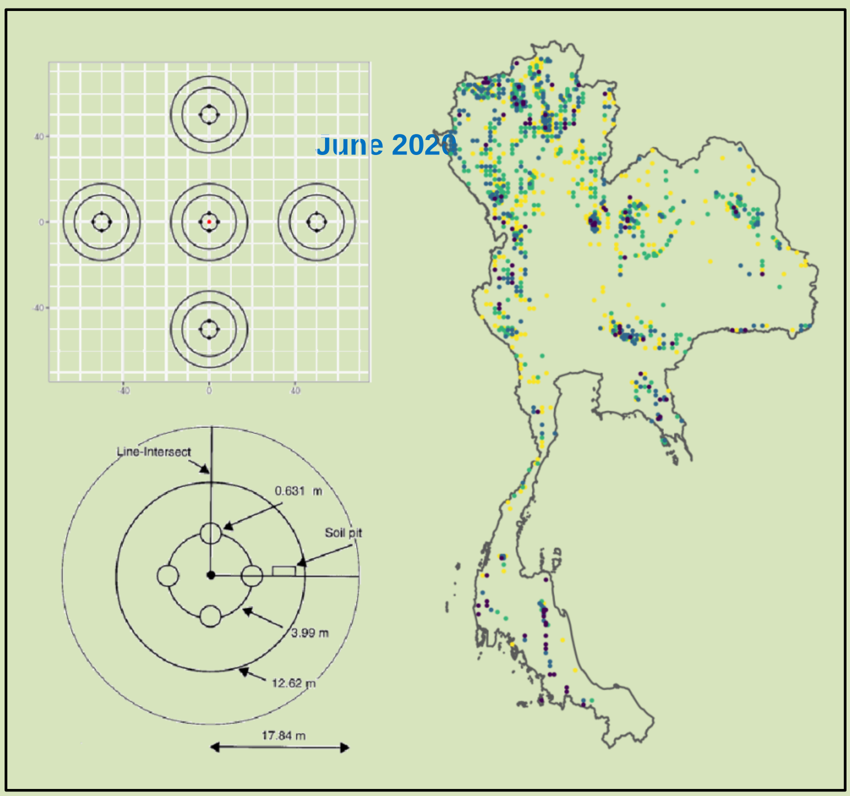
ANNEXES

ANNEX I

Calculation of Emission and Removal Factors for Thailand Forest Reference (Emission) Levels

June 2020



Calculation of Emission and Removal Factors for Thailand Forest Reference (Emission) Levels

Gael Sola[1], Apichat Kerdmongkol[2], Suphattra Phromphan[2], Inthira Trachoo[2], Mathieu Van Rijn[1], Auschada Chitechote[2], Sutthatip Chormali[2] , Somyot Saengnin[2]

[1]Forestry Department, Food and Agriculture Organization of the United Nations

[2]Department of National Parks, Wildlife and Plant Conservation

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Abstract

Context

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 a small emphasis on conserved areas. The second cycle was the lowest in terms of intensity and time frame, with the remeasurements of the plots in conserved areas and the 10 km grid only. It was conducted in 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 conserved areas, and was complemented by a large number of plots in a very small 2.5 km grid in a subset of the conserved areas.

Objective

This study aimed at estimating forest emission and removal factors to contribute to Thailand first FREL and 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 conserved areas in the sampling designs, the information on conserved areas was added to the NFI data based on the plots GPS location.

The NFI cycle 2 and 3 aimed at reseating at least partially the forest plots from 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.

As different sampling intensities were applied to different populations, i.e. different conserved areas, using all the inventory plots measured would require a complex stratification system, and though potential sources of bias would be hard to detect and account for. After considering several different alternatives, the approach selected to analyze the data was to select only the plots measured on the 10 km grid and apply a stratified random sampling with one stratum for conserved areas and one stratum for reservation areas. This stratification allows for the fact that conserved forests have on average higher biomass/ha than reserved forests.

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. No error was found in the data but it was too different from all the other plots.

Re-analyse the data confirmed the emphasis on conserved 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 of conserved areas. The stratified estimators accounted for these differences.

The main trend observed was biomass increasing 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

Overall the carbon stock increased in the two main forest types, meaning Thailand's forest is accumulating CO_2 from the atmosphere. All the plots measured could not be used, 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 conserved areas and across all forested lands in Thailand would help to better understand if the dynamics are different when forests are under conserved 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.

Table of Content

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
FREL/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

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 programe, 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 conserved forests, resulting in 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 estimates 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 Conservation Forests and RFD of the National Reserve Forest. 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.

METHOD

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 conserved 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 conserved areas. The last cycle repeated the 10 km grid, almost exclusively in conserved areas (concervation forest) by DNP, and around 150 plots outside conserved areas were measured by RFD. DNP also measured more than 2000 plots in few targeted conserved 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 conserved forests	Update the 2nd NFI with a few plots added back to reserved forest and an intensification for a few selected conserved 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 conserved areas	Mostly forest conserved areas (176 plots intended outside)	All mangroves in Thailand
Sampling grids	20 km outside forest land, 10 and 5 km forest areas (+)	10 km inside conserved areas	10 km outside conserved areas (by RFD) (*), a mix of 10, 5 and 2.5 km inside (by DNP) (**).	Random sampling of 37 plots
PSU design	Cluster of 5 plots	Center plot only	Center plot only	Single plots

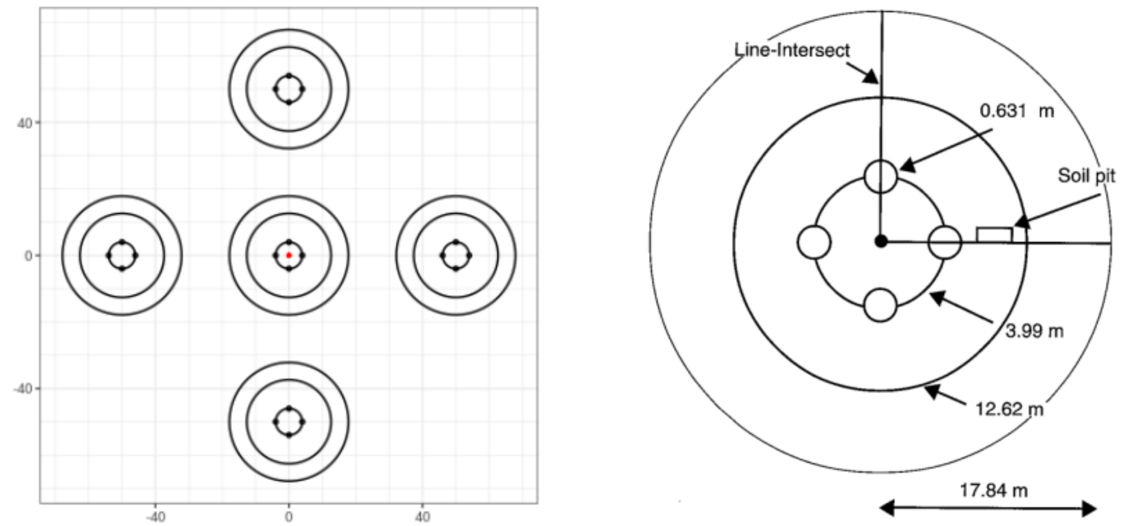
(+) The 10 km grid was systematic while the 5 km doesn't cover all forests.

(*) In practice RFD measured 8 plots inside conserved areas, and DNP had a small fraction of their plot falling outside conserved area boundaries.

(**) Only few conserved areas had the 2.5 km grid applied to them.

As the main objective of the Thailand NFI evolved towards a better understanding of forest in conserved 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. All the other remeasured plots may have shifted a few meters from the original center plots, they were considered remeasured on paper only (same theoretical plot coordinates). For this reason, plots are not treated as 'paired' or permanent plots and carbon stock evolution could not be calculated at the plot level and 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 direction (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.

Supplementary data on mangroves

The NFIs had very little coverage of mangrove forests with only seven plots in the first cycle (see Table 2 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	Pak Prasae 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

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 type could be calculated as the average AGB 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:

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

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

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

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 conserved areas or the specific areas where the sampling was intensified, over populations where the sampling intensity was reduced, for example reserved 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, conserved and reserved 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 fourth 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 conserved 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:

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

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)):

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

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.

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

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.

Explanation over a schematic example

This approach was presented as an example in Figure 2. A simple average could work if all plots were reassured. But as 2 plots were not remeasured in reservation forest, the simple averages would give a biased estimate for cycle 3 and therefore a biased comparison of biomass between cycles 1 and 3.

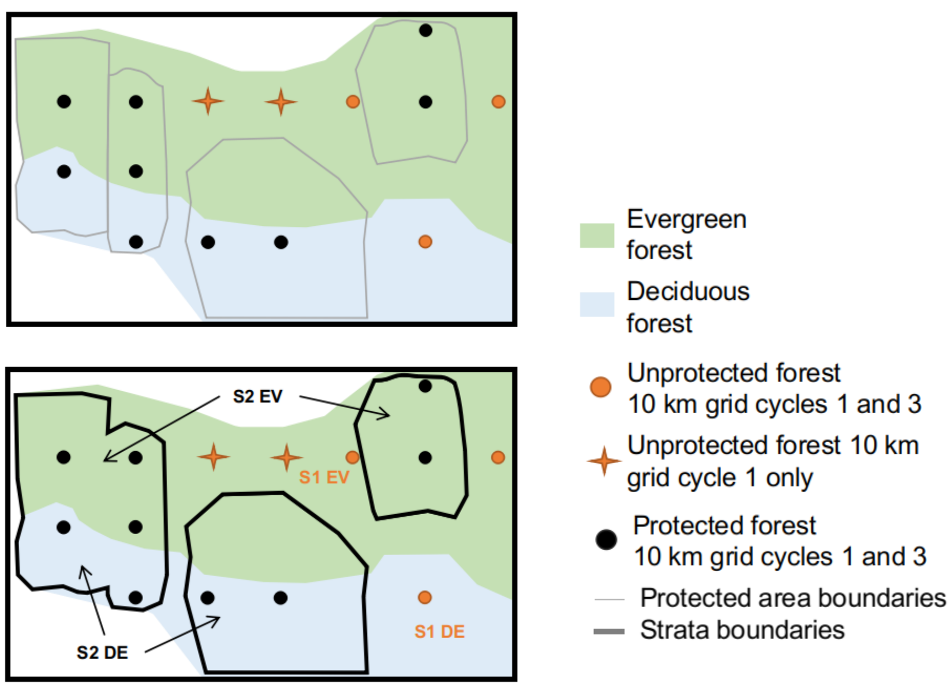


Figure 2: Schematic example of the stratification approach.

To calculate an unbiased estimator, the forest could be divided into 2 strata, S1 for reserved areas and S2 for conserved 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 5 plots in both cycles) multiplied by the weight of Evergreen Forest in S2 and similarly for the aboveground biomass of Deciduous forest.

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

Approach chosen for the data analysis

The approach chosen for the data analysis was to use all the plots measured in the 10 km grid and separate them into 2 strata: conserved areas and reserved areas. The 10 km grid gives the broadest coverage of all forest land in Thailand and therefore will yield the most representative estimates of AGB for all forest land in Thailand. 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 for this lack of data, and as Tropical Evergreen Forest is the highest carbon stock forest type, the overall carbon stock is considered conservative.

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 of 0.47 (IPCC 2006, Vol. 4, Table 4.3) and with the ratio of atomic masses of carbon and CO_2 : 44/12. The IPCC based carbon fraction was validated by a study from Kasetsart University (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%.

$$Cstock(tCO_2/ha) = AGB \times (1 + RS) \times 0.47 \times \frac{44}{12}$$

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.

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). The confidence interval (CI) associated to the difference between carbon stocks was based on the the propagation of error approach in IPCC guidelines 2006, with the following formulas:

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

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

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

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 difficult to measure tree characteristics (such as biomass) from easy-to-measure ones like tree diameter or height (Picard, Saint-André, and Henry 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, Boyemba Bosela, and Rossi 2015).

In Thailand, tree aboveground biomass allometric equations were developed in 1965 (Ogawa et al. 1965) and 1983 (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, Puangchit, and Diloksumpun 2016; Warner, Jamroenprucksa, and Puangchit 2016) or used either the above equations (Terakunpisut 2007; Chaiyo, Garivait, and Wanthongchai 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 sites 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 decide 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)

Presentation of the equations

The equations from Thailand were developed to estimate the biomass of different forest types.

Ogawa (1965) in tropical evergreen Forest:

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

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 Reserve Forest is 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.

Ogawa in mixed deciduous forest:

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

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 Reserve Forest Reserve in 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.

Tsutsumi (1983) in hill and dry evergreen forest:

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

This equation was developed based on one site in 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 The Tsutsumi model. They were compared 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) :

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

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).

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 3) 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 3: 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 an 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.

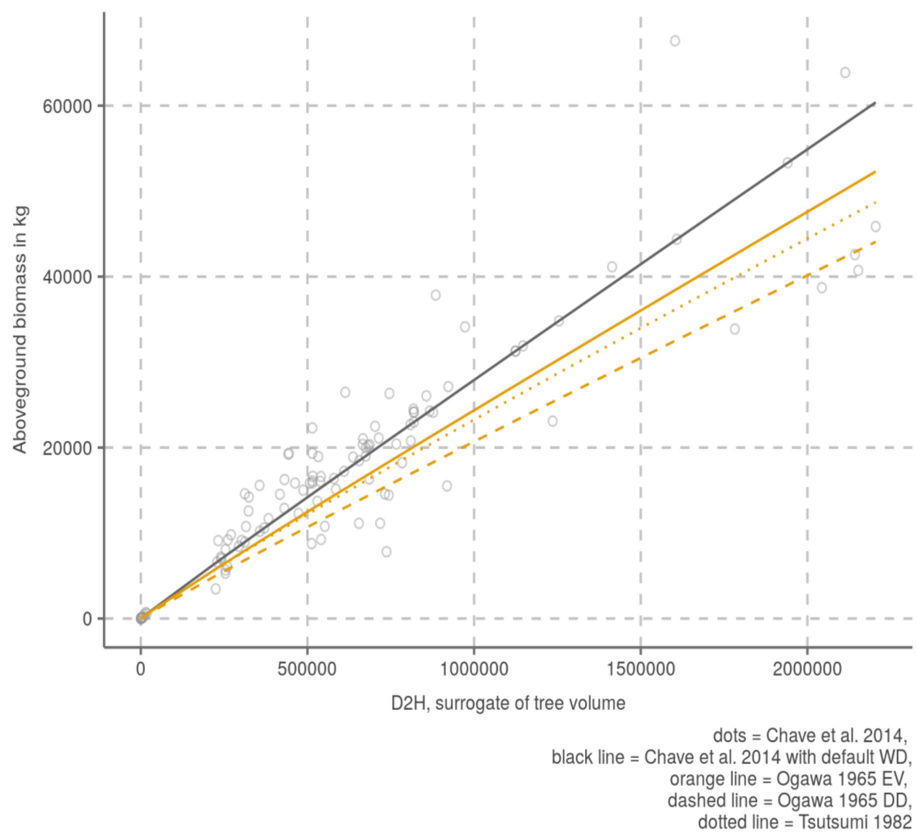


Figure 3: Tree aboveground biomass against tree surrogate of volume D^2H, for a random sample of trees along the values of D^2H.

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 8).

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 4). 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 4: 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 study could not be compared to the models' standard error, 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.

DATA CLEANING AND PREPARATION

Preparation of the plot data

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 5). The number of plots measured in the 2.5 and the 5 km grids were similar but these plots targeted different conserved 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 5: 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

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 1975 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 6).

Table 6: 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
474551906C	474546661906304C	455000	1906000	454666	1906304	1	0	1
477651571C	477646671571303C	765000	1571000	764667	1571303	1	1	1
475451661C	475446661661304C	545000	1661000	544666	1661304	1	1	1
476352126C	476346662126305C	635000	2126000	634666	2126305	1	0	1
484301836C	484295861836315C	430000	1836000	429586	1836315	1	0	1

Adding region, conserved 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 the conserved area was recorded in the data. Since conserved 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 conserved areas (Table 7). 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 conserved areas in the first NFI cycle, they were only a couple of hundred in cycle 3. A large number of the plots located outside conserved areas were non forest plots and/or had no trees. Non forest plots were removed from the analysis at a later stage.

Table 7: Number of forest plots measured inside and outside conserved areas.

	Reserved areas			Conserved areas			
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

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 to 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 is 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 conserved areas, but dropped down considerably outside conserved areas (Table 8). On the 5 km grid, the number of plots was distributed mainly in conserved areas, especially in Evergreen forest, and more equally distributed between conserved and reservation 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 conserved areas.

Table 8: Number of plots per forest type, NFI cycle and protection status.

			Reserved area			Conserved area		
NFI grid	LU code	LU	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3
10	111	Tropical Evergreen Forest	11	11	4	54	43	37
10	112	Dry Evergreen Forest	45	33	22	175	104	138
10	113	Hill Evergreen Forest	27	17	5	33	21	45
10	114	Pine Forest	3	3	2	1	1	3
10	115	Peat Swamp Forest	2	1	1	1	1	2
10	116	Mangrove Forest	1	0	0	0	0	0
10	117	Freshwater Swamp Forest	1	0	1	1	0	0
10	121	Mixed Deciduous Forest	265	170	70	308	209	258
10	122	Dry Dipterocarp Forest	151	91	49	106	79	89
5	111	Tropical Evergreen Forest	28	0	4	151	0	59
5	112	Dry Evergreen Forest	41	0	1	254	0	99
5	113	Hill Evergreen Forest	49	0	5	93	0	53
5	114	Pine Forest	10	0	0	6	0	2
5	115	Peat Swamp Forest	0	0	1	4	0	0
5	116	Mangrove Forest	0	0	0	6	0	0
5	117	Freshwater Swamp Forest	1	0	0	1	0	0
5	118	Beach Forest	1	0	0	0	0	0
5	121	Mixed Deciduous Forest	390	1	12	733	5	258
5	122	Dry Dipterocarp Forest	223	0	2	293	1	67
2.5	111	Tropical Evergreen Forest	0	0	1	0	0	223
2.5	112	Dry Evergreen Forest	0	0	6	0	0	449
2.5	113	Hill Evergreen Forest	0	0	5	0	0	212
2.5	114	Pine Forest	0	0	0	0	0	9
2.5	121	Mixed Deciduous Forest	0	0	36	0	0	1039
2.5	122	Dry Dipterocarp Forest	0	0	3	0	0	317

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 re-easured, even if they were not at the exact same location. The Figure B revealed that the difference of sampling intensity and the emphasis on conserved 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.

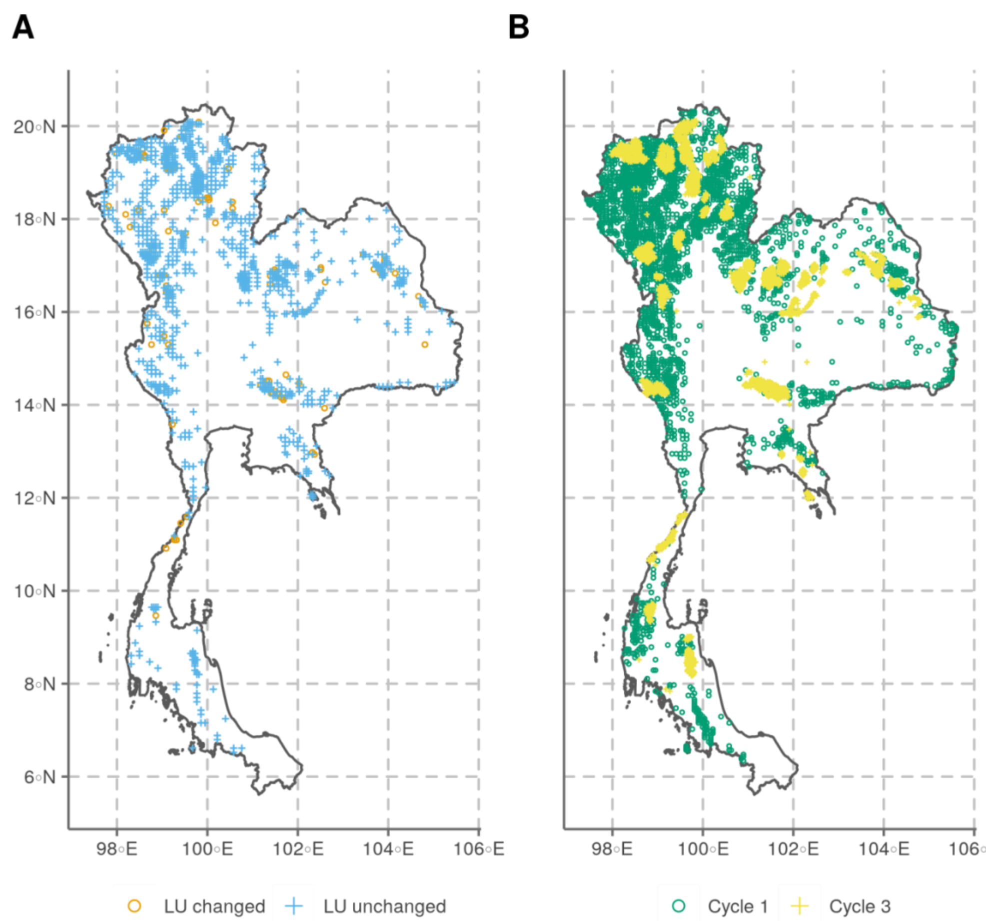


Figure 4: Plot location, remeasured plots (A) and plots measured only one time (B). Plots from all grid densities are shown

Removing pseudo trees 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 9). Other data removed were pseudo trees, 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 9: Number of trees measured after data cleaning process.

NFI cycle	Institution	Initial	Without Pseudo trees	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

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 relative 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.

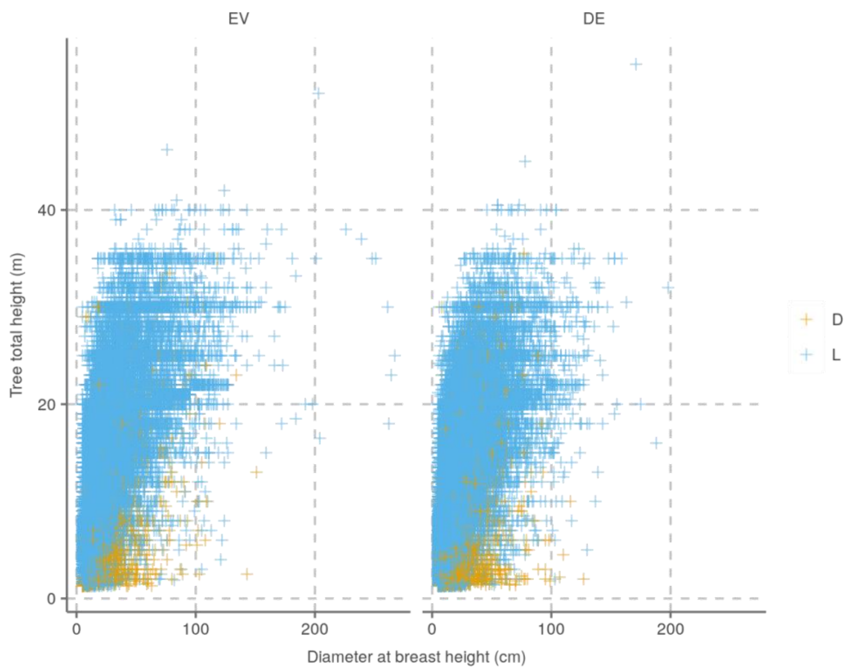


Figure 5: Tree height against diameter at breast height for dead (D) and live (L) trees.

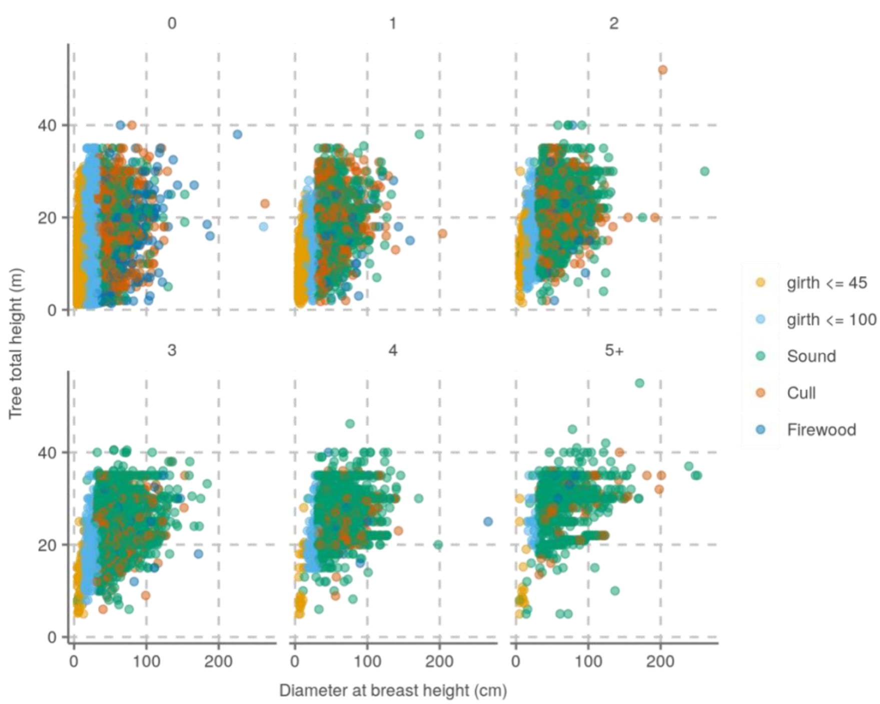


Figure 6: Tree height against diameter at breast height per timber quality and number of logs estimated.

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 10). These two species were predominantly measured in Dry Dipterocarp Forests, while the rest of the top 10 species were measured in different forest types. the measurement could have been incorrectly reported.

Table 10: 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 obtuse	94	4010
Shorea siamensis	25	3044
Streblus ilicifolius	844	64
Xylia xylocarpa var. kerrii	15	1649

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. Only one outlier was found at plot level (Figure 7) and its data removed as well. After the final set of plots cleared, three approaches to plot selection and stratification were tested to find the best compromise between simplicity and performance (Table 11).

The approach 1 focused on the 10 km grid only, the approach 2 combined the 10 km and 5 km grids, but only for remeasured plots (noting that plot centers were not exactly relocated), and the approach 3 used all plots. The three approaches gave similar results and the approach 1 was selected.

Table 11: Evolution of the number of inventory plots during the 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	RA	10	1473	505	505	505	144	505
DNP	Cycle 1	RA	5	1283	743	743	0	12	743
DNP	Cycle 1	CA	10	962	679	679	679	528	679
DNP	Cycle 1	CA	5	1810	1535	1534	0	376	1534
DNP	Cycle 2	RA	10	396	326	0	0	0	0
DNP	Cycle 2	RA	5	2	1	0	0	0	0
DNP	Cycle 2	CA	10	492	458	0	0	0	0
DNP	Cycle 2	CA	5	6	6	0	0	0	0
DNP	Cycle 3	RA	10	22	20	20	20	17	20
DNP	Cycle 3	RA	5	24	17	17	0	8	17
DNP	Cycle 3	RA	2.5	78	51	51	0	0	51
DNP	Cycle 3	CA	10	614	556	556	556	512	556
DNP	Cycle 3	CA	5	622	538	538	0	376	538
DNP	Cycle 3	CA	2.5	2561	2249	2249	0	0	2249
RFD	Cycle 3	RA	10	152	134	134	134	127	134
RFD	Cycle 3	RA	5	8	8	8	0	4	8
RFD	Cycle 3	CA	10	16	16	16	16	16	16
Total	Total	Total	Total	10521	7842	7050	1910	2120	7050

(*) RA : Reserved Areas , CA : Conserved Areas

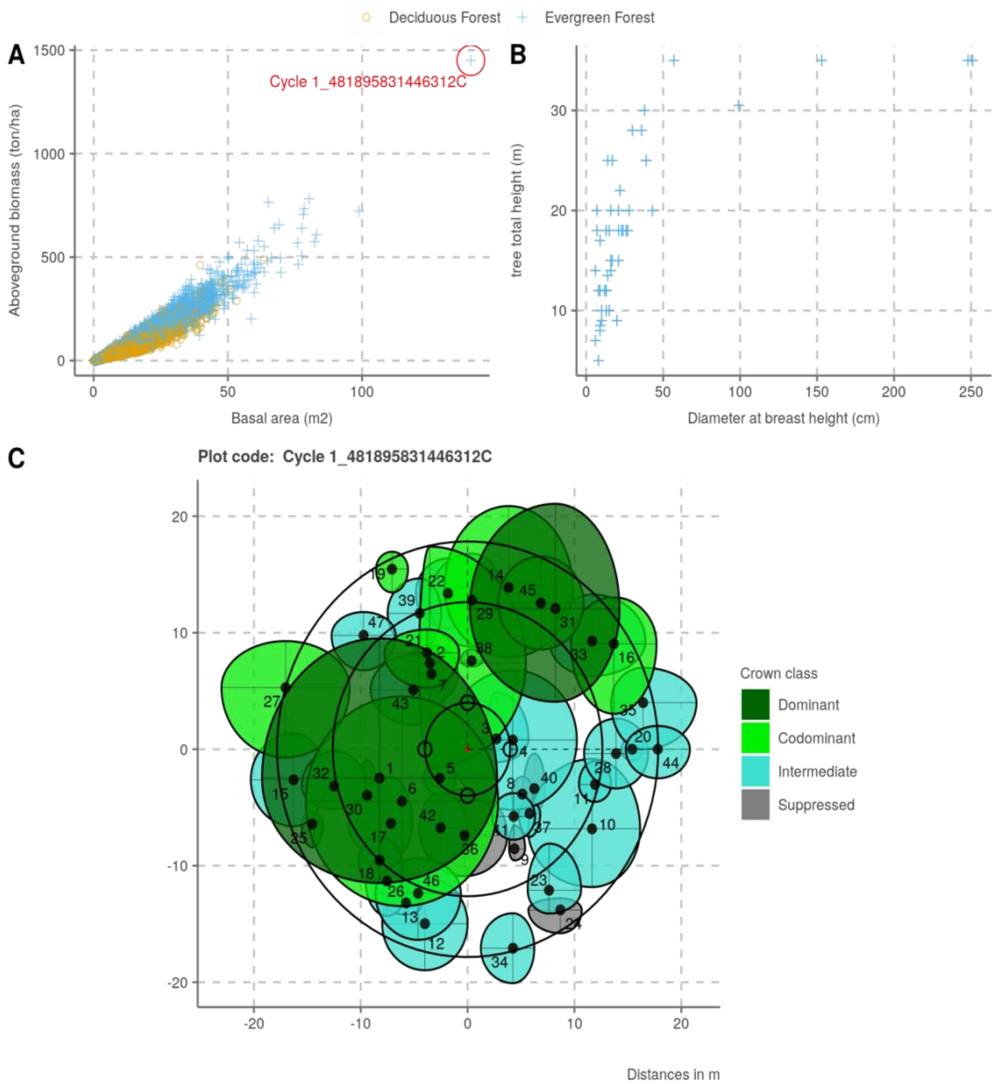


Figure 7: plot aboveground biomass against basal area (A) with outlier in red and tree H against DBH of the outlier plot (B).

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.

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.

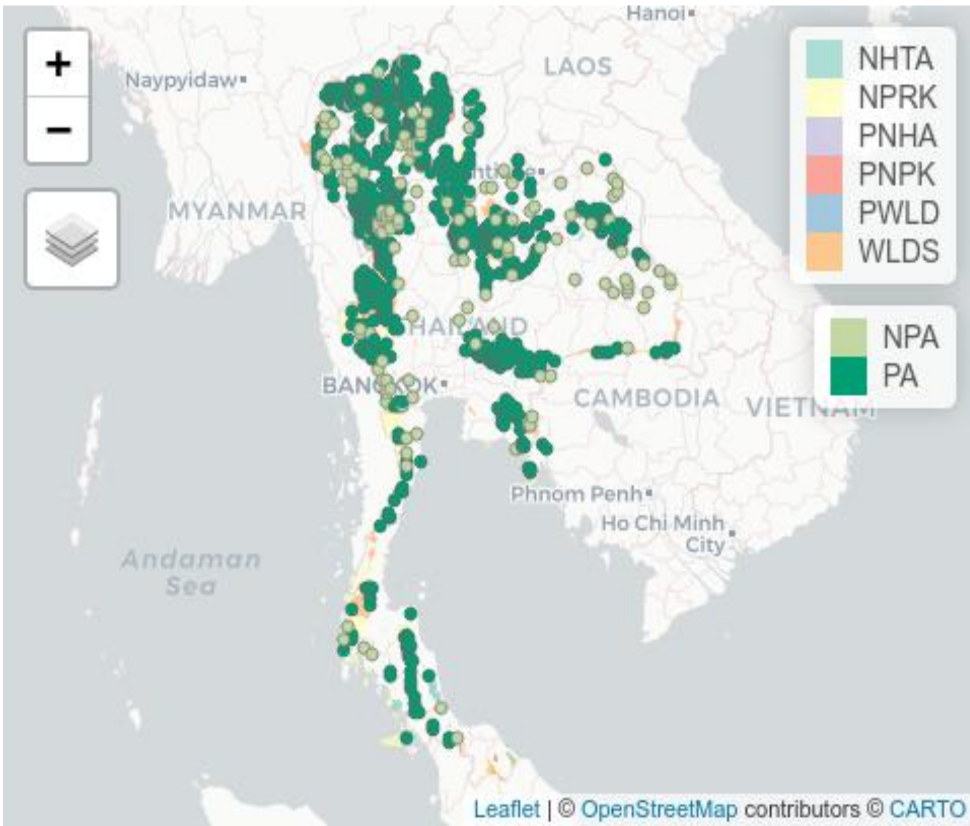


Figure 8: Dynamic map with plot locations.

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 2005 for cycle 1 and the year 2017 for cycle 3 (Table 12). The time period between the two inventories was considered to be 11 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 11 to be expressed in ton biomass or tCO_2 per year.

Table 12: Plot measurement per year to assign a reference year for each cycle (based on the 10 km grid).

NFI cycle	Inventory year	N. plots	Cum. sum plots	Total N. plots (perc.)
Cycle 1	2000	1	1	0
Cycle 1	2002	17	18	1
Cycle 1	2003	99	117	5
Cycle 1	2004	703	820	34
Cycle 1	2005	1225	2045	84
Cycle 1	2006	328	2373	97
Cycle 1	2007	37	2410	99
Cycle 1	2008	4	2414	99
Cycle 1	2009	11	2425	100
Cycle 1	2010	10	2435	100
Cycle 3	2012	11	11	1
Cycle 3	2013	83	94	12
Cycle 3	2014	60	154	19
Cycle 3	2015	34	188	23
Cycle 3	2016	138	326	41
Cycle 3	2017	475	801	100
Cycle 3	2018	3	804	100

EMISSION AND REMOVAL FACTORS WITH APPROACH 1: PLOTS ON THE 10 KM GRID

Plot location (Approach 1)

This approach was based on all the plots on the 10 km grid, split into 2 strata: Conserved Areas (CA) and Reserved Areas (RA). This subset of the data had much less plots measured outside conserved areas in the cycle 3 than in the cycle 1 (Figure 9).

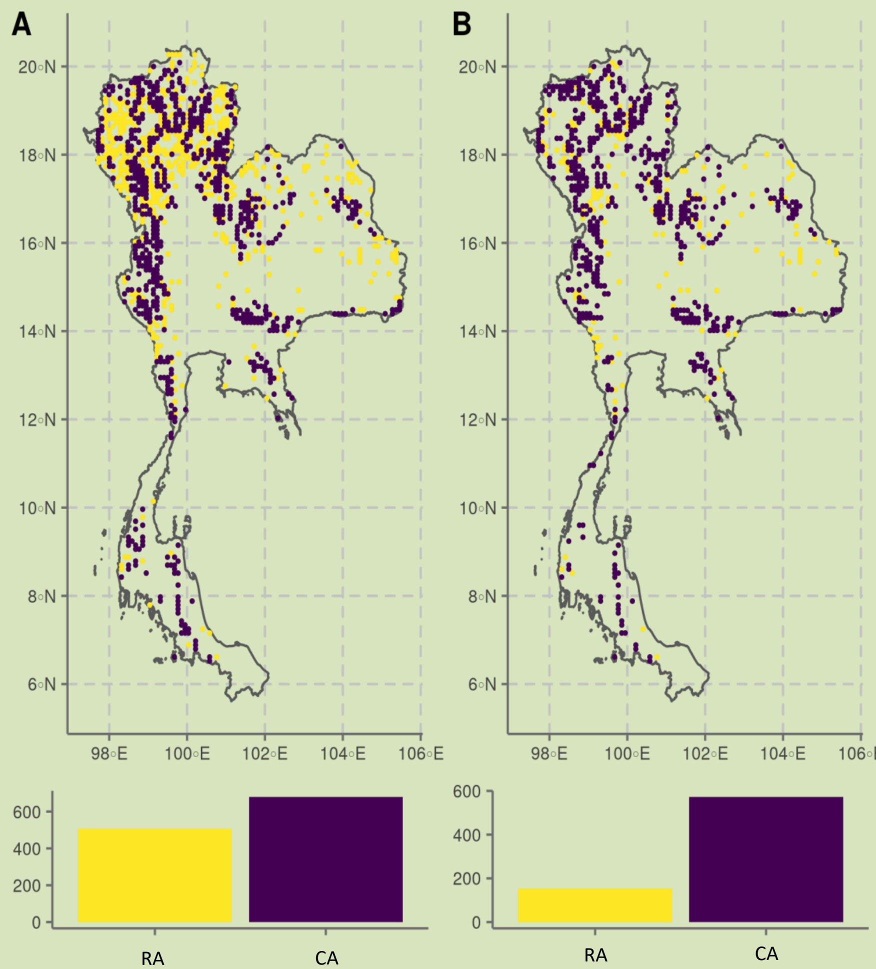


Figure 9: Nationwide distribution of the plots in Approach 1, cycle 1 (A) and cycle 3 (B), with the number of plots per strata

In addition to having less plots measured in cycle 3, reserved areas also had a lower biomass content than conserved areas, especially in Evergreen forest (Figure 10 and Table 13). The number of plots was lower in cycle 3, but the difference didn't translate into a large difference between simple average and weighted average. The weighted average was kept as it was more robust.

Table 13: 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	RA	89	96.397	20	0.234
Cycle 1	EV	CA	265	141.414	10	0.766
Cycle 1	DE	RA	416	44.238	8	0.458
Cycle 1	DE	CA	414	63.751	8	0.542
Cycle 3	EV	RA	35	97.822	27	0.234
Cycle 3	EV	CA	225	148.089	9	0.766
Cycle 3	DE	RA	119	56.912	14	0.458
Cycle 3	DE	CA	347	72.693	6	0.542

(*) EV : Evergreen , DE : Deciduous (**) RA : Reserved Areas , CA : Conserved Areas

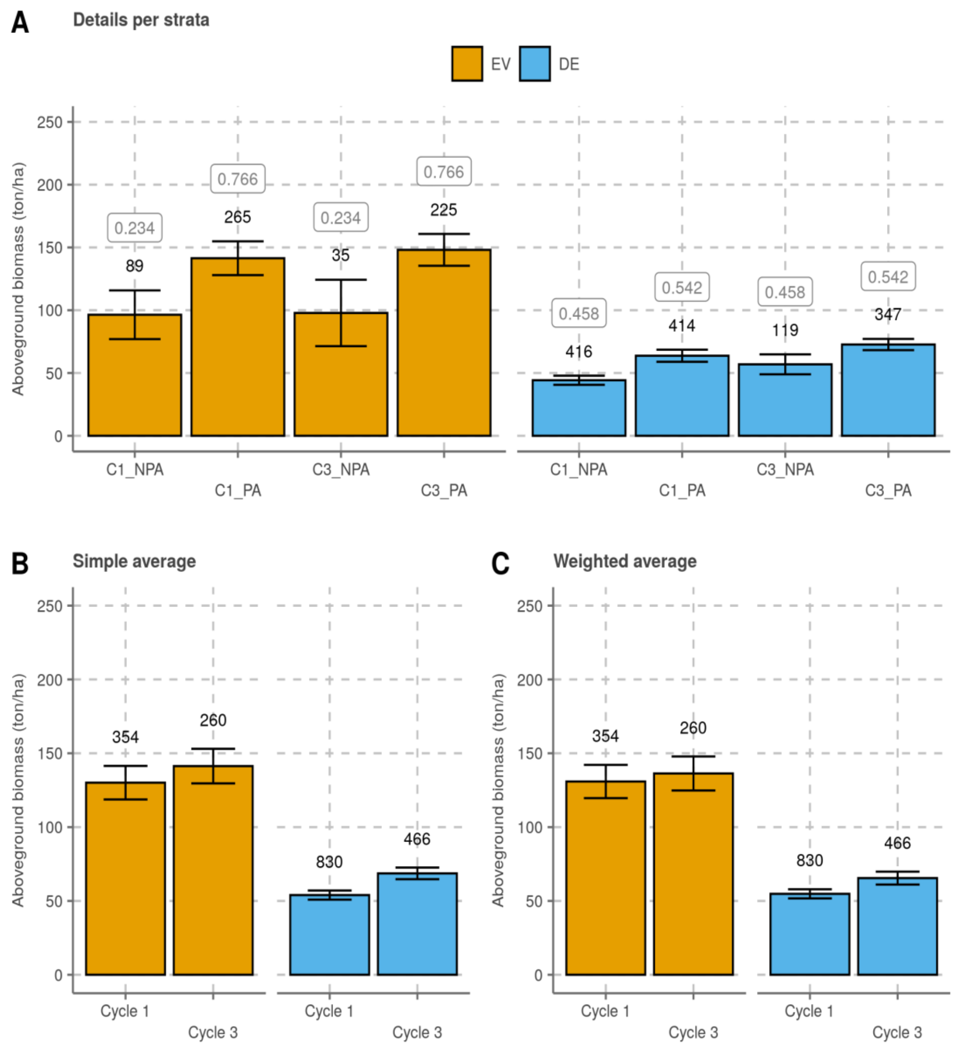


Figure 10: Aboveground biomass per forest type calculations for approach 1. Simple average per strata (A), simple average of all plots (B) and weighted average of the strata (C). The strata weights are represented in grey and a number of plots in black.

Carbon stock (Approach 1)

The weighted average was calculated across strata to generate carbon stock estimates for Evergreen and Deciduous forests (Table 14). 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 14: 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 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
2016	MG	37	120.779	68.614	18	59.182	84.582	310.134

(*) EV : Evergreen , DE : Deciduous , MG : Mangrove

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 15, 16 and 17). 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 10 year period in Evergreen and Deciduous forest respectively. The confidence interval was rather small for Deciduous forest but quite large for Evergreen forest where the change from Cycle 1 to Cycle 2 was smaller.

Table 15: 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 16: Emission and removal factors in $tCO_2/ha/yr$ for Approach 1.

		Cycle 3			
		EV	DE	MG	NF
Cycle 1	EV	-1.169	15.784	-0.103	28.091
	DE	-18.955	-2.002	-17.889	10.305
	MG	-1.066	15.887	0.000	28.194
	NF	-29.260	-12.307	-28.194	0.000

Table 17 : 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

(*) EV : Evergreen , DE : Deciduous , MG : Mangrove , NF: Non Forest

CONCLUSION

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 conserved 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 forested lands in Thailand, and were related to on-the-ground changes and not artificially created by the differences in plot location or sample populations. This way the discrepancies in the number of plots measured were accounted for with the stratification and the weighted averages, and at the same time adding complexity by stratifying conserved areas further was avoided.

The Carbon stock increased between the NFI cycle 1 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 conserved areas in the activity data and increase the number of plots measured outside conserved 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.

Appendix-Annex I.2: Summary of the study to validate Aboveground biomass allometric equations

Background

As a part of Thailand's 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, Saint-André, and Henry 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, Puangchit, and Diloksumpun 2016; Warner, Jamroenprucksa, and Puangchit 2016) or used either the above equations (Terakunpisut 2007; Chaiyo, Garivait, and Wanthongchai 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, Saint-André, and Henry 2012).

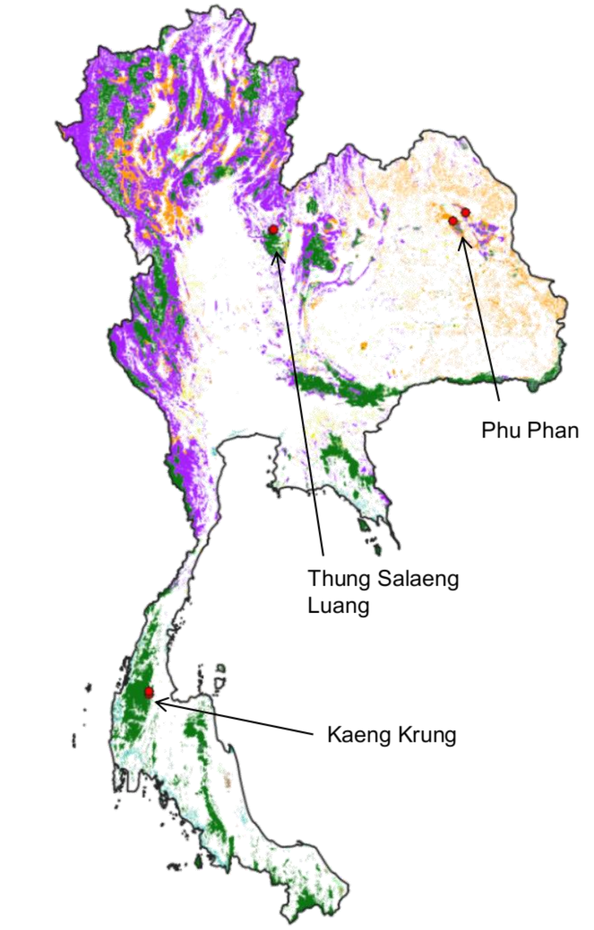
These methods could be used to develop new equations or, if the number of trees measured was too small, to validate existing equations. In Thailand, since the most used equations were very old and their quality was difficult to assess due to the lack of information reported, validating these equations 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.

Method

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

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 11). 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 Northern Central Thailand and one in North-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%

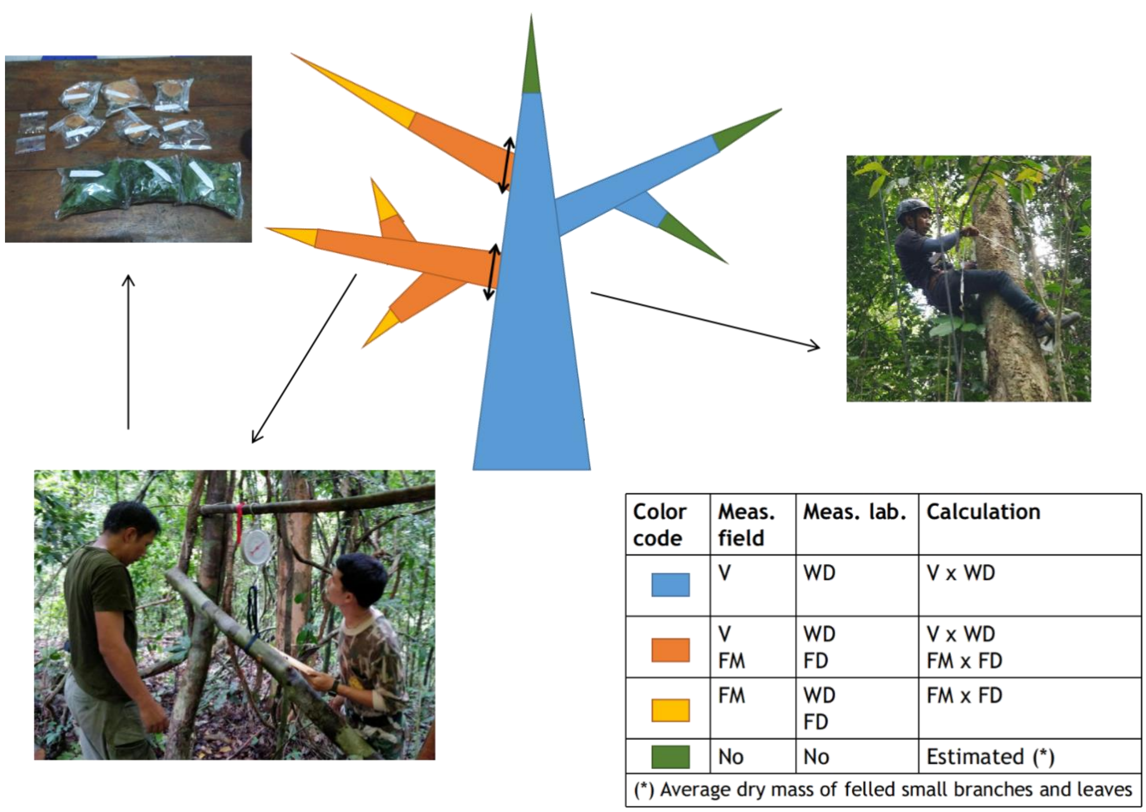
Figure 11: Site location and area of the main forest types in Thailand.

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.

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 fallen branches. For example, in Figure 12, 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 12: 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 (14)).

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

with V_f the fresh volume in m^3,r_1 and r_2 the radius of the two extremities of the log and L its length, all in meters. Each radius was calculated from its girth g with the Equation (15):

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

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'

.

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

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.

Laboratory measurements

Aliquots were taken from each of the four compartments to measure the trees' wood density (Equation (17)) and fresh-to-dry ratio.

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

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.

$$FD_i = B_i / W_i$$

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 the sum of the volume measurements multiplied by the average wood density of the big branches for stem and big branches, and small branches otherwise.

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

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.

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

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 $*$.

The trees measured had their diameter ranging from 5.1 to 124 and their height from 6.8 to 45 (Table 18). They belonged to 35 species with a dominance of *Parashorea stellata*, *Xylia xylocarpa var. kerrii*, *Pterocarpus macrocarpus* and *Lagerstroemia duperreana var. duperreana var. duperreana* in the big trees (Figure 13 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 var. kerrii* had the opposite.

Table 18: Measured tree characteristics.

ID	Park	Species	DBH	H	WD
1	KK	*Scaphium scaphigerum*	35.00	20.0	0.89
2	KK	*Aglaia elliptica*	12.70	15.0	0.53
3	KK	*Parashorea stellate*	90.00	40.0	0.73
4	KK	*Urospermum noronhianum*	12.60	16.7	0.83
5	KK	*Pterospermum lanceifolium*	32.20	27.0	0.57
6	KK	*Adinandra integerrima*	65.41	32.0	0.67
7	KK	*Nephelium melliferum*	42.00	32.0	0.89
8	KK	*Urospermum noronhianum*	28.40	17.0	0.91
9	KK	*Alseodaphne obovata*	45.90	27.0	0.60
10	KK	*Parashorea stellate*	107.00	42.0	0.63
11	KK	*Parashorea stellate*	60.20	38.0	0.60
12	KK	*Parashorea stellate*	67.40	43.0	0.61
13	KK	*Heritiera javanica*	37.20	33.0	0.58
14	KK	*Aglaia aspera*	45.00	27.0	0.77
15	KK	*Brownlowia helferiana*	47.70	26.0	0.46
16	KK	*Parashorea stellate*	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 stellate*	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 var. 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 var. duperreana*	93.00	23.0	0.58
28	PP	*Cratoxylum formosum subsp. Pruniflorum*	30.00	24.0	0.65
29	PP	*Symplocos sulcata*	16.00	15.0	0.69
30	PP	*Symplocos sulcata*	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
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 var. kerrii*	66.00	34.0	0.90
38	PP	*Xylia xylocarpa var. kerrii*	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 var. duperreana*	76.40	29.0	0.66
45	TSL	*Lagerstroemia duperreana var. duperreana*	76.00	25.0	0.65
46	TSL	*Terminalia bellirica*	38.50	27.0	0.59
47	TSL	*Xylia xylocarpa var. kerrii*	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 paniculata*	5.10	6.8	0.46
54	TSL	*Carallia brachiata*	61.00	23.0	0.63
55	TSL	*Hopea odorata*	105.00	36.0	0.82
56	TSL	*Lagerstroemia duperreana var. 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 var. kerrii*	41.00	28.0	0.84

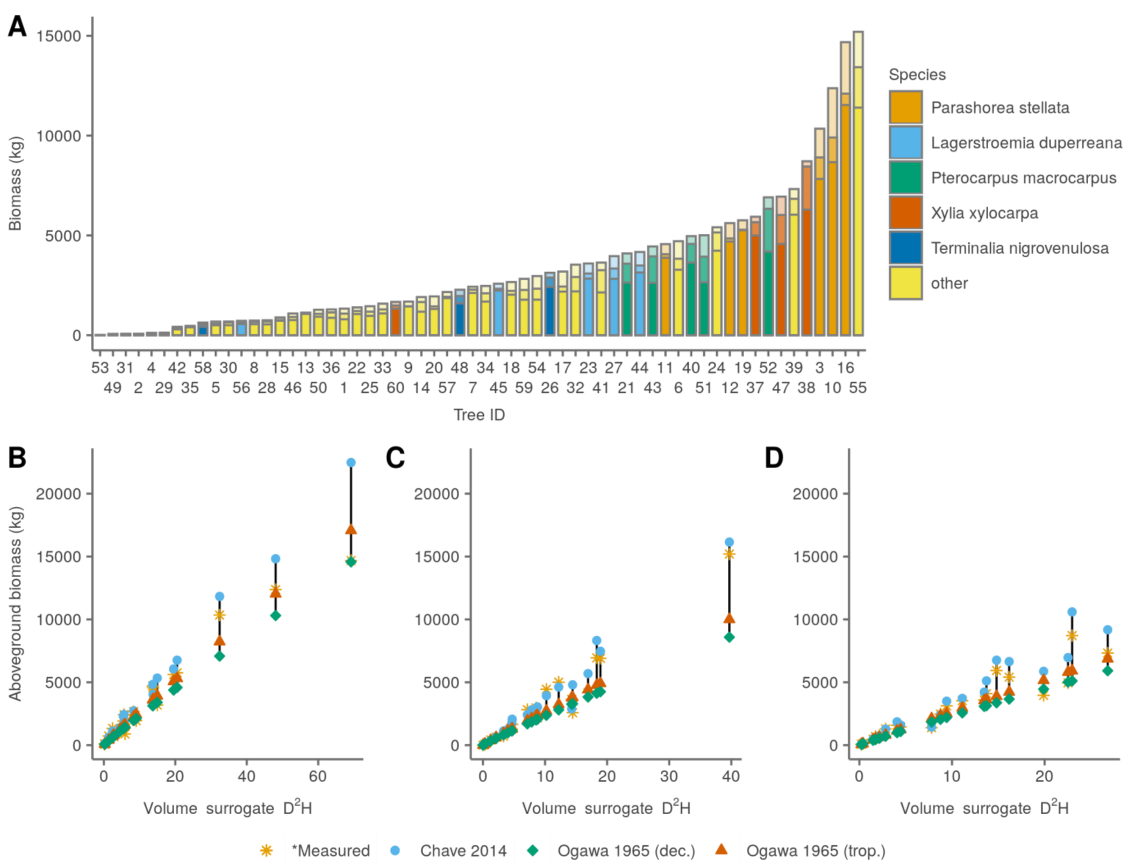


Figure 13: Measured tree compartments' biomass (stem, big branches, small branches plus leaves) (A), Measured and estimated tree aboveground biomass in Kaeng Krung (B), Thung Salaeng Luang (C) and Phu Phan (D) national parks.

The Chave equation systematically overestimated tree biomass, while the Thai equations underestimated it most of the time (Figure 13 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 19), where Ogawa (dec.) and Chave had the worst overall bias. The overall bias of the 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 were designed 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 19: 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

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 purposes, 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 was 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 they did relatively well in the validation process, these equations were recommended to calculate the forest carbon stocks in Thailand.

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ANNEX II

Activity Data

Accuracy Assessment

Stratified area estimates step by step guide is developed by the FAO team and can be accessed by the below-given link[8]. The same steps were used to derive the SAE in the current report. The Accuracy Assessment (AA) was done for all the products including the Forest/Non-Forest (F/NF) maps of the two periods which were also used to create the final forest change map. Figure 1 is providing all the detailed steps for the accuracy assessments and to derive the SAE.

Step 1: Map for stratification

- **Forest Change Map 2006-2016**
- **Forest types/Non-Forest Map 2006/07**
- **Forest types/Non-Forest Map 2016/17**

Step 2: Generate Samples

- **Generate stratified samples**
  The stratified forest map 2006/07 & 2016/17
  Sample size formula of Cochran (1977)
  Sample generation: Sepal platform (http://sepal.io)
- **Sample survey design**
  Using survey designed in Open Foris Collect

Step 3: Sample Assessment

- **Sample assessment**:
  Using Collect Earth Tool in Open Foris Collect. Interpreters' check every sample for a Forest type or Non-Forest cover, using available high-quality validation datasets in Google Earth and Google Earth Engine; accessible through Collect Earth system.

Step 4: Stratified Estimator Analysis

- **Prepare master sample assessment file**
  By combining all files from different interpreters
- **Stratified Estimator - Analysis:** Using SEPAL platform (http://sepal.io)

Figure 1 Accuracy Assessment process workflow is explained systematically used for forest, non-forest (FNF) and Forest change maps, however the process is suitable for accuracy assessment of any type of map data

[8] https://github.com/openforis/accuracy-assessment/blob/30d284322269d694ffd607b5520721c1bfe6feb5/presentations/p_sae_design.pdf

2.1. Map Stratification

The map stratification was performed for the F/NF maps of both years and the change map that resulted from a post-classification process, which was later combined with the forest type classification in order to derive the distribution of the forest strata according to forest types of interest. The accuracy assessment of the maps and associated sample-based estimation of the area was conducted according to the guideline developed by Olofsson et.al. 2014. The main objective of the accuracy assessment of the change map was to quantify the error in the map and to calculate the uncertainty around the AD (area estimates). A number of parameters were considered for data collection and, based on the objectives of the assessment, a customized survey was developed using FAO's Open Foris Collect tool (figure 2). Whereas the objective of F/NF map AA was only to calculate the user and producer accuracies by class, and to ensure that the data used for forest change mapping is of acceptable quality. For the sample design, FAO's SAE - Design tool in SEPAL[9] was used, and a step by step guidance link is given in footnote 2 of this Annex document.

2.2. Sample Design

The sampling design refers to the methods used to select the locations for obtaining the reference data, in this case, the methods through which a total of 1228 samples for 2006 and 1214 samples for 2016 (figure 3) were generated. Samples were derived from the map strata of 2006 and 2016 independently using SEPAL's SAE – Design tool. The number sample to assess was calculated per stratum, following the Cochran (1977) formula (see Equation 1 below) (Olofsson et al., 2014).

Equation 1

$$n = \frac{(\sum W_i S_i)^2}{[S(\hat{O})]^2 + \left(\frac{1}{N}\right)\sum W_i S_i^2} \approx \left(\frac{\sum W_i S_i}{S(\hat{O})}\right)^2$$

Where: $N = number\ of\ units\ in\ the\ region\ of\ interest$

$S(\hat{O})\ is\ the\ standard\ error\ of\ the\ estimates\ overall\ accuracy\ that\ we\ would\ like\ to\ achieve,$

$W_i = mapped\ proportion\ of\ area\ of\ class\ i,$

$S_i = standard\ deviation\ of\ stratum\ i, S_i = \sqrt{U_i(1-U_i)}$

[9] sepal.io/

[8] https://github.com/openforis/accuracy-assessment/blob/30d284322269d694ffd607b5520721c1bfe6feb5/presentations/p_sae_design.pdf

The same application was used for stratification of the forest change map and for sample intensification in target classes as explained in Annex I.

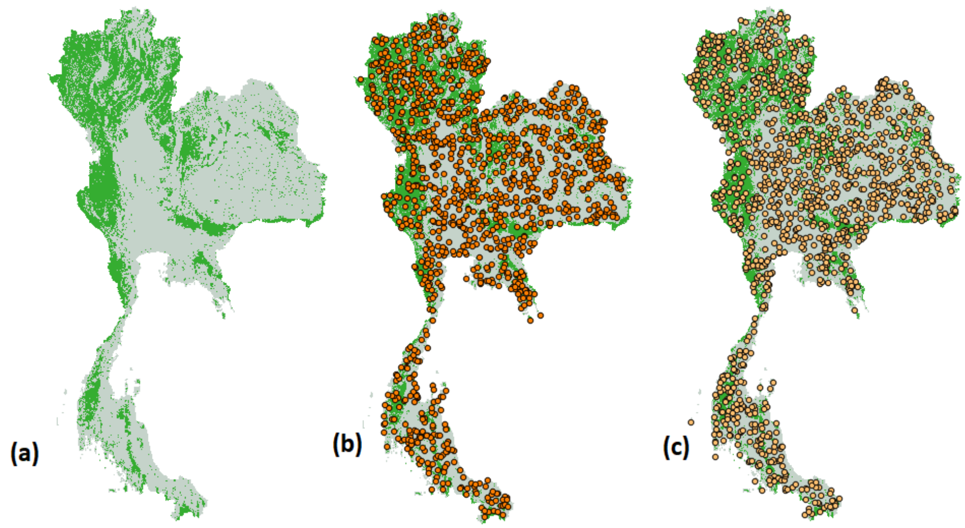


Figure 2 Distribution of stratified random sampling for forest map (a) Forest map of 2016 (b) Stratified random sampling point distribution for the year 2016 (c)) Stratified random sampling point distribution for the year 2006

Figure 3 shows a detailed outlay of the survey used for reference data collection. The survey includes information about all the map strata. In the first instance, information about change classes was asked, whereas in the case of non-forest class no further information was collected but, in the case of forest stable, loss and gain forest type information was collected. The survey card also included information on drivers of deforestation in the case of forest loss. The drivers assessed include plantation, illegal logging, and agriculture expansion, shifting agriculture, and built up area. In the case of plantations, the type of plantation was also recorded.

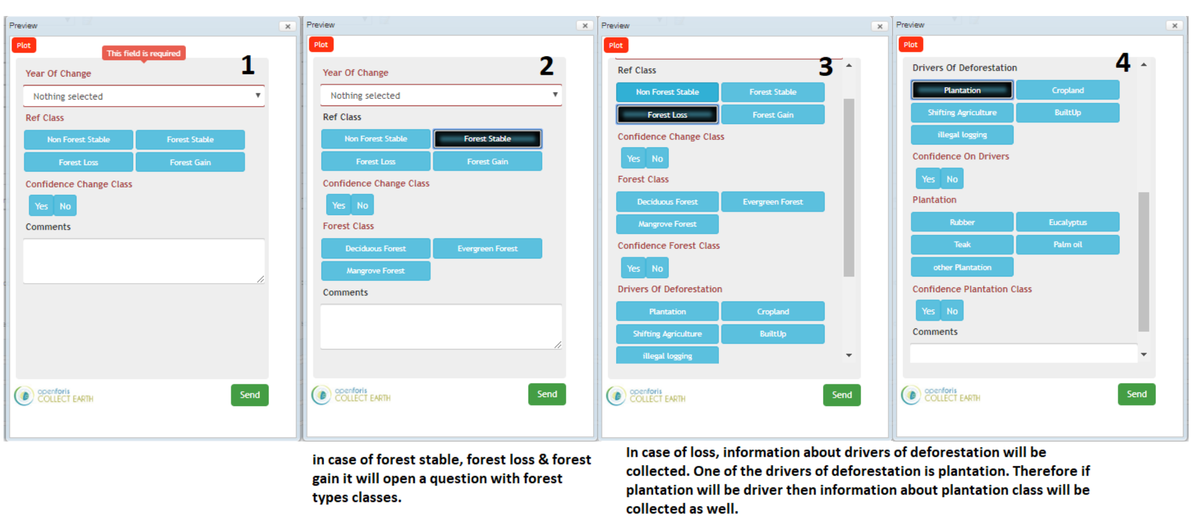


Figure 3 Survey design for reference data collection

2.3. Response Design

The desired goal of this validation was to derive a statistically robust and quantitative assessment of the uncertainties associated with the forest area change estimates. Several factors potentially impact on the quality of forest mapping (GOFC-GOLD, 2016), namely:

- ✓ The spatial, spectral and temporal resolution of the imagery
- ✓ The radiometric and geometric pre-processing of the imagery
- ✓ The automated and manual procedures used to interpret the forest map category
- ✓ Thematic standards (i.e. minimum mapping unit and land use definitions)
- ✓ The availability of field reference data for evaluation of the results.

Approaches were used to minimize these sources of error following IPCC and GOFC-GOLD good practice guidelines, as appropriate. The collect survey design form has been set for each reference label to allow an interpreter-specified confidence level with high and low margins. Figure 4 shows an example of reference data available within the Google Earth-based Collect Earth System, used to interpret the samples for activity data. The figure illustrates a sample with temporal resolution of Google Earth imagery, used for sample assessment during 2006-2016. The response design rules developed for forest change reference data collection are:

- ✓ If a plot was forest in 2006 and is non forest in 2016, it will be classified as loss
- ✓ If any sample plot in non-forest in 2006 and forest in 2016, it will be classified as gain
- ✓ If a sample plot is forest in 2006 and remains forest until 2016, it will be classified as forest stable
- ✓ If a sample plot is non-forest in 2006 and remains non-forest in 2016, it will be classified as non-forest class.
- ✓ If at time-1(2006) it was forest and within the reference time period (2006-2016) changed from forest to plantation, it will be considered as loss and plantation will be recorded separately.

- ✓ If time-1 (2006) is Forest and tree cover within the reference time period/time-2 (2016) is decreased but still > 10% will be considered as a forest stable and interpreted must be mentioned in comment section degradation.
- ✓ If time-1 (2006) is Forest with a high percentage of tree cover and tree cover in reference time period/time-2 (2016) is still > 10% but overall land use has changed (eg. by development of infrastructure, converted to cropland) it will be considered as a loss.
- ✓ For the plots with mix land use/land cover classes and Mix forest type classes a majority rule will be applied.
- ✓ If the interpreter is not sure about the year of change because of unavailability of images, he/she can add comments in the comment section like “not sure about year of change”. Whereas year of change can be recorded based on the first available date of change.
- ✓ Plantations will be considered as Non-Forest areas, except Teak Forests in the North, which are considered as forest in the forest mask. The definition criteria will remain the same to ensure consistency with the base data (forest mask).

The response design in case of F/NF AA was very simple as it only contained two classes, namely forest and non- forest, and reference data were collected independently for both years (2006 and 2016). Six participants from DNP worked on reference data collection using the guidance presented in “Good practices for estimating area and assessing the accuracy of land change” by Olofsson et al. (2014) and “Map Accuracy Assessment and Area Estimation – A Practical Guide” (FAO 2016)

Figure 4 Google Earth high resolution image of Mix deciduous forest, Thailand

2.4. Analysis of Reference Data

2.4.1. Forest Non-Forest error Matrix

The error matrices of the 2006 and 2016 F/NF maps with assessed samples are summarized in table 20 and 21. The reference datasets were used to generate sample-based estimates along with the associated confidence intervals. The user's accuracy, or commission error, represents an over-estimation of any classes, whereas the producer accuracy or omission shows under estimation of any class. For example, 47 samples out of 835 in the 2006 data were assessed as forest when in reality they were not, which gave an over-estimation of the non-forest area. In total three samples from the 2006 accuracy assessment data were excluded because of false confidence.

Table 20 Error Matrix of Forest map 2006

	Reference Data 2006		
Map Data 2006	Class	Forest 2006	Non-Forest 2006
	Forest 2006	383	10
	Non-Forest 2006	47	785
	Total sample	430	795

Table 21 *Error Matrix of Forest map 2016*

	Reference Data 2016		
Map Data 2016	Class Name	Forest 2016	Non-Forest 2016
	Forest 2016	366	7
	Non-Forest 2016	52	789
	Total sample	418	796

The accuracy assessment of the Forest F/NF maps was performed using a stratified random sampling approach. The user accuracy of the F/NF 2006 and 2016 map, were 96% and 98% respectively. Whereas producer accuracy results were 89% and 88% respectively. The stratified area estimates for both thematic maps are given in table 22 and 23 along with the user and producer accuracy and confidence intervals.

Table 22 Stratified Area Estimates of 2006 Forest map

Forest and Non-Forest Map 2006

Class	Weighted Producer's Accuracy	Users Accuracy	Stratified Area Estimates	Confidence Interval
Forest	89%	97%	18,375,114.45	3 %
Non-Forest	99%	94%	34,397,195.50	2 %

Table 23 Stratified Area Estimates of 2016 Forest map

Forest and Non-Forest Map 2016

Class	Weighted Producer's Accuracy	Users Accuracy	Stratified Area Estimates	Confidence Interval
Forest	87%	98%	18,101,098	4%
Non-Forest	99%	94%	34,671,212	2%

Annex II.3: Activity Data Results

The error Matrix of the forest change map is given in table 24 and 25. The highlighted cells with light orange color are indicating the classes where sample intensification was done.

Table 24 Error Matrix of forest change map before Sample Intensification

	Reference Data				
Map Data	Class Name	Evergreen Forest	Deciduous Forest	Mangrove Forest	Non-Forest
	Evergreen Forest	206	-	-	20
	Deciduous Forest	-	390	-	122
	Mangrove Forest	-	-	10	-
	Non-Forest	16	67	8	1028

Table 25 Error Matrix after Sample Intensification

	Reference Data				
Map Data	Class Name	Evergreen Forest	Deciduous Forest	Mangrove Forest	Non-Forest
	Evergreen Forest	245	-	-	31
	Deciduous Forest	-	413	-	119
	Mangrove Forest	-	-	82	35
	Non-Forest	27	69	32	1063

Table 26 User and producer accuracies per class along with total Stratified area estimate (SAE) and CI of all Strata

Class Name	PA (%)	UA (%)	Map Area (ha)	SAE (ha)	SE (ha)	CI (ha)	No. Samples	CI%
Non Forest	98	95	35,923,462	34,612,219	281,869	552,464	1063	2%
DF stable	79	97	8,967,556	10,985,093	282,599	553,893	413	5%
DF loss	49	45	665,821	610,234	107,688	211,068	119	35%
DF gain	30	30	101,236	100,677	47,798	93,684	69	93%
EG Stable	91	79	6,792,708	5,892,252	239,129	468,692	245	8%
EG loss	13	26	80,271	159,230	63,421	124,305	31	78%
EG gain	66	24	25,756	9,364	1,738	3,406	27	36%
MG Stable	99	93	213,144	201,668	7,219	14,149	82	7%
MG loss	0	65	724	161,902	74,604	146,225	35	90%
MG gain	2	51	1,631	39,669	37,276	73,061	32	184%

(*) PA : Producer's Accuracy , UA : Users Accuracy , SAE : Stratified Area Estimates, SE : Standard Error , CI : Confidence Interval

3.1. Activity Data Aggregated Results

Table 27 Stratified Area Estimates by aggregated classes

Class	PA	UA	Map Area (ha)	SAE (ha)	SE (ha)	CI (ha)	CI%
Non Forest	98%	95%	35,923,462	34,596,393	280,948	550,658	2%
Forest Stable	90%	96%	15,973,409	17,070,382	266,082	521,520	3%
Forest loss	40%	51%	746,816	955,078	144,273	282,774	30%
Forest Gain	32%	37%	128,623	150,456	59,340	116,307	77%

(*) PA : Producer's Accuracy , UA : Users Accuracy, SAE : Stratified Area Estimates SE : Standard Error , CI : Confidence Interval

Table 28 Error Matrix of Aggregated classes

	Reference Data				
Map Data	Class Name	Non Forest	Forest Stable	Forest loss	Forest Gain
	Non Forest	913	39	11	1
	Forest Stable	11	472	5	2
	Forest loss	85	75	167	0
	Forest Gain	54	154	2	125

3.2. Annual Rate of Change of Forest

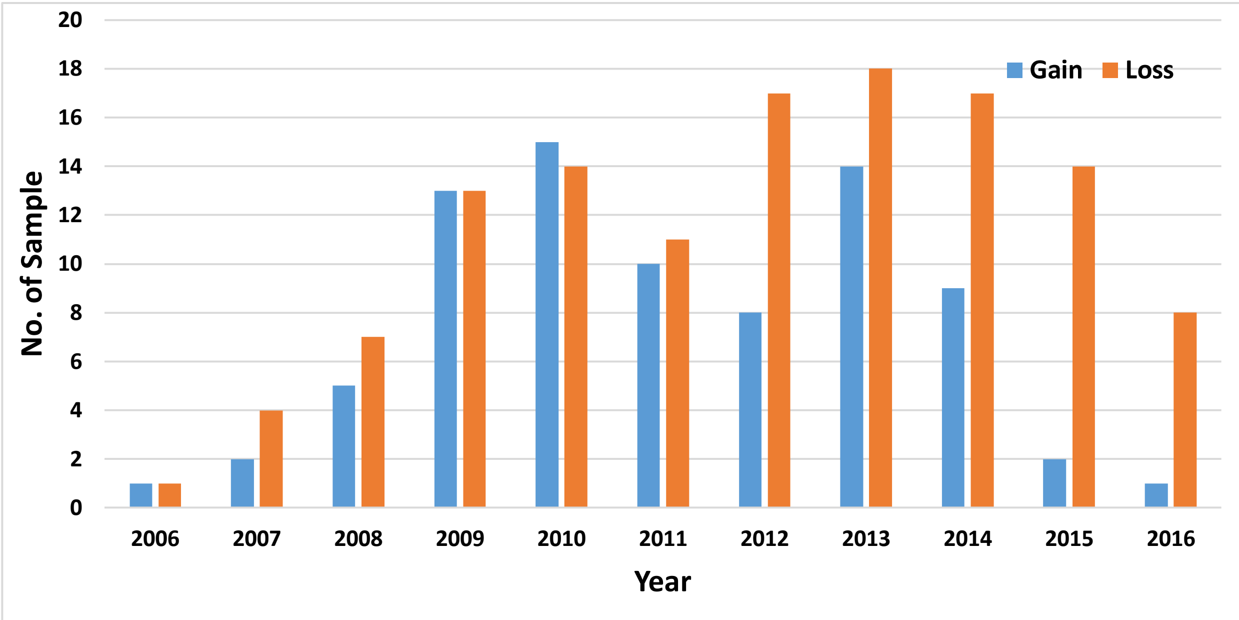


Figure 5 Annual trend of forest loss and gain

The graph shown in figure 5 gives an annual trend of positive and negative change changes for the years 2006 to 2016. It is important to note here a certain degree of uncertainty occurs for the exact year of change, because of reference data availability. It was easier to identify the change over the reference period with a few high-resolution images compared to identify the exact year of change in some cases where only coarser resolution images are available. In those cases, the nearest year from available reference data is considered as change year.

3.3. Drivers of Deforestation

Agricultural expansion was observed as the most common driver of deforestation in Thailand, far ahead of conversion of natural forest to plantations (including rubber and fruit orchards). Whereas the third most common observed class was other, which mainly included shrimp farming and seasonal flooding. While plantation stands as the second most common driver of deforestation in Thailand with leading rubber plantation followed by fruit tree plantation. The other notable drivers of forest loss are seasonal flooding and shrimp farming which are grouped together in the below figure as ‘Other’.

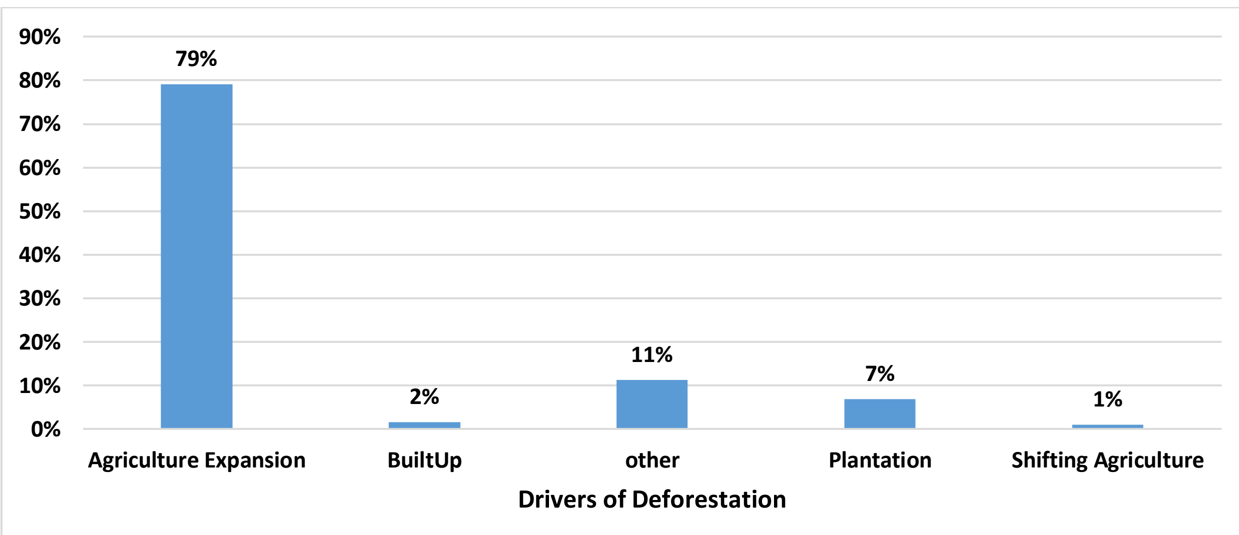


Figure 6 Driver of deforestation observed in Thailand based on activity data reference data

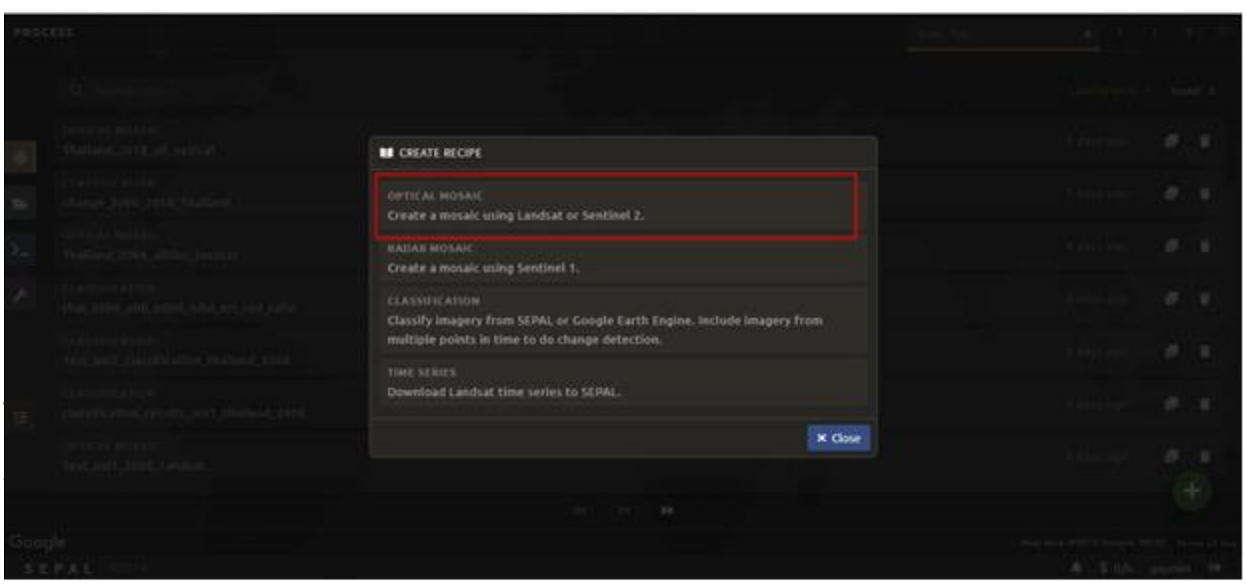
Annex II.4: Forest Type Mapping Manual using Two Stage Classification Approach

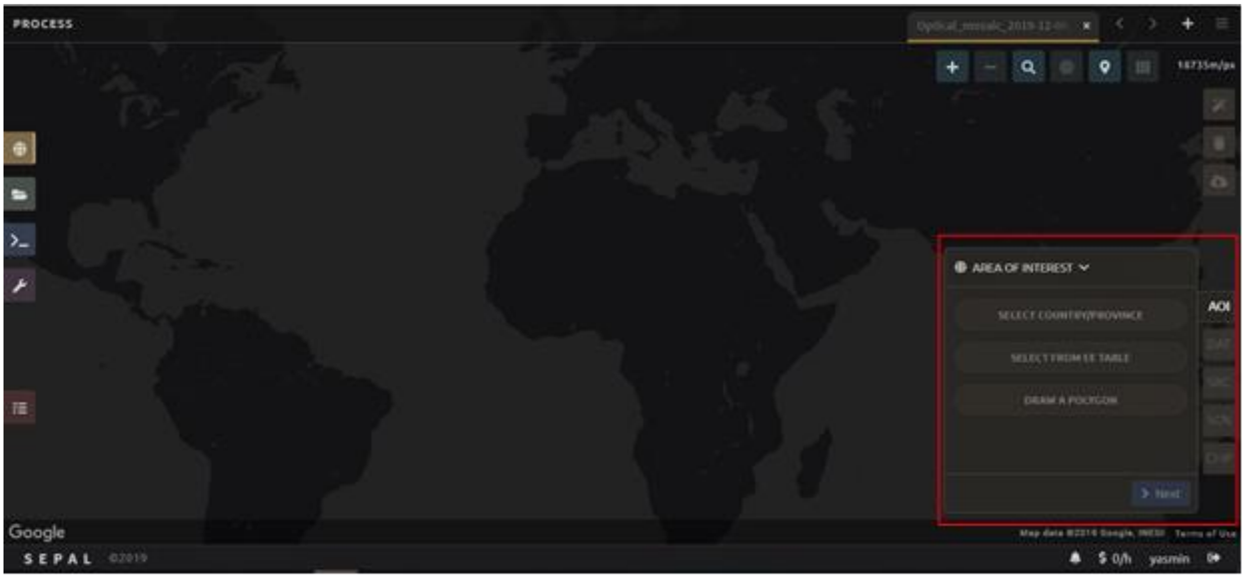
1. Creating optical mosaic (Landsat and Sentinel 2) using SEPAL

First sign up if you do not have an account using https://sepal.io/ and sign in using the same web link if you are already registered.

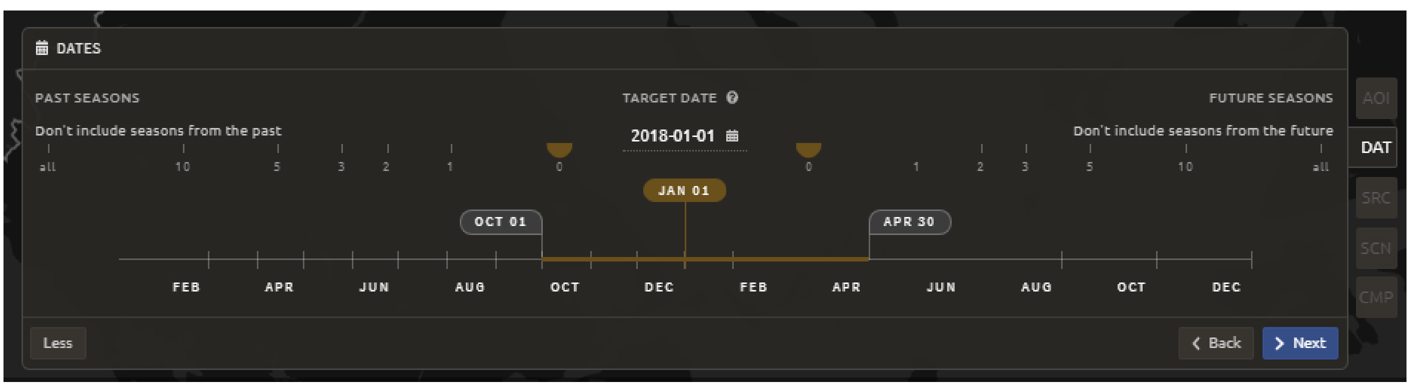
Once you are signed in you will be on this page of the SEPAL platform

This will open a pop up window as shown below





Area of Interest (AOI): Allows users to choose an area of interest by country, to draw an AOI of interest or to use customized shapefile. To use customized shapefile please use the option EE Table that can be uploaded in Google Earth Engine (GEE). For more details please check the section upload shapefile as an asset.



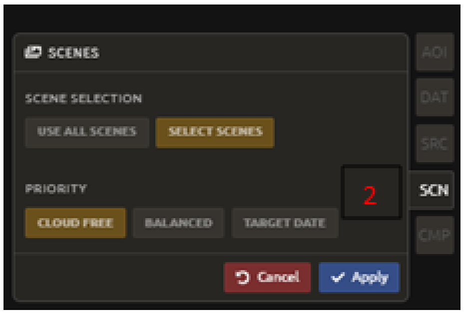
DAT: This tab refers to the date, where one can create the best pixel mosaic with target date using available images and can customized to the preferred date range by adjusting the yellow line.

1: Choose Landsat 8 & Sentinel 2 for the year 2016 separately to prepare two separate mosaics

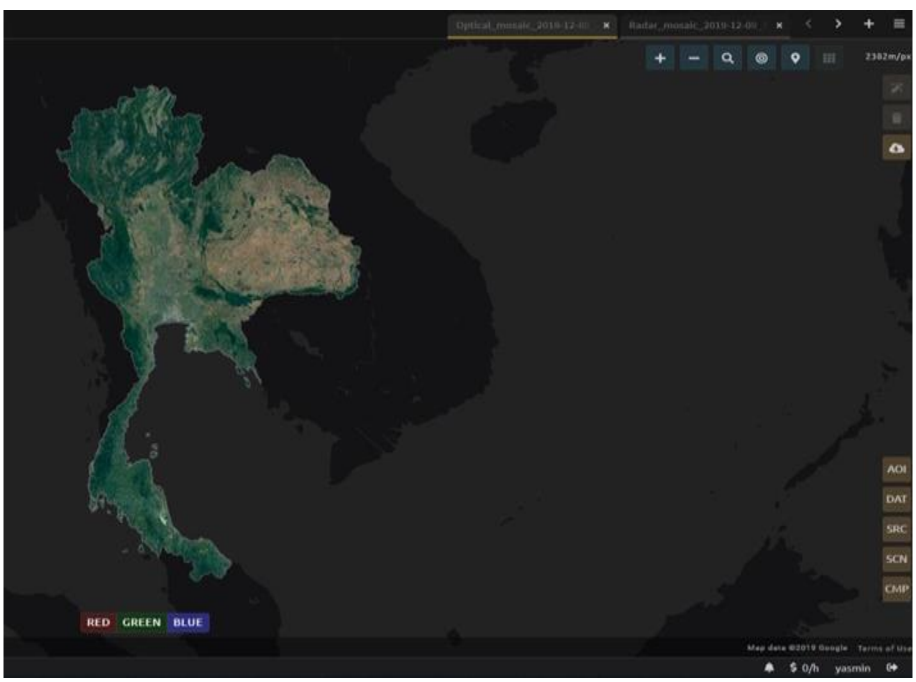
2: SCN: is the tab where one can edit the scene to improve the quality of mosaics if needed, although by default the application will choose all images for AOI to create the best pixel mosaic for the time period of interest where cloud and snow will be masked out.

3: CMP: is the tab which allows users to set parameters to improve the quality of mosaics.

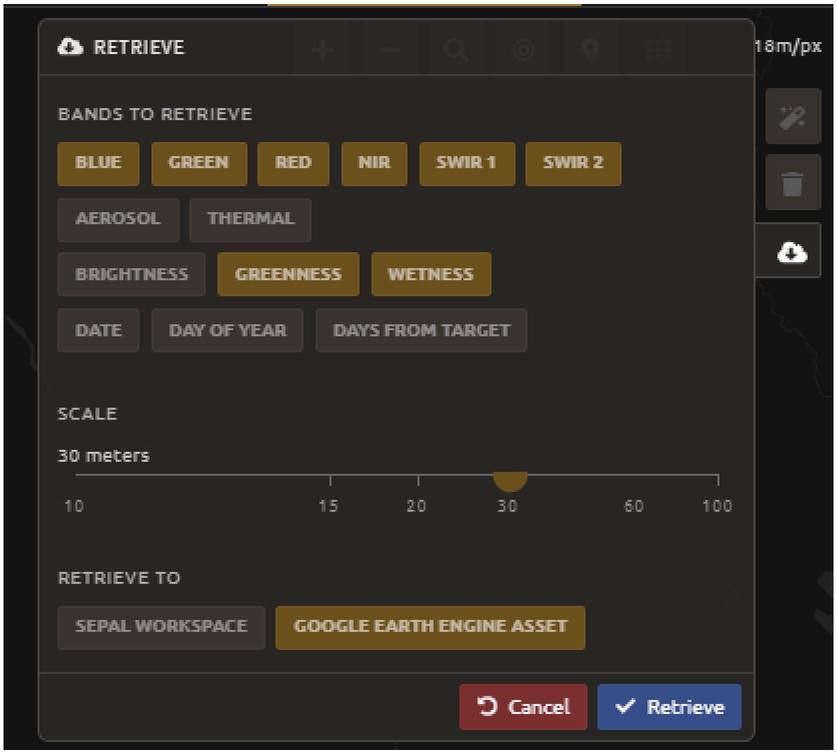
In the case of the 2016 mosaic these parameters were selected



After selecting all the parameters click apply and wait for the mosaic preview, it will look like as shown below. You can view images in different band combinations by clicking on the bands (Red, Green, & Blue).



Example of an Optical best pixel mosaic over Thailand

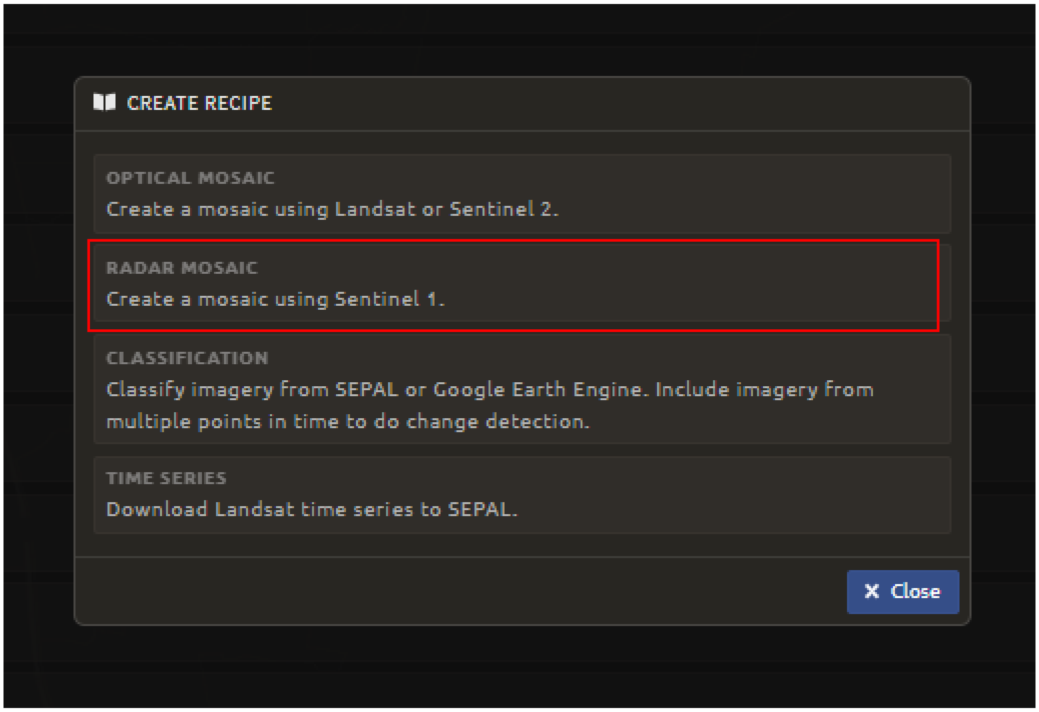


Once mosaic is satisfactory it can be downloaded in the SEPAL and GEE depending on the required processing step.

Note: If you are exporting Landsat, scale will be 30 m whereas in case of sentinel-2 scale should be 10 m, following the spatial resolution of the sensor. For this exercise sentinel-1 was also exported with scale 10m.

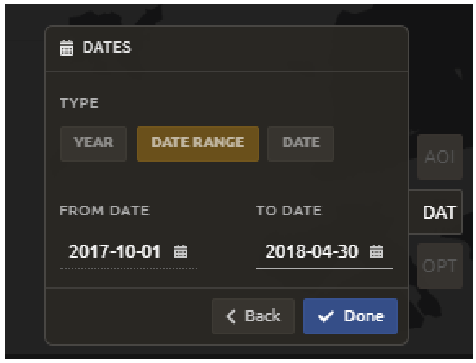
2. Create Radar Time scan

In order to create a radar mosaic click on the plus sign as indicated above (optical data section) this will open a pop up like this:

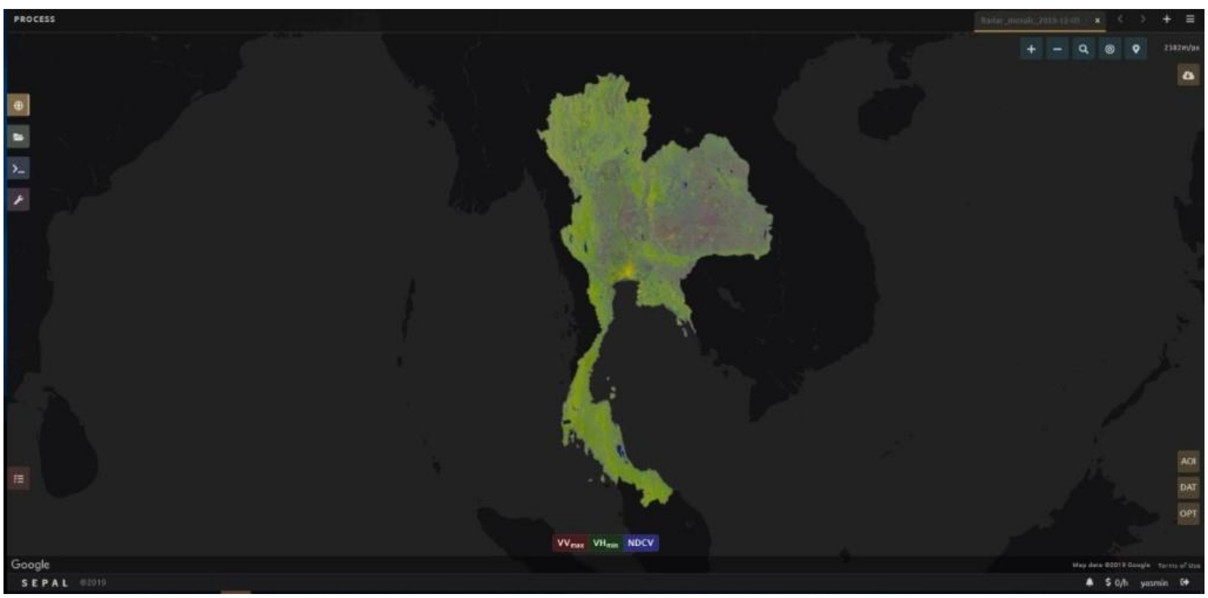


Click on Radar mosaic as highlighted in the red box above.

Select AOI

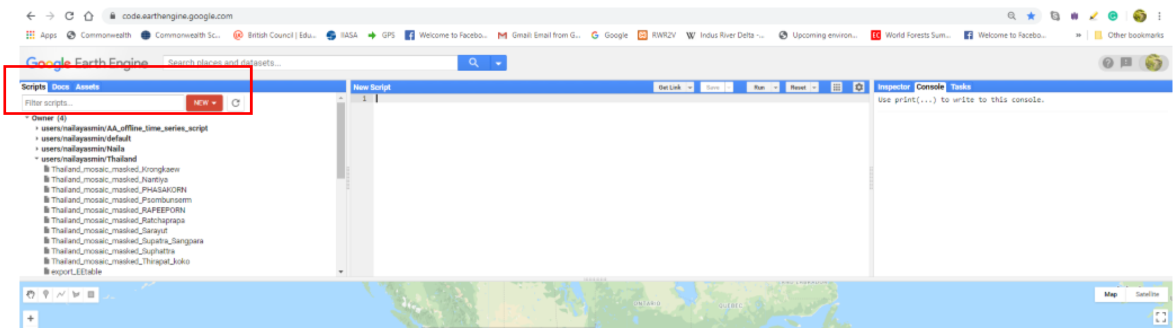


Choose the dates (these are the dates used for the Forest type map 2016)
It could be adjusted for different purposes.
Keep the rest of the settings to default and click on done.
It will take a few minutes to show the first preview of the image

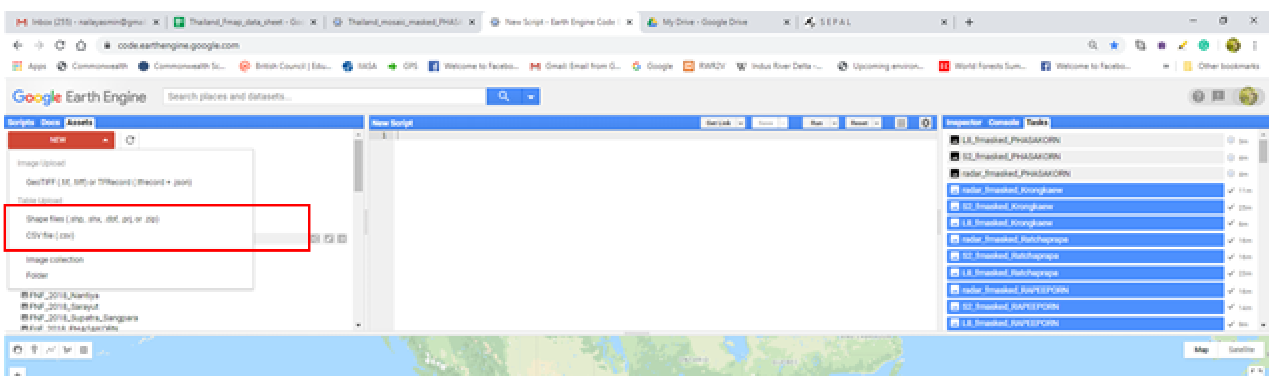


3. Uploading data as an Asset

To use GEE one needs to sign up first using a Gmail account.
One you are signed in open the web page https://code.earthengine.google.com/
It will open up a page as shown below



Now click on assets



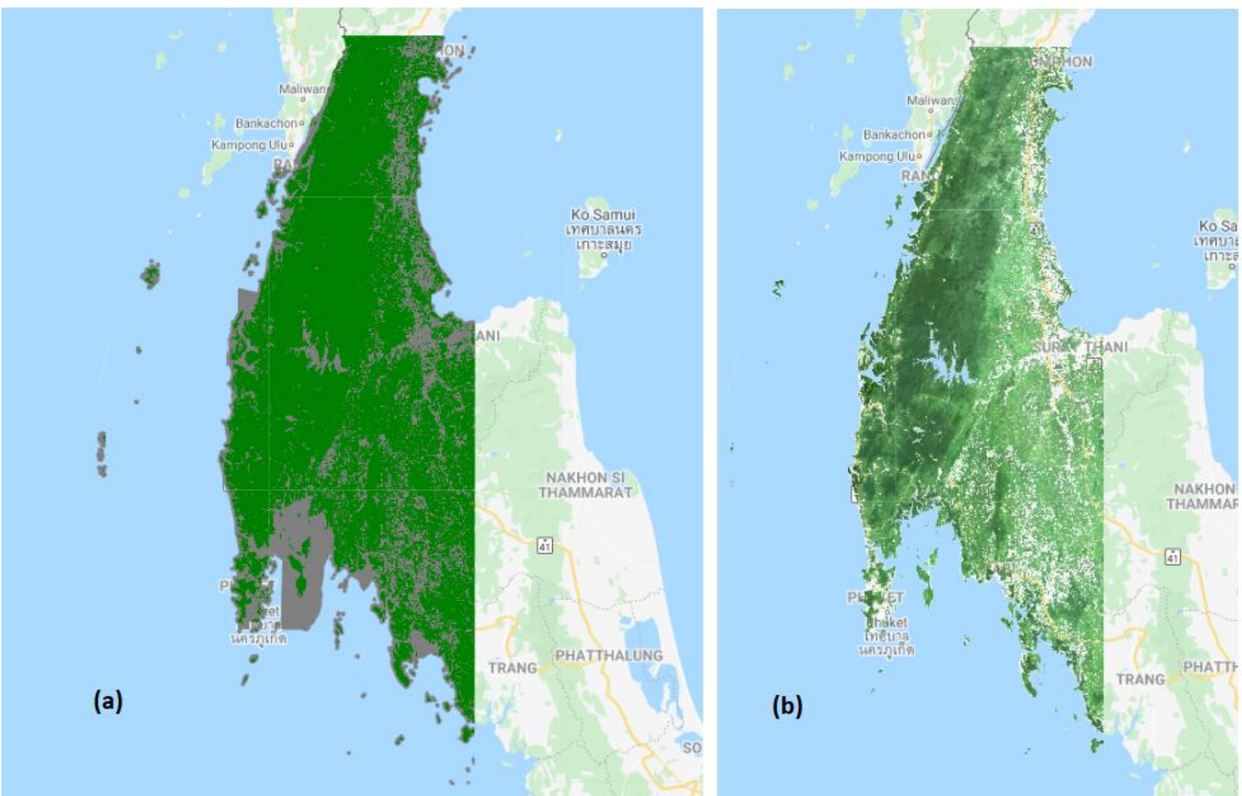
Choose your shapefile and click upload; you can monitor the progress of uploads in the task section.
For more details of the assets, please check the link https://developers.google.com/earth-engine/asset_manager

In the same fashion upload the forest mask in the GEE.

4. GEE Masking Satellite Images using Forest Mask

GEE code is explained with comments within the code. Basically it is used to mask the satellite images only over forest areas which were used for the forest type classification. Code can be accessed via:
https://code.earthengine.google.com/49d82ca2cc8045dfa05dbb30bfbce171

5. Running Classification over Masked Satellite Images

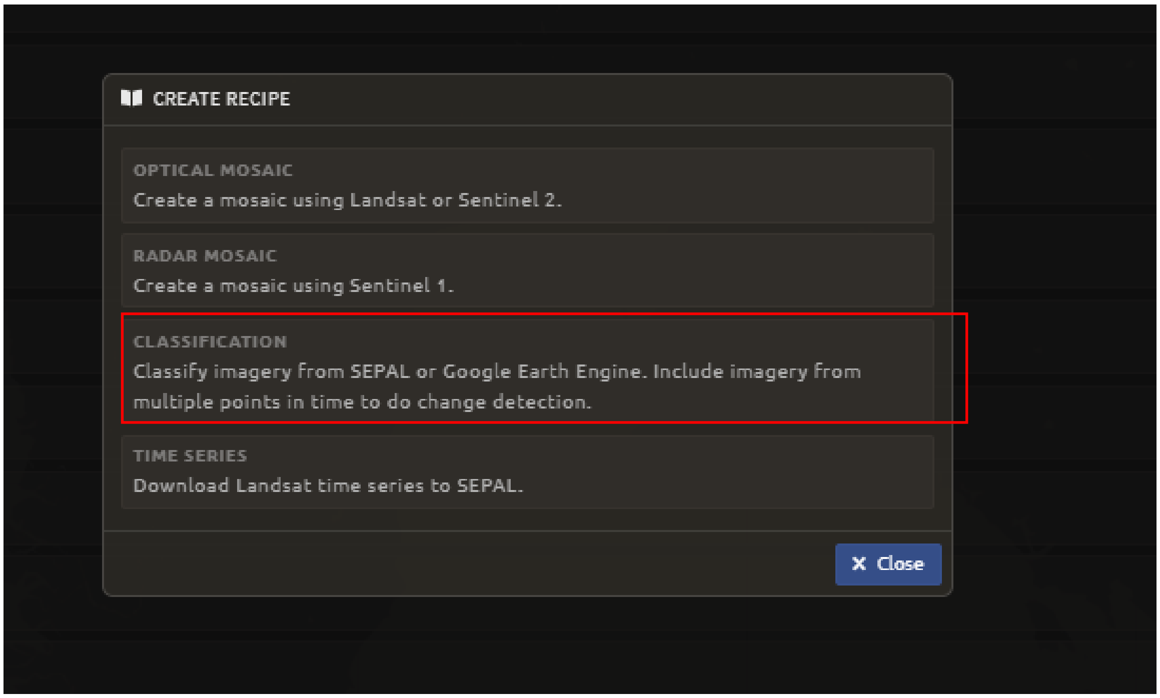


Classification was run over masked satellite images in SEPAL

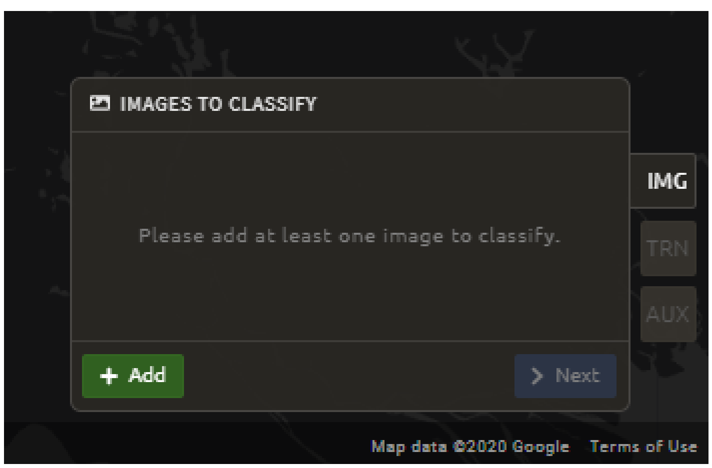
(a)Forest (green) and non-forest mask (grey) which was used to remove non-forest area from (b) satellite images to improve the quality of forest type map.

6. Running Forest type classification

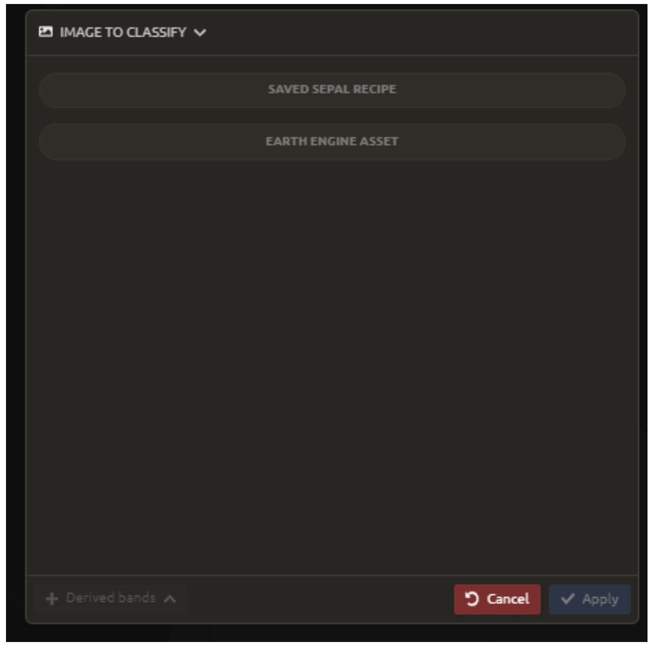
Classification in SEPAL is based on the Random forest algorithm. The new version of SEPAL allows users to use multiple sensor data at the same time for classification including Digital Elevation Data (DEM). For the current exercise following parameters were used:



Click on the classification and it will open up the page as shown below

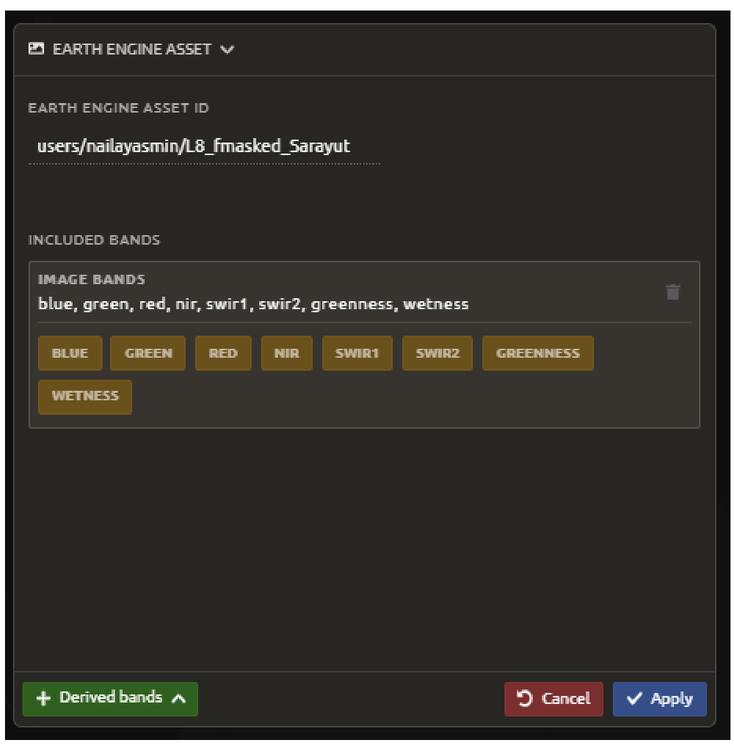


Click add button for images to be classifie

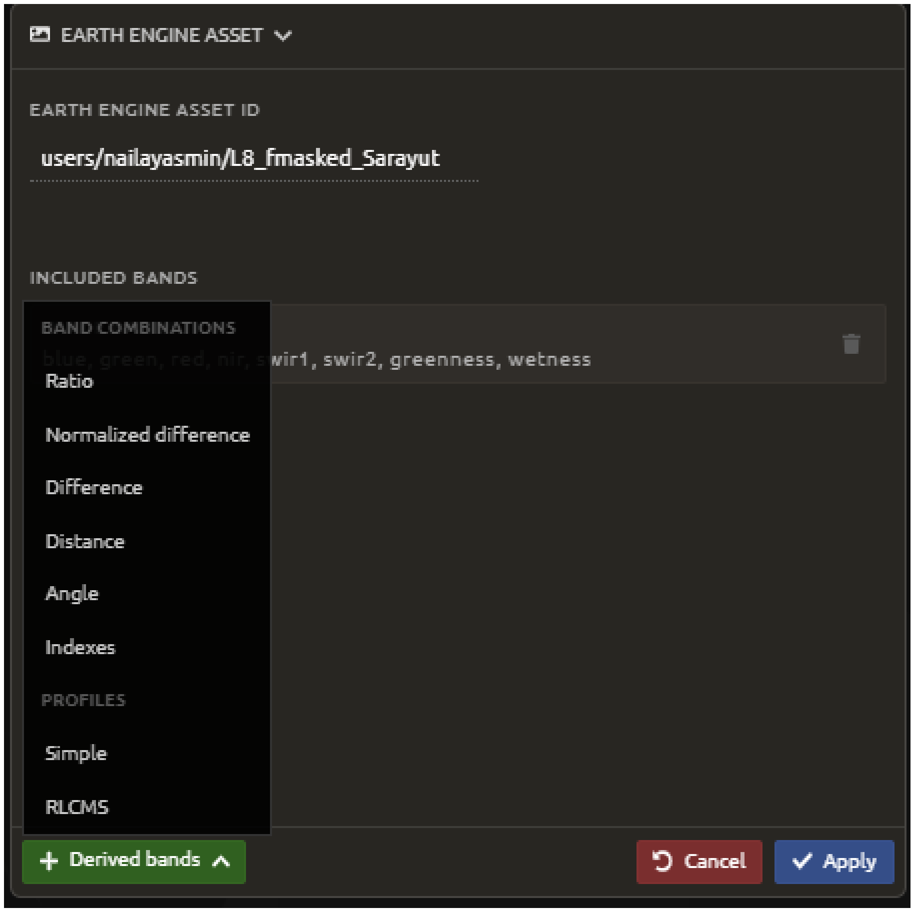


Once you click on the Add button it will open a window like this, where users can use a GEE image asset and SEPAL saved recipes for classification

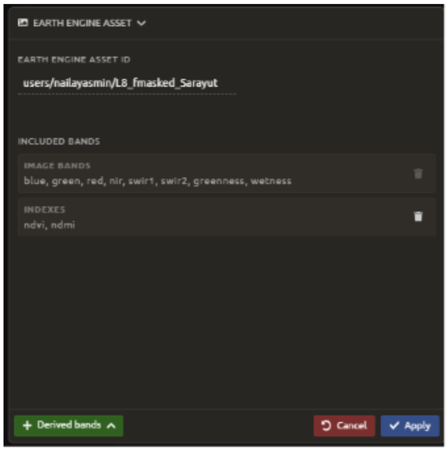
Note: when working on a big AOI it is recommended to use the Asset to make the process fast.



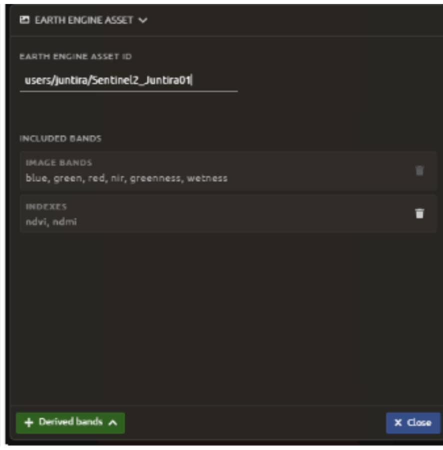
For the optical dataset all the bands were selected (you will view here only bands which were selected at the time of download).



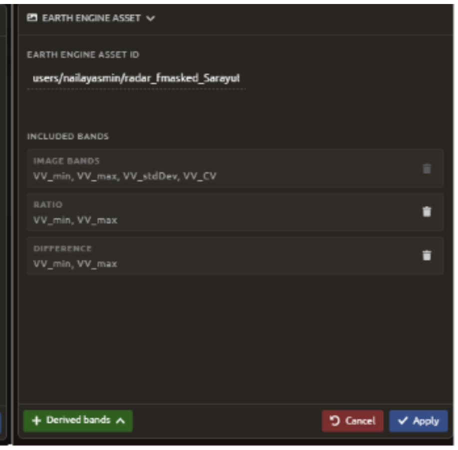
Under the Derived bands button, different index and band calculations can be added to the images to improve the results. In this case Indexes were used where NDVI and NDMI were selected as optical dataset.



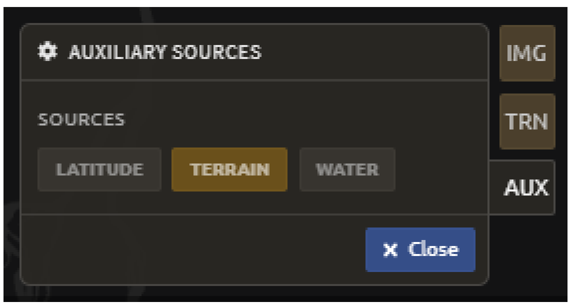
Final Parameters of the Landsat 8

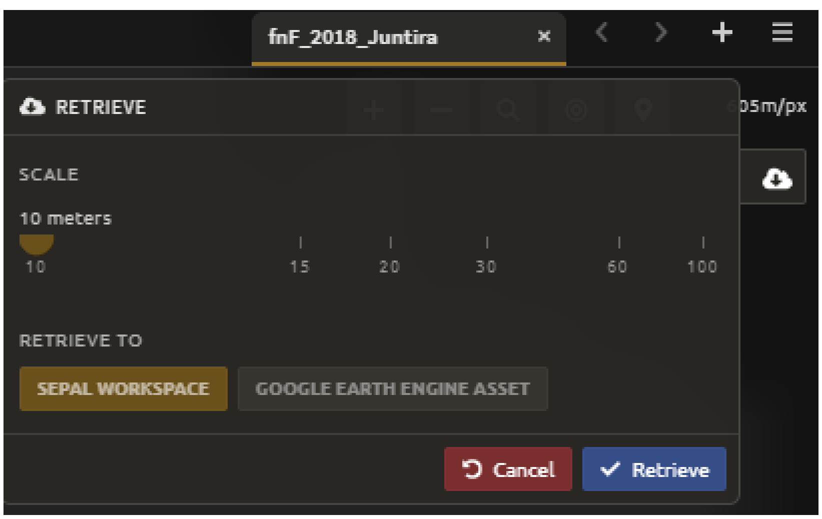


Final Parameters of the Sentinel-2



Final Parameters of the Radar image



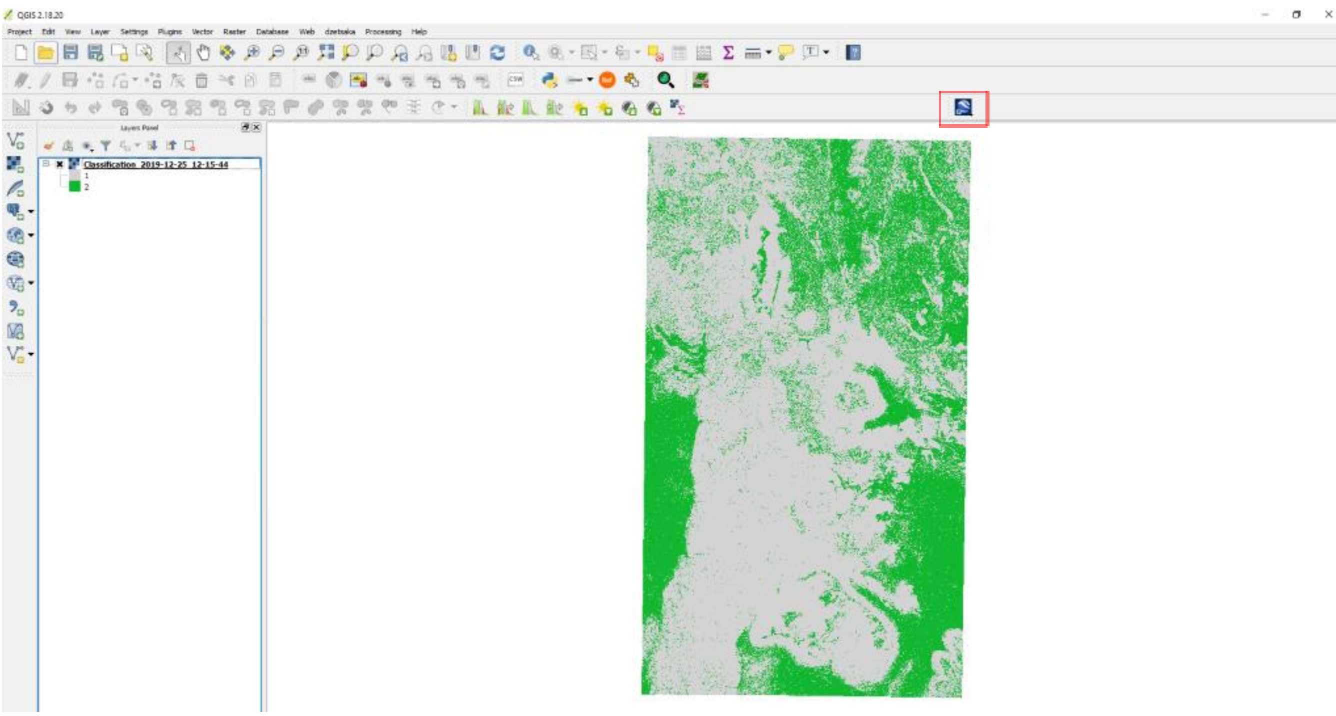


Classification results will appear like this:

Once classification is finished, download it as in SEPAL workspace to review the classification. The next chapter will provide more details on how to review the classification.

7. Classification Review and iteration

Once the download of classification is finished, it can be opened in QGIS. The G-earth view plugin can be used to overlay the classification over the Google Earth images. Additional training data was collected over false classification areas and then the classification was re-run with new training data with additional training points to improve the results.



Note: G-earth view  highlighted above) can be installed from the plugins tab.