Fiji’s Forest Reference Level
Reference Period 2006 — 2016

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## Summary

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

<table>
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<th>Reference Period</th>
<th>January 1\textsuperscript{st}, 2006 to December 31\textsuperscript{th}, 2016 (11 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accounting Area</td>
<td>Sub-national (90% of Fiji’s land-mass)</td>
</tr>
<tr>
<td>Sources/sinks</td>
<td>— Emissions from deforestation</td>
</tr>
<tr>
<td></td>
<td>— Emissions from forest degradation, incl.</td>
</tr>
<tr>
<td></td>
<td>— Emissions from logging in Natural Forest</td>
</tr>
<tr>
<td></td>
<td>— Emissions from fire in Softwood Plantations</td>
</tr>
<tr>
<td></td>
<td>— Removals from the enhancement of carbon stocks, incl.</td>
</tr>
<tr>
<td></td>
<td>— Removals from afforestation/reforestation</td>
</tr>
<tr>
<td></td>
<td>— Removals from forest plantation management</td>
</tr>
<tr>
<td>Pools</td>
<td>— Above-ground biomass (AGB)</td>
</tr>
<tr>
<td></td>
<td>— Below-ground biomass (BGB)</td>
</tr>
<tr>
<td>Gases</td>
<td>— Carbon dioxide (CO\textsubscript{2})</td>
</tr>
<tr>
<td></td>
<td>— Methane CH\textsubscript{4}</td>
</tr>
<tr>
<td></td>
<td>— Nitrous oxide N\textsubscript{2}O</td>
</tr>
<tr>
<td>FRL type</td>
<td>Historical average; no adjustment</td>
</tr>
<tr>
<td>FRL estimate</td>
<td>1,636,804 metric tonnes of CO\textsubscript{2}-equivalents per year [tCO\textsubscript{2}e yr\textsuperscript{-1}]</td>
</tr>
<tr>
<td>FRL uncertainty</td>
<td>Estimated 90% confidence limits:</td>
</tr>
<tr>
<td></td>
<td>— Lower limit: 851,765 tCO\textsubscript{2}e yr\textsuperscript{-1}</td>
</tr>
<tr>
<td></td>
<td>— Upper limit: 2,317,968 tCO\textsubscript{2}e yr\textsuperscript{-1}</td>
</tr>
</tbody>
</table>
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$_2$e yr$^{-1}$]. The Reference Period starts January 1$^{st}$, 2006 and ends December 31$^{st}$, 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$_2$O).

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$_2$e 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$_2$e yr$^{-1}$ (lower limit) and 2,317,968 tCO$_2$e yr$^{-1}$ (upper limit).
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# Abbreviations

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<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>$AD$</td>
<td>Activity data</td>
</tr>
<tr>
<td>$EF$</td>
<td>Emission factor</td>
</tr>
<tr>
<td>$AA$</td>
<td>Accuracy assessment</td>
</tr>
<tr>
<td>$AGB$</td>
<td>Above-ground biomass</td>
</tr>
<tr>
<td>$AR$</td>
<td>Afforestation and reforestation</td>
</tr>
<tr>
<td>$BGB$</td>
<td>Below-ground biomass</td>
</tr>
<tr>
<td>$CH_4$</td>
<td>Methane</td>
</tr>
<tr>
<td>$CO_2$</td>
<td>Carbon dioxide</td>
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<tr>
<td>$ER-PIN$</td>
<td>Emission Reductions Program Idea Note</td>
</tr>
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<td>$ERP$</td>
<td>Emission Reductions Program</td>
</tr>
<tr>
<td>$FAO$</td>
<td>Food and Agriculture Organization of the United Nations</td>
</tr>
<tr>
<td>$FCPF$</td>
<td>Forest Carbon Partnership Facility</td>
</tr>
<tr>
<td>$FCPF$-DST</td>
<td>FCPF REDD+ Decision Support Toolbox</td>
</tr>
<tr>
<td>$FHCL$</td>
<td>Fiji Hardwood Corporation Limited</td>
</tr>
<tr>
<td>$FPL$</td>
<td>Fiji Pine Limited</td>
</tr>
<tr>
<td>$FRA$</td>
<td>Global Forest Resources Assessment</td>
</tr>
<tr>
<td>$FRL$</td>
<td>Forest Reference Level</td>
</tr>
<tr>
<td>$GHG$</td>
<td>Greenhouse gas</td>
</tr>
<tr>
<td>$IPCC$</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>$LEDS$</td>
<td>Low Emission Development Strategy</td>
</tr>
<tr>
<td>$MODIS$</td>
<td>Moderate-resolution Imaging Spectroradiometer</td>
</tr>
<tr>
<td>$MoF$</td>
<td>Ministry of Forestry</td>
</tr>
<tr>
<td>$MSD$</td>
<td>Management Service Division of the Fijian Ministry of Forestry</td>
</tr>
<tr>
<td>$N_2O$</td>
<td>Nitrous oxide</td>
</tr>
<tr>
<td>$NFI$</td>
<td>National Forest Inventory</td>
</tr>
<tr>
<td>$PTHD$</td>
<td>Pan-tropical Tree Harvest Database</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>REDD+</td>
<td>Reducing Emissions from Deforestation and Forest Degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks</td>
</tr>
<tr>
<td>SOC</td>
<td>Soil organic carbon</td>
</tr>
<tr>
<td>SRTM</td>
<td>Shuttle Radar Topography Mission</td>
</tr>
<tr>
<td>TEF</td>
<td>Total Emission Factor</td>
</tr>
<tr>
<td>UNFCCC</td>
<td>United Nations Framework Convention on Climate Change</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Sources and sinks included in Fiji’s Forest Reference Level (FRL):</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Emissions from deforestation</strong> 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.</td>
</tr>
<tr>
<td><strong>Emissions from forest degradation</strong> The source ‘forest degradation’ is included in Fiji’s FRL. Emissions from forest degradation are considered...</td>
</tr>
</tbody>
</table>
1. Scale and scope

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-
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.
1. Scale and scope

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–ground biomass (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% 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.

<table>
<thead>
<tr>
<th>Greenhouse gases (GHGs) included in Fiji’s FRL:</th>
</tr>
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<tbody>
<tr>
<td><strong>CO₂</strong></td>
</tr>
<tr>
<td><strong>CH₄</strong></td>
</tr>
<tr>
<td><strong>N₂O</strong></td>
</tr>
</tbody>
</table>

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”.

5
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 & Gofari (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

<table>
<thead>
<tr>
<th>Description</th>
<th>IPCC LUC</th>
<th>LUSC</th>
<th>a.s.l.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest Land</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Forest</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lowland Natural Forest</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest Plantations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Softwood Plantations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardwood Plantations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-Forest Land</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-Forest</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Forest Land Natural Forest

- **Lowland Natural Forest**
  - Includes all land in which trees are present, and where the land:
    - Covers at a minimum an area of 0.5 hectares,
    - Is not predominantly under agricultural or urban use,
    - Has a canopy cover percent of 10% or more, and
    - Is located at < 600 m a.s.l.
  - Includes primary (native) forest, human modified forests as well as areas planted with native or introduced tree species. Lowland Natural Forest cannot be located within plantation lease areas. Mangrove is not included in this stratum.

### Forest Plantations

- **Softwood Plantations**
  - 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**
  - 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**
  - 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 for FPL’s lease area.
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$_2$e 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].

\[ \eta_{CC} = \frac{-44}{12} \]

\( \eta_{CC} \) = Carbon (C) to CO\(_2\) conversion factor; dimensionless

As carbon losses have a negative sign the multiplication of losses with \( \eta_{CC} \) will result in (positive) emissions. Multiplying carbon gains by \( \eta_{CC} \) 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.
2.1. Overview

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

\[ \eta_{CF} = 0.47 \]

\( \eta_{CF} \) = 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. Emissions by source and removals by sink

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

\[
\text{Emissions} = AD \times EF
\]

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 \([\text{ha yr}^{-1}]\), the \(EF\) is expressed in carbon dioxide emissions per hectare \([\text{tCO}_2\text{e ha}^{-1}]\). The multiplication of \(AD\) and \(EF\) gives emissions of \(\text{CO}_2\) equivalents per year \([\text{tCO}_2\text{e yr}^{-1}]\).

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 the 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\(^1\). 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

\(^1\)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.

<table>
<thead>
<tr>
<th>Class description</th>
<th>Source/Sink</th>
<th>$A$ mapped [ha]</th>
</tr>
</thead>
<tbody>
<tr>
<td>111 Natural Forest (1) remaining Natural Forest (1); Lowland (1)</td>
<td></td>
<td>670,300</td>
</tr>
<tr>
<td>112 Natural Forest (1) remaining Natural Forest (1); Upland (2)</td>
<td></td>
<td>229,698</td>
</tr>
<tr>
<td>171 Natural Forest (1) converted to Non-Forest (7); Lowland (1)</td>
<td>DF</td>
<td>54,406</td>
</tr>
<tr>
<td>172 Natural Forest (1) converted to Non-Forest (7); Upland (2)</td>
<td>DF</td>
<td>9,834</td>
</tr>
<tr>
<td>711 Non-forest (7) converted to Natural Forest (1); Lowland (1)</td>
<td>AR</td>
<td>33,742</td>
</tr>
<tr>
<td>712 Non-forest (7) converted to Natural Forest (1); Upland (2)</td>
<td>AR</td>
<td>3,489</td>
</tr>
<tr>
<td>777 Non-forest (7) remaining Non-forest (7); Low- or Upland (7)</td>
<td></td>
<td>502,344</td>
</tr>
</tbody>
</table>

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 $A$ 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:
2. Emissions by source and removals by sink

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

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

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.

<table>
<thead>
<tr>
<th>Stratum</th>
<th>(\hat{A}_{DF}) [ha yr(^{-1})]</th>
<th>Lower 90%-CI [ha yr(^{-1})]</th>
<th>Upper 90%-CI [ha yr(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF Lowland ((\hat{A}_{j=171}))</td>
<td>8.332</td>
<td>6.650</td>
<td>10.144</td>
</tr>
<tr>
<td>DF Upland ((\hat{A}_{j=172}))</td>
<td>2.682</td>
<td>1.963</td>
<td>3.461</td>
</tr>
<tr>
<td>Total</td>
<td>11.014</td>
<td>9.175</td>
<td>12.970</td>
</tr>
</tbody>
</table>

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

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

\(\hat{A}_{DF, \text{Lowland}}\) = Average annual area of deforestation of Lowland Natural Forest; ha
\(\mathcal{T}\) = Length of the FRL Reference Period, i.e., \(|\mathcal{T}| = \mathcal{T} = 11\) 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
\(\hat{A}_{DF, \text{Upland}}\) = 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
2.2. Emissions from deforestation

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\(^{-1}\)

\[\Delta C_G\] = 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\(^{-1}\)

\[\Delta C_L\] = 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 \[\Delta C_G\] and \[\Delta C_L\] 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)

\[
\begin{align*}
\Delta C_{B,\text{Lowland}} &= C_{\text{AFTER}} - C_{\text{BEFORE,Lowland}} \\
\Delta C_{B,\text{Upland}} &= C_{\text{AFTER}} - C_{\text{BEFORE,Upland}}
\end{align*}
\]

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

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

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

\(C_{\text{BEFORE,Lowland}}\) = Average C stock in Lowland Natural Forest; \(\text{tC ha}^{-1}\)

\(C_{\text{BEFORE,Upland}}\) = Average C stock in Upland Natural Forest; \(\text{tC ha}^{-1}\)

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.

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Carbon stock [tC ha(^{-1})]</th>
<th>Lower 90%-CI [tC ha(^{-1})]</th>
<th>Upper 90%-CI [tC ha(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowland</td>
<td>87.859</td>
<td>80.510</td>
<td>91.081</td>
</tr>
<tr>
<td>Upland</td>
<td>71.571</td>
<td>64.081</td>
<td>76.626</td>
</tr>
</tbody>
</table>

Estimates for \(\Delta C_{B,\text{Lowland}}\) and \(\Delta C_{B,\text{Upland}}\) 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 (\(\Delta C_{B,\text{Lowland}}\) and \(\Delta C_{B,\text{Upland}}\)); CI = confidence interval.

<table>
<thead>
<tr>
<th>Stratum</th>
<th>(\Delta C_B) [tC ha(^{-1})]</th>
<th>Lower 90%-CI [tC ha(^{-1})]</th>
<th>Upper 90%-CI [tC ha(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowland</td>
<td>70.746</td>
<td>58.492</td>
<td>78.732</td>
</tr>
<tr>
<td>Upland</td>
<td>54.458</td>
<td>42.522</td>
<td>63.735</td>
</tr>
</tbody>
</table>

Equation 2.8: Emission factor for deforestation (Lowland)

\[
\psi_{DF,\text{Lowland}} = \Delta C_{B,\text{Lowland}} \times \eta_{CC}
\]

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

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

\(\eta_{CC}\) = Conversion factor C to \(\text{CO}_2\); dimensionless
2.2. Emissions from deforestation

Equation 2.9: Emission factor for deforestation (Upland)

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

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

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

\[ \eta_{CC} = \text{Conversion factor C to CO}_2; \text{ dimensionless} \]

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

<table>
<thead>
<tr>
<th>Stratum</th>
<th>( \psi_{DF} ) [tCO(_2)e ha(^{-1})] Lower 90%-CI [tCO(_2)e ha(^{-1})] Upper 90%-CI [tCO(_2)e ha(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowland</td>
<td>259.401</td>
</tr>
<tr>
<td>Upland</td>
<td>199.679</td>
</tr>
</tbody>
</table>

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)

\[ \hat{\theta}_{DF, Lowland} = \hat{A}_{DF, Lowland} \times \psi_{DF, Lowland} \]

\[ \hat{\theta}_{DF, Lowland} = \text{Average annual emissions from deforestation of Lowland Natural Forest; } \text{tCO}_2 \text{e yr}^{-1} \]

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

\[ \psi_{DF, Lowland} = \text{Emission factor for deforestation in Lowland Natural Forest; } \text{tCO}_2 \text{e ha}^{-1} \]

Equation 2.11: Average annual emissions (deforestation Upland)

\[ \hat{\theta}_{DF, Upland} = \hat{A}_{DF, Upland} \times \psi_{DF, Upland} \]

\[ \hat{\theta}_{DF, Upland} = \text{Average annual emissions from deforestation of Upland Natural Forest; } \text{tCO}_2 \text{e yr}^{-1} \]

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

\[ \psi_{DF, Upland} = \text{Emission factor for deforestation in Upland Natural Forest; } \text{tCO}_2 \text{e ha}^{-1} \]
2. Emissions by source and removals by sink

\[ \dot{\theta}_{DF, Upland} = \text{Average annual emissions from deforestation of Upland Natural Forest; } \text{tCO}_2 \text{e yr}^{-1} \]

\[ \dot{A}_{DF, Upland} = \text{Average annual loss of Upland Natural Forest area; ha yr}^{-1} \]

\[ \psi_{DF, Upland} = \text{Emission factor for deforestation in Upland Natural Forest; tCO}_2 \text{e ha}^{-1} \]

**Equation 2.12: Average annual emissions (deforestation)**

\[ \dot{\theta}_{DF} = \dot{\theta}_{DF, Lowland} + \dot{\theta}_{DF, Upland} \]

\[ \dot{\theta}_{DF} = \text{Average annual emissions from deforestation; tCO}_2 \text{e yr}^{-1} \]

\[ \dot{\theta}_{DF, Lowland} = \text{Average annual emissions from deforestation of Lowland Natural Forest; tCO}_2 \text{e yr}^{-1} \]

\[ \dot{\theta}_{DF, Upland} = \text{Average annual emissions from deforestation of Upland Natural Forest; tCO}_2 \text{e yr}^{-1} \]

**Table 2.7:** Estimated average annual emissions from deforestation, \( \dot{\theta}_{DF} \); CI = confidence interval.

<table>
<thead>
<tr>
<th>Stratum</th>
<th>( \dot{\theta}_{DF} ) [tCO(_2)e yr(^{-1})]</th>
<th>Lower 90%-CI [tCO(_2)e yr(^{-1})]</th>
<th>Upper 90%-CI [tCO(_2)e yr(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowland</td>
<td>2,161,364.32</td>
<td>1,589,714.68</td>
<td>2,662,016.35</td>
</tr>
<tr>
<td>Upland</td>
<td>535,466.31</td>
<td>354,509.18</td>
<td>713,069.26</td>
</tr>
<tr>
<td>Total</td>
<td>2,696,830.64</td>
<td>2,043,841.47</td>
<td>3,254,111.33</td>
</tr>
</tbody>
</table>

**2.2.5. Uncertainty analysis**

The uncertainty attached to the estimate of average annual emissions from deforestation, \( \dot{\theta}_{DF} \), was estimated using Monte Carlo (MC) simulations. The procedures used to estimate the precision of \( \dot{A}_{DF,i} \) and \( \dot{A}_{DF} \) 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 \( R = 4 \times 10^4 \).
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 $T_EF$ 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 $T_EF$ 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 $\geq$ 10 cm DBH (AGB and BGB) and (ii) C loss from sever crown damage; value used for $EM_{DAM} = 0.15$;

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

The value of $T_EF = EM_{FELL} + EM_{DAM} + EM_{INF} = 1.05 \text{ tC (m}^3\text{)}^{-1}$ 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. CO₂ and non-CO₂ 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).](image)
2. Emissions by source and removals by sink

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.
2.3. Emissions from forest degradation

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

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

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

\[
T = \text{Length of the Reference Period, i.e., 11 years; yrs}
\]

\[
\Delta C_{FDL,L,t} = \text{Carbon loss in year } t \text{ due to logging in Natural Forest; tC}
\]

\[
\eta_{CC} = \text{Conversion factor C to CO}_2\text{e; dimensionless}
\]

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

<table>
<thead>
<tr>
<th>Year</th>
<th>(V_{FDL} [m^3])</th>
<th>(A_{FDL} [ha])</th>
<th>(\Delta C_{FDL,L} [tC])</th>
<th>(\hat{\theta}_{FDL,L} [tCO_2e])</th>
<th>(\Delta C_{FDL,G} [tC])</th>
<th>(\hat{\theta}_{FDL,G} [tCO_2e])</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>79480</td>
<td>3513</td>
<td>-83454</td>
<td>305998</td>
<td>36518</td>
<td>-133898</td>
</tr>
<tr>
<td>2007</td>
<td>45122</td>
<td>2546</td>
<td>-47378</td>
<td>173720</td>
<td>23941</td>
<td>-87784</td>
</tr>
<tr>
<td>2008</td>
<td>81706</td>
<td>3259</td>
<td>-57911</td>
<td>314568</td>
<td>27421</td>
<td>-100543</td>
</tr>
<tr>
<td>2009</td>
<td>59614</td>
<td>1165</td>
<td>-62955</td>
<td>229514</td>
<td>8652</td>
<td>-31722</td>
</tr>
<tr>
<td>2010</td>
<td>49814</td>
<td>1641</td>
<td>-52305</td>
<td>191784</td>
<td>10561</td>
<td>-38723</td>
</tr>
<tr>
<td>2011</td>
<td>36499</td>
<td>905</td>
<td>-38324</td>
<td>140521</td>
<td>4930</td>
<td>-18077</td>
</tr>
<tr>
<td>2012</td>
<td>30517</td>
<td>796</td>
<td>-32043</td>
<td>117490</td>
<td>3545</td>
<td>-12997</td>
</tr>
<tr>
<td>2013</td>
<td>26947</td>
<td>1354</td>
<td>-28294</td>
<td>103746</td>
<td>4692</td>
<td>-17203</td>
</tr>
<tr>
<td>2014</td>
<td>46431</td>
<td>1428</td>
<td>-18753</td>
<td>178759</td>
<td>3534</td>
<td>-12957</td>
</tr>
<tr>
<td>2015</td>
<td>51091</td>
<td>1738</td>
<td>-53646</td>
<td>196700</td>
<td>2581</td>
<td>-9464</td>
</tr>
<tr>
<td>2016</td>
<td>50825</td>
<td>1438</td>
<td>-53366</td>
<td>195676</td>
<td>712</td>
<td>-2611</td>
</tr>
</tbody>
</table>

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

\( \delta_t \) = 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

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

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

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

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

\( \delta_t \) = 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

\( \eta_{CC} \) = 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)

\[
\hat{\theta}_{FDL} = \hat{\theta}_{FDL,em} + \hat{\theta}_{FDL,re}
\]

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

\( \hat{\theta}_{FDL,em} \) = Average annual gross emissions from forest degradation; tCO\(_2\)e yr\(^{-1}\)

\( \hat{\theta}_{FDL,re} \) = Average annual gross removals from forest degradation; tCO\(_2\)e yr\(^{-1}\)
Table 2.9.: Average annual gross emissions, $\hat{\theta}_{FDL_{em}}$, average annual gross removals, $\hat{\theta}_{FDL_{re}}$, and average annual net emissions, $\hat{\theta}_{FDL}$ for the net source ‘forest degradation’ (‘Logging in Natural Forest’). CI = confidence interval.

<table>
<thead>
<tr>
<th>Estimate [tCO$_2$ yr$^{-1}$]</th>
<th>Lower 90%-CI [tCO$_2$ yr$^{-1}$]</th>
<th>Upper 90%-CI [tCO$_2$ yr$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\hat{\theta}<em>{FDL</em>{em}}$</td>
<td>195,316.10</td>
<td>167,281.73</td>
</tr>
<tr>
<td>$\hat{\theta}<em>{FDL</em>{re}}$</td>
<td>-42,361.61</td>
<td>-57,253.99</td>
</tr>
<tr>
<td>$\hat{\theta}_{FDL}$</td>
<td>152,954.49</td>
<td>121,401.92</td>
</tr>
</tbody>
</table>

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, $\eta_{CC}$ (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 $R = 4 \times 10^4$. The estimates $\hat{\theta}_{FDL_{em}}, \hat{\theta}_{FDL_{re}}$ and $\hat{\theta}_{FDL}$ were, thus, estimated $R$ 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).
2. Emissions by source and removals by sink

\( M AIC_{FD} \) The \( MAIC_{FD} \) was sampled from a Triangular distribution with lower bound 
\[ a = MAIC_{FD} - MAIC_{FD} \times 0.5, \text{ upper bound } b = MAIC_{FD} + MAIC_{FD} \times 0.5 \text{ and mode } c = MAIC_{FD}. \]

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

The MC simulation delivered \( R \) MC estimates of \( \hat{\theta}_{FDDLem}, \hat{\theta}_{FDDLre} \) and \( \hat{\theta}_{FDDL} \). 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

\[
AGB_{l,t_b} = \Lambda_{l,t_b} \times \frac{MAIB_{SW}}{(1 + R_{dl})}
\]

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

\( \Lambda_{l,t_b} = \) 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\(^{-1}\)

\( R_{dl} = \) 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.
2.3. Emissions from forest degradation

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].

<table>
<thead>
<tr>
<th>IPCC Ecological zone</th>
<th>Climate*</th>
<th>Alt.</th>
<th>Zonation</th>
<th>AGB [t ha(^{-1})]</th>
<th>( R )</th>
<th>Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical rainforest</td>
<td>Wet</td>
<td>Lowland</td>
<td>WL</td>
<td>&lt; 125</td>
<td>.37</td>
<td>( R_{\text{w}l} )</td>
</tr>
<tr>
<td>Tropical moist deciduous forest</td>
<td>Dry</td>
<td>Lowland</td>
<td>DL</td>
<td>&lt; 125</td>
<td>.20</td>
<td>( R_{\text{d}ll} )</td>
</tr>
<tr>
<td></td>
<td>Dry</td>
<td>Lowland</td>
<td>DL</td>
<td>( \geq 125 )</td>
<td>.24</td>
<td>( R_{\text{d}lh} )</td>
</tr>
<tr>
<td>Tropical mountain systems</td>
<td>Dry</td>
<td>Upland</td>
<td>DU</td>
<td></td>
<td>.27</td>
<td>( R_{\text{u}} )</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>Upland</td>
<td>WU</td>
<td></td>
<td>.27</td>
<td>( R_{\text{u}} )</td>
</tr>
</tbody>
</table>

*Climatic zonation: Wet = Aridity Index (AI) \( \geq 2 \), Dry = AI \( < 2 \)

\( \text{Alt.} \) = Altitudinal zonation; Lowland \( < 600 \) m a.s.l., Upland \( \geq 600 \) m a.s.l.

\( \text{WL = Wet Lowland, DL = Dry Lowland, DU = Dry Upland, WU = Wet Upland} \)

\( d \) = root-to-shoot ratio

---

**Equation 2.20**: BGB loss caused by fire

\[
BGB_{l,t_b} = \Lambda_{l,t_b} \times MAIB_{SW} \times R_{dll}
\]

- \( BGB_{l,t_b} \) = Below-ground biomass in compartment \( l \) in year \( t_b \); tB ha\(^{-1}\)
- \( \Lambda_{l,t_b} \) = 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)

\[
EACO2_{l,t_b} = A_{l,t_b} \times AGB_{l,t} \times C_f \times G_{ef,CO2}
\]

- \( EACO2_{l,t_b} \) = 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
- \( G_{ef,CO2} \) = 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)
2. Emissions by source and removals by sink

### Equation 2.22: CO₂ emissions from BGB (fire)

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

\(EBCO2_{l,t_b}\) = CO₂ emissions from BGB in compartment \(l\) that burnt in year \(t_b\) (it is assumed that BGB does not burn); tCO₂e

- \(A_{l,t_b}\) = 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
- \(\eta_{CF}\) = Conversion factor biomass to C; dimensionless
- \(\eta_{CC}\) = Conversion factor C to CO₂; dimensionless

For AGB, not only CO₂ emissions were considered but also emissions of other GHGs including methane (CH₄) and nitrous oxide (N₂O). Estimates of non-CO₂ emissions were converted to CO₂ equivalents. Equation (2.23) and Equation (2.24) show how emissions of non-CO₂ were estimated.

### Equation 2.23: CH₄ emissions from AGB converted to CO₂e (fire)

\[
EACH4_{l,t_b} = A_{l,t_b} \times AGB_{l,t_b} \times C_f \times G_{ef,CH_4} \times GW\_P_{CH_4}
\]

\(EACH4_{l,t_b}\) = CO₂ emissions from CH₄ (methane) from AGB in compartment \(l\) that burnt in year \(t_b\); tCO₂e

- \(A_{l,t_b}\) = 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 CH₄ [IPCC, 2006, Vol. 4, Chap. 2, Tab. 2.5]; g kg⁻¹
- \(GW\_P_{CH_4}\) = Global warming potential of CH₄, i.e., conversion of non-CO₂ GHGs to carbon dioxide equivalents IPCC [2014, Box 3.2, Tab. 1]; dimensionless

### Equation 2.24: N₂O emissions from AGB converted to CO₂e (fire)

\[
EAN2O_{l,t_b} = A_{l,t_b} \times AGB_{l,t_b} \times C_f \times G_{ef,N_2O} \times GW\_P_{N_2O}
\]

- \(EAN2O_{l,t_b}\) = N₂O emissions from AGB converted to CO₂e (fire)
- \(A_{l,t_b}\) = 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 N₂O [IPCC, 2006, Vol. 4, Chap. 2, Tab. 2.5]; g kg⁻¹
- \(GW\_P_{N_2O}\) = Global warming potential of N₂O, i.e., conversion of non-CO₂ GHGs to carbon dioxide equivalents IPCC [2014, Box 3.2, Tab. 1]; dimensionless
2.3. Emissions from forest degradation

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].

<table>
<thead>
<tr>
<th>Greenhouse gas (GHG)</th>
<th>$C_f$</th>
<th>$G_{ef}$</th>
<th>$GWP$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$ Carbon dioxide</td>
<td>0.46</td>
<td>1580.0</td>
<td>1</td>
</tr>
<tr>
<td>CH$_4$ Methane</td>
<td>0.46</td>
<td>6.8</td>
<td>28</td>
</tr>
<tr>
<td>N$_2$O Nitrous oxide</td>
<td>0.46</td>
<td>0.2</td>
<td>265</td>
</tr>
</tbody>
</table>

$EAN2O_{l,t_b} = $ CO$_2$ emissions from N$_2$O (nitrous oxide) 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,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$_2$O, 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$_2$e]. Column Total gives the sum of tCO$_2$e 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.

<table>
<thead>
<tr>
<th>Year</th>
<th>Count</th>
<th>Area [ha]</th>
<th>Avg. age [yrs]</th>
<th>Source of CO$_2$e emissions [tCO$_2$e]</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CO$_2$ (AGB)</td>
<td>CO$_2$ (BGB)</td>
</tr>
<tr>
<td>2015</td>
<td>79</td>
<td>1,447</td>
<td>17.47</td>
<td>143,566</td>
<td>37,581</td>
</tr>
<tr>
<td>2016</td>
<td>33</td>
<td>830</td>
<td>16.27</td>
<td>71,024</td>
<td>18,592</td>
</tr>
<tr>
<td>2017</td>
<td>122</td>
<td>2,709</td>
<td>10.21</td>
<td>171,842</td>
<td>44,984</td>
</tr>
<tr>
<td>2018</td>
<td>60</td>
<td>729</td>
<td>9.75</td>
<td>58,505</td>
<td>15,315</td>
</tr>
</tbody>
</table>

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

$$E_{l,t_b} = EACO2_{l,t_b} + EBCO2_{l,t_b} + ECH4_{l,t_b} + EN2O_{l,t_b}$$
Equation 2.26: Total GHG emissions per year (fire)

\[ E_{t_b} = \sum_{l} E_{l,t_b} \]

\[ E_{t_b} = \text{Total GHG emissions in year } t_b; \text{ tCO}_2\text{e} \]
\[ E_{l,t_b} = \text{Total GHG emissions from compartment } l \text{ in year } t_b; \text{ tCO}_2\text{e} \]

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

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

\[ \hat{\theta}_{FDB} = \text{Average annual emissions from biomass burning (fire); tCO}_2\text{e yr}^{-1} \]
\[ E_{t_b} = \text{Total GHG emissions in year } t_b; \text{ tCO}_2\text{e} \]
\[ |T_b| = \text{Number of years used to compute the annual average, } |T_b| = 4; \text{ yrs} \]

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.

<table>
<thead>
<tr>
<th>(\hat{\theta}_{FDF}) [tCO\textsubscript{2}e yr\textsuperscript{-1}]</th>
<th>Lower 90%-CI [tCO\textsubscript{2}e yr\textsuperscript{-1}]</th>
<th>Upper 90%-CI [tCO\textsubscript{2}e yr\textsuperscript{-1}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>157,488</td>
<td>99,097</td>
<td>221,046</td>
</tr>
</tbody>
</table>

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:
2.3. Emissions from forest degradation

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$_2$O) 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$_4$ ($GWP_{CH_4}$); large source, highly relevant included in the quantification of uncertainty.

8. Uncertainty attached to the global warming potential of N$_2$O ($GWP_{N_2O}$); large source, highly relevant included in the quantification of uncertainty.

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

2.3.3.2. 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]).
2. Emissions by source and removals by sink

\( C_f \) 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 \( c = C_f \).

\( G_{ef,CO_2} \) 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 \( c = G_{ef,CO_2} \).

\( G_{ef,CH_4} \) 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 \( c = G_{ef,CH_4} \).

\( G_{ef,N_2O} \) 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 \( c = G_{ef,N_2O} \).

\( GW_{PCH_4} \) was sampled from a Triangular distribution with lower bound \( a = GW_{PCH_4} - GW_{PCH_4} \times 0.5 \), upper bound \( b = GW_{PCH_4} + GW_{PCH_4} \times 0.5 \), and mode \( c = GW_{PCH_4} \).

\( GW_{PN_2O} \) was sampled from a Triangular distribution with lower bound \( a = GW_{PN_2O} - GW_{PN_2O} \times 0.5 \), upper bound \( b = GW_{PN_2O} + GW_{PN_2O} \times 0.5 \), and mode \( c = GW_{PN_2O} \).

The MC simulation delivered \( R \) 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\(^{-1}\)
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
2. Emissions by source and removals by sink

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**

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

\( \hat{A}_{AR,t} \) = 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)

\( T \) = Length of the FRL Reference Period, i.e., \( |T| = T = 11 \) 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>
<thead>
<tr>
<th>Stratum</th>
<th>( \hat{A}_{AR} ) [ha yr(^{-1})]</th>
<th>Lower 90%-CI [ha yr(^{-1})]</th>
<th>Upper 90%-CI [ha yr(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR Lowland</td>
<td>4,955</td>
<td>3,694</td>
<td>6,352</td>
</tr>
<tr>
<td>AR Upland</td>
<td>1,224</td>
<td>722</td>
<td>1,763</td>
</tr>
<tr>
<td>Total</td>
<td>6,180</td>
<td>4,818</td>
<td>7,687</td>
</tr>
</tbody>
</table>

Carbon gains for year \( t \) over the Reference Period were calculated as follows:
2.4. Enhancement of forest carbon stocks

Equation 2.30: Carbon gains (AR)

\[ \Delta C_{AR,t} = \hat{A}_{AR} \times MAIC_{AR} \times \delta_t \]

\( \Delta C_{AR} \) = Carbon gains for year \( t \) generated over the Reference Period; tC
\( \hat{A}_{AR} \) = Average annual forest area gain (afforestation/reforestation); ha
\( MAIC_{AR} \) = mean annual increment for afforestation/reforestation; tC ha\(^{-1}\) yr\(^{-1}\)
\( \delta_t \) = 2016 - \( t \), with \( T = \{2006, 2007, \ldots, t, \ldots, 2016\} \); 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
\( \eta_{CF} \) = 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., \( \sum_T \delta_t \times MAIV_{AR} \)/\( \tau \) = 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)

\[ \Delta \bar{C}_{AR} = (\tau - 1)^{-1} \sum_{T} \Delta C_{AR,t} \]

\( \Delta \bar{C}_{AR} \) = Average annual C gains from AR over the Reference Period; tC yr\(^{-1}\)
\( \tau \) = Length of the FRL Reference Period, i.e., \( \tau = 11 \); yrs
\( \Delta C_{AR,t} \) = Carbon gains for year \( t \) generated over the Reference Period; tC
2. Emissions by source and removals by sink

Average annual removals from forest area gain were estimated by

**Equation 2.33: Average annual removals (AR)**

\[ \hat{\theta}_{ECAR} = \Delta \tilde{C}_{AR} \times \eta_{CC} \]

- \( \hat{\theta}_{ECAR} \) = Average annual removals from AR; tCO\(_2\)e yr\(^{-1}\)
- \( \Delta \tilde{C}_{AR} \) = Average annual C gains from AR over the Reference Period; tC yr\(^{-1}\)
- \( \eta_{CC} \) = 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.

<table>
<thead>
<tr>
<th>( \hat{\theta}_{AR} ) [tCO(_2)e yr(^{-1})]</th>
<th>Lower 90%-CI [tCO(_2)e yr(^{-1})]</th>
<th>Upper 90%-CI [tCO(_2)e yr(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-327,541</td>
<td>-472,584</td>
<td>-201,679</td>
</tr>
</tbody>
</table>

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, \( \hat{A}_{AR,T_1} \) and \( \hat{A}_{AR,T_2} \); large source, highly relevant; included in the quantification of uncertainty. The methods used to quantify 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 \( R_{eq} \) (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).
2.4. Enhancement of forest carbon stocks

$MAIV_{AR}$ 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 $c = MAIV_{AR}$.

$BCEF_{AR,I}$ 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 $c = BCEF_{AR,I}$.

$R_{wl}$ 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.
2. Emissions by source and removals by sink

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 CO₂ 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 Hardand 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 (m³)⁻¹ was selected (BCEFᵣ for humid tropical natural forest; growing stock level > 200 m³ ha⁻¹).

\[
AGB_{HW,L,t} = V_{HW,L,t} \times BCEF_{HW,R}
\]
2.4. Enhancement of forest carbon stocks


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

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)

\[ TB_{HW,L,t} = AGB_{HW,L,t} \times (1 + R_{swl}) \]
2. Emissions by source and removals by sink

\[ TB_{HW,L,t} = \text{Total biomass loss due to logging in Hardwood Plantations in year } t; \]
\[ tTB \]
\[ AGB_{HW,L,t} = \text{AGB extracted from Hardwood Plantations in year } t; \ tAGB \]
\[ R_{rd} = \text{Root-to-shoot ratio for tropical rainforest (see Table 2.10); dimensionless} \]

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

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

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

\[ \Delta C_{HW,L,t} = \text{Carbon loss in year } t \text{ caused by logging in Hardwood Plantations; } tC \]
\[ TB_{HW,L,t} = \text{Total biomass loss due to logging in Hardwood Plantations in year } t; \ tB \]
\[ \eta_{CF} = \text{Biomass to carbon conversion factor from IPCC [2006]; dimensionless} \]

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)**

\[
\hat{\theta}_{ECHem} = \frac{1}{T} \sum_{t} \Delta C_{HW,L,t} \times \eta_{CC}
\]

\[ \hat{\theta}_{ECHem} = \text{Average annual gross emissions from Hardwood Plantations; } tCO_2e \]
\[ yr^{-1} \]
\[ T = \text{Length of the FRL Reference Period, i.e., 11 years; yrs} \]
\[ \Delta C_{HW,L,t} = \text{Carbon loss in year } t \text{ caused by logging in Hardwood Plantations; } tC \]
\[ \eta_{CC} = \text{Conversion factor carbon to CO}_2 \text{ (see Equation (2.1)); } tC \]

2.4.2.2. 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.
2.4. Enhancement of forest carbon stocks

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, $\Delta C_{HW,G}$.

<table>
<thead>
<tr>
<th>Year</th>
<th>$V_{HW,L}$ [m$^3$]</th>
<th>$A_{HW,LG}$ [ha]</th>
<th>$A_{HW,PL}$ [ha]</th>
<th>$A_{HW,S}$ [ha]</th>
<th>$\Delta C_{HW,L}$ [tC]</th>
<th>$\Delta C_{HW,G}$ [tC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>37216</td>
<td>212</td>
<td>305</td>
<td>57043</td>
<td>-25162</td>
<td>13271</td>
</tr>
<tr>
<td>2007</td>
<td>50092</td>
<td>278</td>
<td>305</td>
<td>56977</td>
<td>-33867</td>
<td>12007</td>
</tr>
<tr>
<td>2008</td>
<td>79869</td>
<td>736</td>
<td>305</td>
<td>56519</td>
<td>-53999</td>
<td>10743</td>
</tr>
<tr>
<td>2009</td>
<td>63758</td>
<td>165</td>
<td>305</td>
<td>57091</td>
<td>-43106</td>
<td>9479</td>
</tr>
<tr>
<td>2010</td>
<td>92283</td>
<td>432</td>
<td>305</td>
<td>56823</td>
<td>-62392</td>
<td>8215</td>
</tr>
<tr>
<td>2011</td>
<td>91025</td>
<td>132</td>
<td>228</td>
<td>57046</td>
<td>-61542</td>
<td>5196</td>
</tr>
<tr>
<td>2012</td>
<td>53737</td>
<td>110</td>
<td>1000</td>
<td>57840</td>
<td>-36331</td>
<td>18646</td>
</tr>
<tr>
<td>2013</td>
<td>63251</td>
<td>310</td>
<td>0</td>
<td>56640</td>
<td>-42764</td>
<td>0</td>
</tr>
<tr>
<td>2014</td>
<td>58542</td>
<td>394</td>
<td>0</td>
<td>56556</td>
<td>-39580</td>
<td>0</td>
</tr>
<tr>
<td>2015</td>
<td>54568</td>
<td>375</td>
<td>0</td>
<td>56755</td>
<td>-36893</td>
<td>0</td>
</tr>
<tr>
<td>2016</td>
<td>39854</td>
<td>172</td>
<td>300</td>
<td>57078</td>
<td>-26945</td>
<td>622</td>
</tr>
</tbody>
</table>

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, $\bar{MAIV}_{HW}$, where the areas stocked in 2017, $A_{HW}$, served as weights. The mean annual volume increment over all species was estimated at 5.85 m$^3$ ha$^{-1}$ yr$^{-1}$. A default biomass conversion and expansion factor for increment (BCEF$_I$) of 1.1 tB (m$^3$) [IPCC, 2006, Vol. 4, Chap. 4, Tab. 4.5; humid tropical natural forests; growing stock level 21-40 m$^3$ ha$^{-1}$] was used to convert volume increment to AGB increment.

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

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

$\bar{MAIV}_{HW}$ = Average mean annual volume increment in Hardwood Plantations; m$^3$ 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 m$^3$ ha$^{-1}$]; tB (m$^3$)$^{-1}$

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).

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

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; tC 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

$\eta_{CF}$ = 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

$\delta_t$ = 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 $t = \{2006, 2007, \ldots, 2010\}$.

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
2. Emissions by source and removals by sink

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

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

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

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

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

\(\Delta C_{HW,G}\) = 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)

\[
\hat{\theta}_{ECHre} = \Delta C_{HW,G} \times \eta_{CC}.
\]
2.4. Enhancement of forest carbon stocks

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

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

\[ \eta_{CC} = \text{Conversion factor C to CO}_2; \text{dimensionless} \]

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.

<table>
<thead>
<tr>
<th>Equation 2.47: Average annual net emissions (HW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ \hat{\theta}<em>{ECH} = \hat{\theta}</em>{ECHem} + \hat{\theta}_{ECHre} ]</td>
</tr>
</tbody>
</table>

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

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

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

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 from 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, \( \lambda_{Pine} \), and an estimate of the wood density of pine trees, \( \rho_{Pine} \) [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\(^{-3} \).
Emissions by source and removals by sink

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)

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

where:
- \(AGB_{SW,L,t}\) = AGB loss in year \(t\) in Softwood Plantations; tAGB
- \(V_{SW,L,t}\) = Wood volumes harvested in Softwood Plantations in year \(t\); m³
- \(\lambda_{Pine}\) = Recovery rate in Softwood Plantations; dimensionless
- \(\rho_{Pine}\) = 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, \(A_{HW,PL}\), areas planted, \(A_{HW,S}\), stocking area, \(\Delta C_{HW,L}\), and C gains over the Reference Period, \(\Delta C_{HW,G}\).

<table>
<thead>
<tr>
<th>Year</th>
<th>(V_{SW,L}) [m³]</th>
<th>(A_{SW,PL}) [ha]</th>
<th>(A_{SW,S}) [ha]</th>
<th>(\Delta C_{SW,L}) [tC]</th>
<th>(\Delta C_{SW,G}) [tC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>282102</td>
<td>1082</td>
<td>1478</td>
<td>-101674</td>
<td>72929</td>
</tr>
<tr>
<td>2007</td>
<td>294685</td>
<td>1130</td>
<td>3</td>
<td>-106209</td>
<td>128</td>
</tr>
<tr>
<td>2008</td>
<td>265046</td>
<td>1016</td>
<td>14</td>
<td>-95527</td>
<td>563</td>
</tr>
<tr>
<td>2009</td>
<td>249769</td>
<td>958</td>
<td>17</td>
<td>-90021</td>
<td>589</td>
</tr>
<tr>
<td>2010</td>
<td>256040</td>
<td>982</td>
<td>177</td>
<td>-92281</td>
<td>5419</td>
</tr>
<tr>
<td>2011</td>
<td>306684</td>
<td>1176</td>
<td>273</td>
<td>-110534</td>
<td>7060</td>
</tr>
<tr>
<td>2012</td>
<td>158214</td>
<td>607</td>
<td>871</td>
<td>-57023</td>
<td>18422</td>
</tr>
<tr>
<td>2013</td>
<td>668833</td>
<td>2564</td>
<td>13</td>
<td>-241058</td>
<td>206</td>
</tr>
<tr>
<td>2014</td>
<td>544902</td>
<td>2089</td>
<td>202</td>
<td>-196391</td>
<td>2370</td>
</tr>
<tr>
<td>2015</td>
<td>393519</td>
<td>1509</td>
<td>1032</td>
<td>-141830</td>
<td>7275</td>
</tr>
<tr>
<td>2016</td>
<td>259301</td>
<td>994</td>
<td>0</td>
<td>-93456</td>
<td>0</td>
</tr>
</tbody>
</table>

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)

\[
TB_{SW,L,t} = AGB_{SW,L,t} \times (1 + R_{dh})
\]

where:
- \(TB_{SW,L,t}\) = Total biomass loss in year \(t\) in Softwood Plantations; tB
- \(AGB_{SW,L,t}\) = AGB loss in year \(t\) in Softwood Plantations; tB
- \(R_{dh}\) = 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.
2.4. Enhancement of forest carbon stocks

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

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

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

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)

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

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

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

\[
MAIC_{SW} = MAIB_{SW} \times \eta_{CF}
\]

$MAIC_{SW}$ = 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$^{-1}$

$\eta_{CF}$ = 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 $\Delta C_{SW,G}$).

\[
\Delta C_{SW,G,t} = \delta_{t} \times A_{SW,PL,t} \times MAIC_{SW}
\]

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

$\delta_{t}$ = 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.
2.4. Enhancement of forest carbon stocks

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)

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

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

\[ MAIC_{SW} = \text{Mean annual C increment in Softwood Plantations; } tC \text{ ha}^{-1} \text{ yr}^{-1} \]

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**

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

\[ \delta'_t = \text{The time a compartment logged in year } t \text{ grew during the Reference Period, } \delta'_t = t - 2016 + 10.5, \text{ i.e., the reversal of } \delta_t; \text{ yrs} \]

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

\[ MAIC_{SW} = \text{Mean annual C increment in Softwood Plantations; } tC \text{ ha}^{-1} \text{ yr}^{-1} \]

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)**

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

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

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

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

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

Average annual gross removals from Softwood Plantations were estimated as follows.
2.4. Enhancement of forest carbon stocks

Equation 2.61: Average annual net emissions (SW)

\[ \hat{\theta}_{EC\text{S}\text{r}e} = \Delta C_{SW,G} \times \eta_{CC} \]

\( \hat{\theta}_{EC\text{S}\text{r}e} \) = Average annual gross removals from Softwood Plantations; tCO₂e 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
\( \eta_{CC} \) = Conversion factor carbon to CO₂ (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, \( \hat{\theta}_{EC\text{S}em} \), and average annual gross removals, \( \hat{\theta}_{EC\text{S}\text{r}e} \).

Equation 2.61: Average annual net emissions (SW)

\[ \hat{\theta}_{EC} = \hat{\theta}_{EC\text{S}em} + \hat{\theta}_{EC\text{S}\text{r}e} \]

\( \hat{\theta}_{EC} \) = Average annual net emissions from Softwood Plantations; tCO₂e yr⁻¹
\( \hat{\theta}_{EC\text{S}em} \) = Average annual gross emissions from Softwood Plantations; tCO₂e yr⁻¹
\( \hat{\theta}_{EC\text{S}\text{r}e} \) = Average annual gross removals from Softwood Plantations; tCO₂e 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

\[ \hat{\theta}_{ECH\text{S}em} = \hat{\theta}_{ECH\text{em}} + \hat{\theta}_{EC\text{S}em} \]

\( \hat{\theta}_{ECH\text{S}em} \) = Average annual gross emissions from Forest Plantations; tCO₂e yr⁻¹
\( \hat{\theta}_{ECH\text{em}} \) = Average annual gross emissions from Hardwood Plantations; tCO₂e yr⁻¹
\( \hat{\theta}_{EC\text{S}em} \) = Average annual gross emissions from Softwood Plantations; tCO₂e 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).
2. Emissions by source and removals by sink

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; tCO₂e yr\(^{-1}\)
\( \hat{\theta}_{ECHre} \) = Average annual gross removals from Hardwood Plantations; tCO₂e yr\(^{-1}\)
\( \hat{\theta}_{ECSre} \) = Average annual gross removals from Softwood Plantations; tCO₂e 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; tCO₂e yr\(^{-1}\)
\( \hat{\theta}_{ECH} \) = Average annual net emissions from Hardwood Plantations; tCO₂e yr\(^{-1}\)
\( \hat{\theta}_{ECS} \) = Average annual net emissions from Softwood Plantations; tCO₂e 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 tCO₂e 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.

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

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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 $R_{wt}$ (used as input in Equation (2.35)); large source, relevant; included in the quantification of uncertainty.
   d) Uncertainty attached to conversion factors, $\eta_{CF}$ and $\eta_{CC}$ (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, $\lambda_{Pine}$ (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, $\rho_{Pine}$ (used as input in Equation (2.48)); medium source, relevant; included in the quantification of uncertainty.
   d) Uncertainty attached to $R_{dih}$ (used as input in Equation (2.49)); large source, relevant; included in the quantification of uncertainty.
2. Emissions by source and removals by sink

e) Uncertainty attached to conversion factors, $\eta_{CF}$ and $\eta_{CC}$ (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 $R = 4 \times 10^4$. The estimates $\hat{\theta}_{EC_{erm}}$, $\hat{\theta}_{EC_{Herm}}$, $\hat{\theta}_{EC_{erm}}$, $\hat{\theta}_{EC_{HRm}}$, $\hat{\theta}_{EC}$, $\hat{\theta}_{ECH}$, and $\hat{\theta}_{ECS}$ were, thus, estimated $R$ 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.

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

$R_{wl}$ 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 $c = MAIV_{HW}$.

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

$A_{HW,PL}$ 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

$$A_{HW,PL,k}^* = \left[ A_{HW,PL,k}^* \times \frac{b}{\sum_{k=1}^{10} A_{HW,PL,k}^*} \right].$$

Five out of the $z$ values of $A_{HW,PL,k}^*$ were randomly drawn and used as input for $A_{HW,PL}$ for the years 2006 to 2010.
### 2.4. Enhancement of forest carbon stocks

Values of $\lambda_{\text{Pin}}$ were drawn from a Normal distribution with $\mu = \lambda_{\text{Pin}}$ and $\sigma^2 = [\lambda_{\text{Pin}} \times 0.1]^2$ \cite{Waterloo, 1994}.

Values of $\rho_{\text{Pin}}$ were drawn from a Normal distribution with $\mu = \rho_{\text{Pin}}$ and $\sigma^2 = 0.0031$ (\(\sigma^2\) was estimated from data provided in \cite{Cown, 1981}).

$R_{dlh}$ 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 \cite[Vol. 4, Chap. 4, Tab. 4.4]{IPCC, 2006}.

$MAIB_{SW}$ 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 $c = MAIB_{SW}$.

$CC_{SW}$ 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 $\hat{\theta}_{EC_{cm}}, \hat{\theta}_{ECH_{cm}}, \hat{\theta}_{EC_{Sem}}, \hat{\theta}_{EC_{rm}}, \hat{\theta}_{ECH_{rm}}, \hat{\theta}_{EC_{Srm}}, \hat{\theta}_{EC_{r}}, \hat{\theta}_{ECH},$ 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.
2. Emissions by source and removals by sink
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.

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

\(\hat{\theta}_{em}\) = Overall average annual gross emissions; tCO₂e yr⁻¹
\(\hat{\theta}_{DF}\) = Average annual emissions from deforestation; tCO₂e 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), \(\hat{\theta}_{FDBem}\); tCO₂e yr⁻¹
\(\hat{\theta}_{ECem}\) = Average annual gross emissions from timber extraction in Forest Plantations (Hard- and Softwood Plantations); tCO₂e 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:

\[
\hat{\theta}_{re} = \hat{\theta}_{FDre} + \hat{\theta}_{ECre}
\]

\(\hat{\theta}_{re}\) = Overall average annual gross removals; tCO₂e yr⁻¹
\(\hat{\theta}_{FDre}\) = Average annual gross removals after logging in Natural Forest (i.e., re-growth after logging); tCO₂e yr⁻¹
\(\hat{\theta}_{ECre}\) = Average annual gross removals from afforestation/reforestation and growth in Hard- and Softwood Plantations; tCO₂e yr⁻¹
3. Fiji’s Forest Reference Level 2006-2016

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.

\[
\hat{\theta}_{FRL} = \hat{\theta}_{em} + \hat{\theta}_{re}
\]

\(\hat{\theta}_{FRL}\) = Overall average annual net emissions over the Reference Period in the Accounting Area, i.e., the Forest Reference Level (FRL); tCO\(_2\)e yr\(^{-1}\)

\(\hat{\theta}_{em}\) = Average annual gross emissions (including all sources); tCO\(_2\)e yr\(^{-1}\)

\(\hat{\theta}_{re}\) = Average annual gross removals (including all sinks); tCO\(_2\)e 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\(_2\)e 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.

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

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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.


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.


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).

$$W_i = A_i / A,$$

$W_i$ = 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
A. Emissions from deforestation

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 \( \sum_n n_i = n = 1948 \); \( W_i = A_i / \sum_A A_i \); \( A_i \) is the area mapped as class \( i \) [ha].

<table>
<thead>
<tr>
<th>Reference class</th>
<th>111</th>
<th>112</th>
<th>171</th>
<th>172</th>
<th>711</th>
<th>712</th>
<th>777</th>
<th>( n_i )</th>
<th>( A_i ) [ha]</th>
<th>( W_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mapped class</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>111</td>
<td>218</td>
<td>0</td>
<td>14</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>8</td>
<td>248</td>
<td>670,300</td>
<td>0.4459115</td>
</tr>
<tr>
<td>112</td>
<td>0</td>
<td>232</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>244</td>
<td>229,098</td>
<td>0.1524053</td>
</tr>
<tr>
<td>171</td>
<td>68</td>
<td>0</td>
<td>137</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>22</td>
<td>233</td>
<td>54,406</td>
<td>0.0361931</td>
</tr>
<tr>
<td>172</td>
<td>0</td>
<td>77</td>
<td>0</td>
<td>141</td>
<td>0</td>
<td>8</td>
<td>28</td>
<td>254</td>
<td>9,834</td>
<td>0.0065422</td>
</tr>
<tr>
<td>711</td>
<td>81</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>144</td>
<td>0</td>
<td>21</td>
<td>253</td>
<td>33,742</td>
<td>0.0224468</td>
</tr>
<tr>
<td>712</td>
<td>0</td>
<td>88</td>
<td>0</td>
<td>9</td>
<td>0</td>
<td>121</td>
<td>18</td>
<td>236</td>
<td>3,489</td>
<td>0.0023212</td>
</tr>
<tr>
<td>777</td>
<td>13</td>
<td>21</td>
<td>12</td>
<td>14</td>
<td>7</td>
<td>46</td>
<td>480</td>
<td>502,344</td>
<td>1.0000000</td>
<td>0.3341799</td>
</tr>
<tr>
<td>Total</td>
<td>380</td>
<td>418</td>
<td>170</td>
<td>171</td>
<td>165</td>
<td>139</td>
<td>505</td>
<td>1,948</td>
<td>1,503,213</td>
<td>1.0000000</td>
</tr>
</tbody>
</table>

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)

\[
\hat{p}_{ij} = W_i \frac{n_{ij}}{n_i},
\]

\( \hat{p}_{ij} \) = 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 \( j \)
\( n_i \) = 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). \( p_i \) = \( W_i \) gives the row sum of class \( i \); \( A_i \) is the area [ha] mapped as class \( i \).

<table>
<thead>
<tr>
<th>Reference</th>
<th>111</th>
<th>112</th>
<th>171</th>
<th>172</th>
<th>711</th>
<th>712</th>
<th>777</th>
<th>( p_i )</th>
<th>( A_i ) [ha]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Map</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>111</td>
<td>0.3920</td>
<td>0.0000</td>
<td>0.0252</td>
<td>0.0000</td>
<td>0.0144</td>
<td>0.0000</td>
<td>0.0144</td>
<td>0.4459</td>
<td>670,300</td>
</tr>
<tr>
<td>112</td>
<td>0.0000</td>
<td>0.1449</td>
<td>0.0000</td>
<td>0.0044</td>
<td>0.0000</td>
<td>0.0019</td>
<td>0.0012</td>
<td>0.1524</td>
<td>229,098</td>
</tr>
<tr>
<td>171</td>
<td>0.0106</td>
<td>0.0000</td>
<td>0.0213</td>
<td>0.0000</td>
<td>0.0009</td>
<td>0.0000</td>
<td>0.0034</td>
<td>0.0362</td>
<td>54,406</td>
</tr>
<tr>
<td>172</td>
<td>0.0000</td>
<td>0.0020</td>
<td>0.0000</td>
<td>0.0036</td>
<td>0.0000</td>
<td>0.0002</td>
<td>0.0007</td>
<td>0.0065</td>
<td>9,834</td>
</tr>
<tr>
<td>711</td>
<td>0.0072</td>
<td>0.0000</td>
<td>0.0066</td>
<td>0.0000</td>
<td>0.0128</td>
<td>0.0000</td>
<td>0.0019</td>
<td>0.0224</td>
<td>33,742</td>
</tr>
<tr>
<td>712</td>
<td>0.0000</td>
<td>0.0009</td>
<td>0.0000</td>
<td>0.0001</td>
<td>0.0000</td>
<td>0.0012</td>
<td>0.0002</td>
<td>0.0023</td>
<td>3,489</td>
</tr>
<tr>
<td>777</td>
<td>0.0091</td>
<td>0.0146</td>
<td>0.0084</td>
<td>0.0097</td>
<td>0.0049</td>
<td>0.0049</td>
<td>0.2827</td>
<td>0.3342</td>
<td>502,344</td>
</tr>
<tr>
<td>Total</td>
<td>0.4188</td>
<td>0.1624</td>
<td>0.0554</td>
<td>0.0178</td>
<td>0.0330</td>
<td>0.0081</td>
<td>0.3045</td>
<td>1.0000</td>
<td>1,503,213</td>
</tr>
</tbody>
</table>

The column sums of the error matrix showing estimated proportions (row ‘Total’ in Table A.2), represent the estimated area proportions, \( \hat{p}_{j} \).
Equation A.3: Estimated proportions of land-cover classes

\[ \hat{p}_j = \sum_{i=1}^{q} \hat{p}_{ij}, \]

\( \hat{p}_j \) = Estimated area proportion of class \( j \)
\( \hat{p}_{ij} \) = Estimated area proportion of map class \( i \) and reference class \( j \), where
1, 2, ..., \( i \), ..., \( q \) 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., \( \hat{A}_{171} \) and \( \hat{A}_{172} \), and the sub-sink afforestation/reforestation, i.e., \( \hat{A}_{711} \) and \( \hat{A}_{712} \) (see Section 2.2.2 and Section 2.4.1).

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

\[ \hat{A}_j = A \times \hat{p}_j, \]

\( \hat{A}_j \) = Estimated area of class \( j \); ha
\( A \) = Total area mapped; ha
\( \hat{p}_j \) = Estimated area proportion of class \( j \)

Olofsson et al. [2014] provides estimators to estimate the standard errors of the area estimates, \( \hat{A}_j \). 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

BADD\textsubscript{DF}.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., \( n_i^* = n_i \).

BADD\textsubscript{DF}.2 An error matrix was derived from \( S^* \) and Equation (A.2) to Equation (A.3) were used to obtain an estimate of \( \hat{A}_j^* \).

BADD\textsubscript{DF}.3 Step BADD\textsubscript{DF}.1 to BADD\textsubscript{DF}.2 were repeated \( R = 4 \times 10^4 \) times, delivering \( R \) estimates of \( \hat{A}_j^* \), i.e., \( \hat{A}_j^* = \{ \hat{A}_{j,1}^*, \hat{A}_{j,2}^*, ..., \hat{A}_{j,r}^*, ..., \hat{A}_{j,R}^* \} \).

BADD\textsubscript{DF}.4 Lower and upper bounds of the confidence interval of \( \hat{A}_j \) 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 where 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

\[
W_{closed} = \frac{A_{closed}}{A_{NFI}} = 0.754; \quad W_{open} = \frac{A_{open}}{A_{NFI}} = 0.246.
\]

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 $\geq 20$ 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 $\geq 5$ 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.
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 then use Eq. 4 in Chave et al. [2014] to predict the AGB of NFI 2006 trees.

\[ AGB_k = \beta_0 (\rho_k h_k d_k^2) \beta_1 + \epsilon_k \]

where \( AGB_k \) is the biomass in kilograms of the \( k \)th tree, \( \rho_k \) is the wood density (defined as the oven-dry mass divided by green volume; \( \text{g cm}^{-3} \)), \( h_k \) is the total tree height [m], \( d_k \) is the DBH [cm], \( \beta_0 \) and \( \beta_1 \) are model parameters, and \( \epsilon_k \) 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). 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

\[ h_k = \beta_0 + \ln(d_k) \beta_1 + \epsilon_k \]

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

\[ \text{Link: http://chave.ups-tlse.fr/pantropical_allometry.htm} \]
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, $\rho$, 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

\[
\hat{A}GB_k = 1000^{-1}[\hat{\beta}_0 + \hat{\beta}_1(\hat{\rho}_k \hat{h}_k d_k^2)]
\tag{A.8}
\]

where $\hat{A}GB_k$ is the predicted AGB [t] of the $k$th 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

\[
AGB_{i,r_c} = \sum_{k=1}^{m_{i,r_c}} \hat{A}GB_k
\tag{A.9}
\]

where $AGB_{i,r_c}$ is the aggregated AGB [t] on the $i$th cluster plot on circles with radius $r_c$, with $c = \{1, 2\}$, $m_{i,r_c}$ is the number of trees on the $i$th plot on circles with radius $r_c$, and $\hat{A}GB_k$ is given in Equation (A.8). The plot AGB was expanded to the hectare using the expansion factors

\[
EF_{r_c} = [5 \times a_{r_c}]^{-1} \times 10000
\]

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 $i$th NFI plot was computed by

\[
AGB_{i,r_c} = AGB_{i,r_c} \times EF_{r_c}.
\]

\[
EF_{r_1} = 5
\]

\[
EF_{r_2} = 20
\]
Total AGB [t ha$^{-1}$] (i.e., from the large and small circle) was computed for each plot by

$$AGB_i = \sum_c AGB_{i,c}.$$  \hspace{1cm} (A.13)

### 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 $\geq 600$ 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\(^\text{i}^\) 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

\(^{i}\text{Available at: https://cgiarcsi.community/data/global-aridity-and-pet-database/} \)
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 $\text{ha}^{-1}$ 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 $\text{ha}^{-1}$ 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 $C$ $\text{ha}^{-1}$ of plots in each stratum.

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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 \([t \text{ ha}^{-1}]\) 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 \([t \text{ ha}^{-1}]\) of the \(i\)th 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.

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]

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

where $\bar{C}_d$ is the average C [t ha$^{-1}$] in the $d$th 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 $d$th 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 $i$th 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:
A. Emissions from deforestation

Uncertainty analysis: emission factors (EF) deforestation

**S\textsubscript{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 trees recorded during the NFI 2006 were predicted using the following procedure:

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

**S\textsubscript{ED}.1.2** A height model was fitted to the sample \(S\textsubscript{PSP}^*\) using Equation (A.7) to obtain \(\hat{\beta}_0^*\) and \(\hat{\beta}_1^*\). The heights of trees in \(S\textsubscript{PSP}^*\) 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 \(j\)th tree in \(S\textsubscript{PSP}^*\) and \(\epsilon_{h,j}^* = h_j^* - \hat{h}_j^*\).

**S\textsubscript{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 \(g\)th group,

\[
\tilde{\sigma}_{h,g}^* = \frac{1}{n_g} \sum_{j=1}^{n_g} \epsilon_{h,j}^* \quad \text{and} \quad \sigma_{h,g}^2 = \frac{1}{n_g - 1} \sum_{j=1}^{n_g} \epsilon_{h,j}^2
\]

were calculated were \(n_g\) is the number of triplets in the \(g\)th group; (4) the association between \(\sigma_{h,g}^*\) and \(\tilde{\sigma}_{h,g}^*\) was estimated using a linear model through the origin as

\[
\tilde{\sigma}_{h,g}^* = \tilde{\gamma}_h^* \times \tilde{h}_g^*
\]

where \(\gamma^*\) is a model parameter.

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

**S\textsubscript{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 \( m_{PTHD}^\ast \) was drawn from the PTHD dataset (see Appendix B.2) using SRSwR, where \( m_{PTHD}^\ast = m_{PTHD} \) and \( m_{PTHD} = 4004 \) is the number of trees in the PTHD dataset. The bootstrap sample is denoted by \( S_{PTHD}^\ast \). Trees in \( S_{PTHD}^\ast \) are indexed by \( 1, 2, \ldots, m_{PTHD}^\ast \).

S_{ED}.2.2 A biomass model was fitted to \( S_{PTHD}^\ast \) using Equation (A.6) to obtain \( \hat{\beta}_0^\ast \) and \( \hat{\beta}_1^\ast \). The AGB of trees in \( S_{PTHD}^\ast \) was predicted using the fitted model. The fitted model is denoted by \( f_{PTHD}^\ast \) and the predicted AGB of the \( l \)th tree in \( S_{PTHD}^\ast \) is denoted by \( \hat{AGB}_l^\ast \); \( AGB_l^\ast \) is the measured AGB of the \( l \)th tree in \( S_{PTHD}^\ast \) and \( \epsilon_{AGB,l}^\ast = AGB_l^\ast - \hat{AGB}_l^\ast \).

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

S_{ED}.2.4 The AGB of the \( k \)th NFI 2006 tree was predicted using \( f_{PTHD}^\ast \). The input height \( h_k \) in \( f_{PTHD}^\ast \) was substituted by \( \hat{h}_k^\prime \) (see S_{ED}.1.4), \( d_k \) and \( \rho_k \) were substituted by \( d_k^\prime \sim N(d_k, [d_k \times .1]^2) \) and \( \rho_k^\prime \sim N(\rho_k, s(\rho_k)^2) \) where \( d_k^\prime \) 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 \( \rho_k^\prime \), was taken from Chave et al. [2009] and Zanne et al. [2009]. Hence,

\[
\hat{AGB}_k^\prime = \hat{\beta}_0^\ast \times (\rho_k^\prime d_k^\prime h_k^\prime)^{\hat{\beta}_1^\ast}.
\]

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)

\[
\begin{align*}
R_{ud}^\ast &= Tri(c = R_{ud}, a = R_{ud} - R_{ud} \times 0.25, b = R_{ud} + R_{ud} \times 0.25) \\
R_{dl}^\ast &= Tri(c = R_{dl}, a = 0.09, b = 0.25) \\
R_{dh}^\ast &= Tri(c = R_{dh}, a = 0.22, b = 0.33) \\
R_u^\ast &= Tri(c = R_u, a = 0.269, b = 0.28)
\end{align*}
\]

where \( R_{ud} = 0.37, R_{dl} = 0.2, R_{dh} = 0.24 \), and \( R_u = 0.27 \) (see IPCC [2006, Vol. 4, Chap. 4, Tab. 4.4]).
A. Emissions from deforestation

$S_{ED.4}$ 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).

$S_{ED.5}$ $S_{ED.4}$ to $S_{ED.4}$ were repeated $\mathcal{R} = 4 \times 10^4$ times, delivering $\mathcal{R}$ estimates of $C_d$. 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 \( \geq 25 \) cm DBH were recorded. On two squared sub-plots of size 20×20 m, attributes were recorded on trees with DBH \( \geq 10 \) cm and < 25 cm. On two circular plots (radius 3 m), attributes were recorded on trees with DBH \( \geq 3 \) 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. Data

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\(^1\). 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, \( \rho \), 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\(^2\). 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,

\(^1\)Web: http://chave.ups-tlse.fr/pantropical_allometry.htm
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* [SÉNECLAUZE 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 [m³] 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 m³ 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 $< 2 = \text{dry}; \geq 2 = \text{wet}$; 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 $R = 4 \times 10^4$ MC estimates of target parameters. Here, $\theta_{FDem}$ 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 $\theta_{FDem}$ is denoted by $\hat{\Theta}^{*}_{FDem} = \{\hat{\theta}^{*}_{FDem,1}, \hat{\theta}^{*}_{FDem,2}, \ldots, \hat{\theta}^{*}_{FDem,r}, \ldots, \hat{\theta}^{*}_{FDem,R}\}$.

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 $\theta_{FDem}$ that was reported for the FRL, is the estimate that is computed using Equation (2.14). The uncertainty that is reported for $\theta_{FDem}$, i.e., its precision, is derived from the distribution of the $R$ MC estimates. The distribution of the $R$ 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 $\theta_{FDem}$ and $\theta_{F Dre}$, the set of combined estimates, $\hat{\Theta}_{FD}$ (Section 2.3.2.3), is obtained as follows

$\hat{\Theta}_{FD} = \{\hat{\theta}^{*}_{FDem,1} + \hat{\theta}^{*}_{F Dre,1}, \ldots, \hat{\theta}^{*}_{FDem,r} + \hat{\theta}^{*}_{F Dre,r}, \ldots, \hat{\theta}^{*}_{FDem,R} + \hat{\theta}^{*}_{F Dre,R}\}$.

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 $R$ is the same for the independent MC simulations.
C. Uncertainty analysis

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, \( \mu \), and its variance, \( \sigma^2 \). 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, \( \sigma \), for an input was available, e.g., for the wood density \( \rho \) 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 Triangular distribution was used. The Triangular distribution is denoted by \( \text{Tri}(c, a, b) \), where \( c \) is the mode (the peak of the Triangular 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
C. Uncertainty analysis

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 \( \mu_y = N^{-1} \sum_{k} y_k \), where 1, 2, ..., \( k \), ..., \( N \) is an index of the population elements. The sample mean \( \bar{y} \) is estimated from the sample, i.e., \( \bar{y} = n^{-1} \sum_{k} y_k \), an provides an estimate of the unknown \( \mu_y \). 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 (\( R \) times), delivering \( R \) 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 \texttt{R} [\textit{R Core Team}, 2019].

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sessioninfo::session_info()

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## collate en_US.UTF-8
## ctype en_US.UTF-8
## tz Europe/Berlin
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##
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D. Software

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