Fiji's Forest Reference Level

Reference Period 2006 — 2016

Philip Mundhenk, Prem Raj Neupane & Michael Köhl

World Forestry — University of Hamburg

September 2019

Authors:

Philip Mundhenk
Prem Raj Neupane
Michael Köhl

Contact:

World Forestry
Institute of Wood Science
Department of Biology
Faculty of Mathematics, Informatics and Natural Sciences
University of Hamburg

Leuschnerstr. 91e
21031 Hamburg
Germany

Phone: +49 40 73962-100
Fax: +49 40 73962-199
Email: philip.mundhenk@uni-hamburg.de
Web: https://www.uni-hamburg.de/en.html

Summary

A brief summary of Fiji's Forest Reference Level (FRL):

Reference Period	January 1$^{\text{st}}$, 2006 to December 31$^{\text{th}}$, 2016 (11 years)
Accounting Area	Sub-national (90% of Fiji's land-mass)
Sources/sinks	— Emissions from deforestation
	— Emissions from forest degradation, incl.
	– Emissions from logging in Natural Forest
	– Emissions from fire in Softwood Plantations
	— Removals from the enhancement of carbon stocks, incl.
	– Removals from afforestation/reforestation
	– Removals from forest plantation management
Pools	— Above-ground biomass (AGB)
	— Below-ground biomass (BGB)
Gases	— Carbon dioxide (CO_2)
	— Methane CH_4
	— Nitrous oxide N_2O
FRL type	Historical average; no adjustment
FRL estimate	1,636,804 metric tonnes of CO_2-equivalents per year [$tCO_2e\ yr^{-1}$]
FRL uncertainty	Estimated 90% confidence limits:
	— Lower limit: 851,765 $tCO_2e\ yr^{-1}$
	— Upper limit: 2,317,968 $tCO_2e\ yr^{-1}$

Fiji's Forest Reference Level (FRL) is an estimate of the historical average annual net forest-related greenhouse gas (GHG) emissions over the Reference Period in the Accounting Area. The FRL is expressed in metric tonnes of carbon-dioxide equivalents per year [$tCO_2e\ yr^{-1}$]. The Reference Period starts January 1st, 2006 and ends December 31st, 2016. The Reference Period entails, thus, 11 years. The Accounting Area is sub-national covering about 90% of Fiji's land-mass and approximately 94% of Fiji's forest area.

Average annual emissions are estimated for two sources: emissions from deforestation and emissions from forest degradation. Average annual removals are estimate for the sink 'removals from the enhancement of forest carbon stocks'. The sinks 'sustainable management of forests' and 'conservation of forest carbon stocks' are not included in Fiji's FRL. The FRL is an estimate of average annual *net* emissions, i.e., average annual removals are subtracted from average annual emissions to compute net emissions.

Two forest carbon pools are included in Fiji's FRL, namely above-ground biomass (AGB) and below-ground biomass (BGB). The GHGs considered are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

Emissions from deforestation are estimated using data from a land-cover change map and data on the carbon stock change caused by deforestation. To estimate emissions the average annual area of forest loss in hectares (i.e., activity data AD) is multiplied by the carbon stock change per hectare (i.e., emission factor EF). The carbon stock change was estimate from data collected during Fiji's National Forest Inventory (NFI) 2006. The land-cover change map was produced by CSIRO in collaboration with the Management Service Division (MSD) of the Fijian Ministry of Forestry (MoF).

The source 'forest degradation' entails two sub-sources of emissions and one sub-sink of removals. Gross emissions are estimated from (i) emissions from logging in Natural Forest and (ii) emissions from biomass burning (i.e., fire) in Softwood Plantations. Gross removals are estimated from Natural Forest re-growth after logging. Emissions from logging are estimated using annual data on timber volumes extracted. An approach proposed by Pearson *et al.* [2014] was used to convert extracted volumes to carbon loss. Emissions from fire are estimated using data on areas burned in Softwood Plantations. These data were provided by Fiji Pine Limited (FPL). Removals from forest re-growth after logging are estimated using a nationally derived estimate of the mean annual carbon increment in logged Natural Forests. Net emissions for the source 'forest degradation' are computed by taking the difference of gross emissions and gross removals.

The sink 'enhancement of forest carbon stocks' includes (i) removals from afforestation/reforestation (AR) and (ii) net removals from Forest Plantations (Hard- and Softwood Plantations). Removals for AR are estimated using data from the land-cover change map that is also used for the estimation of emissions from deforestation. To estimate removals for AR average annual forest area gains are multiplied by an estimate of the mean annual carbon increment in newly established forests. Forest Plantations generate emissions and removals simultaneously: gross emissions are caused by logging in Forest Plantations and gross removals are generated by Forest Plantation growth. To estimate emissions from Forest Plantations, logging statistics provided by FPL (for Softwood Plantations) and Fiji Hardwood Corporation Limited (FHCL; for Hardwood Plantations) are used. Removals are estimated from data on stockings and plantings in

the Plantation lease areas of the two companies. Net removals for the sink 'enhancement of forest carbon stocks' are computed by aggregating estimates of gross removals (AR and Forest Plantations) and gross emissions (Forest Plantations).

The FRL is computed by taking into account gross emissions and gross removals from all sources and sinks, i.e., average annual net removals from all (sub-)sinks are subtracted from average annual gross emissions from all (sub-)sources. The final estimate of the FRL is: 1,636,804 tCO_2e yr^{-1}. In addition to the FRL point estimate, estimates of uncertainty are provided. Monte Carlo (MC) simulations are used to derive estimates of uncertainty. The 90%-confidence limits for the FRL estimate are estimated at 851,765 tCO_2e yr^{-1} (lower limit) and 2,317,968 tCO_2e yr^{-1} (upper limit).

Contents

List of Tables

List of Figures

Abbreviations

AD	Activity data
EF	Emission factor
AA	Accuracy assessment
AGB	Above-ground biomass
AR	Afforestation and reforestation
BGB	Below-ground biomass
CH_4	Methane
CO_2	Carbon dioxide
ER-PIN	Emission Reductions Program Idea Note
ERP	Emission Reductions Program
FAO	Food and Agriculture Organization of the United Nations
FCPF	Forest Carbon Partnership Facility
FCPF-DST	FCPF REDD+ Decision Support Toolbox
FHCL	Fiji Hardwood Corporation Limited
FPL	Fiji Pine Limited
FRA	Global Forest Resources Assessment
FRL	Forest Reference Level
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
LEDS	Low Emission Development Strategy
MODIS	Moderate-resolution Imaging Spectroradiometer
MoF	Ministry of Forestry
MSD	Management Service Division of the Fijian Ministry of Forestry
N_2O	Nitrous oxide
NFI	National Forest Inventory
PTHD	Pan-tropical Tree Harvest Database

REDD+   Reducing Emissions from Deforestation and Forest Degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks

SOC   Soil organic carbon

SRTM   Shuttle Radar Topography Mission

TEF   Total Emission Factor

UNFCCC   United Nations Framework Convention on Climate Change

1. Scale and scope

1.1. Reference Period and Accounting Area

The Forest Reference Level (FRL) of the Republic of Fiji is an estimate of the historical average annual net forest–related greenhouse gas (GHG) emissions. The FRL is defined for a given Reference Period and Accounting Area. The Reference Period is the time–interval over which average annual net emissions are estimated. The Reference Period of Fiji's FRL starts January 1st, 2006 and ends December 31st, 2016 (i.e., 11 years). The Accounting Area is the area over which net emissions are estimated during the Reference Period. Fiji's Accounting Area is sub–national, covering the three largest islands Viti Levu, Vanua Levu and Taveuni. The Accounting Area covers an area of 1,636,557 ha, which is about 90% of Fiji's total land-mass (see Figure 1.1).

1.2. Sources and sinks

The United Nations Framework Convention on Climate Change (UNFCCC) defines a source of GHGs as "[a]ny process or activity which releases a greenhouse gas, an aerosol or a precursor of a greenhouse gas into the atmosphere" (UNFCCC Article 1.9). A sink is defined as "[a]ny process, activity or mechanism which removes a greenhouse gas, an aerosol, or a precursor of a greenhouse gas from the atmosphere (UNFCCC Article 1.8). Two sources (emissions from deforestation and emissions from forest degradation) and one sink (enhancement of forest carbon stocks) are included in Fiji's FRL. The decision which sources and sinks to include was guided by (i) expert judgements (national and international), (ii) the Emission Reductions Program Idea Note [ER-PIN, 2016], (iii) data availability, (iv) implications for the Emission Reductions Program, (v) IPCC Tier 1 methods, (vi) the FCPF REDD+ Decision Support Toolbox (FCPF-DST), and (vii) by decisions made by the Fiji REDD+ Steering Committee.

> Sources and sinks **included** in Fiji's Forest Reference Level (FRL):
>
> **Emissions from deforestation** The source 'deforestation' is included in Fiji's FRL. Deforestation has mainly taken place in Natural Forest such as conversion of forests to commercial and subsistence agricultural cultivation, grasslands and infrastructure development, etc. Emission Reductions Programs must account for emissions from this REDD+ activity.
>
> **Emissions from forest degradation** The source 'forest degradation' is included in Fiji's FRL. Emissions from forest degradation are considered
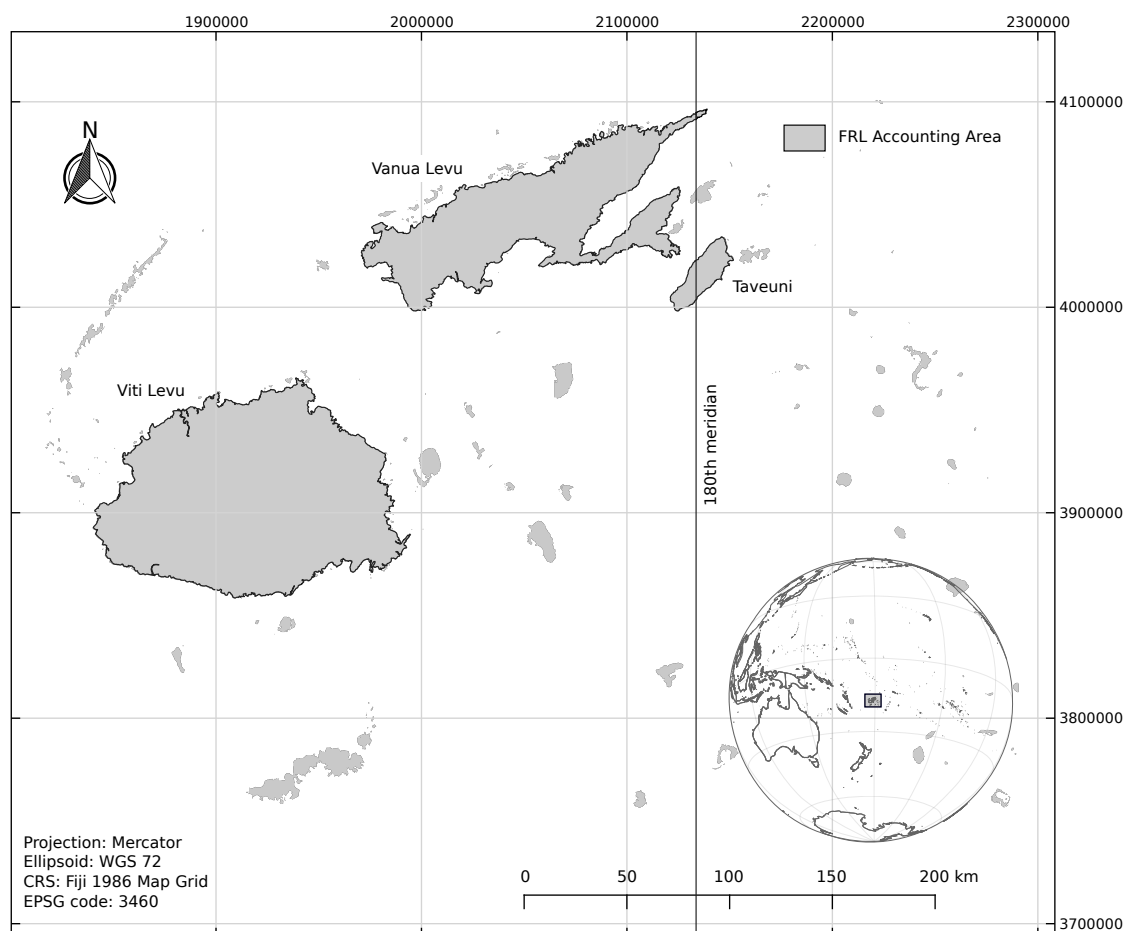
Figure 1.1.: Forest Reference Level (FRL) Accounting Area including Fiji's three largest islands Viti Levu, Vanua Levu and Taveuni. The total land-mass included in the Accounting Area is 1,636,557 ha.

significant [ER-PIN, 2016]. Currently unsustainable forest management practices are widespread in Fiji, causing a decline of carbon stocks in Natural Forest. The Government of Fiji is planning to increase the area of Natural Forest under sustainable management. Additionally, fire contributes to degradation predominately in Softwood Plantations and is included in the estimation of emissions. Management of fire has become a national priority through the establishment of a National Fire Strategy.

Removals from enhancement of forest carbon stocks The sink 'enhancement of forest carbon stocks' is included in Fiji's FRL. The ER-PIN [2016] identifies afforestation/reforestation (AR) activities on degraded lands as key to increase GHG removals. The sink 'enhancement of for-

est carbon stocks' also includes areas belonging to the stratum Forest Plantations. In collaboration with the private sector, the Ministry of Forestry (MoF) is planning to increase the area of sustainably managed Forest Plantations.

Sources and sinks **not included** in Fiji's FRL:

Removals from the conservation of carbon stocks The sink 'removals from conservation of carbon stock' is not included in Fiji's FRL, because the national REDD+ activities are not clearly defined at this stage for the monitoring and reporting of conservation of carbon stock.

Sustainable management of forests Emissions and/or removals from sustainable management of forests are not included, because there is unclear definition of this activity under the national REDD+ scheme and there are no clear boundaries for forest areas under sustainable management. This activity is assumed to be included in the above REDD+ activities, in particular in the REDD+ activity 'removals from enhancement of forest carbon stocks'.

For Fiji's FRL 'deforestation' and 'forest degradation' are considered net sources of emissions, whereas 'enhancement of forest carbon stocks' is considered a net sink. As it is typical for the Agriculture, Forestry and Other Land Use (AFOLU) sector, some net sources and/or sinks generate emissions and removals simultaneously. For the net source 'forest degradation', for example, gross emissions are generated by wood removals from Natural Forest. However, over the Reference Period, gross removals are generated by carbon accumulation in Natural Forest that have been logged for timber (i.e., forest regrowth). Gross emissions and removals for a net source or sink will be called sub-sources and sub-sinks for a source/sink, respectively. For a net source, average annual gross emissions over the Reference Period will be larger than average annual gross removals over the Reference Period. Thus, 'forest degradation' will be considered a net source if on average gross emissions are larger than gross removals, even if in some years gross removals may exceed gross emissions.

1.3. Pools and gases

1.3.1. Pools

IPCC [2006] defines a pool as "[a] reservoir. A component or components of the climate system where a greenhouse gas or a precursor of a greenhouse gas is stored". The carbon pools included in Fiji's FRL are listed below. The decision on which carbon pools to include was guided by (i) expert judgements (national and international), (ii) data availability, (iii) implications for the Emission Reductions Program, (iv) IPCC Tier 1 methods, and (v) the FCPF-DST.

Carbon pools **included** in Fiji's FRL:

Above–ground biomass (AGB) This is the largest carbon pool and is impacted by the sources of deforestation and forest degradation, as well as the sink 'enhancement of forest carbon stocks'.

Below–grond biomas (BGB) This is a significant carbon pool. As there is no country specific data on BGB, default values (i.e., root-to-shoot ratios) from IPCC [2006] are used to compute BGB.

Carbon pools **not included** in Fiji's FRL:

Dead wood Dead wood is not included in Fiji's FRL. No national data are currently available for dead organic matter (DOM; i.e., dead wood) in Fiji. IPCC [2006, Vol. 4, Chap. 2] notes that for Tier 1: Carbon stocks of DOM are assumed to be zero for non-forest land–use categories. Deadwood (DOM) data has not been estimated in Fiji's National Forest Inventory (NFI). In the future, a stepwise approach is proposed to be applied to improve the measurement of this carbon pool.

Litter Litter is not included in Fiji's FLR. No national data are currently available for Litter. IPCC [2006, Vol. 4, Chap. 2] notes that for Tier 1: Carbon stocks of Litter are assumed to be zero for non-forest land–use categories. Litter data has not been estimated in Fiji's NFI. In the future, a stepwise approach is proposed to be applied to improve the measurement of this carbon pool.

Soil organic carbon (SOC) Soil organic carbon (SOC) is not included in Fiji's FRL. SOC data have not been estimated in Fiji's NFI. IPCC [2006, Vol. 4, Chap. 2, Section 4.2.3.1] Tier 1 method states that there is no change in forest SOC with management or soil carbon change is zero for mineral soils. This has been assumed in Fiji as there are no peat soils. Additionally, as per the "Tool for estimation of change in soil organic carbon in the implementation of A/R CDM activities", estimation is required for afforestation/reforestation (AR) activities in which site disturbance is more than 10%t of the area (Clean Development Mechanism Executive Board 55, Annex 21). Site disturbance in approaches to AR in Fiji will result in less than 10% of the area due to the forest establishment techniques. Additionally, such activities will focus on degraded lands and it is assumed that planting trees in these areas will cause a net increase in SOC. On this basis SOC is not included in the FRL. In the future, a stepwise approach is proposed to be applied to improve the estimation of this carbon pool.

1.3.2. Gases

A list of GHGs included in Fiji's FRL is provided below. The decision which GHGs to include was guided by (i) expert judgements, (ii) data availability, (iii) implications for the Emission Reductions Program, (iv) IPCC Tier 1 methods, and (v) the FCPF-DST.

> Greenhouse gases (GHGs) included in Fiji's FRL:
>
> **CO_2** Emission Reduction Programs (ERPs) shall always account for CO_2 emissions and removals. The emissions are caused by deforestation and forest degradation. Removals are generated by the sink 'enhancement of forest carbon stocks' (afforestation/reforestation and Forest Plantations).
>
> **CH_4** Methane (CH_4) emissions associated with forest fires are included.
>
> **N_2O** Nitrous oxide (N_2O) sources include fires and fertilizer application. N_2O emissions from forest fires are included in the FRL. As forest management practices in Fiji do not include application of nitrogen fertilizer, N_2O emissions from fertilizer application are not covered in the FRL.

1.4. Forest definition and stratification of land

1.4.1. Forest definition

In Fiji, the term 'forest' has not yet been formally defined. Fiji's REDD+ Policy document (see MPI [2011]) adopted the forest definition provided in the Global Forest Resources Assessment (FRA) 'Terms and Definitions' document (see FAO [2004]) of the Food and Agriculture Organization (FAO). This definition was used for the FRL.

> "Land spanning more than 0.5 hectares with trees higher than five metres and a canopy cover of more than 10 per cent, or trees able to reach these thresholds in situ.
>
> It does not include land that is predominantly under agriculture or urban use. Forest is determined both by the presence of trees and the absence of other predominant land uses. Areas under reforestation that have not yet reached but are expected to reach a canopy cover of 10 per cent and a tree height of five metres are included, as are temporarily unstocked areas, resulting from human intervention or natural causes, which are expected to regenerate.
>
> Includes: areas with bamboo and palms, provided that height and canopy cover criteria are met; forest roads, fire breaks and other small open areas; forest in national parks, nature reserves and other protected areas such as those of scientific, historical, cultural or spiritual interest; windbreaks, shelterbelts and corridors of trees with an area of more than 0.5 hectares and width of more than 20 metres; plantations primarily used for forestry or protected purposes [...]
>
> Excludes tree stands in agricultural production systems, for example in fruit plantations and agroforestry systems. The term also excludes trees in urban parks and gardens".

Fiji's most recent country report to the FRA [FRA-Fiji, 2015] lists four forest classes within its forest area, namely (i) closed forest, (ii) open forest, (iii) pine plantations, and (iv) hardwood plantations (see Section 1.4.2 for a definition of forest strata). For the FRL, land that falls under one of these four classes is defined as forest. Note that Mangrove is not listed under forest in Fiji's FRA country report, partly because the areas of mangrove, defined here as the habitat and entire plant assemblage in which species of the plant family Rhizophoraceae dominate, is located below the high tide water mark (i.e., not considered as land). Moreover, mangrove was not included in the FRL because (i) at least three governmental agencies have regulatory jurisdiction over mangrove and, therefore, the Ministry of Forests refrained from including mangrove in the FRL to avoid potential conflict between the agencies involved, (ii) mangrove will be considered under "Coastal Wetlands (Blue Carbon)" in the Low Emission Development Strategy (LEDS), and (iii) to ensure consistency with other reporting requirements (i.e., FRA reporting). Also note that coconut plantations are not considered as forest in Fiji (see FRA-Fiji [2015] and Anonymous [2005]).

1.4.2. Stratification of land

For the FRL, the six IPCC land-use categories Forest Land, Cropland, Grassland, Wetlands, Settlements and Other Land, were reclassified to form the two land-use categories 'Forest Land' and 'Non-Forest Land'. The latter entails the five land-use categories Cropland, Grassland, Wetlands, Settlements and Other Land. This simplified representation of land was adopted, because the land-cover change map produced for the FRL does not distinguish between the land-use categories Cropland, Grassland, Wetlands, Settlements, and Other Land.

For the FRL, the land-use category Forest Land consists of two land-use sub-categories, namely Natural (or Native) Forest and Forest Plantations. The sub-category Natural Forest entails two strata: Lowland Natural Forest and Upland Natural Forest (see Table 1.1). The 'strata' closed and open forest (as defined in the latest FRA country report and the National Forest Inventory [NFI] 2006) were not retained for the FRL for the following reasons: with the data available and the methods used to map forest areas it was not possible to reliably distinguish between areas of closed and open forest and, probably more relevant for the FRL, to map area changes of closed and open forest. The decision to distinguish between Low- and Upland Natural Forest was based on findings by Mueller-Dombois & Fosberg [1998], who identified significant changes in structural and floristic characteristics in forests in Fiji below and above approximately 600 m above sea level (a.s.l.). Mueller-Dombois & Fosberg [1998] found that above 600 m a.s.l. Fijian forests show characteristics typical for mountain forests systems, whereas forest located below 600 m a.s.l. show characteristics of either tropical rain forests or tropical moist deciduous forests. A preliminary analysis of the NFI 2006 data revealed significant differences in carbon stocks between Low- and Upland Natural Forest, but not between the two strata closed and open forest.

The land-use sub-category Forest Plantations consists of the two strata Softwood Plantations and Hardwood Plantations. The stratum Softwood Plantations includes

all areas that were leased by Fiji Pine Limited (FPL) between 2006 and 2016. Softwood plantations are dominated by trees of the species *Pinus caribaea var. hondurensis* (Sénéclauze) W.H.Barrett & Golfari (Caribbean pine). The stratum Hardwood Plantations entails all areas leased by Fiji Hardwood Corporation Limited (FHCL) between 2006 and 2016. Hardwood plantations are dominated by trees of the species *Swietenia macrophylla* King (Honduran or big-leaf mahogany).

Note, to areas outside Forest Plantations a land-*cover* definition applies, whereas within the plantation lease areas a land-*use* definition is used. For example, if the crown-cover percent on a patch of land drops from e.g., 80% to below 10% in areas outside the plantation lease areas, the land-use sub-category of that patch would change from Natural Forest (Low- or Upland) to Non-Forest (i.e., land-use category Forest Land to Non-Forest Land). This holds true even for areas outside the plantation lease areas that may only be temporarily unstocked. However, if the crown-cover drops below 10% within the land-use sub-category Forest Plantations (Soft- or Hardwood), the land would still fall under the land-use category Forest Land.

Table 1.1.: Land-use categories, sub-categories and forest strata used for Fiji's FRL.

IPCC LUC[a]	LUSC[b]	Stratum	Description
Forest Land	Natural Forest	Lowland Natural Forest	The stratum 'Lowland Natural Forest' includes all land in which trees are present, and where the land (i) covers at a minimum an area of 0.5 hectares, (ii) is not predominantly under agricultural or urban use, (iii) has a canopy cover percent of 10% or more, and (iv) is located <600 m a.s.l.[c] It includes primary (native) forest, human modified forests as well as areas planted with native or introduced tree species. 'Lowland Natural Forest' cannot be located in plantation lease areas. Mangrove is not included in this stratum.
		Upland Natural Forest	The stratum 'Upland Natural Forest' includes all land in which trees are present, and where the land (i) covers at a minimum an area of 0.5 hectares, (ii) is not predominantly under agricultural or urban use, (iii) has a canopy cover percent of 10% or more, and (iv) is located <600 m a.s.l., (iii) has a canopy cover percent of 10% or more, and (iv) is located <600 m a.s.l. It includes primary (native) forest, human modified forests as well as areas planted with native or introduced tree species. 'Upland Natural Forest' cannot be located in plantation lease areas. Mangrove is not included in this stratum.
	Forest Plantations	Softwood Plantations	The stratum 'Softwood Plantation' includes all areas leased by Fiji Pine Limited (FPL) between 2006 and 2016. Areas not stocked with trees (i.e., the crown cover percent is < 10%) but which are located within FPL's lease area belong to the land-use category Forest Land.
		Hardwood Plantations	The stratum 'Hardwood Plantation' includes all areas leased by Fiji Hardwood Corporation Limited (FHCL) between 2006 and 2016. Areas not stocked with trees (i.e., the crown cover percent is < 10%) but which are located within FHCL's lease area belong to the land-use category Forest Land.
Non-Forest Land	Non-Forest	Non-forest	The land-use category 'Non-Forest Land' includes all areas not classified as 'Forest Land'. Areas classified as mangrove forest are included in the land-use category 'Non-Forest Land'. Note that 'Non-Forest Land' is not an IPCC land-use category as defined in IPCC [2006, Volume 4, Chapter 3.2]. The land-use category 'Non-Forest Land' includes all IPCC land-use categories, i.e., 'Grassland', 'Cropland', 'Wetlands', 'Settlements' and 'Other Land', except the category 'Forest Land'.

[a] LUC = land-use category
[b] LUSC = land-use sub-category
[c] a.s.l. = above sea level

2. Emissions by source and removals by sink

2.1. Overview

IPCC [2006] defines emissions as "[t]he release of greenhouse gases and/or their precursors into the atmosphere over a specified area and period of time". Removals are defined as the "[r]emoval of greenhouse gases and/or their precursors from the atmosphere by a sink". Emissions and removals are expressed in carbon dioxide equivalents per year [tCO_2e yr^{-1}]. Following IPCC terminology, emissions always have a positive (+) sign and removals (i.e., negative emissions) always have a negative (−) sign. Fiji's FRL is an estimate of net emissions. Net emissions are the sum of emissions and removals from all (sub-)sources and (sub-)sinks.

Net emissions are estimated over the FRL Reference Period. The Reference Period of Fiji's FRL starts January 1, 2006 and ends December 31, 2016. The length of the Reference Period is $\mathcal{T} = 11$ years. Fiji's FRL is computed as a historical average. It is, thus, a single numerical value (i.e., point estimate): the historical average annual net forest-related greenhouse gas (GHG) emissions over the Reference Period in the Accounting Area. A potential temporal trend of net emissions or removals over the Reference Period is not considered for the construction of Fiji's FRL.

Two sources of emissions are considered: emissions from deforestation and emissions from forest degradation (see Figure 2.1). The net source forest degradation has two sub-sources: gross emissions from timber extraction in Natural Forest and gross emissions from biomass burning in Softwood Plantations (i.e., fire). The net source forest degradation also includes a sub-sink: gross removals from forest-regrowth after logging. Given that gross emissions exceed gross removals, the source forest degradation is, thus, a net source, including both gross emissions and gross removals. For the source deforestation gross emissions and net emissions are equivalent as there are only gross emissions but no gross removals from deforestation.

The net sink 'removals from the enhancement of forest carbon stocks' includes removals from afforestation/reforestation (AR) and net removals from Forest Plantations. For AR there are only gross removals but no gross emissions. For the net sink 'removals from Forest Plantations' there are emissions from timber extraction from Forest Plantations (sub-source) and removals from plantation regrowth (sub-sink). Plantation regrowth includes growth in Forest Plantation compartments (i.e., coupes) that were planted before 2006 (i.e., planted before the start of the FRL Reference Period) and were not cut until the end of 2016, growth in compartments that were planted before 2006 and were harvested during the Reference Period (i.e., before 2016), and growth in compartments that were planted during the Reference Period 2006-2016 which were not cut until the end of the Reference Period in end of 2016.
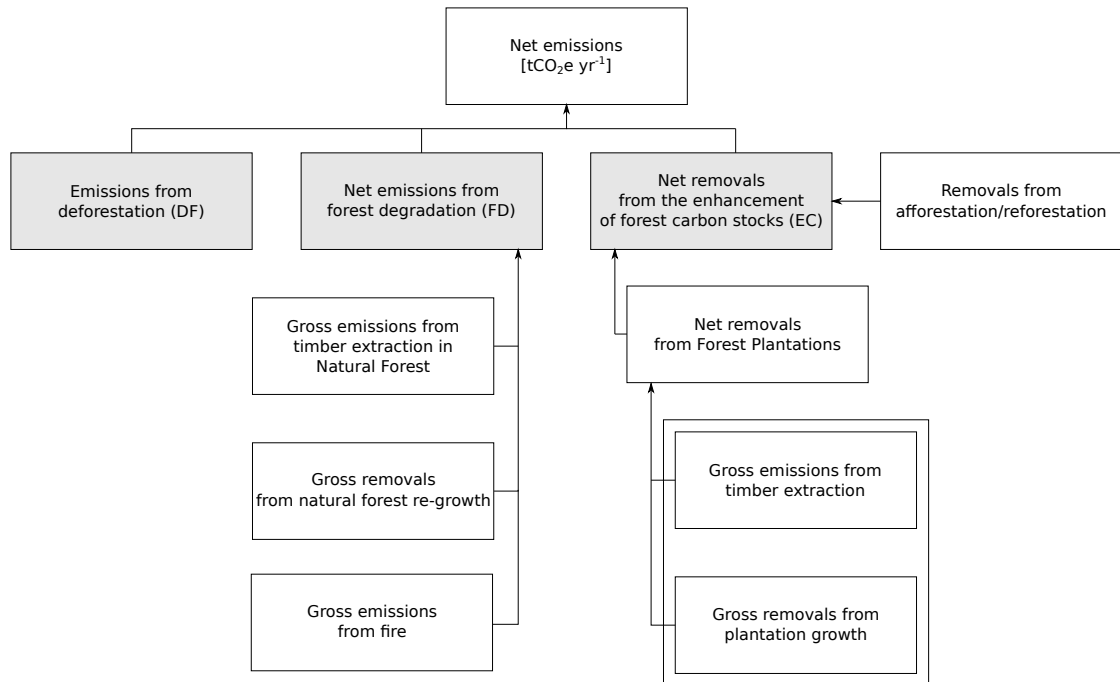
Figure 2.1.: Overview of the sources and sinks considered in Fiji's Forest Reference Level (FRL), including the sub-sources and sub-sinks for forest degradation and enhancement of forest carbon stocks.

Although the methods used to estimate emissions and removals differ among the various (sub-)sources and (sub-)sinks, some generic approaches and default factors will be the same for any (sub-)source or (sub-)sink. Emissions and removals are computed from carbon (C) losses and gains, respectively. Carbon losses always have a negative sign (−), whereas carbon gains always have a positive (+) sign. Carbon losses are converted to emissions using a default conversion factor from IPCC [2006, Vol. 4, Chap. 4, Tab. 4.3].

Equation 2.1: IPCC [2006] default carbon to CO_2 conversion factor

$$\eta_{CC} = -\frac{44}{12}$$

η_{CC} = Carbon (C) to CO_2 conversion factor; dimensionless

As carbon losses have a negative sign the multiplication of losses with η_{CC} will result in (positive) emissions. Multiplying carbon gains by η_{CC} will result in removals which always have a negative sign. Carbon stocks and stock changes are frequently — but not always — computed from biomass stocks and biomass stock changes. To convert biomass to C a default conversion factor from IPCC [2006] is used.

Equation 2.2: IPCC [2006] default biomass to carbon conversion factor

$$\eta_{CF} = 0.47$$

η_{CF} = Biomass to carbon (C) conversion factor; dimensionless

In the remainder of this chapter the methodology for the estimation of emission and removals are explained in detail. Methods are provided for

— Emissions from deforestation (Section 2.2 on page 12)
— Emissions from forest degradation (Section 2.3 on page 19)
— Removals from the enhancement of forest carbon stocks (Section 2.4 on page 33)

Additional information is provided in Appendix A to Appendix D. The final estimates of the FRL are provided in Chapter 3 on page 57.

2.2. Emissions from deforestation

2.2.1. Methodological approach

For the FRL, deforestation is defined as the conversion from land in the land-use sub-category Natural Forest, to land in the land-use sub-category Non-Forest (see Table 1.1). Emissions from deforestation were estimated using IPCC's [2006] generic equation

Equation 2.3: Estimation of emissions from deforestation

$$Emissions = AD \times EF$$

where the activity data (AD) are the average annual areas of deforestation (i.e., loss of Natural Forest), and the emission factor (EF) is the amount of emissions released per unit AD. Activity data are expressed in hectares per year [ha yr^{-1}], the EF is expressed in carbon dioxide emissions per hectare [tCO$_2$e ha^{-1}]. The multiplication of AD and EF gives emissions of CO$_2$ equivalents per year [tCO$_2$e yr^{-1}].

To estimate the AD, data from a land-cover change map were used which shows areas of deforestation and afforestation/reforestation (AR). Of importance, the map only shows the change from Natural Forest to Non-Forest and vice versa. It does not distinguish between the different IPCC land-use categories (i.e., Cropland, Grassland, Wetlands, Settlements and Other Land). It is also important to note that Forest Plantation lease areas (Hard- and Softwood) and areas covered by mangrove were excluded from te land-cover change mapping. Moreover, the land-cover change map assessed change in land-*cover* rather than land-*use*.

The land-cover map used for the FRL was produced by CISRO's (Commonwealth Scientific and Industrial Research Organisation) Remote Sensing Image Integration Group in collaboration with the Management Service Division (MSD) of the Fijian Ministry of Forestry (MoF). The time interval covered by the change map was mid 2015 to mid 2017. As the Reference Period starts in 2006 and ends in 2016, only change data from mid 2006 to mid 2016 were used for the FRL construction. Extracting data for a specific time interval from the land-cover change map was possible, because the change map was produced from a series of annual change maps.

The land-cover change classes depicted on the land-cover change map are listed in Table 2.1. The Table includes the class codes for the land-cover change classes, as well as a link of the change class to the source or sink. The data and methods used to generate the map are described in detail in Appendix 8.2 of the ER-PD [2019].

Table 2.1 also depicts the mapped areas of the different classes. However, these mapped areas were not directly used to estimate emissions from deforestation. To estimate areas of deforestation (and afforestation/reforestation) an accuracy assessment (AA) was conducted following the methods described in Olofsson *et al.* [2014]. Data for the AA were collected by AUSVET[i]. The methods used for AA data collection are described in detail in Appendix 8.2 of the ER-PD [2019]. Appendix A.1 provides details on

---

[i]Web: https://www.ausvet.com.au

Table 2.1.: Land-cover change classes that were mapped for the FRL construction. The column "Source/Sink" indicates to which source/sink the change class is linked (DF = deforestation; AR = afforestation/reforestation). The areas mapped, A, are totals over the Reference Period.

	Class description	Source/Sink	A mapped [ha]
111	Natural Forest (1) remaining Natural Forest (1); Lowland (1)		670,300
112	Natural Forest (1) remaining Natural Forest (1); Upland (2)		229,098
171	Natural Forest (1) converted to Non-Forest (7); Lowland (1)	DF	54,406
172	Natural Forest (1) converted to Non-Forest (7); Upland (2)	DF	9,834
711	Non-forest (7) converted to Natural Forest (1); Lowland (1)	AR	33,742
712	Non-forest (7) converted to Natural Forest (1); Upland (2)	AR	3,489
777	Non-forest (7) remaining Non-forest (7); Low- or Upland (7)		502,344

how the land-cover change data in combination with the AA data were used to estimate area totals of deforestation and afforestation/reforestation over the Reference Period.

As can be seen in Table 2.1 shows, areas of deforestation were mapped and estimated separately for Lowland Natural Forest and Upland Natural Forest. Hence, *AD* were available for both forest strata (see Table 1.1 for the different Natural Forest strata considered for the FRL). The reason why the two strata were considered for Fiji's FRL construction was that from National Forest Inventory (NFI) data a significant difference in carbon stocks were found between Low- and Upland Natural Forest — carbon stocks in Lowland Forest were on average higher than carbon stocks in Upland Forest.

To estimate carbon stocks in Low- and Upland Natural Forest data from Fiji's NFI 2006 were used. Carbon stocks in Natural Forest represent pre-deforestation stocks. To estimate stock changes for the source 'deforestation', the difference between pre- and post-deforestation stocks was estimated. Carbon stocks in deforested land were taken from a study conducted by Rounds [2013]. The *EF* for deforestation was estimated by converting the (negative) carbon stock change caused by deforestation to (positive) emissions using the conversion factor from Equation (2.1).

As mentioned above, the land-cover change map used for the FRL provides data on the change from Natural Forest to Non-Forest, but it does not show to which land-cover or land-use class Natural Forest is converted (e.g., Natural Forest converted to Cropland). To derive *EF*s it was assumed that all Natural Forest that was deforested during the Reference Period was converted to Grassland. Estimated C stocks in Grassland were taken from a study conducted in Fiji by Rounds [2013].

2.2.2. Activity data

The *AD* for the source deforestation are the average annual losses of Low- and Upland Natural Forest area. These areas were computed from total losses over the Reference Period (see Table 2.2; column $\hat{A}$ est.). Total loss was estimated using data from the AA (see Appendix A.1 for details). The annual average area of deforestation of Low- and Upland Natural Forest was computed by:

Table 2.2.: Results of the accuracy assessment (AA). A description of class codes is provided in Table 2.1. The area mapped (A map) is the area of the (change) classes shown in the land-cover change map, the area estimated ($\hat{A}$ est.) is the area estimated from the AA; DF = deforestation, AR = afforestation/reforestation; CI = confidence interval. The total area mapped is 1,503,213 ha.

Code	Class	A map [ha]	$\hat{A}$ est. [ha]	Lower 90%-CI [ha]	Upper 90%-CI [ha]
111	Stable Lowland Forest	670,300	629,501	605,325	652,654
112	Stable Upland Forest	229,098	244,090	234,787	253,548
171	DF Lowland	54,406	83,321	66,504	101,437
172	DF Upland	9,834	26,816	19,628	34,610
711	AR Lowland	33,742	49,555	36,941	63,525
712	AR Upland	3,489	12,241	7,222	17,628
777	Stable Non-Forest	502,344	457,687	439,347	476,321

Table 2.3.: Estimated average annual area of deforestation (DF) of Low- and Upland Natural Forest during the FRL Reference Period 2006-2016. CI = confidence interval.

Stratum	$\hat{\bar{A}}_{DF}$ [ha yr^{-1}]	Lower 90%-CI [ha yr^{-1}]	Upper 90%-CI [ha yr^{-1}]
DF Lowland ($\hat{A}_{j=171}$)	8,332	6,650	10,144
DF Upland ($\hat{A}_{j=172}$)	2,682	1,963	3,461
Total	11,014	9,175	12,970

Equation 2.4: Estimated areas of annual deforestation (Low- and Upland)

$$\hat{\bar{A}}_{DF,Lowland} = (\mathcal{T}-1)^{-1}\hat{A}_{j=171} \quad \text{and} \quad \hat{\bar{A}}_{DF,Upland} = (\mathcal{T}-1)^{-1}\hat{A}_{j=172}$$

$\hat{\bar{A}}_{DF,Lowland}$ = Average annual area of deforestation of Lowland Natural Forest; ha
$\mathcal{T}$ = Length of the FRL Reference Period, i.e., $|T| = \mathcal{T} = 11$ years; yrs
$\hat{A}_{j=171}$ = Area of deforestation of Lowland Natural Forest between mid 2006 and mid 2016 (class code 171; see Table 2.1); ha
$\hat{\bar{A}}_{DF,Upland}$ = Average annual area of deforestation of Upland Natural Forest; ha
$\hat{A}_{j=172}$ = Area of deforestation of Upland Natural Forest between mid 2006 and mid 2016 (class code 172; see Table 2.1); ha

Note that one year is subtracted from the length of the Reference Period ($\mathcal{T}$), because total areas of deforestation are provided for the time interval mid 2006 to mid 2016, i.e., 10 years. Estimated average annual areas of deforestation are provided in Table 2.3.

2.2.3. Emission factors

Emission factors were estimated from NFI 2006 data (pre-deforestation C stocks) and data provided by Rounds [2013] (post-deforestation C stocks). Following IPCC [2006] methodology, C stock changes caused by deforestation are estimated by

---

Equation 2.5: Carbon stock change caused by deforestation

$$\Delta C_{B,i} = \Delta C_G + \Delta C_{CONVERSION,i} + \Delta C_L$$

$\Delta C_{B,i}$ = Change in carbon stocks in biomass in Natural Forest stratum i converted to Non-Forest; tC ha^{-1}

ΔC_G = Annual increase in carbon stocks in biomass due to growth in Non-Forest; tC ha^{-1} yr^{-1}

$\Delta C_{CONVERSION,i}$ = Initial change in carbon stocks in biomass in Natural Forest stratum i converted to Non-Forest; tC ha^{-1}

ΔC_L = Annual decrease in carbon stocks in biomass due to disturbances in Non-Forest; tC ha^{-1} yr^{-1}

$\Delta C_{B,i}$ is computed for the two strata Lowland Natural Forest and Upland Natural Forest. In Equation (2.5) the two terms ΔC_G and ΔC_L are assumed to be zero. That is, no annual changes (gains or losses) are assumed in the post-deforestation land-use (i.e., Grassland). The change in C stock in biomass due to the conversion of Natural Forest to Grassland is, thus, captured in $\Delta C_{CONVERSION}$,

---

Equation 2.6: Carbon stock change caused by deforestation (no gain/loss)

$$\Delta C_{B,i} = \Delta C_{CONVERSION,i} = C_{AFTER} - C_{BEFORE,i}$$

$\Delta C_{B,i}$ = Change in carbon stocks in biomass in Natural Forest stratum i converted to Non-Forest; tC ha^{-1}

$\Delta C_{CONVERSION,i}$ = Initial change in carbon stocks in biomass in Natural Forest stratum i converted to Non-Forest; tC ha^{-1}

C_{AFTER} = Carbon stocks in biomass in Non-Forest; tC ha^{-1}

$C_{BEFORE,i}$ = Carbon stocks in biomass in Natural Forest stratum i; tC ha^{-1}

C_{AFTER} represents the peak C stock in Grassland, which was estimated by Rounds [2013] at $C_{AFTER} = 17.11$ (8.35; 25.9) tC ha^{-1}. The values in brackets give the lower and upper bounds of the 90% confidence interval derived from MC simulations. Confidence interval bounds were computed as the $Q(0.05)-$ and $Q(0.95)-$quantiles of a Triangular distribution with mode $c = C_{AFTER}$ and upper and lower bounds $a = C_{AFTER} - C_{AFTER} \times 0.75$ and $b = C_{AFTER} + C_{AFTER} \times 0.75$, respectively (see Appendix C for more details). The estimate for C_{AFTER} is the same for Low- and Upland. $C_{BEFORE,i}$ is the average C stock in Natural Forest stratum i (Low- or Upland Natural Forest). Estimates of C_{BEFORE} are provided in Table 2.4. For the two strata the C loss caused by deforestation is given by

---

Equation 2.7: Carbon stock change (Lowland/Upland)

$$\Delta C_{B,Lowland} = C_{AFTER} - C_{BEFORE,Lowland}$$
$$\Delta C_{B,Upland} = C_{AFTER} - C_{BEFORE,Upland}$$

$\Delta C_{B,Lowland}$ = Change in C stock in biomass in Lowland Natural Forest caused by deforestation; tC ha^{-1}

$\Delta C_{B,Upland}$ = Change in C stock in biomass in Upland Natural Forest caused by deforestation; tC ha^{-1}

C_{AFTER} = Average C stock in Grassland; tC ha^{-1}

$C_{BEFORE,Lowland}$ = Average C stock in Lowland Natural Forest; tC ha^{-1}

$C_{BEFORE,Upland}$ = Average C stock in Upland Natural Forest; tC ha^{-1}

Table 2.4.: Estimated C stocks stored in above-ground biomass (AGB) and below-ground biomass (BGB) in Low- and Upland Natural Forest; CI = confidence interval.

Stratum	Carbon stock [tC ha^{-1}]	Lower 90%-CI [tC ha^{-1}]	Upper 90%-CI [tC ha^{-1}]
Lowland	87.859	80.510	91.081
Upland	71.571	64.081	76.626

Estimates for $\Delta C_{B,Lowland}$ and $\Delta C_{B,Upland}$ are provided in Table 2.5. C stock change was converted to emission factors using Equation (2.8) and Equation (2.9). Estimated emission factors for the source deforestation are provided in Table 2.6.

Table 2.5.: Estimated C loss (including AGB and BGB) caused by deforestation of Low- and Upland Natural Forest ($\Delta C_{B,Lowland}$ and $\Delta C_{B,Upland}$); CI = confidence interval.

Stratum	ΔC_B [tC ha^{-1}]	Lower 90%-CI [tC ha^{-1}]	Upper 90%-CI [tC ha^{-1}]
Lowland	70.746	58.492	78.732
Upland	54.458	42.522	63.735

Equation 2.8: Emission factor for deforestation (Lowland)

$$\psi_{DF,Lowland} = \Delta C_{B,Lowland} \times \eta_{CC}$$

$\psi_{DF,Lowland}$ = Emission factor for the source deforestation in Lowland Natural Forest; tCO$_2$e ha^{-1}

$\Delta C_{B,Lowland}$ = Change in C stock in biomass in Lowland Natural Forest due to deforestation; tC ha^{-1}

η_{CC} = Conversion factor C to CO$_2$; dimensionless

Equation 2.9: Emission factor for deforestation (Upland)

$$\psi_{DF,Upland} = \Delta C_{B,Upland} \times \eta_{CC}$$

$\psi_{DF,Upland}$ = Emission factor for the source deforestation in Upland Natural Forest; $tCO_2e\ ha^{-1}$

$\Delta C_{B,Upland}$ = Change in C stock in biomass in Upland Natural Forest due to deforestation; $tC\ ha^{-1}$

η_{CC} = Conversion factor C to CO_2; dimensionless

Table 2.6.: Estimated emission factors, ψ_{DF}, for deforestation in Lowland Natural Forest and Upland Natural Forest; CI = confidence interval.

Stratum	ψ_{DF} [$tCO_2e\ ha^{-1}$]	Lower 90%-CI [$tCO_2e\ ha^{-1}$]	Upper 90%-CI [$tCO_2e\ ha^{-1}$]
Lowland	259.401	214.470	288.685
Upland	199.679	155.912	233.694

2.2.4. Average annual emissions

Average annual emissions from deforestation in Lowland Natural Forest were computed using Equation (2.10). Average annual emissions from deforestation in Upland Natural Forest were computed using Equation (2.11). Total emissions from deforestation (including emissions from deforestation of Lowland Natural Forest and emissions from deforestation of Upland Natural Forest) were computed using Equation (2.12). The final estimates of emissions from deforestation are provided in Table 2.7.

Equation 2.10: Average annual emissions (deforestation Lowland)

$$\hat{\theta}_{DF,Lowland} = \hat{\bar{A}}_{DF,Lowland} \times \psi_{DF,Lowland}$$

$\hat{\theta}_{DF,Lowland}$ = Average annual emissions from deforestation of Lowland Natural Forest; $tCO_2e\ yr^{-1}$

$\hat{\bar{A}}_{DF,Lowland}$ = Average annual loss of Lowland Natural Forest area; $ha\ yr^{-1}$

$\psi_{DF,Lowland}$ = Emission factor for deforestation in Lowland Natural Forest; $tCO_2e\ ha^{-1}$

Equation 2.11: Average annual emissions (deforestation Upland)

$$\hat{\theta}_{DF,Upland} = \hat{\bar{A}}_{DF,Upland} \times \psi_{DF,Upland}$$

17

$\hat{\theta}_{DF,Upland}$ = Average annual emissions from deforestation of Upland Natural Forest; $tCO_2e \ yr^{-1}$

$\hat{\bar{A}}_{DF,Upland}$ = Average annual loss of Upland Natural Forest area; $ha \ yr^{-1}$

$\psi_{DF,Upland}$ = Emission factor for deforestation in Upland Natural Forest; $tCO_2e \ ha^{-1}$

Equation 2.12: Average annual emissions (deforestation)

$$\hat{\theta}_{DF} = \hat{\theta}_{DF,Lowland} + \hat{\theta}_{DF,Upland}$$

$\hat{\theta}_{DF}$ = Average annual emissions from deforestation; $tCO_2e \ yr^{-1}$

$\hat{\theta}_{DF,Lowland}$ = Average annual emissions from deforestation of Lowland Natural Forest; $tCO_2e \ yr^{-1}$

$\hat{\theta}_{DF,Upland}$ = Average annual emissions from deforestation of Upland Natural Forest; $tCO_2e \ yr^{-1}$

Table 2.7.: Estimated average annual emissions from deforestation, $\hat{\theta}_{DF}$; CI = confidence interval.

Stratum	$\hat{\theta}_{DF}$ [$tCO_2e \ yr^{-1}$]	Lower 90%-CI [$tCO_2e \ yr^{-1}$]	Upper 90%-CI [$tCO_2e \ yr^{-1}$]
Lowland	2,161,364.32	1,589,714.68	2,662,016.35
Upland	535,466.31	354,509.18	713,069.26
Total	2,696,830.64	2,043,841.47	3,254,111.33

2.2.5. Uncertainty analysis

The uncertainty attached to the estimate of average annual emissions from deforestation, $\hat{\theta}_{DF}$, was estimated using Monte Carlo (MC) simulations. The procedures used to estimate the precision of $\hat{\bar{A}}_{DF,i}$ and $\hat{\bar{A}}_{DF}$ are described in detail in Appendix A.1. In Appendix A.2.4.6 it is shown how the uncertainties of total carbon stocks, $C_{BEFORE,i}$ in Low- and Upland Natural Forest, were estimated. The methods used to combine MC estimates from individual MC simulations are described in Appendix C. The number of iterations for all MC simulations was $\mathcal{R} = 4 \times 10^4$.

2.3. Emissions from forest degradation

2.3.1. Methodological approach

2.3.1.1. Emissions from logging in Natural Forest

The net source 'forest degradation' entails the sub-source 'emissions from logging in Natural Forest' and the sub-sink 'removals from forest regrowth' within Natural Forest areas (see Figure 2.1). Emissions from biomass burning (i.e., fire) in Softwood Plantations are also included in estimates of emissions from forest degradation (see Section 2.3.3).

Emissions from logging were estimated using a proxy method to reflect contribution of logging to unsustainable management of Natural Forest. The proxy used to estimate emissions are timber volumes extracted from Natural Forest. The rational of using data on harvested volumes to assess emissions from the source 'forest degradation' was based on the assumption that unsustainable forest management practices are widespread in Fiji [ER-PIN, 2016]. A "Fiji Forest Harvesting Code of Practice" [MoF, 2013] has been developed and specifies, e.g., diameter cutting limits; however, (commercial) loggers resist its adoption and over-exploitation using conventional logging techniques persist. Current practices are assumed to not only cause a constant decline in harvestable volumes of commercial timber species, but also a constant decline in forest carbon stocks in Fiji's Natural Forests [ER-PIN, 2016].

The approach to estimate gross emissions from unsustainable logging in Natural Forest was adopted from Pearson *et al.* [2014]. In this approach a so-called Total Emission Factor TEF is used to convert records of volumes extracted during logging operations to total C loss. Carbon losses due to logging include the loss from the felled tree (AGB and BGB), logging residues of the felled tree, logging damages to the remaining stand (AGB and BGB), and losses due to the establishment of logging infrastructure (e.g., skid trails, logging roads and log-landings). The TEF used for the construction of Fiji's FRL has the following components:

EM_{FELL} Includes (i) C loss from the logs and (ii) C loss from timber waste from the felled trees (crown-, bole-, stump-, and below-ground biomass); value used for $EM_{FELL} = 0.69$;

EM_{DAM} Includes (i) C loss from killed (uprooted and snapped) trees ≥ 10 cm DBH (AGB and BGB) and (ii) C loss from sever crown damage; value used for $EM_{DAM} = 0.15$

EM_{INFR} Includes (i) C loss from clearings of all trees ≥ 10 cm DBH (AGB and BGB) for logging road construction, (ii) C loss from clearings of all trees ≥ 10 cm DBH for skid trail construction, and (iii) C loss from all trees ≥ 10 cm for the construction of log-landings; value used $EM_{INFR} = 0.21$.

The value of $TEF = EM_{FELL} + EM_{DAM} + EM_{INFR} = 1.05$ tC (m^3)$^{-1}$ and all its components were taken from Haas [2015]. For emissions from forest degradation, committed emissions were assumed. That is, the carbon loss associated with timber extraction and infrastructure development is emitted directly to the atmosphere and is not stored in Harvested Wood Products (HWPs).

Data on harvested volumes (i.e., logging statistics) only include volumes from 'official' logging. Official logging entails commercial harvesting activities in Natural Forest under a logging licence. If a private logger or a logging company wants to extract timber from Natural Forest for economic gains (i.e., the wood is to be sold on the markets), the logger has to apply for a logging licence. Licences are issued by the Ministry of Forests (MoF).

Before a licence will possibly be issued by the MoF the logger has to provide a logging plan, which includes a map of the area to be harvested and the expected volume to be extracted. The information provided by the logger is evaluated by the MoF before a licence is issued. Once a licence is issued and the logger has hauled the timber to the log-landings, log-scalers from the Division Forest Offices (DFOs) assess the amount of timber extracted and enter the data into a Timber Revenue System (TRS) database. Timber volumes are assessed by log-scalers to determine the amount of royalty fees the logger has to transfer to the MoF. The data in the TRS for the years 2006 to 2016 served as a proxy to estimate emissions from forest degradation.

The logging data in the TRS does not include volumes from illegal logging (i.e., commercial logging without a licence) and non-commercial logging by customary land-owners. If landowners extract wood for subsistence use on their own land (i.e., no wood products are sold), no licence is required. In Fiji, neither data on illegal nor on subsistence logging are currently available.

Removals from forest regrowth after logging were estimated based on data of areas of logged Natural Forest (i.e., demarcated boundaries of logging concessions). The estimation of removals also requires knowledge of the year of logging to estimate the length of time available for regrowth on the conventionally logged areas as well the mean annual increment following logging operations. To estimate removals on logged areas the area logged is multiplied by the mean annual C increment reported for logged Natural Forest and is then multiplied by the time since logging. Total C accumulation over the Reference Period is then divided by the length of the Reference Period. Finally, average annual C accumulation is converted to removals.

Note that the areas logged were masked out from the wall-to-wall *AD* used to monitor changes in Natural Forest to report deforestation emission and carbon stock enhancement (AR). Hence, there is no double counting of changes in Natural Forest subject to harvesting using this proxy approach.

2.3.1.2. Emissions from biomass burning in Softwood Plantations

In Fiji, fire is known to have a significant impact on Softwood Plantation areas. Although most fires seem to occur in grassland areas, the proximity of Softwood Plantations to grassland areas makes these Forest Plantations particularly vulnerable. Data on areas burned were provided by Fiji Pine Limited (FPL). However, only data for the years 2015 to 2018 were available. The data from these four years were used to estimate emissions from biomass burning in Softwood Plantations for the Reference Period. It is important to note that the MODIS (Moderate-resolution Imaging Spectroradiometer) Burned Area product is not available for most of the Pacific region. However, data from the MODIS Active Fire product are available and were used for the same time period to confirm the

data provided by FPL were reliable. A fire monitoring program is currently developed in Fiji and for future assessments better data on forest fires are likely to be available.

IPCC [2006] Tier 1 default methods and factors in combination with national spatial data were used to provide an initial estimate of emissions from fire in Softwood Plantations (see Annex 8-4 in ER-PD [2019]). The AGB available for burning was estimated based on the age of the plantation at the time of the burn and an estimate of the mean annual biomass increment in Softwood Plantations. CO_2 and non-CO_2 gases were included in the emission estimates from fires.

2.3.2. Average annual emissions (logging in Natural Forest)

2.3.2.1. Average annual gross emissions

Annual C loss caused by timber extraction from Natural Forest was estimated from the volumes logged in Natural Forest (see Table 2.8 on page 23 and Figure 2.3). Logged volumes were multiplied by the TEF reported by Haas [2015].
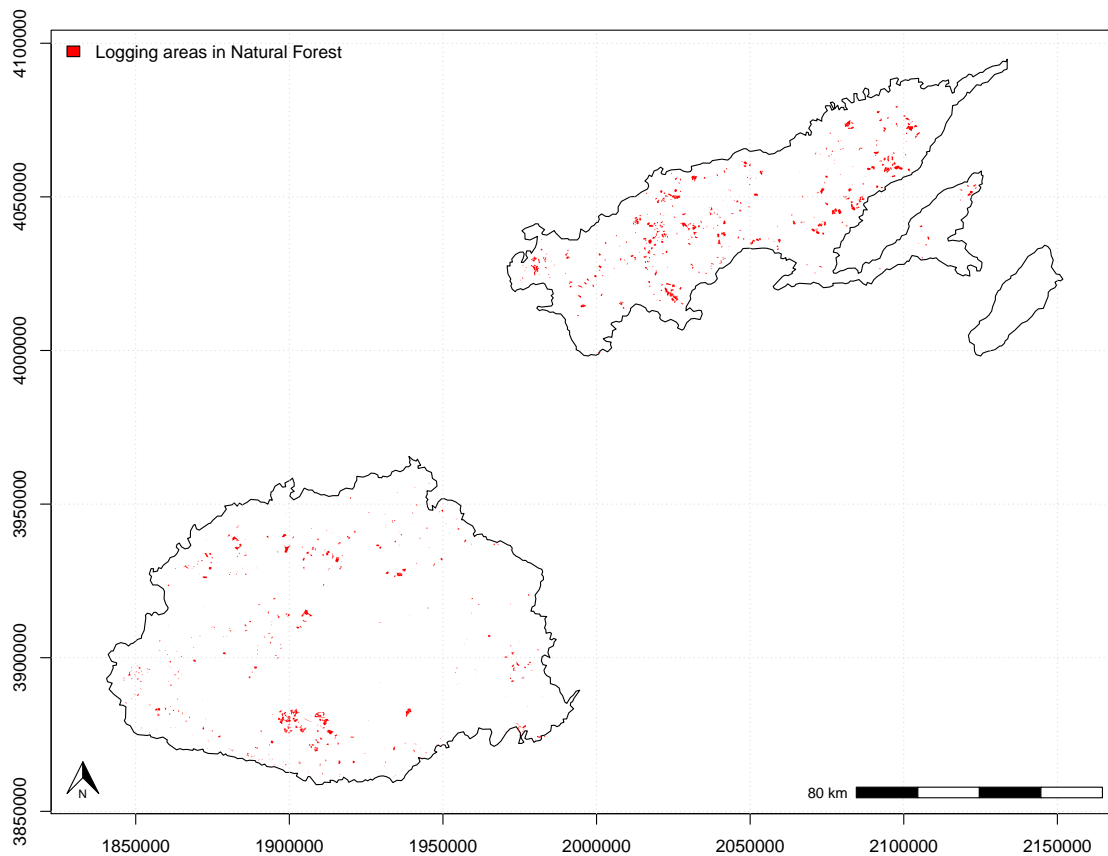
Figure 2.2.: Areas logged in Natural Forest between 2006 and 2016 (total area: 19783 ha). Coordinate Reference System: Fiji 1986 Map Grid (EPSG code: 3460).

Equation 2.13: Carbon loss from logging in Natural Forest

$$\Delta C_{FDL,L,t} = \left[V_{FDL,t} \times TEF \right] \times (-1)$$

$\Delta C_{FDL,L,t}$ = Carbon loss in year t due to logging in Natural Forest; tC
$V_{FDL,t}$ = Wood volume extracted in Natural Forest in year t; m^3
TEF = Total Emission Factor, $TEF = 1.05$ [Haas, 2015]; tC (m^3)$^{-1}$

The first term in squared brackets in Equation (2.13) is multiplied by -1 to ensure that C loss has a negative sign. Average annual gross emissions from forest degradation were estimated using Equation (2.14). Carbon losses and emissions per year are shown in Table 2.8 on page 23.
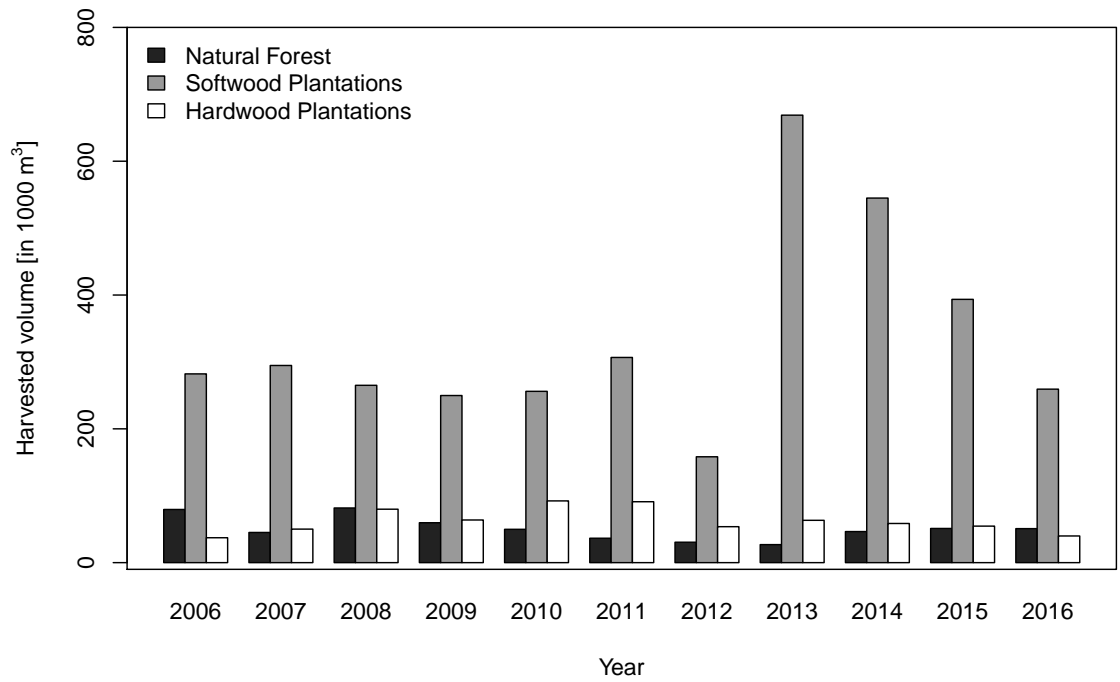
Figure 2.3.: Timber volumes harvested in Natural Forest, Hardwood Plantations and Softwood Plantations per year. Data were provided by the Management Service Division (MSD) for Natural Forest, by the Fiji Hardwood Corporation Limited (FHCL) for Hardwood Plantations and by Fiji Pine Limited (FPL) for Softwood Plantations.

Equation 2.14: Average annual gross emissions from forest degradation (logging in Natural Forest)

$$\hat{\theta}_{FDLem} = \mathcal{T}^{-1} \left[\sum_T \Delta C_{FDL,L,t} \times \eta_{CC} \right]$$

$\hat{\theta}_{FDLem}$ = Average annual gross emissions from forest degradation; tCO_2e yr^{-1}
$\mathcal{T}$ = Length of the Reference Period, i.e., 11 years; yrs
$\Delta C_{FDL,L,t}$ = Carbon loss in year t due to logging in Natural Forest; tC
η_{CC} = Conversion factor C to CO_2; dimensionless

Table 2.8.: Emissions and removals from logging in Natural Forest (forest degradation). V_{FDL} = timber volume extracted, A_{FDL} = area harvested, $\Delta C_{FDL,L}$ = total carbon loss, $\hat{\theta}_{FDL,L}$ = emissions, $\Delta C_{FDL,G}$ = carbon gains over the Reference Period, $\hat{\theta}_{FDL,G}$ = removals over the Reference Period.

Year	V_{FDL} [m³]	A_{FDL} [ha]	$\Delta C_{FDL,L}$ [tC]	$\hat{\theta}_{FDL,L}$ [tCO₂e]	$\Delta C_{FDL,G}$ [tC]	$\hat{\theta}_{FDL,G}$ [tCO₂e]
2006	79480	3513	-83454	305998	36518	-133898
2007	45122	2546	-47378	173720	23941	-87784
2008	81706	3259	-85791	314568	27421	-100543
2009	59614	1165	-62595	229514	8652	-31722
2010	49814	1641	-52305	191784	10561	-38723
2011	36499	905	-38324	140521	4930	-18077
2012	30517	796	-32043	117490	3545	-12997
2013	26947	1354	-28294	103746	4692	-17203
2014	46431	1428	-48753	178759	3534	-12957
2015	51091	1738	-53646	196700	2581	-9464
2016	50825	1438	-53366	195676	712	-2611

2.3.2.2. Average annual gross removals

Average annual C gains after logging in Natural Forest were computed by multiplying the area logged in year t, $A_{FDL,t}$, by the mean annual C increment after logging, $MAIC_{FDL}$, times the time elapsed since logging. The estimate for $MAIC_{FDL}$ of 0.99 tC ha^{-1} yr^{-1} was reported by Mussong (unpublished data). The estimate was obtained from a long-term study at the REDD+ pilot site at Nakavu. These data are the only data on C increment in logged Natural Forest currently available in Fiji.

Equation 2.15: Carbon gains in logged Natural Forest

$$\Delta C_{FDL,G,t} = \delta_t \times MAIC_{FDL} \times A_{FDL,t}$$

$\Delta C_{FDL,G,t}$ = Carbon gains over the Reference Period on areas logged in year t; tC

δ_t = $2016 - t + 0.5$, i.e., the length of the time interval available for growth on areas conventionally logged in year t; yrs

$MAIC_{FDL}$ = Mean annual C increment after logging (including above- and below-ground carbon; AGC and BGC), i.e., 0.99; tC ha^{-1} yr^{-1}

$A_{FDL,t}$ = The area logged in Natural Forest in year t; ha

Carbon gains were converted to removals by

Equation 2.16: Gross removals after logging in Natural Forest

$$\hat{\theta}_{FDLre} = \mathcal{T}^{-1} \left[\sum_T \delta_t \times MAIC_{FDL} \times A_{FDL,t} \times \eta_{CC} \right] \times (-1)$$

$$= \mathcal{T}^{-1} \left[\sum_T \Delta C_{FDL,G,t} \times \eta_{CC} \right] \times (-1)$$

$\hat{\theta}_{FDLre}$ = Average annual gross removals from Natural Forest areas that have been conventionally logged; tCO$_2$e yr^{-1}

$\mathcal{T}$ = Length of the Reference Period, i.e., 11 years. $\mathcal{T}$ is the cardinality of the set T, $\mathcal{T} = |T|$, and $T = \{1, 2, \dots, t, \dots, \mathcal{T}\}$; yrs

δ_t = $2016 - t + 0.5$, i.e., the length of the time interval available for growth on areas conventionally logged in year t; yrs

$MAIC_{FDL}$ = Mean annual C increment after logging (including above- and below-ground carbon; AGC and BGC), i.e., 0.99; tC ha^{-1} yr^{-1}

$A_{FDL,t}$ = The area logged in Natural Forest in year t; ha

η_{CC} = Conversion factor C to CO$_2$; dimensionless

2.3.2.3. Average annual net emissions

Average annual net emissions are computed as the sum of (positive) average annual emissions from logging in Natural Forest and (negative) average annual removals from regrowth in Natural Forest.

Equation 2.18: Average annual net emissions from forest degradation (logging)

$$\hat{\theta}_{FDL} = \hat{\theta}_{FDLem} + \hat{\theta}_{FDLre}$$

$\hat{\theta}_{FDL}$ = Average annual net emissions from forest degradation (logging in Natural Forest); tCO$_2$e yr^{-1}

$\hat{\theta}_{FDLem}$ = Average annual gross emissions from forest degradation; tCO$_2$e yr^{-1}

$\hat{\theta}_{FDLre}$ = Average annual gross removals from forest degradation; tCO$_2$e yr^{-1}

Table 2.9.: Average annual gross emissions, $\hat{\theta}_{FDLem}$, average annual gross removals, $\hat{\theta}_{FDLre}$, and average annual net emissions, $\hat{\theta}_{FDL}$ for the net source 'forest degradation' ('Logging in Natural Forest'). CI = confidence interval.

	Estimate [tCO$_2$e yr^{-1}]	Lower 90%-CI [tCO$_2$e yr^{-1}]	Upper 90%-CI [tCO$_2$e yr^{-1}]
$\hat{\theta}_{FDLem}$	195,316.10	167,281.73	222,984.02
$\hat{\theta}_{FDLre}$	-42,361.61	-57,253.99	-27,642.94
$\hat{\theta}_{FDL}$	152,954.49	121,401.92	184,298.10

2.3.2.4. Uncertainty analysis

2.3.2.4.1. Sources of uncertainty For the uncertainty analysis for the source 'forest degradation' (logging in Natural Forest), the following sources of uncertainty were considered:

1. Uncertainty attached to the assessment of volumes extracted from Natural Forest, V_{FD} (used as input in Equation (2.13)); small source of uncertainty, not relevant; not included in the quantification of uncertainty. Note that the data on the extracted volumes (i.e., volumes extracted under a logging licence) are census data (i.e., no sampling error).

2. Uncertainty attached to the Total Emission Factor (TEF); large source of uncertainty, highly relevant; included in the quantification of uncertainty.

3. Uncertainty attached to the assessment of areas logged, $A_{FD,t}$ (used as input in Equation (2.15)); moderate source, relevant; included in the quantification of uncertainty.

4. Uncertainty attached to the mean annual C increment, $MAIC_{DF}$ (used as input in Equation (2.15)); large source, highly relevant; included in the quantification of uncertainty.

5. Uncertainty attached to conversion factors, η_{CC} (used as input in Equation (2.14)); small source, not relevant; not included in the quantification of uncertainty.

2.3.2.4.2. Quantification of uncertainty The uncertainty attached to the estimates of the average annual gross and net emissions and removals from forest degradation was assessed in an MC simulation (see also Appendix C.1). In the MC simulation the same estimators were used as in Section 2.3.2. The number of MC runs was $\mathcal{R} = 4 \times 10^4$. The estimates $\hat{\theta}_{FDLem}$, $\hat{\theta}_{FDLre}$ and $\hat{\theta}_{FDL}$ were, thus, estimated $\mathcal{R}$ times. The following inputs were not treated as fixed as in Section 2.3.2, but were drawn randomly from probability density functions (PDFs).

TEF The TEF was sampled from a Triangular distribution with lower bound $a = TEF - TEF \times 0.25$, upper bound $b = TEF + TEF \times 0.25$, and mode $c = TEF$ (see Appendix C.1.2).

25

$MAIC_{FD}$ The $MAIC_{FD}$ was sampled from a Triangular distribution with lower bound $a = MAIC_{FD} - MAIC_{FD} \times 0.5$, upper bound $b = MAIC_{FD} + MAIC_{FD} \times 0.5$ and mode $c = MAIC_{FD}$.

$A_{FD,t}$ The $A_{FD,t}$ was sampled from a Triangular distribution with lower bound $a = A_{FD,t} - A_{FD,t} \times 0.25$, upper bound $b = A_{FD,t} + A_{FD,t} \times 0.25$ and mode $c = A_{FD,t}$.

The MC simulation delivered $\mathcal{R}$ MC estimates of $\hat{\theta}_{FDLem}$, $\hat{\theta}_{FDLre}$ and $\hat{\theta}_{FDL}$. The $Q(0.05)$ and $Q(0.95)$ quantiles of the empirical PDF of MC estimates were used to derive upper and lower 90%-confidence limits.

2.3.3. Average annual emissions (biomass burning)

2.3.3.1. Average annual gross emissions

Emissions from biomass burning (fire) in Softwood Plantations is a sub-source of the source 'emissions from forest degradation' (see Figure 2.1). To estimate emissions for this sub-source data provided by Fiji Pine Limited (FPL) were used. FPL provided a list of plantation compartments that burned between 2015 and 2018. For each compartment the year of the burn, the time since planting (i.e., the plantation age) and the area burned is available. Data on the standing stocks (e.g., tB ha^{-1}) are not available.

To estimate emissions, standing stocks were predicted for each compartment. First, AGB was predicted using the compartment age and the estimated mean annual increment of total biomass. The estimate of 10 tB ha^{-1} yr^{-1} was taken from Waterloo [1994].

Equation 2.19: AGB available for combustion

$$AGB_{l,t_b} = \Lambda_{l,t_b} \times \frac{MAIB_{SW}}{(1 + R_{dll})}$$

AGB_{l,t_b} = Above-ground biomass in compartment l, with $L = \{1, 2, ..., l, ..., \mathcal{L}\}$ and $\mathcal{L}$ the number of compartments, in year t_b, where $T_b = \{2015, ..., t_b, ..., 2018\}$; tB ha^{-1}

Λ_{l,t_b} = Age of compartment l that burnt in year t_b; yrs

$MAIB_{SW}$ = Mean annual total biomass increment in Softwood Plantations; tB ha^{-1} yr^{-1}

R_{dll} = Root-to-shoot ratio in tropical moist deciduous forest <125 tAGB ha^{-1}; dimensionless

Next, BGB was estimated. The distinction between AGB and BGB was made because it was assumed that AGB will burn during a fire incident — at least some part of it —, whereas BGB will decay (not burn) after AGB has been lost. To predict BGB the same estimate of $MAIB_{SW}$ was used as for AGB. Predicted total biomass was then multiplied by the root-to-shoot ratio for dry Lowland Natural Forest (see Table 2.10) to obtain an estimate of BGB per hectare.

Table 2.10.: Root-to-shoot ratios, R, used to compute below-ground biomass (BGB) from above-ground biomass (AGB) [IPCC, 2006, Vol. 4; Chap. 4; Tab. 4.4].

IPCC Ecological zone	Climate[a]	Alt.[b]	Zonation[c]	AGB [t ha^{-1}]	R[d]	Notation
Tropical rainforest	Wet	Lowland	WL		.37	R_{wl}
Tropical moist deciduous forest	Dry	Lowland	DL	< 125	.20	R_{dll}
	Dry	Lowland	DL	≥ 125	.24	R_{dlh}
Tropical mountain systems	Dry	Upland	DU		.27	R_u
	Wet	Upland	WU		.27	R_u

[a]Climatic zonation: Wet = Aridity Index (AI) ≥ 2, Dry = AI < 2
[b]Altitudinal zonation; Lowland < 600 m a.s.l., Upland ≥ 600 m a.s.l.
[c]WL = Wet Lowland, DL = Dry Lowland, DU = Dry Upland, WU = Wet Upland
[d]R = root-to-shoot ratio

Equation 2.20: BGB loss caused by fire

$$BGB_{l,t_b} = \Lambda_{l,t} \times MAIB_{SW} \times R_{dll}$$

BGB_{l,t_b} = Below-ground biomass in compartment l in year t_b; tB ha^{-1}
Λ_{l,t_b} = Age of compartment l that burnt in year t_b; yrs
$MAIB_{SW}$ = Mean annual total biomass increment in Softwood Plantations; tB ha^{-1} yr^{-1}
R_{dll} = Root-to-shoot ratio in tropical moist deciduous forest <125 tAGB ha^{-1}; dimensionless

Once predictions of AGB and BGB were available, IPCC [2006] standard methodology and default factors were used to estimate emissions (see Table 2.11). CO$_2$ emissions from AGB were estimated using Equation 2.27 from IPCC [2006, Vol. 4, Chap.2].

Equation 2.21: CO$_2$ emissions from AGB (fire)

$$EACO2_{l,t_b} = A_{l,t_b} \times AGB_{l,t} \times C_f \times G_{ef,CO_2}$$

$EACO2_{l,t_b}$ = CO$_2$ emissions from AGB in compartment l that burnt in year t_b; tCO$_2$e
A_{l,t_b} = Area that burnt in compartment l in year t_b; ha
$AGB_{l,t}$ = Above-ground biomass in compartment l in year t_b; tB ha^{-1}
C_f = Combustion factor, i.e., the proportion of prefire biomass consumed [IPCC, 2006, Vol. 4, Chap. 2, Tab. 2.6]; dimensionless
G_{ef,CO_2} = Emission factor for CO$_2$ [IPCC, 2006, Vol. 4, Chap. 2, Tab. 2.5]; g kg^{-1} dry matter burnt

CO$_2$ emissions from BGB were estimated using Equation (2.22) (BGB is assumed to decay after AGB is lost; i.e., it does not burn)

Equation 2.22: CO_2 emissions from BGB (fire)

$$EBCO2_{l,t_b} = A_{l,t_b} \times BGB_{l,t_b} \times C_f \times \eta_{CF} \times [\eta_{CC} \times -1]$$

$EBCO2_{l,t_b}$ = CO_2 emissions from BGB in compartment l that burnt in year t_b (it is assumed that BGB does not burn); tCO_2e

A_{l,t_b} = Area that burnt in compartment l in year t_b; ha

$BGB_{l,t}$ = Below-ground biomass in compartment l in year t_b; tB ha^{-1}

C_f = Combustion factor, i.e., the proportion of prefire biomass consumed [IPCC, 2006, Vol. 4, Chap. 2, Tab. 2.6]; dimensionless

η_{CF} = Conversion factor biomass to C; dimensionless

η_{CC} = Conversion factor C to CO_2; dimensionless

For AGB, not only CO_2 emissions were considered but also emissions of other GHGs including methane (CH_4) and nitrous oxide (N_2O). Estimates of non-CO_2 emissions were converted to CO_2 equivalents. Equation (2.23) and Equation (2.24) show how emissions of non-CO_2 were estimated.

Equation 2.23: CH_4 emissions from AGB converted to CO_2e (fire)

$$EACH4_{l,t_b} = A_{l,t_b} \times AGB_{l,t_b} \times C_f \times G_{ef,CH_4} \times GWP_{CH_4}$$

$EACH4_{l,t_b}$ = CO_2 emissions from CH_4 (methane) from AGB in compartment l that burnt in year t_b; tCO_2e

A_{l,t_b} = Area that burnt in compartment l in year t_b; ha

$AGB_{l,t}$ = Above-ground biomass in compartment l in year t_b; tB ha^{-1}

C_f = Combustion factor, i.e., the proportion of prefire biomass consumed [IPCC, 2006, Vol. 4, Chap. 2, Tab. 2.6]; dimensionless

G_{ef,CH_4} = Emission factor for CH_4 [IPCC, 2006, Vol. 4, Chap. 2, Tab. 2.5]; g kg^{-1}

GWP_{CH_4} = Global warming potential of CH_4, i.e., conversion of non-CO_2 GHGs to carbon dioxide equivalents IPCC [2014, Box 3.2, Tab. 1]; dimensionless

Equation 2.24: N_2O emissions from AGB converted to CO_2e (fire)

$$EAN2O_{l,t_b} = A_{l,t_b} \times AGB_{l,t_b} \times C_f \times G_{ef,N_2O} \times GWP_{N_2O}$$

Table 2.11.: Default values for C_f (combustion factor), G_{ef} (emission factor) and GWP (global warming potential) taken from IPCC [2006] and IPCC [2014].

Greenhouse gas (GHG)		C_f	G_{ef}	GWP
CO_2	Carbon dioxide	0.46	1580.0	1
CH_4	Methane	0.46	6.8	28
N_2O	Nitrous oxide	0.46	0.2	265

$EAN2O_{l,t_b}$ = CO_2 emissions from N_2O (nitrous oxide) from AGB in compartment l that burnt in year t_b; tCO_2e

A_{l,t_b} = Area that burnt in compartment l in year t_b; ha

$AGB_{l,t}$ = Above-ground biomass in compartment l in year t_b; tB ha^{-1}

C_f = Combustion factor, i.e., the proportion of prefire biomass consumed [IPCC, 2006, Vol. 4, Chap. 2, Tab. 2.6]; dimensionless

G_{ef,N_2O} = Emission factor for CH_4 [IPCC, 2006, Vol. 4, Chap. 2, Tab. 2.5]; g kg^{-1}

GWP_{N_2O} = Global warming potential of N_2O, i.e., conversion of non-CO_2 GHGs to carbon dioxide equivalents IPCC [2014, Box 3.2, Tab. 1]; dimensionless

Table 2.12.: Emissions from fire in Software Plantations. Emissions from non-CO_2 GHGs are given in metric tonnes of CO_2 equivalents [tCO_2e]. Column Total gives the sum of tCO_2e over all GHGs. Count = number of fires recorded; Area = area burnt; Avg. age = average Plantation age at time of burning, AGB = above-ground biomass; BGB = below-ground biomass.

Year	Count	Area [ha]	Avg. age [yrs]	Source of CO_2e emissions [tCO_2e]				
				CO_2 (AGB)	CO_2 (BGB)	CH_4	N_2O	Total
2015	79	1,447	17.47	143,566	37,581	17,301	4,816	203,263
2016	33	830	16.27	71,024	18,592	8,559	2,382	100,557
2017	122	2,709	10.21	171,842	44,984	20,708	5,764	243,298
2018	60	729	9.75	58,505	15,315	7,050	1,963	82,833

Table 2.12 provides estimates of GHG emissions per year (2015-2018). Estimates are provided separately for the different GHGs. Total emissions from biomass burning (per year and compartment) were computed as shown in Equation (2.25). The annual total was computed using Equation (2.26) (the total for each year is shown in the last column of Table 2.12).

Equation 2.25: Total GHG emissions from compartments

$$E_{l,t_b} = EACO2_{l,t_b} + EBCO2_{l,t_b} + ECH4_{l,t_b} + EN2O_{l,t_b}$$

E_{l,t_b} = Total GHG emissions from compartment l in year t_b; tCO_2e

$EACO2_{l,t_b}$ = CO_2 emissions from AGB in compartment l that burnt in year t_b;
      tCO_2e

$EBCO2_{l,t_b}$ = CO_2 emissions from BGB in compartment l that burnt in year t_b;
      tCO_2e

$EACH4_{l,t_b}$ = CO_2 emissions from CH_4 (methane) from AGB in compartment l that
      burnt in year t_b; tCO_2e

$EAN2O_{l,t_b}$ = CO_2 emissions from N_2O (nitrous oxide) from AGB in compartment l
      that burnt in year t_b; tCO_2e

Equation 2.26: Total GHG emissions per year (fire)

$$E_{t_b} = \sum_L E_{l,t_b}$$

E_{t_b} = Total GHG emissions in year t_b; tCO_2e

E_{l,t_b} = Total GHG emissions from compartment l in year t_b; tCO_2e

Average annual emissions from biomass burning in Softwood Plantations were computed using Equation (2.27). Note that the annual average for the Reference Period is computed from four years only (2015-2018).

Equation 2.27: Average annual emissions from fire

$$\hat{\theta}_{FDB} = \frac{\sum_{T_b} E_{t_b}}{|T_b|}$$

$\hat{\theta}_{FDB}$ = Average annual emissions from biomass burning (fire); $tCO_2e\ yr^{-1}$

E_{t_b} = Total GHG emissions in year t_b; tCO_2e

$|T_b|$ = Number of years used to compute the annual average, $|T_b| = 4$; yrs

Table 2.13.: Average annual emissions from biomass burning (fire) in Softwood Plantations, $\hat{\theta}_{FDF}$. CI = confidence interval. The estimate of emissions for the FRL Reference Period was computed from the annual average of the years 2015 to 2018.

$\hat{\theta}_{FDF}$ [$tCO_2e\ yr^{-1}$]	Lower 90%-CI [$tCO_2e\ yr^{-1}$]	Upper 90%-CI [$tCO_2e\ yr^{-1}$]
157,488	99,097	221,046

2.3.3.2. Uncertainty analysis

2.3.3.2.1. Sources of uncertainty   For the uncertainty analysis for the source 'forest degradation' (biomass burning in Softwood Plantations), the following sources of uncertainty were considered:

1. Uncertainty attached to the Mean annual total biomass increment in Softwood Plantations, $MAIB_{SW}$ (used as input in Equation (2.19)); large source of uncertainty, highly relevant; included in the quantification of uncertainty.

2. Uncertainty attached to the root-to-shoot ratio in tropical moist deciduous forest <125 tAGB ha^{-1} (R_{dll}); large source of uncertainty, highly relevant; included in the quantification of uncertainty.

3. Uncertainty attached to the combustion factor (C_f); large source of uncertainty, highly relevant; included in the quantification of uncertainty.

4. Uncertainty attached to the emission factor (CO_2) for biomass burning (G_{ef,CO_2}); large source of uncertainty, highly relevant; included in the quantification of uncertainty.

5. Uncertainty attached to the emission factor (CH_4) for biomass burning (G_{ef,CH_4}); large source of uncertainty, highly relevant; included in the quantification of uncertainty.

6. Uncertainty attached to the emission factor (N_2O) for biomass burning (G_{ef,N_2O}); large source of uncertainty, highly relevant; included in the quantification of uncertainty.

7. Uncertainty attached to the global warming potential of CH_2 (GWP_{CH_4}); large source, highly relevant included in the quatification of uncertainty.

8. Uncertainty attached to the global warming potential of N_2O (GWP_{N_2O}); large source, highly relevant included in the quatification of uncertainty.

9. Uncertainty attached to conversion factors, η_{CC} (used as input in Equation (2.14)); small source, not relevant; not included in the quantification of uncertainty.

2.3.3.2.2. Quantification of uncertainty   The uncertainty attached to the estimates of the average annual gross and net emissions and removals from forest degradation was assessed in an MC simulation (see also Appendix C.1). In the MC simulation the same estimators were used as in Section 2.3.3. The number of MC runs was $\mathcal{R} = 4 \times 10^4$. The estimates $\hat{\theta}_{FDB}$, were, thus, estimated $\mathcal{R}$ times. The following inputs were not treated as fixed as in Section 2.3.2, but were drawn randomly from probability density functions (PDFs).

$MAIB_{SW}$ The $MAIB_{SW}$ was sampled from a Triangular distribution with lower bound $a = MAIB_{SW} - MAIB_{SW} \times 0.25$, upper bound $b = MAIB_{SW} + MAIB_{SW} \times 0.25$, and mode $c = MAIB_{SW}$ (see Appendix C.1.2).

R_{dll} The R_{dll} was sampled from a Triangular distribution with lower bound $a = 0.09$, upper bound $b = 0.25$, and mode $c = R_{dll}$ (default values taken from IPCC [2006, Vol. 4, Chap. 4, Tab. 4.4]).

C_f	The C_f was sampled from a Triangular distribution with lower bound $a = C_f - C_f \times 0.5$, upper bound $b = C_f + C_f \times 0.5$, and mode $c = C_f$.
G_{ef,CO_2}	The G_{ef,CO_2} was sampled from a Triangular distribution with lower bound $a = G_{ef,CO_2} - G_{ef,CO_2} \times 0.5$, upper bound $b = G_{ef,CO_2} + G_{ef,CO_2} \times 0.5$, and mode $c = G_{ef,CO_2}$.
G_{ef,CH_4}	The G_{ef,CH_4} was sampled from a Triangular distribution with lower bound $a = G_{ef,CH_4} - G_{ef,CH_4} \times 0.5$, upper bound $b = G_{ef,CH_4} + G_{ef,CH_4} \times 0.5$, and mode $c = G_{ef,CH_4}$.
G_{ef,N_2O}	The G_{ef,N_2O} was sampled from a Triangular distribution with lower bound $a = G_{ef,N_2O} - G_{ef,N_2O} \times 0.5$, upper bound $b = G_{ef,N_2O} + G_{ef,N_2O} \times 0.5$, and mode $c = G_{ef,N_2O}$.
GWP_{CH_4}	The GWP_{CH_4} was sampled from a Triangular distribution with lower bound $a = GWP_{CH_4} - GWP_{CH_4} \times 0.5$, upper bound $b = GWP_{CH_4} + GWP_{CH_4} \times 0.5$, and mode $c = GWP_{CH_4}$.
GWP_{N_2O}	The GWP_{N_2O} was sampled from a Triangular distribution with lower bound $a = GWP_{N_2O} - GWP_{N_2O} \times 0.5$, upper bound $b = GWP_{N_2O} + GWP_{N_2O} \times 0.5$, and mode $c = GWP_{N_2O}$.

The MC simulation delivered $\mathcal{R}$ MC estimates of $\hat{\theta}_{FDB}$. The $Q(0.05)$ and $Q(0.95)$ quantiles of the empirical PDF of MC estimates were used to derive upper and lower 90%-confidence limits.

2.3.4. Average annual emissions from forest degradation

Average annual net emissions for the source 'forest degradation' were computed as the sum of average annual net emissions from logging in Natural Forest (Section 2.3.2) and average annual emissions from biomass burning (Section 2.3.3). Table 2.14 shows estimated average annual emissions for the source 'forest degradation'.

Equation 2.28: Average annual emissions from forest degradation

$$\hat{\theta}_{FD} = \hat{\theta}_{FDL} + \hat{\theta}_{FDB}$$

$\hat{\theta}_{FD}$ = Average annual net emissions from forest degradation; tCO$_2$e yr^{-1}

$\hat{\theta}_{FDL}$ = Average annual emissions from forest degradation (emissions from logging in Natural Forest); tCO$_2$e yr^{-1}

$\hat{\theta}_{FDB}$ = Average annual emissions forest degradation (emissions from biomass burning in Softwood Plantations); tCO$_2$e yr^{-1}

Table 2.14.: Estimated average annual net emissions from forest degradation, $\hat{\theta}_{FD}$, including net emissions from logging in Natural Forest, $\hat{\theta}_{FDL}$, and emissions from biomass burning in Softwood Plantations, $\hat{\theta}_{FDB}$. CI = confidence interval.

	$\hat{\theta}_{FD}$ [tCO$_2$e yr^{-1}]	Lower 90%-CI [tCO$_2$e yr^{-1}]	Upper 90%-CI [tCO$_2$e yr^{-1}]
$\hat{\theta}_{FDL}$	152,954.49	121,401.92	184,298.10
$\hat{\theta}_{FDB}$	157,487.87	99,096.51	221,046.42
$\hat{\theta}_{FD}$	310,442.36	244,234.01	381,789.49

2.4. Enhancement of forest carbon stocks

The sink 'enhancement of forest carbon stocks' includes removals from afforestation/reforestation (AR), as well as gross emissions and removals from Forest Plantation management. As the methodology differs substantially between AR and Forest Plantations, the estimation of removals (and emissions) from the two sub-sinks will be presented separately in this section. Estimates of emissions/removals will also be reported separately for the two sinks (see Chapter 3).

2.4.1. Afforestation/reforestation

The sink 'enhancement of forest carbon stock' is linked to afforestation/reforestation (AR) activities. As the land-cover change map did not differentiate between afforestation and reforestation, AR will collectively be called 'forestation' and includes both afforestation and reforestation. No distinction is made between afforestation and reforestation in the estimation. Moreover, since it was not known from the land-cover change map whether forestation had anthropogenic or natural causes, no distinction was made between anthropogenic and natural causes of AR. The initial C stock on land that was afforested or reforested land was considered to be zero.

Forestation is defined as the conversion of land in the land-use sub-category Non-Forest to land in the sub-category Natural Forest. In the plantation lease areas land cannot be afforested or reforested because the land is already considered Forest Land by definition (see Section 1.4.2). Outside the plantation lease areas, forestation occurs if the crown-cover percent on a patch of land (min. 0.5 ha) reaches or exceeds the threshold value of 10%. Note that in Fiji planted forest is still designated as Natural Forest, if planted outside the plantation lease areas, even if exotic tree species are used for AR.

Data on forest area gain were derived from the land-cover change map. The conversion categories relevant for AR are 711 (Non-Forest converted to Lowland Natural Forest) and 712 (Non-Forest converted to Upland Natural Forest; see Table 2.1). For the estimation of removals from forestation no distinction was made between Lowland Natural Forest and Upland Natural Forest.

Carbon gains on AR land were estimated by taking the average annual forest area gain multiplied by the mean annual C increment ($MAIC$). Annual C gains were subsequently multiplied by the time elapsed since forestation to compute C gains over the

FRL Reference Period for each year. Finally, the average annual C gain over the Reference Period was computed by taking the average of the C gains of each year over the Reference Period.

Mean annual C increments ($MAIC$) on AR areas have not yet been rigorously assessed in Fiji. For the FRL, data on the MAI provided by FHCL were used. FHCL reported the MAI for individual tree species, as well as for mixed hardwood stands. The estimates of the MAI used in the FRL were assessed in plantations established in FHCL's lease area. Note that the MAI provided by FHCL refers to volume increments, i.e., $MAIV$, and not to C increments. As it was not known from the land-cover change maps which species were planted or naturally regenerated on AR areas, selecting an appropriate $MAIC$ was, therefore, challenging. The average $MAIV$ over all species reported by FHCL was computed. The value of $MAIV$ used for the FRL was 5.85 m^3 ha^{-1} yr^{-1}. Volume increments were converted to C increments using a default value from IPCC [2006, Vol. 4, Chap. 4, Tab. 4.5] (see below).

2.4.1.1. Average annual removals

The activity data used for the estimation of removals from forestation were taken from the AA conducted on the two land-cover change map (see Appendix A.1).

Equation 2.29: Average annual forest area gain

$$\hat{\bar{A}}_{AR} = (\mathcal{T} - 1)^{-1} \left[\hat{A}_{j=711} + \hat{A}_{j=712} \right]$$

$\hat{\bar{A}}_{AR,t}$ = Average annual forest area gain (afforestation/reforestation); ha

$\hat{A}_{j=711}$ = Area of Natural Forest gain in Lowland between 2006 and 2016; ha (see Table 2.1)

$\hat{A}_{j=712}$ = Area of Natural Forest gain in Upland between 2006 and 2016; ha (see Table 2.1)

$\mathcal{T}$ = Length of the FRL Reference Period, i.e., $|T| = \mathcal{T} = 11$ years; yrs

Table 2.15 shows estimated areas of AR for Low- and Upland Natural Forest during the time interval mid 2006 to mid 2016.

Table 2.15.: Estimated average annual area of afforestation/reforestation (AR) during the FRL Reference Period 2006-2016. CI = confidence interval.

Stratum	$\hat{\bar{A}}_{AR}$ [ha yr^{-1}]	Lower 90%-CI [ha yr^{-1}]	Upper 90%-CI [ha yr^{-1}]
AR Lowland	4,955	3,694	6,352
AR Upland	1,224	722	1,763
Total	6,180	4,818	7,687

Carbon gains for year t over the Reference Period were calculated as follows:

Equation 2.30: Carbon gains (AR)

$$\Delta C_{AR,t} = \hat{\bar{A}}_{AR} \times MAIC_{AR} \times \delta_t$$

ΔC_{AR} = Carbon gains for year t generated over the Reference Period; tC
$\hat{\bar{A}}_{AR}$ = Average annual forest area gain (afforestation/reforestation); ha
$MAIC_{AR}$ = mean annual increment for afforestation/reforestation; tC ha^{-1} yr^{-1}
δ_{t_1} = $2016 - t$, with $T = \{2006, 2007, ..., t, ..., 2016\}$; yrs

$MAIC_{AR}$ was calculated as the average of the mean annual volume increments of different species reported by FHCL.

Equation 2.31: Mean annual carbon increment (AR)

$$MAIC_{AR} = MAIV_{AR} \times BCEF_{AR,I} \times (1 + R_{wl}) \times \eta_{CF}$$

$MAIC_{AR}$ = Mean annual carbon increment for afforestation/reforestation (AR), including carbon stored in AGB and BGB; tC ha^{-1} yr^{-1}
$MAIV_{AR}$ = Mean annual volume increment for AR; m^3 ha^{-1} yr^{-1}
$BCEF_{AR,I}$ = Biomass conversion and expansion factor for volume increments in humid tropical natural forests (growing stock level 11-20 m^3 ha^{-1}) taken from IPCC [2006, Vol. 4, Chap. 4, Tab. 4.5]; tB (m^3)$^{-1}$
R_{wl} = Root-to-shoot ratio for tropical rainforest (see Table 2.10); dimensionless
η_{CF} = Biomass to carbon conversion factor (IPCC default); dimensionless

The $MAIC_{AR}$ was estimated at 2.63 tC ha^{-1} yr^{-1}. The $MAIV_{AR} = 5.85$ m^3 ha^{-1} yr^{-1}, from which $MAIC_{AR}$ was derived, was computed from data provided by FHCL. For $BCEF_{AR,I}$ a value of 1.6 tB (m^3)$^{-1}$ was selected from IPCC [2006, Vol. 4, Chap. 4, Tab. 4.5] (BCEF$_I$ for humid tropical natural forests; growing stock level 11-20 m^3). The average volume gain generated over the Reference Period on one hectare and a $MAIV_{AR}$ of 5.85 m^3 ha^{-1} yr^{-1}, i.e., $(\sum_T \delta_t \times MAIV_{AR})/\mathcal{T} = 32.17$ m^3, is only slightly larger than the threshold value of 20 m^3. To minimize the risk of underestimating removals for the FRL, the BCEF$_I$ for a growing stock level of 11-20 m^3 was used instead of the BCEF$_I$ for a growing stock level of 21-40 m^3. To account for BGB in Equation (2.31), the root-to-shoot ratio for tropical rainforest, R_{wl} was selected.

Average annual C gains from AR over the Reference Period were estimated as follows.

Equation 2.32: Average annual C gains (AR)

$$\Delta \bar{C}_{AR} = (\mathcal{T} - 1)^{-1} \sum_T \Delta C_{AR,t}$$

$\Delta \bar{C}_{AR}$ = Average annual C gains from AR over the Reference Period; tC yr^{-1}
$\mathcal{T}$ = Length of the FRL Reference Period, i.e., $\mathcal{T} = 11$; yrs
$\Delta C_{AR,t}$ = Carbon gains for year t generated over the Reference Period; tC

Average annual removals from forest area gain were estimated by

> Equation 2.33: Average annual removals (AR)
>
> $$\hat{\theta}_{ECAR} = \Delta \bar{C}_{AR} \times \eta_{CC}$$

$\hat{\theta}_{ECAR}$ = Average annual removals from AR; $tCO_2e\ yr^{-1}$
$\Delta \bar{C}_{AR}$ = Average annual C gains from AR over the Reference Period; $tC\ yr^{-1}$
η_{CC} = Conversion factor C to CO_2; dimensionless

Table 2.16 shows estimated average annual removals from AR.

Table 2.16.: Average annual removals from afforestation/reforestation (AR). CI = confidence interval.

$\hat{\theta}_{AR}$ [$tCO_2e\ yr^{-1}$]	Lower 90%-CI [$tCO_2e\ yr^{-1}$]	Upper 90%-CI [$tCO_2e\ yr^{-1}$]
-327,541	-472,584	-201,679

2.4.1.2. Uncertainty analysis

2.4.1.2.1. Sources of uncertainty For the uncertainty analysis for the sub-sink "afforestation/reforestation" (sink "enhancement of forest carbon stocks"), the following sources of uncertainty were considered:

1. Uncertainty attached to the estimates of forest area gain, $\hat{\bar{A}}_{AR,T_1}$ and $\hat{\bar{A}}_{AR,T_2}$; large source, highly relevant; included in the quantification of uncertainty. The methods used to quatify the uncertainty are described at the end of Appendix A.1.

2. Uncertainty attached to the mean annual volume increment, $MAIV_{AR}$ (used as input in Equation (2.31)); large source of uncertainty, highly relevant; included in the quantification of uncertainty.

3. Uncertainty attached the biomass conversion and expansion factor, $BCEF_{AR,I}$ (used as input in Equation (2.31)); large source, highly relevant; included in the quantification of uncertainty.

4. Uncertainty attached R_{wl} (used as input in Equation (2.31)); large source, highly relevant; included in the quantification of uncertainty.

2.4.1.2.2. Quantification of uncertainty The uncertainty attached to the estimate of the average annual removals from forestation (afforestation/reforestation; AR) was assessed in an MC simulation. In the MC simulation the same estimators were used as in Section 2.4.1. The number of MC runs was $\mathcal{R} = 4 \times 10^4$. The estimate of $\hat{\theta}_{ECAR}$ was, thus, estimated $\mathcal{R}$ times. The following inputs were not treated as fixed as in Section 2.4.1, but were drawn randomly from probability density functions (PDFs).

$MAIV_{AR}$ $MAIV_{AR}$ was sampled from a Triangular distribution with lower bound $a = MAIV_{AR} - MAIV_{AR} \times 0.5$, upper bound $b = MAIV_{AR} + MAIV_{AR} \times 0.5$ and mode $c = MAIV_{AR}$.

$BCEF_{AR,I}$ The $BCEF_{AR,I}$ was sampled from a Triangular distribution with lower bound $a = BCEF_{AR,I} - BCEF_{AR,I} \times 0.25$, upper bound $b = BCEF_{AR,I} + BCEF_{AR,I} \times 0.25$ and mode $c = BCEF_{AR,I}$.

R_{wl} The R_{wl} was sampled from a Triangular distribution with lower bound $a = R_{wl} - R_{wl} \times 0.25$, upper bound $b = R_{wl} + R_{wl} \times 0.25$ and mode $c = R_{wl}$.

The MC simulation delivered $\mathcal{R}$ MC estimates of $\hat{\theta}_{AR}$. The $Q(0.05)$ and $Q(0.95)$ quantiles of the empirical PDF of MC estimates were used to derive upper and lower 90%-confidence limits.

2.4.2. Forest Plantations

2.4.2.1. Methodological approach

Fiji's forest definition lists two types of Forest Plantations, namely Hardwood Plantations and Softwood (or Pine) Plantations (Section 1.4.2). Hardwood Plantations are managed by the Fiji Hardwood Corporation Limited (FHCL), Softwood Plantations by Fiji Pine Limited (FPL). According to Fiji's most recent FAO Global Forest Resources Assessment (FRA) country report, the lease area of FHCL was reported at 58,997 ha and the lease area of FPL at 72,663 ha in 2010 [FRA-Fiji, 2015].

Following Fiji's forest definition, the entire lease areas of the two companies are defined as Forest Plantations, including areas currently not stocked with trees. Hence, they belong to the land-use category Forest Land. In Forest Plantations a land-use definition applies, whereas outside Forest Plantations a land-cover definition is used. By definition, deforestation and afforestation/reforestation are not possible within Forest Plantations. Forest Plantations will remain in the land-use category Forest Land even if the crown-cover is completely removed, e.g., temporarily unstocked.

In the context of REDD+, there are no strict rules to which source or sink forest plantations have to be linked (e.g., enhancement of forest carbon stocks, forest degradation, or sustainable management of forests). If the long-run average of C stocks is constantly decreasing over the Reference Period in Forest Plantations, plantation management may be linked to the source 'forest degradation'. If the area of plantations and the growing stock in already established plantations is constantly increasing, plantations may be linked to the sink 'enhancement of forest carbon stocks'. If plantations are managed sustainably, i.e., the long-run average of C stocks remains more or less constant, over time plantation management may be linked to the sink 'sustainable management of forests'.

The decision to link management of Forest Plantation in Fiji to the sink "enhancement of forest carbon stocks" was based on the following grounds:

— Forest Plantations are assumed to be managed sustainably, i.e., annual timber volumes extracted do not exceed annual growth of timber. This may not hold true for all years, but on the long run.

> — The Government of Fiji (GoF) is planning to increase the area of forest plantations in the future. This includes areas already under lease by FPL and FHCL as well as areas outside the current lease areas, i.e., the lease areas of FPL and FHCL are likely to increase in the future.

Forest plantations generate emissions and removals simultaneously. Emissions originate from timber harvests, whereas removals originate from forest growth in already established forests and/or from newly planted plantations.

Emissions and removals from Forest Plantations may be estimated using different methods. Remotely sensed data could be used to monitor stockings, as well as plantation area gains and losses. However, the land-cover change map produced for the FRL did not map changes within Forest Plantations. Moreover, from satellite imagery alone it is difficult to detect when trees were harvested or planted unless very dense time series of remotely sensed data are available. Data on the timing of harvesting and planting is, however, necessary to reliably estimate emissions and removals from Forest Plantations. For the FRL it was assumed that field data, i.e., records on the current stocking, volumes and areas harvested and areas planted available at FPL and FHCL, would provide more reliable estimates of emissions and removals from Forest Plantations.

To estimate gross emissions from Forest Plantations, records provided by FPL and FHCL on the timber volumes extracted in the years 2006 to 2016 were used. Timber volumes extracted were converted to total tree biomass, to total C and finally to CO_2 emissions. The conversion from wood removals to emissions was calculated differently for Hardwood and Softwood Plantations (see below).

Removals from Forest Plantations were estimated based on the MAI reported for Hard- and Softwood Plantations. Removals originate from (i) areas that were planted during the FRL Reference Period, (ii) areas that were planted before 2006 and were harvested during the FRL Reference Period and (iii) plantations that were planted before the FRL start year 2006 and were not harvested until the end of the Reference Period.

2.4.2.2. Emissions and removals from Hardwood Plantations

2.4.2.2.1. Average annual gross emissions from Hardwood Plantations   Gross emissions from Hardwood Plantations were estimated using data on recovered (extracted) volumes reported by FHCL for the years of the FRL Reference Period. Volumes in cubic meters were converted to AGB in metric tonnes by multiplying the volume extracted by a default biomass conversion and expansion factor (BCEF) from IPCC [2006, Vol. 4, Chap. 4, Tab. 4.5]. For Hardwood Plantations a value of 1.05 tB $(m^3)^{-1}$ was selected ($BCEF_R$ for humid tropical natural forest; growing stock level > 200 m^3 ha^{-1}).

Equation 2.34: AGB loss in Hardwood Plantations (HW)
$$AGB_{HW,L,t} = V_{HW,L,t} \times BCEF_{HW,R}$$
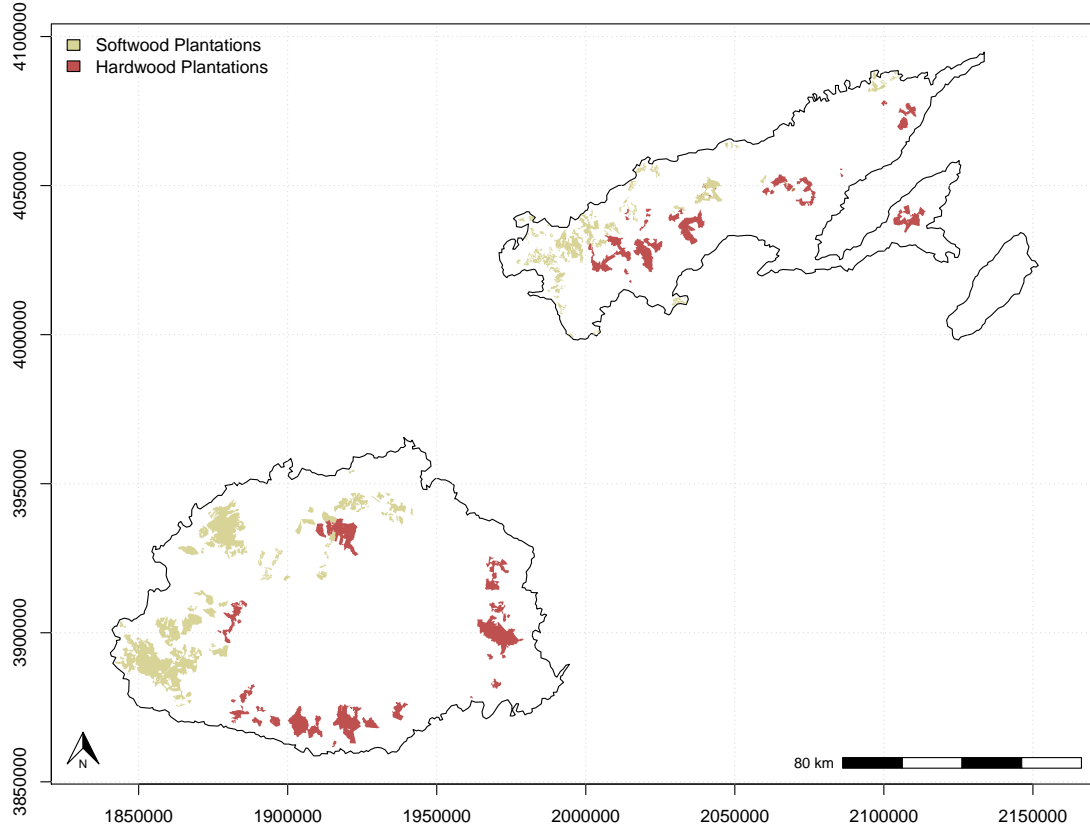
Figure 2.4.: Map of Hard- and Softwood Plantations in Fiji (2006). Hardwood Plantations are managed by the Fiji Hardwood Corporation Limited (FHCL), Softwood Plantations are managed by Fiji Pine Limited (FPL). Coordinate Reference System: Fiji 1986 Map Grid (EPSG code: 3460).

$AGB_{HW,L,t}$ = AGB extracted from Hardwood Plantations in year t; tAGB
$V_{HW,L,t}$ = Volume extracted from Hardwood Plantations in year t; m^3
$BCEF_{HW,R}$ = Biomass conversion and expansion factor for wood removals taken from IPCC [2006, Vol. 4, Chap. 4, Tab. 4.5; BCEF$_R$ for humid tropical natural forest; growing stock level > 200 m^3 ha^{-1}]; tB (m^3)$^{-1}$

AGB was expanded to total biomass (TB = AGB + BGB). As the plantation lease area of FHCL is entirely located within the wet area of Fiji, a root-to-shoot ratio for tropical rainforest was used to compute BGB (see Table 2.10). The total biomass loss was computed for Hardwood Plantations in each year t.

Equation 2.35: AGB loss to total biomass loss (HW)

$$TB_{HW,L,t} = AGB_{HW,L,t} \times (1 + R_{wl})$$

39

$TB_{HW,L,t}$ = Total biomass loss due to logging in Hardwood Plantations in year t; tTB

$AGB_{HW,L,t}$ = AGB extracted from Hardwood Plantations in year t; tAGB

R_{wl} = Root-to-shoot ratio for tropical rainforest (see Table 2.10); dimensionless

Carbon loss from Hardwood Plantations in year t was estimated by multiplying total biomass loss with the default IPCC [2006] conversion factor η_{CF}.

Equation 2.36: Total biomass loss to C loss (HW)

$$\Delta C_{HW,L,t} = \left[TB_{HW,L,t} \times \eta_{CF} \right] \times (-1)$$

$\Delta C_{HW,L,t}$ = Carbon loss in year t caused by logging in Hardwood Plantations; tC

$TB_{HW,L,t}$ = Total biomass loss due to logging in Hardwood Plantations in year t; tB

η_{CF} = Biomass to carbon conversion factor from IPCC [2006]; dimensionless

As carbon loss always have a negative sign, the first term in squared brackets in Equation (2.36) is multiplied by (-1). Annual carbon losses in Hardwood Plantations are provided in Table 2.17 ($\Delta C_{HW,L}$).

Average annual gross emissions from Hardwood Plantations were estimated by

---

Equation 2.37: Average annual gross emissions from total C loss (HW)

$$\hat{\theta}_{ECHem} = \mathcal{T}^{-1} \left[\sum_T \Delta C_{HW,L,t} \times \eta_{CC} \right]$$

$\hat{\theta}_{ECHem}$ = Average annual gross emissions from Hardwood Plantations; tCO$_2$e yr^{-1}

$\mathcal{T}$ = Length of the FRL Reference Period, i.e., 11 years; yrs

$\Delta C_{HW,L,t}$ = Carbon loss in year t caused by logging in Hardwood Plantations; tC

η_{CC} = Conversion factor carbon to CO$_2$ (see Equation (2.1)); tC

2.4.2.2.2. Average annual gross removals from Hardwood Plantations The following three sources of removals are considered for Hardwood Plantations:

1. Removals from plantation compartments that were planted before 2006 and were not harvested until the end of the FRL Reference Period.

2. Removals from plantation compartments that were planted before 2006 and were harvested during the FRL Reference Period.

Table 2.17.: Volumes extracted from Hardwood Plantations, $V_{HW,L}$, areas logged, $A_{HW,LG}$, areas planted, $A_{HW,PL}$, stocking area, $A_{HW,S}$, C losses, $\Delta C_{HW,L}$, and C gains over the Reference Period, $\Delta C_{HW,G}$.

Year	$V_{HW,L}$ [m³]	$A_{HW,LG}$ [ha]	$A_{HW,PL}$ [ha]	$A_{HW,S}$ [ha]	$\Delta C_{HW,L}$ [tC]	$\Delta C_{HW,G}$ [tC]
2006	37216	212	305	57043	-25162	13271
2007	50092	278	305	56977	-33867	12007
2008	79869	736	305	56519	-53999	10743
2009	63758	165	305	57091	-43106	9479
2010	92283	432	305	56823	-62392	8215
2011	91025	132	228	57046	-61542	5196
2012	53737	110	1000	57840	-36331	18646
2013	63251	310	0	56640	-42764	0
2014	58542	394	0	56556	-39580	0
2015	54568	375	0	56575	-36893	0
2016	39854	172	300	57078	-26945	622

3. Removals from plantation compartments that were planted during the FRL Reference Period. As the cutting cycle for Hardwood Plantations exceed the length of the FRL Reference Period, non of the compartments that were planted during the Reference Period were harvested before 2016.

The estimation of removals requires an estimate of the carbon accumulation in Hardwood Plantations (i.e., the amount of carbon that accumulates on one hectare of Hardwood Plantation per year). Neither growth curves, nor an estimate of the mean annual carbon increment are available for Hardwood Plantations. However, FHCL provided data on the mean annual volume increment for different species (see Table 2.18). A weighted average of increments (volume) were computed, $\overline{MAIV}_{HW}$, where the areas stocked in 2017, A_{HW}, served as weights. The mean annual volume increment over all species was estimated at 5.85 m³ ha⁻¹ yr⁻¹. A default biomass conversion and expansion factor for increment (BCEF$_I$) of 1.1 tB (m³) [IPCC, 2006, Vol. 4, Chap. 4, Tab. 4.5; humid tropical natural forests; growing stock level 21-40 m³ ha⁻¹] was used to convert volume increment to AGB increment.

Equation 2.38: Mean annual AGB increment (HW)

$$MAIAGB_{HW} = \overline{MAIV}_{HW} \times BCEF_{HW,I}$$

$MAIAGB_{HW}$ = Mean annual AGB increment in Hardwood Plantations; tB ha⁻¹ yr⁻¹

$\overline{MAIV}_{HW}$ = Average mean annual volume increment in Hardwood Plantations; m³ ha⁻¹ yr⁻¹

$BCEF_{HW,I}$ = Biomass conversion and expansion factor for increment taken from IPCC [2006, Vol. 4, Chap. 4, Tab. 4.5; BCEF$_I$ for humid tropical natural forest; growing stock level 21-40 m³ ha⁻¹]; tB (m³)⁻¹

To compute total carbon increment per hectare and year from biomass increment, BGB

Table 2.18.: Mean annual increments of tree species in Hardwood Plantations, $MAIV_{HW}$, cutting cycle (CC), expected volumes at rotation age (cut volumes), and stocking area in 2017. Data were provided by Fiji Hardwood Corporation Limited (FHCL).

Species	$MAIV_{HW}$ [m^3 ha^{-1} yr^{-1}]	CC [yrs]	Cut volume [m^3 ha^{-1}]	A_{HW} [ha]
Mahogany	6.3	37	220	48801
Mixed hardwoods	2.0	35	70	3634
Cadamba	5.0	35	180	1263
Cordia	1.4	35	50	940
Maesopsis	2.9	35	100	912
Pine	7.1	27	180	532
Dakua Makadre	3.0	60	180	241
Eucalyptus	7.5	25	150	161
Yemini	4.0	60	100	46
Kauvula	1.7	50	100	33
Teak	4.0	30	120	2

was added using a root-to-shoot ratio for tropical rainforest, and total biomass (TB = AGB + BGB) was converted to carbon.

Equation 2.39: Total C increment (HW)

$$MAIC_{HW} = [MAIAGB_{HW} \times (1 + R_{wl})] \times \eta_{CF}$$

$MAIC_{HW}$ = Mean annual total carbon increment (TC = AGC + BGC) in Hardwood Plantations; tB ha^{-1} yr^{-1}

$MAIAGB_{HW}$ = Mean annual above-ground biomass increment; tB ha^{-1} yr^{-1}

R_{wl} = Root-to-shoot ratio for tropical rainforest taken from IPCC [2006, Vol. 4, Chap. 4, Tab. 4.4] (see Table 2.10); dimensionless

η_{CF} = Conversion factor biomass to C; dimensionless

Total C gains for year t on plantation compartments that were planted during the FRL Reference Period were computed as follows:

Equation 2.40: Total C gain on planted compartments (HW)

$$\Delta C_{HW,G,t} = \delta_t \times A_{HW,PL,t} \times MAIC_{HW}$$

$\Delta C_{HW,G,t}$ = Carbon gains for year t in Hardwood Plantations over the Reference Period (only includes compartments that were planted during the Reference Period, i.e., between 2006-2016); tC

δ_t = $2016 - t + 0.5$; yrs

$A_{HW,PL,t}$ = Area planted in Hardwood Plantations in year t; ha

$MAIC_{HW}$ = Mean annual C increment in Hardwood Plantations; tC ha^{-1} yr^{-1}

FHCL reported annual data on planted areas for the years 2011 to 2016, for the time interval 2006 to 2010 no annual data were provided. However, FHCL reported the total

area planted between 2001 and 2010, i.e., 3050.3 ha. For the first five years of the FRL Reference Period (2006-2010), an annual average was used that was computed by dividing the total area planted between 2001 and 2010 by 10 years, i.e., $A_{HW,PL,t}$ was 305.03 ha for $t = \{2006, 2007, ..., 2010\}$.

FHCL did not report the area stocked within the Hardwood Plantation lease area at end of 2005. However, this area needs to be known in order to estimate removals from plantation compartments that were neither planted nor harvested during the FRL Reference Period. The area stocked at the end of 2005 was computed as follows:

Equation 2.41: Area stocked by the end of 2005 (HW)

$$A_{HW,S,2005} = A_{HW,S,2011} + \sum_{t=2006}^{2010} A_{HW,LG,t} - \sum_{t=2006}^{2010} A_{HW,PL,t}$$

$A_{HW,S,2005}$ = Stocking area in Hardwood Plantations in 2005; ha
$A_{HW,S,2011}$ = Stocking area in Hardwood Plantations in 2011; ha
$A_{HW,LG,t}$ = Area logged in Hardwood Plantations in year t; ha
$A_{HW,PL,t}$ = Area planted in Hardwood Plantations in year t; ha

Using data on the stocking area and data on the areas logged during the Reference Period, the area that was neither planted nor harvested can be computed.

Equation 2.42: Area stocked (HW) neither planted nor harvested 2006-2016

$$A_{HW,GR} = A_{HW,S,2005} - \sum_{T} A_{HW,LG,t}$$

$A_{HW,GR}$ = Stocking area in Hardwood Plantations that was planted before 2006 and was not harvested until the end of the Reference Period; ha
$A_{HW,S,2005}$ = Stocking area in Hardwood Plantations in 2005; ha
$A_{HW,LG,t}$ = Area logged in Hardwood Plantations in year t; ha

Average annual C gains on $A_{HW,GR}$ are estimated as follows:

Equation 2.43: C gains on $A_{HW,GR}$ (HW)

$$\Delta C_{HW,GR} = A_{HW,GR} \times MAIC_{HW}$$

$\Delta C_{HW,GR}$ = Average annual C gain on areas that were planted before 2006 and were not harvested until the end of the Reference Period; tC yr^{-1}
$A_{HW,GR}$ = Stocking area in Hardwood Plantations that was planted before 2006 and was not harvested until the end of the Reference Period; ha
$MAIC_{HW}$ = Mean annual C increment in Hardwood Plantations; tC ha^{-1} yr^{-1}

Carbon accumulation in plantation compartments that were planted before 2006 and were harvested during the FRL Reference Period are estimated below. To compute

43

average annual C gains, data on the area logged, the mean annual total carbon increment and the time until logging are used.

Equation 2.43: C gains in compartments that were harvested in 2006-2016

$$\Delta C_{HW,GRH} = \mathcal{T}^{-1} \left[\sum_T \delta'_t \times A_{HW,LG,t} \times MAIC_{HW} \right]$$

$\Delta C_{HW,GRH}$ = Average annual C gain on areas that were planted before 2006 and harvested during the Reference Period; tC yr^{-1}

δ'_t = The time a compartment logged in year t grew during the Reference Period, $\delta'_t = t - 2016 + 10.5$, i.e., the reversal of δ_t; yrs

$\hat{A}_{HW,LG,t}$ = Area logged in Hardwood Plantations in year t; ha

$MAIC_{HW}$ = Mean annual C increment in Hardwood Plantations; tC ha^{-1} yr^{-1}

Average annual total C gain from Hardwood Plantations is computed as follows:

Equation 2.45: Total C gain (HW)

$$\Delta C_{HW,G} = \left[\mathcal{T}^{-1} \sum_T \Delta C_{HW,G,t} \right] + \Delta C_{HW,GRH} + \Delta C_{HW,GR}$$

$\Delta C_{HW,G}$ = Total average annual C gains including gains from areas that were planted in Hardwood Plantations during the Reference Period, areas that were harvested during the Reference Period, and areas that were planted before 2006 and were not harvested until the end of the Reference Period; tC yr^{-1}

$\Delta C_{HW,G,t}$ = Carbon gains in compartments planted between 2006-2016 for year t in HW Plantations over the Reference Period; tC

$\Delta C_{HW,GRH}$ = Average annual C gain on areas that were planted before 2006 and harvested during the Reference Period; tC yr^{-1}

$\Delta C_{HW,GR}$ = Average annual C gain on areas that were planted before 2006 and were not harvested until the end of the Reference Period; tC yr^{-1}

Average annual total C gains are converted to average annual gross removals by multiplying $\Delta C_{HW,G}$ by the default C to CO$_2$ conversion factor provided by IPCC [2006].

Equation 2.46: Average annual gross removals (HW)

$$\hat{\theta}_{ECHre} = \Delta C_{HW,G} \times \eta_{CC}.$$

$\hat{\theta}_{ECHre}$ = Average annual gross removals from Hardwood Plantations; tCO$_2$e yr^{-1}

$\Delta C_{HW,G}$ = Total average annual C gains including gains from areas that were planted before 2006 and were not harvested until the end of the Reference Period and areas that were planted in HW plantations during the Reference Period; tC yr^{-1}

η_{CC} = Conversion factor C to CO$_2$; dimensionless

Estimates of gross removals and gross emissions, as well as net emissions from Hardwood Plantations are provided in Table 2.20 on page 52.

2.4.2.2.3. Average annual net emissions from Hardwood Plantations Average annual net emissions from Hardwood Plantations were computed by taking the sum of average annual gross emissions and average annual gross removals.

Equation 2.47: Average annual net emissions (HW)

$$\hat{\theta}_{ECH} = \hat{\theta}_{ECHem} + \hat{\theta}_{ECHre}$$

$\hat{\theta}_{ECH}$ = Average annual net emissions from Hardwood Plantations; tCO$_2$e yr^{-1}

$\hat{\theta}_{ECHem}$ = Average annual gross emissions from Hardwood Plantations; tCO$_2$e yr^{-1}

$\hat{\theta}_{ECHrm}$ = Average annual gross removals from Hardwood Plantations; tCO$_2$e yr^{-1}

2.4.2.3. Emissions and removals from Softwood Plantations

Gross emissions and gross removals from Softwood Plantations are estimated similarly to gross emissions and removals from Hardwood Plantations. That is, gross emissions are estimated from harvested timber volumes, gross removals are estimated form plantation compartments that were planted during the Reference Period, compartments that were planted before 2006 and were not harvested until the end of the Reference Period, and compartments that were planted before 2006 and which were harvested during the Reference Period. However, Fiji Pine Limited (FPL) provided data that differed structurally from the data provided by FHCL. Therefore, some estimation procedures differ from those used for Hardwood Plantations.

2.4.2.3.1. Average annual gross emissions from Softwood Plantations Gross emissions from Softwood Plantations were estimated from harvested timber volumes. Volumes extracted were converted to AGB based on an estimate of the recovery rate, λ_{Pine}, and an estimate of the wood density of pine trees, ρ_{Pine} [g cm^{-1}]. The recovery rate, as defined here, is an estimated average of the ratio of the timber volume delivered by a pine tree and the total tree volume. The recovery rate for pine was taken from Waterloo [1994], who estimated a recovery rate of $\lambda_{Pine} = 0.76$ for trees harvested in pine plantations in Fiji. Data on the wood density of pine was taken from Cown [1981]. The estimated wood density was $\rho_{Pine} = 0.47$ g cm^{-3} (standard deviation $\rho_{Pine,sd} = 0.05$ g

cm^{-3}). Harvested timber volumes and harvested areas reported by FPL are provided in Table 2.19. AGB loss for the years 2006 to 2016 from Softwood Plantations was computed by

---

Equation 2.48: AGB loss in Softwood Plantations (SW)

$$AGB_{SW,L,t} = V_{SW,L,t} \times \frac{1}{\lambda_{Pine}} \times \rho_{Pine}$$

$AGB_{SW,L,t}$ = AGB loss in year t in Softwood Plantations; tAGB
$V_{SW,L,t}$ = Wood volumes harvested in Softwood Plantations in year t; m^3
λ_{Pine} = Recovery rate in Softwood Plantations; dimensionless
ρ_{Pine} = Wood density of pine wood harvested in Softwood Plantations; g cm^{-3}

Table 2.19.: Volumes extracted from Softwood Plantations, $V_{HW,L}$, areas logged, $A_{HW,LG}$, areas planted, $A_{HW,PL}$, stocking area, $A_{HW,S}$, C losses, $\Delta C_{HW,L}$, and C gains over the Reference Period, $\Delta C_{HW,G}$.

Year	$V_{SW,L}$ [m^3]	$A_{SW,LG}$ [ha]	$A_{SW,PL}$ [ha]	$A_{SW,S}$ [ha]	$\Delta C_{SW,L}$ [tC]	$\Delta C_{SW,G}$ [tC]
2006	282102	1082	1478	49503	-101674	72929
2007	294685	1130	3	47980	-106209	128
2008	265046	1016	14	48105	-95527	563
2009	249769	958	17	48166	-90021	589
2010	256040	982	177	48303	-92281	5419
2011	306684	1176	273	48204	-110534	7060
2012	158214	607	871	49371	-57023	18422
2013	668833	2564	13	46555	-241058	206
2014	544902	2089	202	47219	-196391	2370
2015	393519	1509	1032	48630	-141830	7275
2016	259301	994	0	48113	-93456	0

Total biomass loss was computed by adding loss of BGB using a root-to-shoot ratio for moist deciduous forest from IPCC [2006, Vol. 4, Chap. 4, Tab. 4.4].

Equation 2.49: Total biomass loss from AGB loss (SW)

$$TB_{SW,L,t} = AGB_{SW,L,t} \times (1 + R_{dlh})$$

$TB_{SW,L,t}$ = Total biomass loss in year t in Softwood Plantations; tB
$AGB_{SW,L,t}$ = AGB loss in year t in Softwood Plantations; tB
R_{dlh} = Root-to-shoot ratio for tropical moist deciduous forest > 125 tB ha^{-1}, taken from IPCC [2006, Vol. 4, Chap. 4, Tab. 4.4] (see Table 2.10); dimensionless

Total biomass loss for the years 2006 to 2016 was converted to C loss using the following equation. The left term is multiplied by -1 to ensure that C loss has a negative sign.

Equation 2.50: Total C loss from total biomass loss (SW)

$$\Delta C_{SW,L,t} = \left[TB_{SW,L,t} \times \eta_{CF} \right] \times (-1)$$

$\Delta C_{SW,L,t}$ = Carbon loss in Softwood Plantations in year t due to wood removals; tC
$TB_{SW,L,t}$ = Total biomass loss in year t in Softwood Plantations; tB
η_{CF} = Conversion factor biomass to C; dimensionless

From the annual C loss (see column $\Delta C_{SW,L}$ in Table 2.19), average annual gross emissions from Softwood Plantations were estimated.

Equation 2.51: Average annual gross emissions (SW)

$$\hat{\theta}_{ECSem} = \mathcal{T}^{-1} \left[\sum_{T} \Delta C_{SW,L,t} \times \eta_{CC} \right]$$

$\hat{\theta}_{ECSem}$ = Average annual gross emissions from Softwood Plantations; tCO$_2$e yr^{-1}
$\mathcal{T}$ = Length of the FRL Reference Period, i.e., 11 years; yrs
$\Delta C_{SW,L,t}$ = Carbon loss in Softwood Plantations in year t due to wood removals; tC
η_{CC} = Conversion factor C to tCO$_2$; dimensionless

The estimate of average annual gross emissions from Softwood Plantations is provided in Table 2.20 on page 52.

2.4.2.3.2. Average annual gross removals from Softwood Plantations Average annual gross removals from Softwood Plantations were estimated using data on the mean annual total biomass (AGB + BGB) increment, $MAIB_{SW}$ (taken from Waterloo [1994]), areas planted during the Reference Period and growth on areas that were planted before 2006 and were either harvested or not harvested before the end of the Reference Period.

$MAIB_{SW}$ was reported by Waterloo [1994] for pine plantations in Fiji (10 tB ha^{-1} yr^{-1}) and includes AGB and BGB. FPL provided inventory data from which growth curves for volume could have been derived. However, the data were erroneous and a reliable estimate of, e.g., the current annual increment of volume, could not be obtained.

Spatial data on areas planted and areas harvested per year were provided by FPL. Data on planted areas were cross-checked and verified by MSD. However, data on areas harvested were erroneous and could not be used. For example, for the year 2012, FPL reported that about 158,214 m^3 of pine wood were harvested. The area reported as harvest in 2012 was, however, zero hectares. As the area harvested was needed to estimate the area on which removals were generated in Softwood Plantations (see Equation (2.55)), these data were estimated using data on harvested volumes.

To estimate C accumulation on areas planted during the Reference Period and areas that have been planted before 2006 (and were not harvested until the end of the Reference Period), the $MAIB_{SW}$ was converted to C increment by

---

Equation 2.52: Mean annual carbon increment (SW)

$$MAIC_{SW} = MAIB_{SW} \times \eta_{CF}$$

$MAIC_{SW}$ = Mean annual C increment in Softwood Plantations; tC ha^{-1} yr^{-1}
$MAIB_{SW}$ = Mean annual biomass increment (including above- and below-ground biomass) in Softwood Plantations; tB ha^{-1} yr^{-1}
η_{CF} = Conversion factor biomass to C; dimensionless

Carbon gains for year t over the Reference Period, i.e., C accumulation over the Reference Period on areas that were planted in year t, were estimated using Equation (2.53). For example, in 2006, $A_{SW,PL,2006} = 1478$ ha were planted. These plantation compartments grow for $\delta_{2006} = 10.5$ years. Each year 4.7 tC accumulated per hectare. Hence, about $\Delta C_{SW,G,2006} = 10.5 \times 1478 \times 4.7 = 72939$ metric tonnes of C accumulated on Softwood Plantation compartments that were planted in 2006. Estimates of annual C gains in Softwood Plantations are provided in Table 2.19 on page 46 (see column $\Delta C_{SW,G}$).

Equation 2.53: C gains on areas planted (SW)

$$\Delta C_{SW,G,t} = \delta_t \times A_{SW,PL,t} \times MAIC_{SW}$$

$\Delta C_{SW,G,t}$ = Carbon gains for year t in Softwood Plantations over the Reference Period; tC
δ_t = $2016 - t + 0.5$; yrs
$A_{SW,PL,t}$ = Area planted in Softwood Plantations in year t; ha
$MAIC_{SW}$ = Mean annual C increment in Softwood Plantations; tC ha^{-1} yr^{-1}

To estimate removals from plantation compartments that were planted before 2006 and were not harvested until the end of the Reference Period, the area of these compartments need to be known. To calculate the area, all areas logged since the beginning of 2006 have to be subtracted from the stocking area at the end of 2005. However, as the data reported by FPL on areas harvested could not be used, harvested areas are estimated from the available data. This is done by dividing the C loss in year t by the expected C stock per hectare at rotation age. The expected C stock per hectare at rotation age is calculated by taking the product of the cutting cycle length (reported to be 20 years by FPL) and the mean annual C increment in Softwood Plantations. The area logged in year t in Softwood Plantation was estimated using the following equation.

Equation 2.54: Area logged in year t (SW)

$$\hat{A}_{SW,LG,t} = \left[CC_{SW} \times MAIC_{SW} \right]^{-1} \times \Delta C_{SW,L,t}$$

$\hat{A}_{SW,LG,t}$ = Area logged in Softwood Plantations in year t; ha
CC_{SW} = Average length of the cutting cycle in Softwood Plantations; yrs
$MAIC_{SW}$ = Mean annual C increment in Softwood Plantations; tC ha^{-1} yr^{-1}
$\Delta C_{SW,L,t}$ = Carbon loss in Softwood Plantations in year t due to wood removals; tC

FPL reported the stocking area for December 31, 2006, but not for December 31, 2005. The stocking area for the latter date was computed by

Equation 2.55: Stocking area in 2005 (SW)

$$\hat{A}_{SW,S,2005} = A_{SW,S,2006} + \hat{A}_{SW,LG,2006} - A_{SW,PL,2006}$$

$\hat{A}_{SW,S,2005}$ = Stocking area of Softwood Plantations in 2005; ha
$A_{SW,S,2006}$ = Stocking area of Softwood Plantations in 2006; ha
$\hat{A}_{SW,LG,2006}$ = Area harvested in Softwood Plantations in 2006; ha
$A_{SW,PL,2006}$ = Area planted in FPL's plantation lease area in 2006; ha

Using the estimates from Equation (2.54) and Equation (2.55), the area that was planted before 2006 and was not harvested until the end of the Reference Period was estimated as follows.

Equation 2.56: Area stocked (SW) neither planted nor harvested 2006-2016

$$\hat{A}_{SW,GR} = \hat{A}_{SW,S,2005} - \sum_T \hat{A}_{SW,LG,t}$$

$\hat{A}_{SW,GR}$ = Stocking area in Softwood Plantations that was planted before 2006 and was not harvested until the end of the Reference Period; ha
$\hat{A}_{SW,S,2005}$ = Stocking area of Softwood Plantations in 2005; ha
$\hat{A}_{SW,LG,t}$ = Area harvested in Softwood Plantations in year t; ha

Multiplying $\hat{A}_{SW,GR}$ by the mean annual C increment gives the average annual C increment on these plantation compartments.

Equation 2.57: C gains on $\hat{A}_{SW,GR}$ (SW)

$$\Delta C_{SW,GR} = \hat{A}_{SW,GR} \times MAIC_{SW}$$

$\Delta C_{SW,GR}$ = Average annual C gain on areas that were planted before 2006 and were not harvested until the end of the Reference Period; tC yr^{-1}

$A_{SW,GR}$ = Stocking area in Softwood Plantations that was planted before 2006 and was not harvested until the end of the Reference Period; ha

$MAIC_{SW}$ = Mean annual C increment in Softwood Plantations; tC ha^{-1} yr^{-1}

To estimate C gains on plantation compartments that were planted before 2006 and were harvested in year t during the Reference Period, the estimated area logged was multiplied by the mean annual C increment and the time the compartment grew until trees in the compartment were harvested.

Equation 2.58: C gains in compartments harvested between 2006 and 2016

$$\Delta C_{SW,GRH} = \mathcal{T}^{-1}[\sum_{T} \delta'_t \times \hat{A}_{SW,LG,t} \times MAIC_{SW}]$$

$\Delta C_{SW,GRH}$ = Average annual C gain on areas that were planted before 2006 and harvested during the Reference Period; tC yr^{-1}

δ'_t = The time a compartment logged in year t grew during the Reference Period, $\delta'_t = t - 2016 + 10.5$, i.e., the reversal of δ_t; yrs

$\hat{A}_{SW,LG,t}$ = Area logged in Softwood Plantations in year t; ha

$MAIC_{SW}$ = Mean annual C increment in Softwood Plantations; tC ha^{-1} yr^{-1}

Average annual C gains in Softwood Plantations were estimated as shown in Equation (2.59). In the first term in squared brackets, C gains from planted compartments are annualized.

Equation 2.59: Total C gain (SW)

$$\Delta C_{SW,G} = \left[\mathcal{T}^{-1} \sum_{T} \Delta C_{SW,G,t} \right] + \Delta C_{SW,GRH} + \Delta C_{SW,GR}$$

$\Delta C_{SW,G}$ = Total average annual C gains, including C gains from areas that were planted in Softwood Plantations during the Reference Period, areas that were harvested during the Reference Period, and areas that were planted before 2006 and were not harvested until the end of the Reference Period; tC yr^{-1}

$\Delta C_{SW,G,t}$ = Carbon gains in compartments planted during 2006-2016 for year t in Softwood Plantations over the Reference Period; tC

$\Delta C_{SW,GRH}$ = Average annual C gain on areas that were planted before 2006 and harvested during the Reference Period; tC yr^{-1}

$\Delta C_{SW,GR}$ = Average annual C gain on areas that were planted before 2006 and were not harvested until the end of the Reference Period; tC yr^{-1}

Average annual gross removals from Softwood Plantations were estimated as follows.

Equation 2.61: Average annual net emissions (SW)

$$\hat{\theta}_{ECSre} = \Delta C_{SW,G} \times \eta_{CC}$$

$\hat{\theta}_{ECSre}$ = Average annual gross removals from Softwood Plantations; $tCO_2e\ yr^{-1}$
$\Delta C_{SW,G}$ = Total average annual C gains, including C gains from areas that were planted in Softwood Plantations during the Reference Period, areas that were harvested during the Reference Period, and areas that were planted before 2006 and were not harvested until the end of the Reference Period; $tC\ yr^{-1}$
η_{CC} = Conversion factor carbon to CO_2 (see Equation (2.1)); tC

2.4.2.3.3. Average annual net emissions from Softwood Plantations Average annual net emissions from Softwood Plantations were computed by taking the sum of average annual gross emissions, $\hat{\theta}_{ECSem}$, and average annual gross removals, $\hat{\theta}_{ECSre}$.

Equation 2.61: Average annual net emissions (SW)

$$\hat{\theta}_{ECS} = \hat{\theta}_{ECSem} + \hat{\theta}_{ECSre}$$

$\hat{\theta}_{ECS}$ = Average annual net emissions from Softwood Plantations; $tCO_2e\ yr^{-1}$
$\hat{\theta}_{ECSem}$ = Average annual gross emissions from Softwood Plantations; $tCO_2e\ yr^{-1}$
$\hat{\theta}_{ECSre}$ = Average annual gross removals from Softwood Plantations; $tCO_2e\ yr^{-1}$

2.4.2.4. Average annual net emissions from Forest Plantations

Average annual gross emissions from Forest Plantations, including gross emissions from Hardwood Plantations and gross emissions from Softwood Plantations, were computed using Equation (2.62).

Equation 2.62: Average annual gross emissions from Forest Plantations

$$\hat{\theta}_{ECHSem} = \hat{\theta}_{ECHem} + \hat{\theta}_{ECSem}$$

$\hat{\theta}_{ECHSem}$ = Average annual gross emissions from Forest Plantations; $tCO_2e\ yr^{-1}$
$\hat{\theta}_{ECHem}$ = Average annual gross emissions from Hardwood Plantations; $tCO_2e\ yr^{-1}$
$\hat{\theta}_{ECSem}$ = Average annual gross emissions from Softwood Plantations; $tCO_2e\ yr^{-1}$

Average annual gross removals from Forest Plantations, including gross removals from Hardwood Plantations and gross removals from Softwood Plantations, were computed using Equation (2.63).

Equation 2.63: Average annual gross removals from Forest Plantations

$$\hat{\theta}_{ECHSre} = \hat{\theta}_{ECHre} + \hat{\theta}_{ECSre}$$

$\hat{\theta}_{ECHSre}$ = Average annual gross removals from Forest Plantations; $tCO_2e\ yr^{-1}$
$\hat{\theta}_{ECHre}$ = Average annual gross removals from Hardwood Plantations; $tCO_2e\ yr^{-1}$
$\hat{\theta}_{ECSre}$ = Average annual gross removals from Softwood Plantations; $tCO_2e\ yr^{-1}$

Average annual net emissions from Forest Plantations, including net emissions from Hardwood Plantations and net emissions from Softwood Plantations, were computed by

---

Equation 2.64: Average annual net emissions from Forest Plantations

$$\hat{\theta}_{ECHS} = \hat{\theta}_{ECH} + \hat{\theta}_{ECS}$$

$\hat{\theta}_{ECHS}$ = Average annual net emissions from Forest Plantations; $tCO_2e\ yr^{-1}$
$\hat{\theta}_{ECH}$ = Average annual net emissions from Hardwood Plantations; $tCO_2e\ yr^{-1}$
$\hat{\theta}_{ECS}$ = Average annual net emissions from Softwood Plantations; $tCO_2e\ yr^{-1}$

A summary of estimates of gross and net emissions and removals is provided in Table 2.20. An estimate of net removals, i.e., negative net emissions, for the sink 'enhancement of forest carbon stocks', including removals from afforestation/reforestation and Forest Plantations, is provided in the final FRL result Table 3.1 on page 58.

Table 2.20.: Average annual gross emissions/removals from Hard- and Softwood Plantations. All estimates are in $tCO_2e\ yr^{-1}$. Hardw. = Hardwood Plantations; Softw. = Softwood Plantations; Plant. = Plantations; L90%-CI = lower bound of the 90% confidence interval; U90%-CI = upper bound of the 90% confidence interval; CI = confidence interval.

	Estimate	L90%-CI	U90%-CI
Gross emissions Hardwood, $\hat{\theta}_{ECHem}$	154,194	127,442	181,298
Gross emissions Softwood, $\hat{\theta}_{ECSem}$	442,001	363,510	543,743
Gross emissions Plantations, $\hat{\theta}_{ECHSem}$	596,195	513,792	701,521
Gross removals Hardwo, $\hat{\theta}_{ECHre}$	-864,898	-1,237,198	-545,646
Gross removals Softwood, $\hat{\theta}_{ECSre}$	-774,225	-906,206	-641,048
Gross removals Plantations, $\hat{\theta}_{ECHSre}$	-1,639,123	-2,027,493	-1,293,993
Net emissions Hardwood, $\hat{\theta}_{ECH}$	-710,705	-1,084,912	-390,530
Net emissions Softwood, $\hat{\theta}_{ECS}$	-332,224	-479,604	-162,695
Net emissions Plantations, $\hat{\theta}_{ECHS}$	-1,042,928	-1,436,618	-674,377

2.4.2.5. Uncertainty analysis

2.4.2.5.1. Sources of uncertainty For the uncertainty analysis of the sub-sink 'Forest Plantation management' (sink 'enhancement of forest carbon stocks'), the following sources of uncertainty were considered:

1. Hardwood Plantations

    a) Uncertainty attached to harvested volumes, $V_{HW,L}$ (used as input in Equation (2.34)); small source, not relevant; not included in the quantification of uncertainty. Note that the data are census data (i.e., no sampling error).

    b) Uncertainty attached to $BCEF_{HW,R}$ (used as input in Equation (2.34)); large source, highly relevant; included in the quantification of uncertainty.

    c) Uncertainty attached to R_{wl} (used as input in Equation (2.35)); large source, relevant; included in the quantification of uncertainty.

    d) Uncertainty attached to conversion factors, η_{CF} and η_{CC} (used as input in Equation (2.36) and Equation (2.37)); small source, not relevant; not included in the quantification of uncertainty.

    e) Uncertainty attached to $MAIV_{HW}$ (used as input in Equation (2.38)); large source, highly relevant; included in the quantification of uncertainty.

    f) Uncertainty attached to $BCEF_{HW,I}$ (used as input in Equation (2.38)); large source, highly relevant; included in the quantification of uncertainty.

    g) Uncertainty attached to areas planted, $A_{HW,PL}$ (used as input in Equation (2.40)); large source, highly relevant; included in the quantification of uncertainty. Note that $A_{HW,PL}$ was only considered highly uncertain for the years 2006-2010, i.e., the years for which the annual average of the time interval 2001 to 2010 was used (see Equation (2.40)). For the remaining years 2011 to 2016, the uncertainty was considered small (and was ignored).

2. Softwood Plantations

    a) Uncertainty attached to harvested volumes, $V_{SW,L}$ (used as input in Equation (2.48)); small source, not relevant; not included in the quantification of uncertainty. Note that the data are census data (i.e., no sampling error).

    b) Uncertainty attached to the recovery rate, λ_{Pine} (used as input in Equation (2.48)); medium source, relevant; included in the quantification of uncertainty.

    c) Uncertainty attached to the wood density of pine, ρ_{Pine} (used as input in Equation (2.48)); medium source, relevant; included in the quantification of uncertainty.

    d) Uncertainty attached to R_{dlh} (used as input in Equation (2.49)); large source, relevant; included in the quantification of uncertainty.

e) Uncertainty attached to conversion factors, η_{CF} and η_{CC} (used as input in Equation (2.50) and Equation (2.51)); small source, not relevant; not included in the quantification of uncertainty.

f) Uncertainty attached to $MAIB_{SW}$ (used as input in Equation (2.52)); large source, highly relevant; included in the quantification of uncertainty.

g) Uncertainty attached to areas planted, $A_{SW,PL}$ (used as input in Equation (2.53)); small source, not relevant; not included in the quantification of uncertainty. Note that the data are census data (i.e., no sampling error).

h) Uncertainty attached to the cutting cycle length, CC_{SW} (used as input in Equation (2.54)); large source, highly relevant; included in the quantification of uncertainty.

2.4.2.5.2. Quantification of uncertainty The uncertainty attached to the estimates of the average annual gross and net emissions or removals from Forest Plantation management was assessed in an MC simulation. In the MC simulation the same estimators were used as in Section 2.4.2.2 and Section 2.4.2.3. The number of MC runs was $\mathcal{R} = 4 \times 10^4$. The estimates $\hat{\theta}_{ECem}$, $\hat{\theta}_{ECHem}$, $\hat{\theta}_{ECSem}$, $\hat{\theta}_{ECrm}$, $\hat{\theta}_{ECHrm}$, $\hat{\theta}_{ECSrm}$, $\hat{\theta}_{EC}$, $\hat{\theta}_{ECH}$, and $\hat{\theta}_{ECS}$ were, thus, estimated $\mathcal{R}$ times. The following inputs were not treated as fixed as in Section 2.4.2.2 and Section 2.4.2.3, but were drawn randomly from PDFs defined below.

$BCEF_{HW,R}$ The $BCEF_{HW,R}$ was sampled from a Triangular distribution with lower bound $a = BCEF_{HW,R} - BCEF_{HW,R} \times 0.25$, upper bound $b = BCEF_{HW,R} + BCEF_{HW,R} \times 0.25$, and mode $c = BCEF_{HW,R}$.

R_{wl} The R_{wl} was sampled from a Triangular distribution with lower bound $a = R_{wl} - R_{wl} \times 0.25$, upper bound $b = R_{wl} + R_{wl} \times 0.25$, mode $c = R_{wl}$.

$MAIV_{HW}$ The $MAIV_{HW}$ was sampled from a Triangular distribution with lower bound $a = MAIV_{HW} - MAIV_{HW} \times 0.25$, upper bound $b = MAIV_{HW} + MAIV_{HW} \times 0.25$, mode $c = MAIV_{HW}$.

$BCEF_{HW,I}$ The $BCEF_{HW,I}$ was sampled from a Triangular distribution with lower bound $a = BCEF_{HW,I} - BCEF_{HW,I} \times 0.25$, upper bound $b = BCEF_{HW,I} + BCEF_{HW,I} \times 0.25$, mode $c = BCEF_{HW,I}$.

$A_{HW,PL}$ To obtain random draws of the area planted in the years 2006 to 2010, $z = 10$ realizations were drawn from a Uniform distributions with lower bound $a = 0$ and upper bound $b = 3050.3$, where b is the entire area planted between 2001 and 2010. The z draws are denoted by $A^*_{HW,PL,k}$, where k indexes the z draws. To prevent that the sum of $A^*_{HW,PL,k}$ exceeds b, the values $A^*_{HW,PL,k}$ were multiplied by

$$A^{*\prime}_{HW,PL,k} = [A^*_{HW,PL,k} \times b] / [\sum_{k=1}^{10} A^*_{HW,PL,k}].$$

Five out of the z values of $A^{*\prime}_{HW,PL,k}$ were randomly drawn and used as input for $A_{HW,PL}$ for the years 2006 to 2010.

λ_{Pine}	Values of λ_{Pine} were drawn from a Normal distribution with $\mu = \lambda_{Pine}$ and $\sigma^2 = [\lambda_{Pine} \times 0.1]^2$ [Waterloo, 1994].
$\rho Pine$	Values of ρ_{Pine} were drawn from a Normal distribution with $\mu = \rho_{Pine}$ and $\sigma^2 = 0.0031$ (σ^2 was estimated from data provided in Cown [1981]).
R_{dlh}	R_{dlh} was sampled from a Triangular distribution with lower bound $a = 0.22$, upper bound $b = 0.33$, mode $c = 0.24$; a, b and c were taken from IPCC [2006, Vol. 4, Chap. 4, Tab. 4.4].
$MAIB_{SW}$	$MAIB_{SW}$ was sampled from a Triangular distribution with lower bound $a = MAIB_{SW} - MAIB_{SW} \times 0.25$, upper bound $b = MAIB_{SW} + MAIB_{SW} \times 0.25$, mode $c = MAIB_{SW}$.
CC_{SW}	CC_{SW} was sampled from a Triangular distribution with lower bound $a = CC_{SW} - 5$, upper bound $b = CC_{SW} + 5$, mode $c = CC_{SW}$.

The MC simulation delivered $\mathcal{R}$ MC estimates of $\hat{\theta}_{ECem}$, $\hat{\theta}_{ECHem}$, $\hat{\theta}_{ECSem}$, $\hat{\theta}_{ECrm}$, $\hat{\theta}_{ECHrm}$, $\hat{\theta}_{ECSrm}$, $\hat{\theta}_{EC}$, $\hat{\theta}_{ECH}$, and $\hat{\theta}_{ECS}$. The $Q(0.05)$ and $Q(0.95)$ quantiles of the empirical PDF of MC estimates were used to derive upper and lower 90%-confidence limits.

3. Fiji's Forest Reference Level 2006-2016

3.1. Average annual gross emissions

Fiji's Forest Reference Level (FRL) is estimated as the sum of gross emissions and gross removals generated over the Reference Period. Gross emissions have a positive sign $(+)$, gross removals have a negative sign $(-)$. Net emissions are computed as the sum of gross emissions and gross removals. The sources of emissions included in Fiji's FRL are: (i) emissions from deforestation, (ii) emissions from logging in Natural Forest ('forest degradation'), (iii) emissions from biomass burning ('forest degradation), (iv) emissions from logging in Forest Plantations. Gross emissions were computed as follows.

Equation 3.1: Average annual gross emissions

$$\hat{\theta}_{em} = \hat{\theta}_{DF} + \hat{\theta}_{FDem} + \hat{\theta}_{ECem}$$

$\hat{\theta}_{em}$ = Overall average annual gross emissions; $tCO_2e\ yr^{-1}$
$\hat{\theta}_{DF}$ = Average annual emissions from deforestation; $tCO_2e\ yr^{-1}$
$\hat{\theta}_{FDem}$ = Average annual gross emissions from forest degradation. Includes emissions from logging in Natural Forest, $\hat{\theta}_{FDLem}$ and emissions from biomass burning in Softwood Plantations (fire), $\hat{\theta}_{FDBem}$; $tCO_2e\ yr^{-1}$
$\hat{\theta}_{ECem}$ = Average annual gross emissions from timber extraction in Forest Plantations (Hard- and Softwood Plantations); $tCO_2e\ yr^{-1}$

3.2. Average annual gross removals

Gross removals include removals from (i) re-growth after logging in Natural Forest, (ii) removals from afforestation/reforestation, as well as removals from (iii) (re-)growth in Forest Plantations. Gross removals were computed as follows:

Equation 3.2: Average annual gross removals

$$\hat{\theta}_{re} = \hat{\theta}_{FDre} + \hat{\theta}_{ECre}$$

$\hat{\theta}_{re}$ = Overall average annual gross removals; $tCO_2e\ yr^{-1}$
$\hat{\theta}_{FDre}$ = Average annual gross removals after logging in Natural Forest (i.e., re-growth after logging); $tCO_2e\ yr^{-1}$
$\hat{\theta}_{ECre}$ = Average annual gross removals from afforestation/reforestation and growth in Hard- and Softwood Plantations; $tCO_2e\ yr^{-1}$

3.3. Average annual net emissions

Fiji's FRL is computed as the sum of gross emissions and gross removals from all sources and sinks, respectively.

Equation 3.3: Average annual net emissions (FRL)

$$\hat{\theta}_{FRL} = \hat{\theta}_{em} + \hat{\theta}_{re}$$

$\hat{\theta}_{FRL}$ = Overall average annual net emissions over the Reference Period in the Accounting Area, i.e., the Forest Reference Level (FRL); $tCO_2e \ yr^{-1}$

$\hat{\theta}_{em}$ = Average annual gross emissions (including all sources); $tCO_2e \ yr^{-1}$

$\hat{\theta}_{re}$ = Average annual gross removals (including all sinks); $tCO_2e \ yr^{-1}$

A summary of Fiji's FRL, including all sources and sinks of gross emissions and removals, is provided in Table 3.1.

Table 3.1.: Fiji's Forest Reference Level (FRL). All estimates in $tCO_2e \ yr^{-1}$. $\hat{\theta}$ = estimated emissions/removals for each (sub-)source/(sub-)sink; L90%-CI = lower bound of the 90% confidence interval; U90%-CI = upper bound of the 90% confidence interval.

	Estimate $\hat{\theta}$	L90%-CI	U90%-CI
Gross emissions			
Deforestation $\hat{\theta}_{DF}$	2,696,830.64	2,043,841.47	3,254,111.33
Forest degradation (logging) $\hat{\theta}_{FDLem}$	195,316.10	167,281.73	222,984.02
Forest degradation (fire) $\hat{\theta}_{FDBem}$	157,487.87	99,096.51	221,046.42
Forest Plantations $\hat{\theta}_{ECHSem}$	596,194.92	513,791.56	701,521.35
Sum $\hat{\theta}_{em}$	3,645,829.52	2,985,511.68	4,220,211.23
Gross removals			
Forest degradation (logging) $\hat{\theta}_{FDLre}$	-42,361.61	-57,253.99	-27,642.94
Afforestation/reforestation $\hat{\theta}_{ECAR}$	-327,540.86	-472,584.20	-201,679.47
Forest Plantations $\hat{\theta}_{ECHSre}$	-1,639,123.14	-2,027,492.88	-1,293,993.00
Sum $\hat{\theta}_{re}$	-2,009,025.61	-1,636,284.92	-2,419,481.02
Net emissions			
Deforestation $\hat{\theta}_{DF}$	2,696,830.64	2,043,841.47	3,254,111.33
Forest degradation $\hat{\theta}_{FD}$	310,442.36	322,692.65	468,185.04
Enhancement $\hat{\theta}_{EC}$	-1,370,469.09	-975,957.44	-1,780,860.02
Sum of net emissions (FRL) $\hat{\theta}_{FRL}$	1,636,803.91	851,765.31	2,317,968.28

Bibliography

Anonymous, 2005. Fiji National Forest Inventory: Standard Operation Procedures.

Chave, J., Andalo, C., Brown, S., Cairns, M., Chambers, J., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T. *et al.*, 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*, 145(1):87–99.

Chave, J., Coomes, D., Jansen, S., Lewis, S.L., Swenson, N.G. & Zanne, A.E., 2009. Towards a worldwide wood economics spectrum. *Ecology Letters*, 12(4):351–366.

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C. *et al.*, 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology*, 20(10):3177–3190.

Cown, D., 1981. Wood density of Pinus caribaea var. hondurensis grown in Fiji. *New Zealand Journal of Forestry Science*, 11(3):244–253.

Efron, B., 1979. Bootstrap methods: Another look at the jackknife. *The Annals of Statistics*, 7(1):1–26.

ER-PD, 2019. Emission Reductions Program Document (ER-PD). Ministry of Forestry, Republic of Fiji, Forest Carbon Partnership Facility (FCPF), Carbon Fund.

ER-PIN, 2016. Emission Reductions Program Idea Note (ER-PIN). Submitted to the Forest Carbon Partnership Facility (FCPF) / Carbon Fund by the Republic of Fiji.

FAO, 2004. Global Forest Resources Assessment (FRA) 2005: Terms and Definitions. Forest Resources Assessment Programme, Working Paper 83/E.

FRA-Fiji, 2015. FRA 2015 Country Reports: Republic of Fiji. Global Forest Resources Assessment (FRA) 2015, Food and Agricultural Organization of the United Nations (FAO), Rome, Italy.

Haas, M., 2015. Carbon Emissions from Forest Degradation caused by Selective Logging in Fiji. Regional project Climate Protection through Forest Conservation in Pacific Island Countries, GIZ, SPC.

Hosmer, Jr, D.W. & Lemeshow, S., 1989. *Applied logistic regression*. John Wiley & Sons, New York.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. The Intergovernmental Panel on Climate Change (IPCC), IGES, Hayama, Japan.

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

McRoberts, R.E. & Westfall, J.A., 2014. Effects of uncertainty in model predictions of individual tree volume on large area volume estimates. *Forest Science*, 60(1):34–42.

MoF, 2013. Fiji forest harvesting code of practice. Ministry of Fisheries & Forests. 2nd ed., Suva, Fiji.

MPI, 2011. Fiji REDD-Plus Policy: reducing emissions from deforestation and forest degradation in Fiji. Ministry of Primary Industries (MPI), Fiji Forestry Department and Secretariat of the Pacific Community, Suva, Fiji.

Mueller-Dombois, D. & Fosberg, F.R., 1998. *Vegetation of the tropical Pacific islands.* Ecological Studies. Springer Science, New York, USA.

Olofsson, P., Foody, G.M., Herold, M., Stehman, S.V., Woodcock, C.E. & Wulder, M.A., 2014. Good practices for estimating area and assessing accuracy of land change. *Remote Sensing of Environment*, 148:42–57.

Pearson, T.R., Brown, S. & Casarim, F.M., 2014. Carbon emissions from tropical forest degradation caused by logging. *Environmental Research Letters*, 9(3):034017.

Phillips, O.L., Malhi, Y., Vinceti, B., Baker, T., Lewis, S.L., Higuchi, N., Laurance, W.F., Vargas, P.N., Martinez, R.V., Laurance, S. *et al.*, 2002. Changes in growth of tropical forests: evaluating potential biases. *Ecological Applications*, 12(2):576–587.

R Core Team, 2019. *R: A Language and Environment for Statistical Computing.* R Foundation for Statistical Computing, Vienna, Austria.

Rejou-Mechain, M., Tanguy, A., Piponiot, C., Chave, J. & Herault, B., 2017. Biomass: an R package for estimating above-ground biomass and its uncertainty in tropical forests. *Methods in Ecology and Evolution*, 8(9).

Rounds, I., 2013. Baseline carbon assessment of talasiga grassland vegetation of REDD+ pilot site, Emalu. Draubuta, Navosa.

Särndal, C.E., Swensson, B. & Wretman, J., 1992. *Model Assisted Survey Sampling.* Springer Series in Statistics. Springer, New York, 2 edition.

Waterloo, M., 1994. *Water and Nutrient Dynamics of Pinus caribaea plantation forests on former grassland soils in Southwest Viti Levu, Fiji.* Ph.D. thesis, Vrije Universiteit Amsterdam.

Zanne, A., Lopez-Gonzalez, G., Coomes, D., Ilic, J., Jansen, S., Lewis, S., Miller, R., Swenson, N., Wiemann, M. & Chave, J., 2009. Data from: Towards a worldwide wood economics spectrum. Dryad Digital Repository.

Zomer, R.J., Trabucco, A., Bossio, D.A. & Verchot, L.V., 2008. Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. *Agriculture, ecosystems & environment*, 126(1):67–80.

A. Emissions from deforestation

A.1. Activity data

The methods used to produce the land-cover change map for Fiji's FRL are described in Annex 8.2 of Fiji's ER-PD [2019]. Annex 8.2 also provides information on how the data for the accuracy assessment (AA) were collected. In this section, information is provided on how the data collected were used to estimate areas of deforestation and afforestation/reforestation (AR). Areas were estimated for the following classes (see also Table 2.1 on page 13):

111	Natural Forest (1) remaining Natural Forest (1); Lowland (1)
112	Natural Forest (1) remaining Natural Forest (1); Upland (2)
171	Natural Forest (1) converted to Non-Forest (7); Lowland (1)
172	Natural Forest (1) converted to Non-Forest (7); Upland (2)
711	Non-forest (7) converted to Natural Forest (1); Lowland (1)
712	Non-forest (7) converted to Natural Forest (1); Upland (2)
777	Non-forest (7) remaining Non-forest (7); Low- or Upland (7)

To estimate areas of deforestation (171 and 172) and afforestation/reforestation (711 and 712), the methods proposed by Olofsson *et al.* [2014] were used.

The total area mapped is $A = 1,503,213$ ha. A is calculated as the sum of the areas mapped for the individual classes A_i (see above and column A_i in Table A.1). The area weight of class i is calculated using Equation (A.1).

Equation A.1: Area weights of map classes

$$W_i = \frac{A_i}{A},$$

W_i = Area weight of class i
A_i = Area mapped as class i; ha
A = Total area mapped; ha

The AA sample was collected as follows (details are provided in Annex 8.2 in ER-PD [2019]). Stratified simple random sampling was used, where the mapped classes served as strata. Within each stratum, n_i sample points were randomly and independently selected (in total $\sum_i n_i = n = 1948$ sample points). The number of sample points within the strata are provided in column n_i in Table A.1. At each sample point location the mapped class and the reference ("true") class was assessed. A simple cross tabulation

of the reference and map class is called the error (or confusion) matrix. For a perfect map without errors all observations would lie on the diagonal, i.e., the reference and map class match for all points. The error matrix used for Fiji's FRL is shown in Table A.1.

Table A.1.: Error matrix of sample counts (reference classes in columns, mapped classes in rows). The total sample size is $\sum_i n_i = n = 1948$; $W_i = A_i / \sum_i A_i$; A_i is the area mapped as class i [ha].

| | | Reference class | | | | | | | | | |
		111	112	171	172	711	712	777	n_i	A_i [ha]	W_i
Mapped class	111	218	0	14	0	8	0	8	248	670,300	0.4459115
	112	0	232	0	7	0	3	2	244	229,098	0.1524053
	171	68	0	137	0	6	0	22	233	54,406	0.0361931
	172	0	77	0	141	0	8	28	254	9,834	0.0065422
	711	81	0	7	0	144	0	21	253	33,742	0.0224468
	712	0	88	0	9	0	121	18	236	3,489	0.0023212
	777	13	21	12	14	7	7	406	480	502,344	0.3341799
	Total	380	418	170	171	165	139	505	1,948	1,503,213	1.0000000

The error matrix in Table A.1 shows sample counts. Sample counts are converted to area proportions using Equation (A.2).

Equation A.2: Area proportions (error matrix)

$$\hat{p}_{ij} = W_i \frac{n_{ij}}{n_{i\cdot}},$$

$\hat{p}_{ij}$ = Estimated area proportion for map class i and reference class j
W_i = Area weight of class i (see Equation (A.1))
n_{ij} = Sample count for map class i and reference class j
$n_{i\cdot}$ = Row sum of sample counts of map class i

Table A.2.: Error matrix of estimated area proportions (reference classes in columns, mapped classes in rows). $p_{i\cdot} = W_i$ gives the row sum of class i; A_i is the area [ha] mapped as class i.

| | | Reference | | | | | | | | |
		111	112	171	172	711	712	777	$p_{i\cdot}$	A_i [ha]
Map	111	0.3920	0.0000	0.0252	0.0000	0.0144	0.0000	0.0144	0.4459	670,300
	112	0.0000	0.1449	0.0000	0.0044	0.0000	0.0019	0.0012	0.1524	229,098
	171	0.0106	0.0000	0.0213	0.0000	0.0009	0.0000	0.0034	0.0362	54,406
	172	0.0000	0.0020	0.0000	0.0036	0.0000	0.0002	0.0007	0.0065	9,834
	711	0.0072	0.0000	0.0006	0.0000	0.0128	0.0000	0.0019	0.0224	33,742
	712	0.0000	0.0009	0.0000	0.0001	0.0000	0.0012	0.0002	0.0023	3,489
	777	0.0091	0.0146	0.0084	0.0097	0.0049	0.0049	0.2827	0.3342	502,344
	Total	0.4188	0.1624	0.0554	0.0178	0.0330	0.0081	0.3045	1.0000	1,503,213

The column sums of the error matrix showing estimated proportions (row 'Total' in Table A.2), represent the estimated area proportions, $\hat{p}_{\cdot j}$.

Equation A.3: Estimated proportions of land-cover classes

$$\widehat{p}_{\cdot j} = \sum_{i=1}^{q} \widehat{p}_{ij},$$

$\widehat{p}_{\cdot j}$ = Estimated area proportion of class j
$\widehat{p}_{ij}$ = Estimated area proportion of map class i and reference class j, where
$\quad\quad 1, 2, \dots, i, \dots, q$ is the set of the $q = 7$ change classes.

Area estimates of the classes are obtained by multiplying the estimated area proportion of a class by the total area mapped, A. These area estimates were used as activity data AD for the source deforestation, i.e., $\widehat{A}_{171}$ and $\widehat{A}_{172}$, and the sub-sink afforestation/reforestation, i.e., $\widehat{A}_{711}$ and $\widehat{A}_{712}$ (see Section 2.2.2 and Section 2.4.1).

Equation A.4: Area estimates of land-cover classes

$$\widehat{A}_{j} = A \times \widehat{p}_{\cdot j},$$

$\widehat{A}_{j}$ = Estimated area of class j; ha
A = Total area mapped; ha
$\widehat{p}_{\cdot j}$ = Estimated area proportion of class j

Olofsson *et al.* [2014] provides estimators to estimate the standard errors of the area estimates, $\widehat{A}_{j}$. For the FRL a different approach was selected to estimate the uncertainty of the area estimates of deforestation and afforestation/reforestation. The reason for using a different approach was that area estimates were combined with emission factor estimates in Monte Carlo simulations (see Appendix C).

Uncertainty analysis: activity data (AD) deforestation

B$_{ADDF}$.1 From the original AA sample, a sample, S_i^*, was drawn independently from each of the q strata using simple random sampling with replacement (SRSwR). The union of the q samples drawn independently in the q strata is denoted by S^*. The number of observations drawn from each stratum was the same as in the original AA sample, i.e., $n_i^* = n_i$.

B$_{ADDF}$.2 An error matrix was derived from S^* and Equation (A.2) to Equation (A.3) were used to obtain an estimate of $\widehat{A}_j^*$.

B$_{ADDF}$.3 Step B$_{ADDF}$.1 to B$_{ADDF}$.2 were repeated $\mathcal{R} = 4 \times 10^4$ times, delivering $\mathcal{R}$ estimates of $\widehat{A}_j^*$, i.e., $\widehat{\mathbf{A}}_j^* = \{\widehat{A}_{j,1}^*, \widehat{A}_{j,2}^*, \dots, \widehat{A}_{j,r}^*, \dots, \widehat{A}_{j,\mathcal{R}}^*\}$.

B$_{ADDF}$.4 Lower and upper bounds of the confidence interval of $\widehat{A}_j$ were obtained as described in Appendix C.

A.2. Emission factors

A.2.1. Fiji's National Forest Inventory 2006

Carbon stocks in Natural Forest were estimated based on data collected during Fiji's National Forest Inventor (NFI) 2006. The estimates obtained were used as input for $C_{BEFORE,i}$ in Equation (2.5) (ff.) on page 15. The methods used to derive estimates of C stocks in Low- and Upland Natural Forest and associated estimates of precision are described in the following sections.

A.2.2. Population of interest and sampling design

The population of interest for Fiji's NFI 2006 was defined by a forest cover map produced in 2001 by the Fiji South Pacific Applied Geoscience Commission (SOPAC). The area mapped as Natural Forest in 2001 defined the study population. Forest plantations (i.e., Hardwood and Softwood Plantations managed by FHCL and FPL, respectively) and areas covered by mangrove were excluded and were not assessed during the NFI 2006. The 2001 map showing the area of Natural Forest depicted two forest classes within Natural Forest, namely closed forest and open forest. To differentiate between closed and open forest, unsupervised classification techniques were used. No documentation has been made available that details how the unsupervised classification was conducted.

The sampling design used for the NFI 2006 was a stratified simple random sampling design were the mapped classes closed and open forest served as strata. Strata sizes were $A_{closed} = 697624$ ha and $A_{open} = 227984$ ha. The total area covered by the NFI 2006 was $A_{NFI} = 925609$ ha. Strata weights were

---

Equation A.5: NFI 2006 strata weights

$$W_{closed} = \frac{A_{closed}}{A_{NFI}} = 0.754; \qquad W_{open} = \frac{A_{open}}{A_{NFI}} = 0.246.$$

The number of observations in the strata closed and open forest were $n_{closed} = 731$ and $n_{open} = 292$, respectively. The total sample size was $n = 1023$. Sample plot locations were randomly placed within the strata in a geographic information system (GIS).

A.2.3. Plot design

Cluster plots with five nested circular cluster sub-plots were used for the NFI 2006 (Figure A.1; left). On the large sub-plot circle with radius $r_1 = 11.28$ m ($a_{r_1} = 400$ m^2), the diameter at breast height (DBH; the tree bole diameter at 1.3 m above ground recorded in cm using a diameter tape) and species was recorded on all living trees with ≥ 20 cm DBH. On the circle with radius $r_2 = 5.64$ m ($a_{r_2} = 100$ m^2), the DBH and species was recorded on all trees ≥ 5 cm and < 20 cm DBH. An the smallest circle with radius $r_3 = 1.78$ trees > 1.3 m height were counted and the DBH was not recorded. Data were collected by field teams between beginning of 2006 and end of 2007.
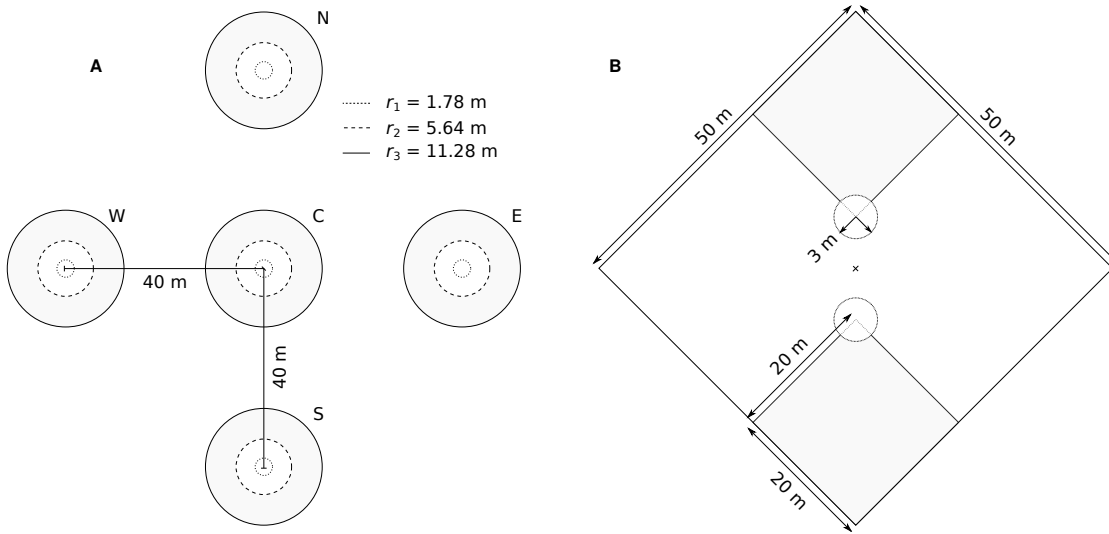
Figure A.1.: Design of the National Forest Inventory (NFI) 2006 plots (A; left) and plot design of Fiji's Permanent Sample Plot (PSP) program (B; right).

A.2.4. NFI 2006 data analysis

A.2.4.1. AGB of NFI 2006 trees

To predict the AGB of individual NFI 2006 trees, a biomass model (allometric equation) published in Chave *et al.* [2014] (Eq. 4) was used. A model from the literature was used, because no in-country biomass models are available in Fiji that allow for a nation-wide application. At the REDD+ pilot site at Nakavu, a biomass model has been developed in 2012; however, only 12 trees were used for model building and parameter estimation.

Before Eq. 4 from Chave *et al.* [2014] was selected to predict the AGB of individual trees, several other candidate models were considered (e.g., models found in Chave *et al.* [2005], Chave *et al.* [2014]). Because of lack of in-country data, the validity of the candidate models could not be verified. Initially, Equation 7 in Chave *et al.* [2014] was selected as the most promising candidate model, because total tree height was not measured during the NFI 2006 field campaigns and Eq. 7 provides a substitute for tree height (i.e., a so-called environmental stress factor enters the equation). However, when Eq. 7 from Chave *et al.* [2014] was tested on data collected during Fiji's Permanent Sample Plot (PSP) program, predicted tree AGB was much higher when using the environmental stress factor (as a substitute for trees height) compared to using the measured heights in Eq. 4 in Chave *et al.* [2014]. During the PSP heights of trees ≥ 10 cm DBH were recorded. It was found that the environmental stress factor assumes much taller trees compared to the heights measured during the PSP. The same holds true for Eq. II.5 Wet in Chave *et al.* [2005]. In the latter, tree height is not used as an input (only DBH and the wood density are used as inputs) but an inherent relationship between DBH, total tree height and AGB is assumed. It was, therefore, decided to use

the PSP data to derive a height model, predict the heights of NFI 2006 trees using the fitted model and than use Eq. 4 in Chave *et al.* [2014] to predict the AGB of NFI 2006 trees.

Equation A.6: Allometric equation taken from Chave *et al.* [2014]; Eq. 4

$$AGB_k = \beta_0(\rho_k h_k d_k^2)^{\beta_1} + \epsilon_k$$

---

where AGB_k is the biomass in kilograms of the kth tree, ρ_k is the wood density (defined as the oven-dry mass divided by green volume; g cm^{-3}), h_k is the total tree height [m], d_k is the DBH [cm], β_0 and β_1 are model parameters, and ϵ_k is the residual error term. Estimated model parameters are $\hat{\beta}_0 = 0.0673$ and $\hat{\beta}_1 = 0.976$ [Chave *et al.*, 2014, Eq. 4].

The data that were used by Chave *et al.* [2014] to derive the parameter estimates for Eq. 4 are publicly available on the web (Pan-tropical Tree Harvest Database; PTHD)[i]. The PTHD dataset was downloaded and the model (Equation (A.6)) was refitted to the data using non-linear generalized least squares (including a power variance function structure for the input variable DBH). The parameter estimates obtained slightly differ from those reported by Chave *et al.* [2014]: $\hat{\beta}_0' = 0.0632$ and $\hat{\beta}_1' = 0.978$. The reason for refitting Chave *et al.*'s [2014] Eq. 4 was that the AGB model (Equation (A.6)) was refitted several times during the Monte Carlo (MC) simulations using bootstrap samples from the PTHD. To ensure that the parameter estimates $\hat{\beta}_0'$ and $\hat{\beta}_1'$ and the average parameter estimates from the MC simulations are asymptotically equivalent, the parameter estimates from the refitted model were used to predict the AGB of individual NFI 2006 trees.

Missing tree heights of NFI 2006 trees were predicted using the PSP height model. Fiji's PSP program covers the entire REDD+ Accounting Area (systematic sample over the three islands Viti Levu, Vanua Levu and Taveuni). The number of sample plots that were used to fit the PSP height model was $n_{PSP}' = 84$. The PSP plot design is shown in Figure A.1 (right). On the large square 50×50 m, the DBH [cm], total tree height [m] and species was recorded on all living trees with DBH ≥ 25 cm. On the two 20×20 m subplots the DBH [cm], total tree height [m] and species was recorded on all living trees ≥ 5 cm and < 25 cm DBH. As only a single pine tree was recorded during the NFI, pine trees were removed from the PSP dataset before the height model was fitted to the data. After removing pine trees from the PSP dataset, the number of PSP plots reduced to $n_{PSP} = 82$. The number of PSP tree records in the first measurement round of the PSP program (2010) was $m_{PSP} = 5331$. These data were used to fit the PSP height model. The height model took the following simple form

---

Equation A.7: PSP height model

$$h_k = \beta_0 + \ln(d_k)\beta_1 + \epsilon_k$$

---

where $\ln(\cdot)$ denotes the logarithm. Model parameters were estimated at $\hat{\beta}_0 = -4.682$ and $\hat{\beta}_0 = 5.372$. The fit was rather poor with an $R^2 = 0.44$, however, this lack of fit

---

[i]Link: http://chave.ups-tlse.fr/pantropical_allometry.htm

was accounted for in the uncertainty analysis. Using Equation (A.7), the height of all $m = 76968$ NFI 2006 trees recorded was predicted.

Equation (A.6) requires the wood density of trees as input. Wood density, ρ, was extracted from a wood density database published by Chave *et al.* [2009] and Zanne *et al.* [2009]. If the density of a tree species recorded during the NFI 2006 was not available in the database, the average density of the genus was taken. If the genus was not in the database, the average wood density of the family was used and if the family was not in the database, the average wood density of all NFI 2006 trees for which the species, genus or family was available was used.

The AGB of individual NFI 2006 trees was finally predicted using

Equation A.8: Biomass model used to predict AGB of NFI 2006 trees

$$A\hat{G}B_k = 1000^{-1}[\hat{\beta}'_0(\hat{\rho}_k\hat{h}_k d_k^2)^{\hat{\beta}'_1}]$$

where $A\hat{G}B_k$ is the predicted AGB [t] of the kth NFI 2006 tree, $\hat{\rho}_k$ is the estimated wood density [g cm^{-3}], $\hat{h}_k$ is the predicted tree height [m], and d_k is the measured DBH [cm].

A.2.4.2. Plot level AGB

The AGB for an NFI 2006 plot was predicted by first aggregating the AGB of individual trees (predicted using Eq. (A.8)) at the different circle sizes

Equation A.9: Plot level AGB for circle size r_c

$$ABG'_{i,r_c} = \sum_{k=1}^{m_{i,r_c}} A\hat{G}B_k$$

where AGB'_{i,r_c} is the aggregated AGB [t] on the ith cluster plot on circles with radius r_c, with $c = \{1, 2\}$, m_{i,r_c} is the number of trees on the ith plot on circles with radius r_c, and $A\hat{G}B_k$ is given in Equation (A.8). The plot AGB was expanded to the hectare using the expansion factors

Equation A.10: NFI plot expansion factors for circle sizes r_1 and r_2

$$EF_{r_1} = [5 \times a_{r_1}]^{-1} \times 10000 = 5$$
$$EF_{r_2} = [5 \times a_{r_2}]^{-1} \times 10000 = 20$$

where $a_{r_1} = 400$ m^2, $a_{r_2} = 100$ m^2, and 10000 is the area of one hectare in m^2. The AGB ha^{-1} for circles with radius r_c for the ith NFI plot was computed by

Equation A.12: Plot level AGB ha^{-1} for circle size r_c

$$AGB_{i,r_c} = AGB'_{i,r_c} \times EF_{r_c}.$$

Total AGB [t ha^{-1}] (i.e., from the large and small circle) was computed for each plot by

---

Equation A.13: Total plot level AGB ha^{-1} of NFI 2006 plots

$$AGB_i = \sum_c AGB_{i,c}.$$

A.2.4.3. Plot level total biomass and carbon

Below-ground biomass (BGB) was estimated for each cluster plot using default values of root-to-shoot ratios R from IPCC [2006, Vol. 4, Chap. 4, Tab. 4.4]. The value of R used for an NFI 2006 cluster plot depended on the location of the central cluster sub-plot. If the plot was located ≥ 600 m above sea level (a.s.l.) the value of $R_u = 0.27$ was used (Tropical mountain systems). This decision was based on findings by Mueller-Dombois & Fosberg [1998], who identified significant changes in structural and floristic characteristics in forests in Fiji below and above approximately 600 m a.s.l. Mueller-Dombois & Fosberg [1998] found that above 600 m a.s.l. Fijian forests show characteristics typical for mountain forests systems, whereas forest located below 600 m a.s.l. show characteristics of either tropical rain forests or tropical moist deciduous forests.

According to IPCC [2006, Vol. 4, Chap. 3, Fig. 3.A.5.1], Fiji lies entirely within the tropical wet climatic zone. However, because of the southeast trade winds combined with the mountainous topography of Fiji, a pronounced windward-leeward effect can be observed in precipitation patterns. The southeastern side of the main islands receive about 3000 mm of rainfall per year, whereas leeward sides receive about 2000 mm per year or less [Mueller-Dombois & Fosberg, 1998]. The boundary between tropical rain forest and tropical most deciduous forest was first defined by the mean annual precipitation IPCC [2006, Vol. 4, Chap. 3, Fig. 3.A.5.2]. However, to allow for an even finer climatic zonation, the Aridity Index (AI; see Zomer *et al.* [2008]) was used to distinguish between areas of tropical rain forest and tropical most deciduous forest. For the AI a threshold value of 2 was selected after intensive expert consultation in Fiji (this decision was confirmed by the Fiji REDD+ Steering Committee). Table 2.10 (on page 27) and Figure A.2 provide an overview of the climatic and altitudinal zonation.

Based on the known NFI cluster plot location (i.e., the geographic coordinates of the center of the central cluster subplot), and the value of AI (extracted from a raster map[ii]) and the elevation at plot location (extracted from 90 m spatial resolution data from the Shuttle Radar Topography Mission [SRTM]), the appropriate value of R was selected for each cluster plot to compute the BGB from the estimated plot level AGB. Total biomass was obtained by

---

[ii]Available at: https://cgiarcsi.community/data/global-aridity-and-pet-database/
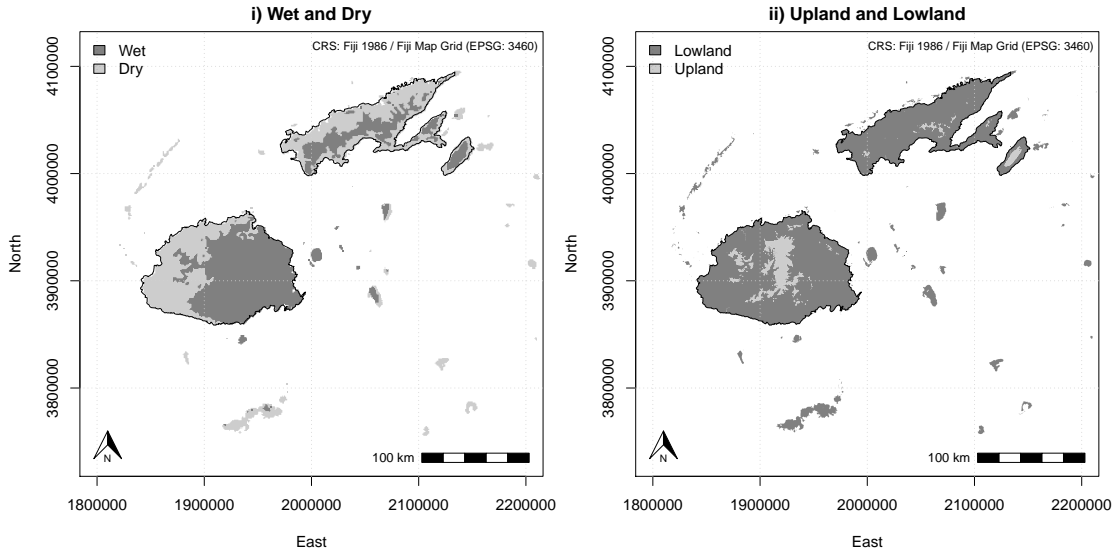
Figure A.2.: Climatic and altitudinal zonation used to select root-to-shoot ratios from IPCC [2006, Vol. 4, Chap. 4, Tab. 4.4]. See Table 2.10.

Equation A.14: Total plot level biomass ha^{-1} of NFI 2006 plots

$$TB_i = AGB_i \times (1 + R_i)$$

where TB_i is the total biomass [t ha^{-1}], AGB_i is given in Equation (A.13), and R_i depends on where a cluster plot is located and is selected based on the zonation given in Table 2.10. To compute total carbon for each NFI 2006 cluster plot, C_i [t ha^{-1}], TB_i was multiplied by the IPCC default value $\eta_{CF} = 0.47$ [IPCC, 2006, Vol. 4, Chap. 4, Tab. 4.3], i.e.,

Equation A.14: Total plot level carbon ha^{-1} of NFI 2006 plots

$$C_i = TB_i \times \eta_{CF}.$$

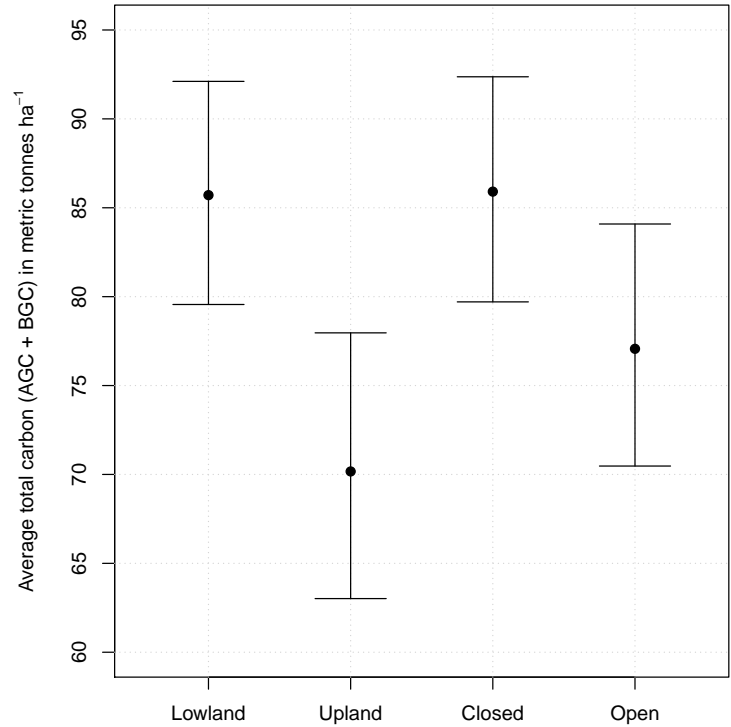### A.2.4.4. Carbon stocks in closed and open forest

For the NFI 2006, stratified sampling was used, where the two strata closed and open forest served as strata (see Appendix A.2.2). Although these two strata were not retained for the FRL, estimates of average C stocks in closed and open forest were estimated and are reported here in order to justify the division into the two *domains* Low- and Upland Natural Forest (see the subsequent section for why Low- and Upland Natural Forest are called "domains" here). Strata means of C [t ha^{-1}] in closed and open forest were computed by simply taking the average C ha^{-1} of plots in each stratum

71

Equation A.16: Average C ha^{-1} for the strata closed and open forest

$$\bar{C}_h = n_h^{-1} \sum_{S_h} C_i$$

---

where $\bar{C}_h$ is the average [t ha^{-1}] in stratum h, n_h is the sample size in stratum h, S_h denotes the set of sample plots in stratum h and C_i is the predicted C [t ha^{-1}] of the ith NFI plot. Note that for the strata closed and open forest the subscript h is used. Results of the analysis show that C stocks in closed and open forest did not differ significantly, i.e., confidence intervals overlap (see Figure A.3). However, this does not mean that C stocks in closed and open forest are not different in general, it simply means that no significant difference could be found between the two *strata* defined for the NFI 2006 design, likely because the separation between closed and open forest in the maps that were used for the stratification was poor. Figure A.3 shows the estimated average carbon stocks (TC = AGC + BGC) in the two NFI 2006 strata closed and open forest, as well as for Low- and Upland Natural Forest. The average C stock in closed forest was estimated at 88.01 (80.69; 91.31) tC ha^{-1}, and at 78.97 (71.49; 82.94) tC ha^{-1} in open forest.

Figure A.3: Estimated average total carbon stocks (TC = AGC + BGC) in t ha^{-1} in Low- and Upland Natural Forest and closed and open forest. Vertical bars give 90%-confidence intervals obtained from MC simulations.

A.2.4.5. Carbon stocks in Low- and Upland Natural Forest

For the analysis of the NFI 2006 data, the two "strata" Low- and Upland Natural Forest were treated as domains that cut across the two NFI strata closed and open forest (note

that Low- and Upland Natural Forest were not considered as strata in the NFI 2006 design). Moreover, only NFI 2006 plots that were located within the FRL Accounting Area were considered for the estimation of C stocks, i.e., the domains were Low- and Upland Natural Forest within the FRL Accounting Area. The four islands Kadavu, Gau, Koro and Ovalau were included in the NFI 2006, but are not part of the FRL Accounting Area. To estimate the average C [t ha^{-1}] for the two domains, the estimator for the domain mean for stratified sampling was used [Särndal *et al.*, 1992, page 349]

Equation A.17: Average C ha^{-1} for the domains Low- and Upland Natural Forest

$$\bar{C}_d = \sum_{h=1}^{H} \frac{N_h}{n_h} \sum_{S_{dh}} C_i \times \left[\sum_{h=1}^{H} \frac{N_h}{n_h} n_{S_{dh}} \right]^{-1}$$

---

where $\bar{C}_d$ is the average C [t ha^{-1}] in the dth domain (Low- or Upland Natural Forest within the FRL Accounting Area), H is the set of strata (closed and open forest), N_h is the strata size (A_{closed} and A_{open}), n_h is the sample size in stratum h, S_{dh} is the intersection of the sample plots in the dth domain and the sample plots drawn in stratum h, $n_{S_{dh}}$ is the random size of this intersection, and C_i is the C [t ha^{-1}] on the ith NFI plot. The sample sizes in the domains Low- and Upland Natural Forest were $n_{Lowland} = 903$ and $n_{Upland} = 120$. Note that in Equation (A.17), the subscript d was used for Low- and Upland Natural Forest and not the subscript i as in $C_{BEFORE,i}$. The subscript was changed to d to avoid confusion between the index of NFI plots, which are also index by i, and the domains Low- and Upland Natural Forest. In $C_{BEFORE,i}$ the subscript i is equivalent to the subscript d used in Equation (A.17). The average C stock in Lowland Natural Forest was estimated at 87.86 (171.3; 193.79) tC ha^{-1}, and at 71.57 (136.34; 163.03) tC ha^{-1} in Upland Natural Forest (see Table 2.4).

A.2.4.6. Uncertainty analysis

$C_{Lowland}$ and C_{Upland} were used as input for $C_{BEFORE,i}$ in Equation (2.6)). For the uncertainty analysis, MC simulations were used to estimate the uncertainty attached to $C_{Lowland}$ and C_{Upland} (see Equation (A.17)). Sources of uncertainty considered in the MC simulations included:

1. Measurement error (uncertainty in measurements of the DBH of trees);
2. Uncertainties in wood density estimates;
3. Modelling uncertainty (PSP height model and Chave *et al.*'s [2014] AGB model);
4. Uncertainty in root-to-shoot ratios (IPCC [2006] default values);
5. NFI 2006 sampling error.

The following algorithm outlines how the uncertainty attached to $C_{Lowland}$ and C_{Upland} was estimated within the MC framework:

Uncertainty analysis: emission factors (EF) deforestation

S$_{ED}$.1 To estimate the AGB of individual NFI 2006 trees, the DBH, total trees height and wood density was used as input (see Appendix A.2.4). The heights of rees recorded during the NFI 2006 were predicted using the following procedure:

S$_{ED}$.1.1 A bootstrap sample from the $n_{PSP} = 82$ PSP plots of size $n_{PSP}^* = n_{PSP}$ was drawn, using simple random sampling with replacement (SRSwR). The bootstrap sample is denoted by S_{PSP}^*. Trees in the bootstrap sample S_{PSP}^* are index by $1, 2, \ldots, j, \ldots, m_{PSP}*$, where m_{PSP}^* is the number of trees in S_{PSP}^*.

S$_{ED}$.1.2 A height model was fitted to the sample S_{PSP}^* using Equation (A.7) to obtain $\hat{\beta}_0^*$ and $\hat{\beta}_1^*$. The heights of trees in S_{PSP}^* were predicted using the fitted model. The fitted model is denoted by $f_{PSP,h}^*$ and the predicted heights are denoted by $\hat{h}_j^*$; h_j^* is the measured height of the jth tree in S_{PSP}^* and $\epsilon_{h,j}^* = h_j^* - \hat{h}_j^*$.

S$_{ED}$.1.3 The residual standard deviation of the predicted heights $\hat{h}_j^*$ was modeled using the procedure outlined in Hosmer & Lemeshow [1989]; McRoberts & Westfall [2014]: (1) the triplets $(\epsilon_{h,j}^*, h_j^*, \hat{h}_j^*)$ were ordered with respect to $\hat{h}_j^*$; (2) the ordered triplets were grouped to produce at least 10 groups but with group size not exceeding 25 observations; (3) for the gth group,

$$\bar{h}_g^* = \frac{1}{n_g} \sum_{j=1}^{n_g} h_j^*, \qquad \bar{\hat{h}}_g^* = \frac{1}{n_g} \sum_{j=1}^{n_g} \hat{h}_j^* \quad \text{and} \quad \sigma_{h,g}^{2*} = \frac{1}{n_g - 1} \sum_{j=1}^{n_g} \epsilon_{h,j}^{2*}$$

were calculated were n_g is the number of triplets in the gth group; (4) the association between $\sigma_{h,g}^*$ and $\bar{\hat{h}}_g^*$ was estimated using a liner model through the origin as

$$\hat{\sigma}_{h,g}^* = \hat{\gamma}_h^* \times \bar{\hat{h}}_g^*$$

where γ^* is a model parameter.

S$_{ED}$.1.4 The heights of the m trees recorded during the NFI 2006 were predicted using the height model $f_{PSP,h}^*$ from S$_{ED}$.1.2. To the predicted height an observation drawn from $\hat{\epsilon}_{h,k}^* \sim \mathcal{N}(0, [\hat{\gamma}_h^* \times \hat{h}_k]^2)$ was added, i.e., $\hat{h}_k' = \hat{h}_k + \hat{\epsilon}_{h,k}^*$, where $\hat{h}_k'$ is the predicted height of the mth NFI 2006 tree.

S$_{ED}$.2 The AGB of the m trees recorded during the NFI 2006 were predicted using the following procedure:

S$_{ED}$.2.1 A bootstrap sample of size m^*_{PTHD} was drawn from the PTHD dataset (see Appendix B.2) using SRSwR, where $m^*_{PTHD} = m_{PTHD}$ and $m_{PTHD} = 4004$ is the number of trees in the PTHD dataset. The bootstrap sample is denoted by S^*_{PTHD}. Trees in S^*_{PTHD} are index by $1, 2, ..., l, ..., m^*_{PTHD}$.

S$_{ED}$.2.2 A biomass model was fitted to S^*_{PTHD} using Equation (A.6) to obtain $\hat{\beta}^*_0$ and $\hat{\beta}^*_1$. The AGB of trees in S^*_{PTHD} was predicted using the fitted model. The fitted model is denoted by f^*_{PTHD} and the predicted AGB of the lth tree in S^*_{PTHD} is denoted by $\hat{AGB}^*_l$; AGB^*_l is the measured AGB of the lth tree in S^*_{PTHD} and $\epsilon^*_{AGB,l} = AGB^*_l - \hat{AGB}^*_l$.

S$_{ED}$.2.3 The residual standard deviation of the predicted AGB, i.e., $\hat{AGB}^*_l$ was modeled as in S$_{ED}$.1.3 above, substituting $\epsilon^*_{h,j}$ by $\epsilon^*_{AGB,l}$, h^*_j by AGB^*_l and $\hat{h}^*_j$ by $\hat{AGB}^*_l$ to obtain $\hat{\epsilon}_{AGB,k}$.

S$_{ED}$.2.4 The AGB of the kth NFI 2006 tree was predicted using f^*_{PTHD}. The input height h_k in f^*_{PTHD} was substituted by $\hat{h}'_k$ (see S$_{ED}$.1.4), d_k and ρ_k were substituted by

$$d'_k \sim \mathcal{N}(d_k, [d_k \times .1]^2) \qquad \text{and} \qquad \rho'_k \sim \mathcal{N}(\rho_k, s(\rho_k)^2)$$

where d'_k accounts for a constant 10% error in the DBH measurements of NFI 2006 trees [Phillips *et al.*, 2002]. The standard deviation of the wood density estimates, $s(\rho_k)$, which was used to obtain ρ'_k, was taken from Chave *et al.* [2009] and Zanne *et al.* [2009]. Hence,

$$\hat{AGB}'_k = \hat{\beta}^*_0 \times (\rho'_k d'^2_k \hat{h}'_k)^{\hat{\beta}^*_1}.$$

S$_{ED}$.3 C [t ha^{-1}] of the n NFI 2006 plots was estimated using Equation (A.12) to Equation (A.15). In Equation (A.12) the AGB of trees was substituted by the predicted AGB obtained from Equation (A.21). Root-to-shoot ratios were sampled from Triangular distributions (see IPCC [2006, Vol. 4, Chap. 4, Tab. 4.4], Table 2.10 and Appendix C.1.2)

$$R^*_{wl} = Tri(c = R_{wl}, a = R_{wl} - R_{wl} \times 0.25, b = R_{wl} + R_{wl} \times 0.25)$$
$$R^*_{dll} = Tri(c = R_{dll}, a = 0.09, b = 0.25)$$
$$R^*_{dlh} = Tri(c = R_{dlh}, a = 0.22, b = 0.33)$$
$$R^*_u = Tri(c = R_u, a = 0.269, b = 0.28)$$

where $R_{wl} = 0.37$, $R_{dll} = 0.2$, $R_{dlh} = 0.24$, and $R_u = 0.27$ (see IPCC [2006, Vol. 4, Chap. 4, Tab. 4.4]).

S$_{ED}$.4 Two independent bootstrap samples (SRSwR of size n_h) were drawn from the two strata h_{closed} and h_{open}, with sample sizes $n_{closed}^* = n_{closed}$ and $n_{open}^* = n_{open}$. The domain means of C [t ha^{-1}] were predicted for the domains Low- and Upland Natural Forest (within the FRL Accounting Area) using the estimator given in Equation (A.17).

S$_{ED}$.5 S$_{ED}$.1 to S$_{ED}$.4 were repeated $\mathcal{R} = 4 \times 10^4$ times, delivering $\mathcal{R}$ estimates of $\bar{C}_d$. That is, $\mathcal{R}$ estimates of $C_{BEFORE,i}$ were obtained which were used in subsequent MC simulations as input.

B. Data

B.1. Fiji's Permanent Sample Plot program

The primary purpose of initiating Fiji's Permanent Sample Plot (PSP) program was to obtain estimates of timber growth in Natural Forest to derive annual allowable cuts. It is intended that the program be continued for the next at least 25 years. For the PSP program, sample plots have been established on a systematic grid on Fiji's three largest islands Viti Levu, Vanua Levu and Taveuni. The grid size (i.e., the distance between adjacent sample plots) differs between the islands. On Viti Levu, for example, the grid size is 12×12 km, and on Taveuni 15×15 km. As of today, attributes of trees have been recorded on $n_{PSP} = 84$ plots in 2010, 2012, 2014, 2016, and 2018.

The layout of a PSP sample plot is shown in Figure A.1 (right) on page 67. Attributes of trees recorded on the plots included the DBH [cm], the total tree height [m] and the tree species, among other attributes. On a large squared sub-plot of size 50×50 m attributes on all trees ≥ 25 cm DBH were recorded. On two squared sub-plots of size 20×20 m, attributes were recorded on trees with DBH ≥ 10 cm and < 25 cm. On two circular plots (radius 3 m), attributes were recorded on trees with DBH ≥ 3 cm and < 10 cm. Data on litter and soil organic carbon (SOC) were also collected on the PSP plots in 2010, however, these data have not yet been processed in such a way that the data can be readily analyzed.

The PSP data collection procedures implemented suffer from several short-comings that prevent their use to estimate carbon stocks and stock changes in Fijian Natural Forests. During plot establishment in 2010, some plots were shifted off-grid from non-forest areas to nearby forest. Because of this procedure it is currently difficult to use the PSP data for the estimation of, e.g., forest biomass stocks in Fiji's Natural Forest. Moreover, the plot design was altered during data collection. The initial north-east/south-west orientation of the sub-plots was shifted to north-west/south-east if no or only few trees were found on the sub-plots in the original sub-plot arrangement. This procedure prevents that per hectare values of target variables can be estimated reliably, i.e., data from the 20×20 m sub-plots would have to be excluded, which would mean that all trees < 25 cm DBH would not be included. Lastly, the currently implemented technique to number individual trees does not allow to trace trees over time. Therefore, it is not possible to assess increments of individual trees.

The data from the PSP program were not used to estimate biomass and carbon stocks in Natural Forest. Tree data from the first round of the PSP program (2010) were used for the FRL to derive height models (Appendix A.2.4) which were used to predict the tree height of NFI 2006 trees. The number of PSP trees used for model fitting was $m_{PSP} = 5331$.

B.2. Pan-tropical tree harvest database

The pan-tropical tree harvest database (PTHD) provides data on $m_{PTHD} = 4004$ harvested trees (see Chave *et al.* [2014] for more information). The data were collected on 58 different sites around the tropics. For each tree the DBH (minimum DBH 5 cm) in centimeters, the total tree height in meters, the AGB in metric tonnes (oven-dry), and an estimate of the wood specific gravity in g cm^{-3} are available. The data are freely available on the internet[i]. The PTHD data were used to obtain parameter estimates for the biomass model used to predict the AGB of NFI 2006 trees and to quantify the uncertainty attached to predicted values of tree level AGB of NFI 2006 trees (see Appendix A.2.4).

B.3. Wood densities

Estimates of wood density, ρ, defined here as the oven-dry mass divided by green volume [g cm^{-3}], were taken from Chave *et al.* [2009] and Zanne *et al.* [2009] whenever a national estimate of the wood density was not available. The data used is freely available on the web[ii]. The data can also be extracted from the contributed R [R Core Team, 2019] package BIOMASS [Rejou-Mechain *et al.*, 2017]. Estimates of wood density were used as input in an allometric equations (see Equation (A.6)) to predict the AGB of NFI 2006 trees. The wood density database from Zanne *et al.* [2009] also provides estimated standard deviations for wood density estimates; these estimates were not available for national wood density estimates and standard deviations of estimates were, therefore, extracted from Zanne *et al.* [2009] for these species. The estimated standard deviation was used in Monte Carlo (MC) to quantify the uncertainty attached to predicted tree level AGB (Appendix A.2.4).

B.4. Logging data: Natural Forest

Records of harvested volumes from Natural Forest were provided by the Management Service Division (MSD) of the Fijian Ministry of Forests (MoF). In Fiji, commercial loggers have to apply for a logging licence if they plan to harvest timber from Natural Forest. Licences are issued by the MoF. Before a licence can be issued by the MoF, the logger has to submit a logging plan including a (digital) map of the area to be logged. Once a licence has been issued, trees have been felled and the timber has been hauled to the log-landings, timber scalers from the Divisional Forest Offices (DFOs) record the volumes extracted to determine the amount of royalty fees the logger has to transfer to the MoF. These volumes are entered into the Timber Revenue System (TRS) database. The data from the TRS served as the database to estimate emissions from commercial logging. Note that no data on commercial logging activities that escape official statistics (i.e., illegal logging awithout a licence) are available in Fiji. Moreover,

---

[i]Web: http://chave.ups-tlse.fr/pantropical_allometry.htm
[ii]Web: https://datadryad.org/resource/doi:10.5061/dryad.234

volumes logged by land-owners that use the wood for subsistence use (i.e., the timber is not sold on the markets) is also not recorded by the DFOs and no data are available on the activities. The data on logged timber collected by experienced log-graders and -scalers is generally considered to be of high quality. Occasionally, log-scalers may have missed stems (e.g., stems have been cut by a logging company but were not hauled to the landings). Therefore, there might be a small downwards "bias" of published volumes. Timber that was purposefully not hauled to the log landings is considered illegal logging, which is, because of lack of data, not covered in the FRL.

Unsustainable timber harvesting in Natural Forest is widespread in Fiji, even if wood is removed legally under a logging licence. It is assumed that current logging practices lead to a constant decline of carbon stocks in logged-over Natural Forests in Fiji. The logging statistics data were, therefore, used to estimate emissions from forest degradation. The digital maps on harvested areas from the logging plans provided by the loggers were used to determine the area of enhanced growth after logging. Currently limited data are available for volume and carbon increments in logged Natural Forests. For the FRL unpublished data from the REDD+ Pilot site at Nakavu were used to determine mean annual increments of carbon (0.99 tC ha^{-1} yr^{-1} including above- and below-ground biomass; Mussong, personal communication; September 2018).

B.5. Forest Plantations

B.5.1. Softwood Plantations

Data on softwood plantations (mostly *Pinus caribaea var. hondurensis* [Sénéclauze] W.H.Barrett & Golfari; Caribbean pine) were provided by Fiji Pine Limited (FPL) to the Fiji REDD+ Unit. FPL — a private company of which the Government of Fiji is the majority shareholder — currently manages a lease area of slightly more than 72,663 ha. FPL reported that about 49,503 ha of the lease area were stocked with pine trees on December 31, 2006. FPL is certified by Forest Stewardship Council (FSC).

For the FRL, FPL provided data on (i) harvested volumes [m^3] for the years 2006 to 2016, (ii) spatial data (vector polygons) on areas planted per year [ha], and (iii) areas harvested (vector polygons) between 2006 and 2016 [ha]. The data (i) and (ii) have been verified by MSD and MoF. Data on areas harvested were erroneous and could not be used for the FRL construction (e.g., the area reported as harvested in 2012 was zero hectare; however 158,214 m^3 of pine wood were harvested in 2012). Areas harvested between 2006 and 2016 were estimated from growth data and data on volumes harvested. The cutting cycle in pine plantations is currently 20 years.

Growth data on softwood plantations were not provided by FPL. These data were taken from Waterloo [1994], who reported average annual increments of 10 tB ha^{-1} yr^{-1} (including above- and below-ground biomass) for pine plantations in Fiji. Estimates of wood density of pine trees in Fiji were taken from Cown [1981] ($\rho_{Pine} = 0.47$ g cm^{-3}).

B.5.2. Hardwood Plantations

Data from hardwood plantations were provided by Fiji Hardwood Corporation Limited (FHCL). FHCL is currently managing a lease area of about 58,997 ha. Most of the lease area is stocked with *Swietenia macrophylla* KING (Honduran or big-leaf mahogany).

The data provided by FHCL included (i) data on volumes harvested [m^3] between 2006 and 2016, (ii) data on areas harvested [ha], (iii) data on areas planted [ha], and (iv) data on the mean annual increment (MAI) in mahogany plantations (6.3 m^3 ha^{-1} yr^{-1}). FHCL also provided values for the MAI for several other hardwood species and pine. However, by far greatest share of FHCL lease area is stock with mahogany; plantations of other species account for less than 15% of the area.

B.6. Aridity Index and SRTM

B.6.1. Aridity Index

An aridity index provides a numerical indicator of the dryness of the climate at a given location. For the FRL the Global Aridity Index (AI) [Zomer *et al.*, 2008] was used to differentiate between wet and dry areas. The information on the dryness was used to select appropriate values of root-to-shoot ratios (R) from IPCC [2006, Vol. 4, Chap. 4, Tab. 4.4]. A threshold value of 2 was used for the FRL (i.e., for $< 2 = $ dry; ≥ 2 wet; see Table 2.10). The threshold value was selected based on expert judgement (Fiji REDD+ Steering Committee; experts from the Ministry of Agriculture).

A raster map with spatial resolution at 30 arc seconds (~ 1 km at the equator) was downloaded from the web[iii]. The raster data were reprojected to Fiji Grid Map 1986 and were rescaled to a spatial resolution of 500 m.

B.6.2. Shuttle Radar Topography Mission

Digital elevation data from the Shuttle Radar Topography Mission (SRTM) were obtained from the CIGAR Consortium for Spatial Information[iv]. Similar to the AI (see Appendix B.6.1), the SRTM data were used to select appropriate values of R (see Table 2.10). SRTM data at a spatial resolution of 90 m were also used to differentiate between Lowland and Upland (i.e., Lowland and Upland Natural Forest).

[iii]Web: https://cgiarcsi.community/data/global-aridity-and-pet-database/
[iv]Web: http://srtm.csi.cgiar.org/

C. Uncertainty analysis

C.1. Monte Carlo simulations

C.1.1. General procedure

To quantify the uncertainty attached to the FRL estimate, Monte Carlo (MC) simulations were used. The MC simulations, outlined in the sections "Quantification of uncertainty" in Chapter 2 and in Appendix A.1 and A.2, delivered $\mathcal{R} = 4 \times 10^4$ MC estimates of target parameters. Here, θ_{FDem} is used as an example to illustrate how uncertainties were estimated for a target parameter (i.e., the average annual gross emissions from forest degradation; see Section 2.3.2.1). The set of the MC estimates of $\hat{\theta}_{FDem}$ is denoted by

$$\hat{\Theta}^*_{FDem} = \{\hat{\theta}^*_{FDem,1}, \hat{\theta}^*_{FDem,2}, \dots, \hat{\theta}^*_{FDem,r}, \dots, \hat{\theta}^*_{FDem,\mathcal{R}}\}.$$

The MC estimates in the set $\hat{\Theta}^*_{FDem}$ were estimated using random inputs for TEF (as described in Section 2.3.2.4.2 on page 25). The estimate of $\hat{\theta}_{FDem}$ that was reported for the FRL, is the estimate that is computed using Equation (2.14). The uncertainty that is reported for $\hat{\theta}_{FDem}$, i.e., its precision, is derived from the distribution of the $\mathcal{R}$ MC estimates. The distribution of the $\mathcal{R}$ estimates in $\hat{\Theta}^*_{FDem}$ is shown in Figure C.1. To obtain an estimate of the lower and upper limit of the 90%-confidence interval, the $Q(0.05)$ and $Q(0.95)$ quantiles were used (shown as dashed vertical lines in Figure C.1). Note that confidence limits around the parameter estimates do not necessarily have to be symmetrically when they are estimated from the quantiles of the MC distributions, e.g., the quantiles from $\hat{\Theta}^*_{FDem}$. This may hold true in particular if inputs in the MC simulation runs are sampled from non-symmetrical probability density functions (e.g., a non-symmetrical Triangular distribution; see Appendix C.1.2).

If estimates from two (independent) MC simulations are combined, for example $\hat{\theta}_{FDem}$ and $\hat{\theta}_{FDre}$, the set of combined estimates, $\hat{\theta}_{FD}$ (Section 2.3.2.3), is obtained as follows

$$\hat{\Theta}^*_{FD} = \{\hat{\theta}^*_{FDem,1} + \hat{\theta}^*_{FDre,1}, \dots, \hat{\theta}^*_{FDem,r} + \hat{\theta}^*_{FDre,r}, \dots \hat{\theta}^*_{FDem,\mathcal{R}} + \hat{\theta}^*_{FDre,\mathcal{R}}\}.$$

As for $\hat{\theta}_{FDem}$, the estimate that is reported for $\hat{\theta}_{FD}$ is the estimate computed by Equation (2.18). The uncertainty reported for $\hat{\theta}_{FD}$ is derived from the distribution of estimates in $\hat{\Theta}^*_{FD}$. For the MC simulations used to compute the uncertainty of the FRL estimate, outputs of individual MC simulations were assumed to be independent (i.e., no correlation was assumed between the combined inputs of the individual MC simulations). The methods used to combine estimates from independent MC simulations can be extended to any number of parameter estimates, given that $\mathcal{R}$ is the same for the independent MC simulations.
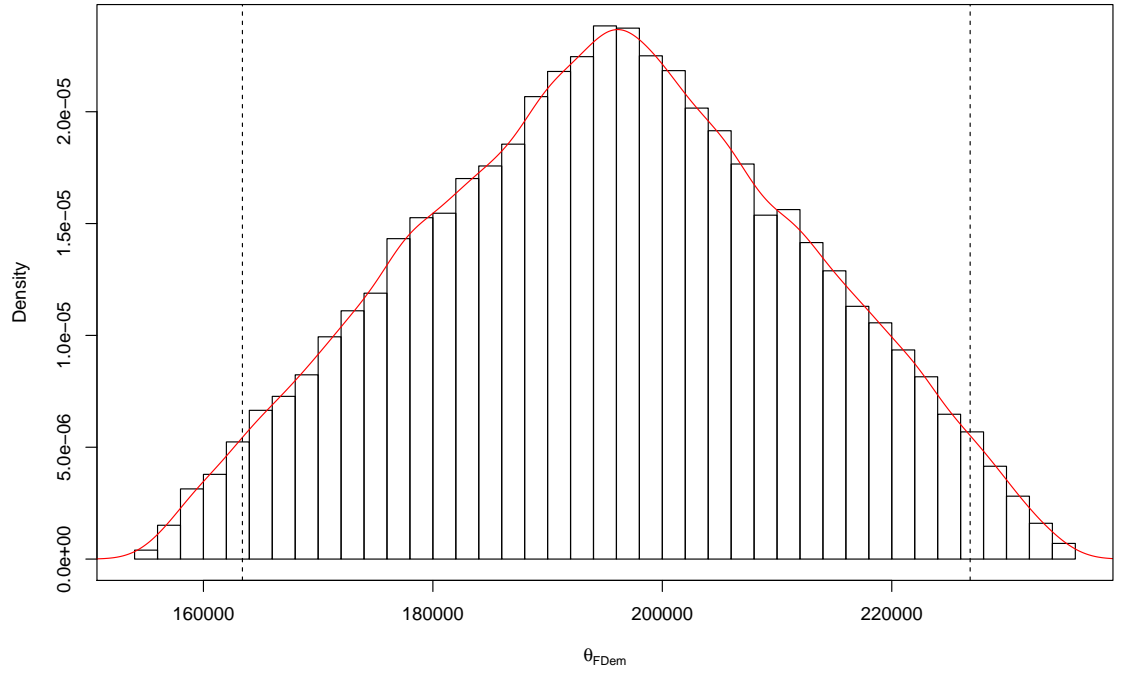
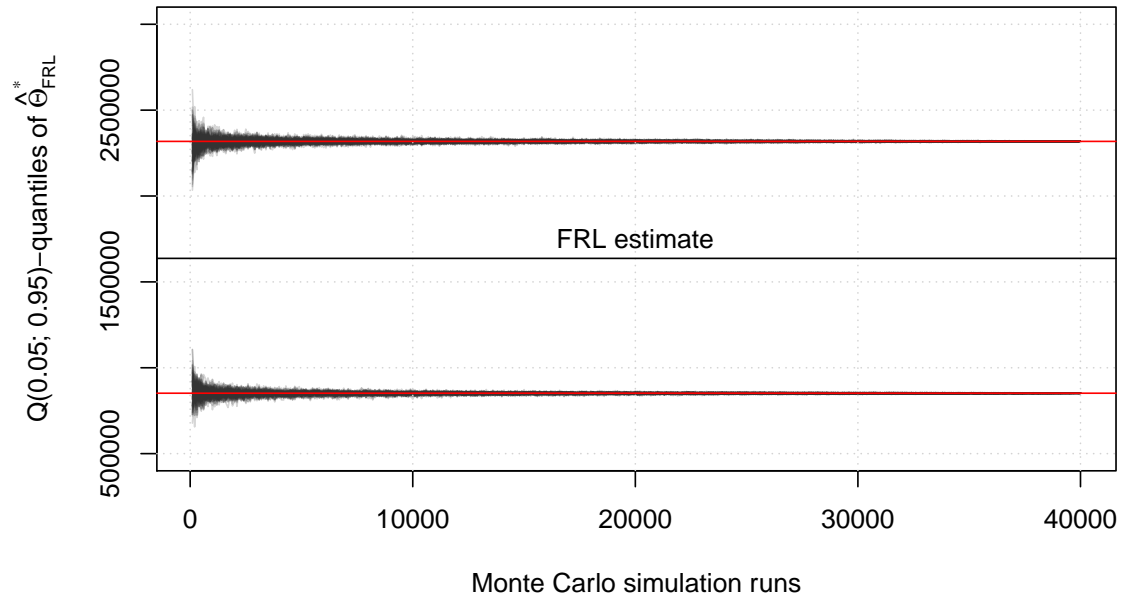Figure C.1.: Histogram of MC estimates of $\hat{\theta}^*_{FDem}$.

Figure C.2.: Convergence behavior of the lower $Q(0.05)$ and upper $Q(0.95)$ confidence limits for different numbers of Monte Carlo (MC) simulation runs $100, 200, ..., 40000$. The estimated FRL is shown as a solid horizontal line.

C.1.2. Distributions used for the MC simulations

For the MC simulations, inputs (as specified in the sections "Quantification of uncertainty" in Chapter 2) were sampled from different probability density functions (PDFs). The PDFs used for the uncertainty analysis of the FRL included the Normal (or Gaussian) distribution, the Triangular distribution, and the Uniform distribution.

The Normal distribution is described by its mean, μ, and its variance, σ^2. The notation used for the Normal distribution is $\mathcal{N}(\mu, \sigma^2)$. The Normal distribution was used for inputs when an estimate of the standard deviation, σ, for an input was available, e.g., for the wood density ρ to estimate the AGB of NFI trees.

For many inputs an estimate of the precision was not available, i.e., a value of the standard deviation or standard error was not reported by the study from which the estimate for the input was taken. However, for some inputs the range (lower and upper limits) and the mode was available (e.g., root-to-shoot ratios R that can be found in Vol. 4, Chap. 4, Tab. 4.4 in IPCC [2006]). For these inputs the Triagnular distribution was used. The Triagnular distribution is denoted by $Tri(c, a, b)$, where c is the mode (the peak of the Triagnular distribution; i.e., the most frequent value), a is the lower bound, and b is the upper bound.

The Triangular distribution was also used if no quantitative information at all was available for the uncertainty attached to the input. If the uncertainty was assumed to be "moderate" for an input, a was defined as $a = c - c \times \phi$ and $b = c + c \times \phi$, where $\phi = 0.25$. The value for c was the value reported for the input in IPCC [2006] or other studies. If the uncertainty was assumed to be "large" $\phi = 0.5$ and if "very large" $\phi = .75$. Whether the uncertainty attached to the input was "moderate", "large" or "very large" was determined by expert judgement (e.g., REDD+ Steering Committee or authors that conducted the study from which the value of the input was taken). If an expert's opinion was not available, $\phi = 0.75$ was used. It should be noted that the choice of whether the uncertainty of the parameter estimate of the input was moderate, large or very large was entirely subjective and was frequently taken without having sufficient data and information on the system under consideration. This highlights the fact that measures of uncertainty (i.e., standard errors) should be more rigorously assessed in future studies, given their profound influence on subsequent estimates of uncertainty.

The Uniform continuous distribution, $\mathcal{U}(a, b)$, was used in Section 2.4.2.5.2 to randomly sample areas planted in Hardwood Plantations, $A_{HW,PL,t}$. For the Uniform distribution the support is defined by a lower bound a and an upper bound b. All values within this range are assumed to be equally probable. Examples of the Normal, Triangular and Uniform distributions are shown in Figure C.3.

C.2. The non-parametric bootstrap

The non-parametric bootstrap [Efron, 1979] was frequently used to derive the sampling distribution of an estimators. Suppose a sample S of size n is drawn from a population U consisting of N elements. The value of a target variable y is observed on all elements in the sample S, but remains unknown $\forall k \in U - S$. Suppose the goal is to
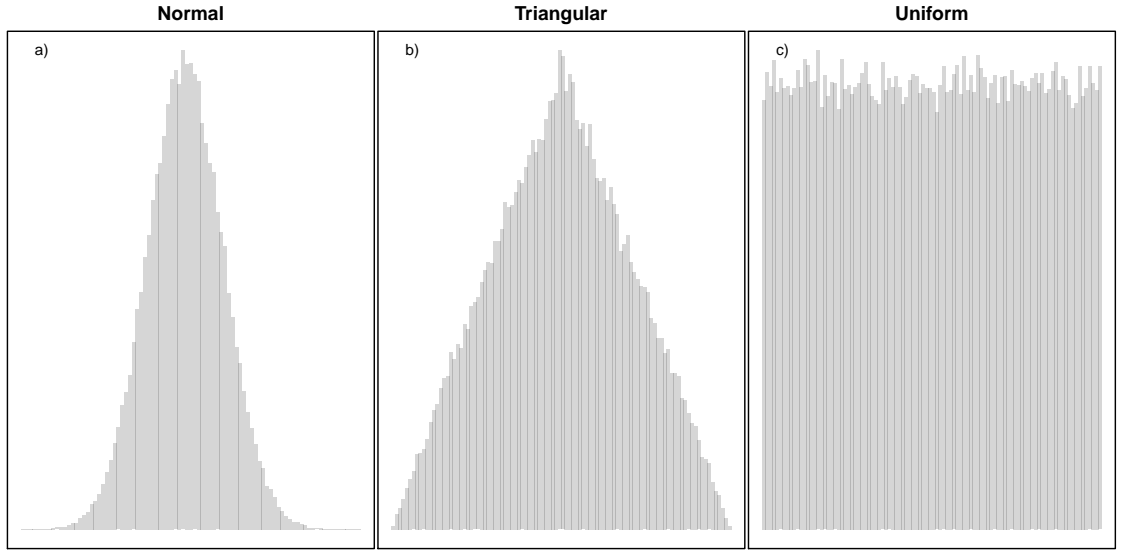
Figure C.3.: Examples of different distributions used for the MC simulations. a) Normal (Gaussian) distribution; b) Triangular distribution; c) Uniform distribution (results from 10000 random draws).

estimate the unknown population parameter $\mu_y = N^{-1} \sum_U y_k$, where $1, 2, ..., k, ..., N$ is an index of the population elements. The sample mean $\bar{y}$ is estimated from the sample, i.e., $\bar{y} = n^{-1} \sum_S y_k$, an provides an estimate of the unknown μ_y. The precision of $\bar{y}$ is estimated using the bootstrap. For the bootstrap, simple random sampling *with* replacement (SRSwR) is used to draw a sample S^* from S. The sample size of the bootstrap sample S^* is $n^* = n$. From the sample S^* the target parameter, i.e., $\bar{y}^*$, is estimated from the values of y in S^*. Samples are repeatedly drawn from S using SRSwR ($\mathcal{R}$ times), delivering $\mathcal{R}$ estimates of $\bar{y}^*$. The sampling distribution of the $\bar{y}^*$s is used to derive lower and upper confidence limits of $\bar{y}$. As for the MC estimates the $Q(0.05)$ and $Q(0.95)$-quantiles were used to obtain the 90%-confidence limits.

D. Software

This document was compiled using LaTeX. All analysis was conducted using the freely available language and environment for statistical computing and graphics R [R Core Team, 2019].

```
library("devtools")
sessioninfo::session_info()

## - Session info ------------------------------------------------------------
##  setting  value
##  version  R version 3.6.1 (2019-07-05)
##  os       Ubuntu 18.04.3 LTS
##  system   x86_64, linux-gnu
##  ui       X11
##  language en_US
##  collate  en_US.UTF-8
##  ctype    en_US.UTF-8
##  tz       Europe/Berlin
##  date     2019-10-18
##
## - Packages ----------------------------------------------------------------
##  package     * version  date       lib source
##  assertthat    0.2.1    2019-03-21 [1] CRAN (R 3.6.0)
##  backports     1.1.5    2019-10-02 [1] CRAN (R 3.6.1)
##  callr         3.3.2    2019-09-22 [1] CRAN (R 3.6.1)
##  cli           1.1.0    2019-03-19 [1] CRAN (R 3.6.0)
##  colorout    * 1.2-0    2018-09-25 [1] local
##  crayon        1.3.4    2017-09-16 [1] CRAN (R 3.6.0)
##  crul          0.8.4    2019-08-02 [1] CRAN (R 3.6.1)
##  curl          4.2      2019-09-24 [1] CRAN (R 3.6.1)
##  data.table  * 1.12.4   2019-10-03 [1] CRAN (R 3.6.1)
##  DBI           1.0.0    2018-05-02 [1] CRAN (R 3.6.0)
##  desc          1.2.0    2018-05-01 [1] CRAN (R 3.6.0)
##  devtools    * 2.2.1    2019-09-24 [1] CRAN (R 3.6.1)
##  digest        0.6.21   2019-09-20 [1] CRAN (R 3.6.1)
##  ellipsis      0.3.0    2019-09-20 [1] CRAN (R 3.6.1)
##  evaluate      0.14     2019-05-28 [1] CRAN (R 3.6.0)
##  filehash      2.4-2    2019-04-17 [1] CRAN (R 3.6.0)
##  foreign       0.8-72   2019-08-02 [1] CRAN (R 3.6.1)
##  fs            1.3.1    2019-05-06 [1] CRAN (R 3.6.0)
##  geojsonlint   0.3.0    2019-02-08 [1] CRAN (R 3.6.0)
##  glue          1.3.1    2019-03-12 [1] CRAN (R 3.6.0)
##  highr         0.8      2019-03-20 [1] CRAN (R 3.6.0)
```

```
##   httpcode       0.2.0     2016-11-14 [1] CRAN (R 3.6.0)
##   jsonlite       1.6       2018-12-07 [1] CRAN (R 3.6.0)
##   jsonvalidate   1.1.0     2019-06-25 [1] CRAN (R 3.6.0)
##   knitr        * 1.25      2019-09-18 [1] CRAN (R 3.6.1)
##   lattice        0.20-38   2018-11-04 [4] CRAN (R 3.6.0)
##   magrittr       1.5       2014-11-22 [1] CRAN (R 3.6.0)
##   maptools     * 0.9-8     2019-10-05 [1] CRAN (R 3.6.1)
##   Matrix       * 1.2-17    2019-03-22 [4] CRAN (R 3.6.1)
##   memoise        1.1.0     2017-04-21 [1] CRAN (R 3.6.0)
##   mitools        2.4       2019-04-26 [1] CRAN (R 3.6.0)
##   nlme         * 3.1-141   2019-08-01 [1] CRAN (R 3.6.1)
##   pkgbuild       1.0.6     2019-10-09 [1] CRAN (R 3.6.1)
##   pkgload        1.0.2     2018-10-29 [1] CRAN (R 3.6.0)
##   prettymapr   * 0.2.2     2017-09-20 [1] CRAN (R 3.6.0)
##   prettyunits    1.0.2     2015-07-13 [1] CRAN (R 3.6.0)
##   processx       3.4.1     2019-07-18 [1] CRAN (R 3.6.1)
##   ps             1.3.0     2018-12-21 [1] CRAN (R 3.6.0)
##   R6             2.4.0     2019-02-14 [1] CRAN (R 3.6.0)
##   Rcpp           1.0.2     2019-07-25 [1] CRAN (R 3.6.1)
##   remotes        2.1.0     2019-06-24 [1] CRAN (R 3.6.0)
##   rgdal        * 1.4-6     2019-10-01 [1] CRAN (R 3.6.1)
##   rlang          0.4.0     2019-06-25 [1] CRAN (R 3.6.0)
##   rmapshaper   * 0.4.1     2018-10-16 [1] CRAN (R 3.6.0)
##   rprojroot      1.3-2     2018-01-03 [1] CRAN (R 3.6.0)
##   sessioninfo    1.1.1     2018-11-05 [1] CRAN (R 3.6.0)
##   sp           * 1.3-1     2018-06-05 [1] CRAN (R 3.6.0)
##   stringi        1.4.3     2019-03-12 [1] CRAN (R 3.6.0)
##   stringr        1.4.0     2019-02-10 [1] CRAN (R 3.6.0)
##   survey       * 3.36      2019-04-27 [1] CRAN (R 3.6.0)
##   survival     * 2.44-1.1  2019-04-01 [4] CRAN (R 3.6.1)
##   testthat       2.2.1     2019-07-25 [1] CRAN (R 3.6.1)
##   tikzDevice   * 0.12.3    2019-08-07 [1] CRAN (R 3.6.1)
##   usethis      * 1.5.1     2019-07-04 [1] CRAN (R 3.6.0)
##   V8             2.3       2019-07-02 [1] CRAN (R 3.6.0)
##   VGAM         * 1.1-1     2019-02-18 [1] CRAN (R 3.6.0)
##   withr          2.1.2     2018-03-15 [1] CRAN (R 3.6.0)
##   xfun           0.10      2019-10-01 [1] CRAN (R 3.6.1)
##   xtable       * 1.8-4     2019-04-21 [1] CRAN (R 3.6.0)
##
## [1] /home/phm/R/x86_64-pc-linux-gnu-library/3.6
## [2] /usr/local/lib/R/site-library
## [3] /usr/lib/R/site-library
## [4] /usr/lib/R/library
```