

Annex 8-3 – Estimation of Emission and Removal Factors

The procedures followed for generating the emission and removal factors for estimation of the forest reference level of Fiji is elaborated below.

A8.2.1 Emission Factors for Natural Forests

The emissions factors for above- and below ground biomass of natural forests were generated using two datasets - the National Forest Inventory and the Permanent Sample Plot Inventory.

National Forest Inventory

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) 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 is available that details how the unsupervised classification was conducted. Moreover, no map accuracy assessment was conducted to quantify the quality of the forest cover map. The NFI 2006 covered the islands of Viti Levu, Vuanua Levu, Tavauni, Kadavu, Gau, Koro and Ovalau. Stratified simple random sampling was used for the NFI 2006, where the mapped classes closed and open forest served as strata. The number of observations in the strata closed and open forest were $n_{\text{closed}} = 731$ and $n_{\text{open}} = 292$, respectively. The total sample size was $n = 1023$. Sample plot locations were randomly placed within the strata in a geographic information system (GIS).

Cluster plots with five nested circular cluster sub-plots were used for the NFI 2006 (Figure 1). On the large sub-plot circle with radius $r_1 = 11.28$ m ($A_{r1} = 400$ m²), 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 for all living trees with 20 cm DBH. On the circle with radius $r_2 = 5.64$ m ($A_{r2} = 100$ m²), the DBH and species were recorded on all trees between 5 cm and < 20 cm DBH. In 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 2006-04-03 and 2007-12-11.

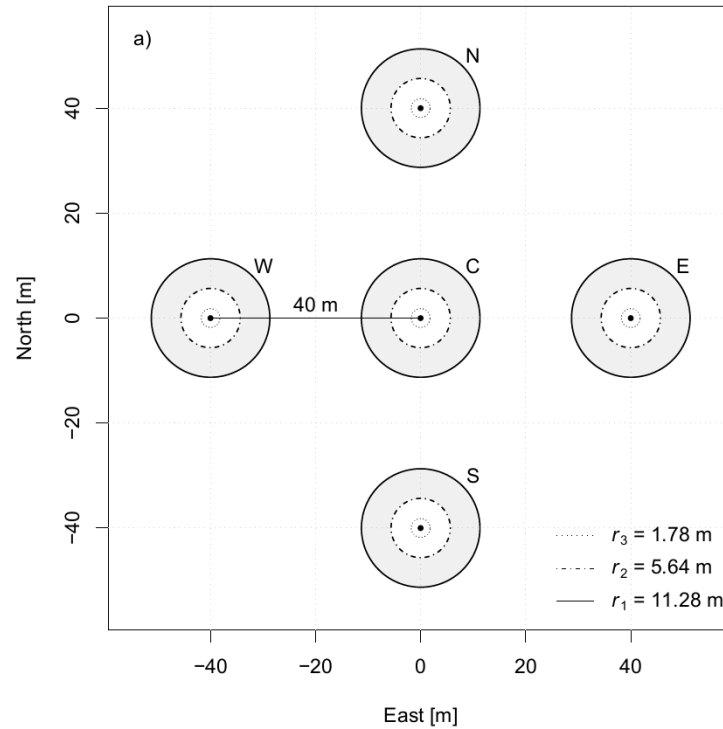


Figure 1.: Sample plot design used for the NFI 2006

Fiji's Permanent Sample Plot Inventory

Fiji's PSP program overlaps the entire ER Program Accounting Area (systematic sample plot location over the three 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 12x12 km, and on Taveuni 15x15 km. The attributes of trees have been recorded on $n_P \text{ SP} = 86$ plots in 2010, 2012, 2014, 2016 and 2018.

Fiji's Permanent Sample Plot (PSP) program started in 2010. The primary purpose of initiating the 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.

The PSP plot design is shown in Figure 2. On the large square 50x50 m, the DBH [cm], total tree height [m] and species was recorded on all living trees with DBH 25 cm. On the two 20x20 m subplots the DBH [cm], total tree height [m] and species was recorded on all living trees between 5 cm and < 25 cm DBH. The number of PSP tree records in the first measurement round of the PSP program (2010) was $m_{PSP} = 5331$.

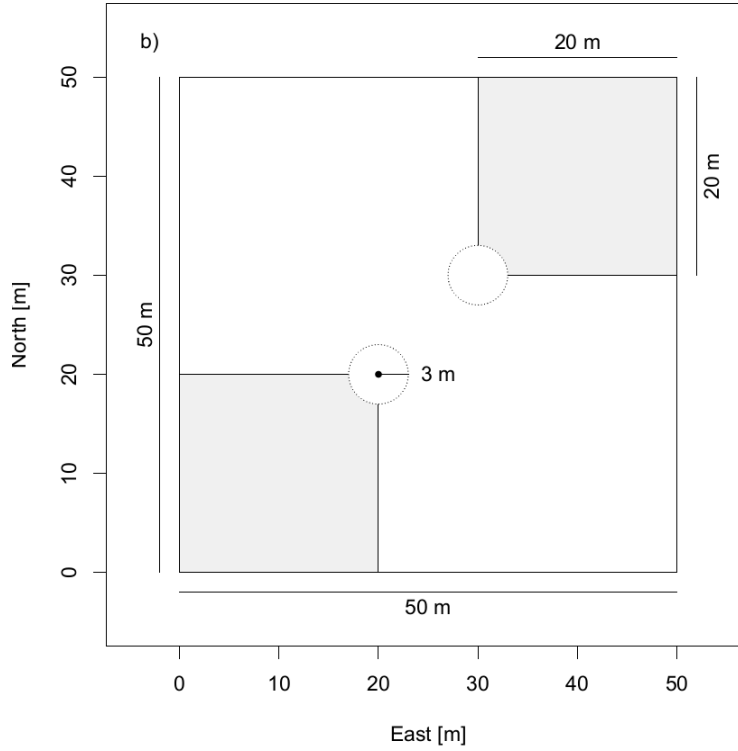


Figure 2: Sample plot design used for Fiji's Permanent Sample Plot (PSP) program

Carbon stocks in closed / open forest compared to upland / lowland forest

For the NFI 2006, stratified sampling was used. The two strata applied to the sampling design were closed and open forest. Although these two strata are reported in FAO FRA statistics, these were not retained for the FRL estimation as the activity data to differentiate closed and open forest were not available through the available remote sensing imagery.

The mean carbon stock [tC ha^{-1}] in closed and open forest were computed by simply taking the average tC ha^{-1} of plots in each stratum:

$$\bar{C}_h = n_h^{-1} \sum_{S_h} C_i \quad (\text{A})$$

Where;

$\bar{C}_h$ = average [t ha^{-1}] in stratum h,

n_h = sample size in stratum h,

S_h = set of sample plots in stratum h and C_i is the predicted C [t ha^{-1}] of the i^{th} NFI plot.

Note that for the strata closed and open forest the subscript h is used.

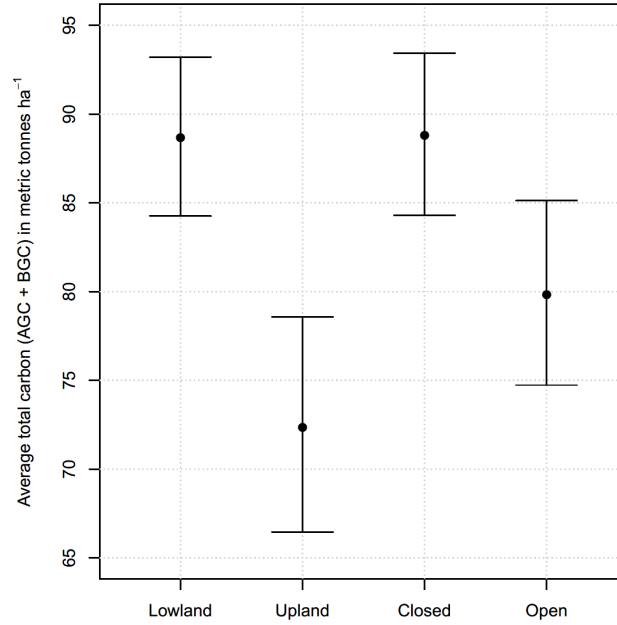


Figure 3: Estimated average total carbon stocks (TC = AGC + BGC) in t ha⁻¹ in Lowland Upland Natural Forest and closed and open forest. Vertical bars give 90%-confidence intervals obtained from MC simulations.

Figure 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 (84.29; 93.44) tC ha⁻¹ and at 78.97 (74.73; 85.12) tC ha⁻¹ in open forest.

The decision to investigate any significant difference between Upland and Lowland forest was made 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. Above 600 m a.s.l. Fijian forests tend to 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.

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 Lowland Natural Forest and Upland Natural Forest within the ER Program Accounting Area.

To estimate the average C stock [t ha⁻¹] for the two domains, the estimator for the domain mean for stratified sampling was used [Särndal et al., 1992, page 349]

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

Where;

$\bar{C}_d$ = average C [t ha⁻¹] in the dth domain (Low-or Upland Natural Forest within the FRL Accounting Area),

H = the set of strata (closed and open forest),

N_h = strata size (Aclosed and Aopen),

n_h = sample size in stratum h,

S_{dh} = intersection of the sample plots in the d^{th} domain and the sample plots drawn in stratum h

ns_{dh} = the random size of this intersection

C_i = the C [t ha^{-1}] on the i^{th} NFI plot

The sample sizes in the domains Low-and Upland Natural Forest were $n_{\text{Lowland}} = 903$ and $n_{\text{Upland}} = 120$. The average C stock in Lowland Natural Forest was estimated at 87.86 (84.25; 93.22) tC ha^{-1} and at 71.57 (66.45; 78.58) tC ha^{-1} in Upland Natural Forest. They were found to be significantly different.

Additional investigation work is planned to improve the NFI design and data analysis with the aim of determining Open and Closed Forest carbon stocks. This work will be conducted in conjunction with the step-wise approach to incorporating direct measurement and estimation of forest degradation in Fiji's National Forest Monitoring System.

Carbon Stocks in Upland and Lowland Forest

Carbon stocks in Natural Forest were estimated based on data collected during Fiji's National Forest Inventory (NFI) 2006. The methods used to derive estimates of C stocks in Low-and Upland Natural Forest and associated estimates of precision from this data set are described in the following sections.

Aboveground Biomass

To predict the aboveground biomass (AGB) of individual trees captured in the NFI 2006, a biomass model (allometric equation) published in Chave et al. [2014]¹ was used in the absence of a country specific allometric model in Fiji. The selection of the allometric equation followed a process of assessing several candidate models selected from the literature (e.g., models found in Chave et al. [2005] and Chave et al. [2014]).

Initially, Equation 7 in Chave et al. [2014] was selected as the most promising candidate model because it does not rely on measures of tree height. Total tree height was not measured during the NFI 2006 field campaigns. Equation 7 instead applies a substitute for tree height (i.e., a so-called environmental stress factor).

A suitability test was conducted using Fiji's PSP data set which provides data on DBH and total tree height. This data set enabled a comparison between Equation 4 and 7 from Chave et al. [2014]. This suitability test found that predicted tree aboveground biomass was much higher when using Equation 7 with the environmental stress factor (as a substitute for trees height) compared to using the measured heights in Equation 4. It was found that the environmental stress factor assumes much taller trees in Fiji 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 Equation 4 in Chave et al. [2014] to predict the AGB of NFI 2006 trees.

¹ Specifically, Equation 4 listed in this publication was used.

Equation 4 in Chave et al. [2014] takes the following form:

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

where

AGB_k = the biomass in kilograms of the k^{th} tree

ρ_k = wood density (defined as the oven-dry mass divided by green volume; $g\ cm^{-3}$),

h_k = total tree height [m],

d_k = diameter at breast height (DBH) [cm],

β_0 and β_1 = model parameters, where $\hat{\beta}_0 = 0.0643$ and $\hat{\beta}_1 = 0.979$

ϵ_k is the residual error term.

The data that were used by Chave et al. [2014] to derive the parameter estimates for Eq. 4 are publicly available on the web (see Pan-tropical tree harvest database [PTHD]). The PTHD dataset was downloaded and the model (Equation A) 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]: where $\hat{\beta}_0 = 0.0632$ and $\hat{\beta}_1 = 0.979$.

The reason for refitting Chave et al. [2014] Equation 4 was that the AGB model (Equation A) was refitted several times during the Monte Carlo (MC) simulations using bootstrap samples from PTHD. To ensure that the parameter estimates $\hat{\beta}_0$ and $\hat{\beta}_1$ and the 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. The number of sample plots that were used to fit the PSP height model was $n_{PSP} = 86$. 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 which took the following simple form:

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

Model parameters were estimated as: $\hat{\beta}_0 = -4.682$ and $\hat{\beta}_1 = 5.372$.

The fit was poor with an $R^2 = 0.44$. This lack of fit was accounted for in the uncertainty analysis. Using Equation (B), the height of all $m = 76968$ NFI 2006 trees recorded was predicted.

Wood density for use in Equation A, 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 formed the input.

The AGB of individual NFI 2006 trees was finally predicted using:

$$\hat{AGB}_k = 1000^{-1} \left[\hat{\beta}_0' \left(\hat{\rho}_k \hat{h}_k \hat{d}_k^2 \right)^{\hat{\beta}_1'} \right] \quad (E)$$

Where;

$\hat{AGB}_k$ = predicted AGB [t] of the k^{th} NFI 2006 tree,

$\hat{\rho}_k$ = estimated wood density [$g\ cm^{-3}$]

$\hat{h}_k$ = predicted tree height [m]

$\hat{d}_k$ = measured DBH [cm]

The AGB for an NFI 2006 plot was predicted by first aggregating the AGB of individual trees at the different circle sizes:

$$AGB'_{i,r_c} = \sum_{k=1}^{m_{i,r_c}} \hat{AGB}_k \quad (F)$$

Where;

AGB'_{i,r_c} = the aggregated AGB [t] on the i^{th} cluster plot on circles with radius r_c , with $c = \{1, 2\}$

m_{i,r_c} = the number of trees on the i^{th} plot on circles with radius r_c

$\hat{AGB}_k$ is given in Equation (C).

The plot AGB was expanded to the hectare using the expansion factors:

$$EF_{r1} = [5 \times a_{r1}]^{-1} \times 10000 = 5 \quad (G)$$

$$EF_{r2} = [2 \times a_{r2}]^{-1} \times 10000 = 20 \quad (H)$$

Where;

$a_{r1} = 400\ m^2$

$a_{r2} = 100\ m^2$

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:

$$AGB_{i,r_c} = AGB'_{i,r_c} \times EF_{r_c} \quad (I)$$

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

$$AGB_i = \sum_i AGB_{i,c} \quad (J)$$

Belowground Biomass

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.

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 (Figure 1). Table 1 provides an overview on climatic and altitudinal zonation, as well as the values of R used for the different zones.

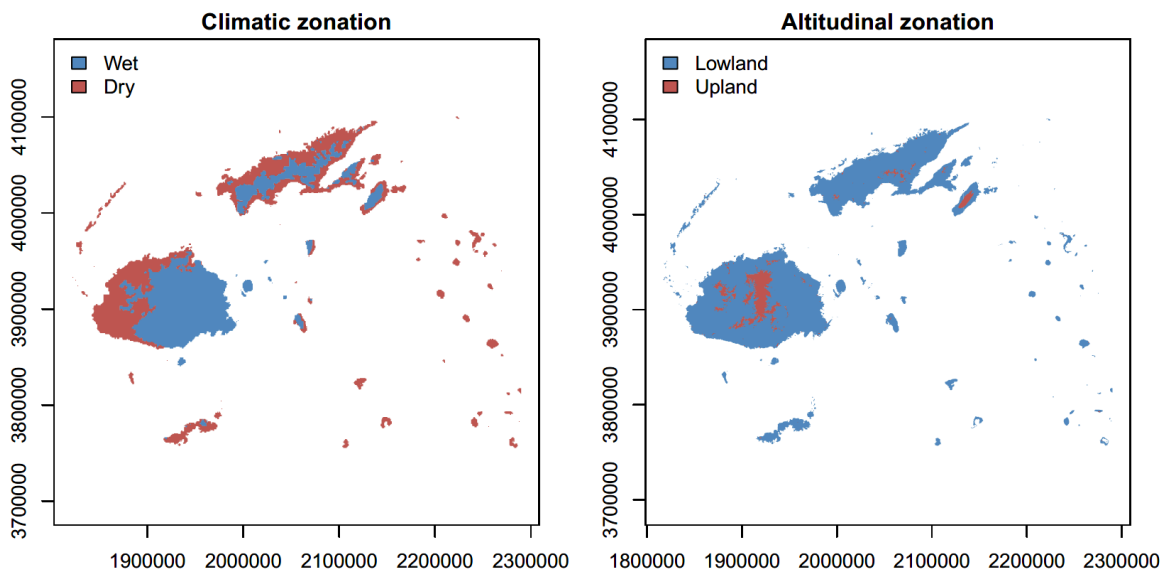


Figure 4: Climatic and altitudinal zonation used to select root-to-shoot ratios from IPCC [2006, Vol.4, Chap. 4, Tab. 4.4].

Table 1.: Root-to-shoot ratios, R , used to compute below-ground biomass (BGB) from above-ground biomass (AGB) [IPCC, 2006, Vol. 4; Chap. 4; Tab. 4.4].

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

^aClimatic zonation: Wet = Aridity Index (AI) ≥ 2, Dry = AI < 2

^bAltitudinal zonation; Lowland < 600 m a.s.l., Upland ≥ 600 m a.s.l.

^cWL = Wet Lowland, DL = Dry Lowland, DU = Dry Upland, WU = Wet Upland

^d R = root-to-shoot ratio

Total Biomass

Total biomass was obtained by:

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

Where;

TB_i = the total biomass [t ha⁻¹]

AGB_i is given in Equation G,

R_i depends on where a cluster plot is located and is selected based on the zonation given in Table 1

To compute total carbon for each NFI 2006 cluster plot, C_i [t ha⁻¹], TB_i was multiplied by the IPCC default value CF = 0.47 [IPCC, 2006, Vol. 4, Chap. 4, Tab. 4.3].

A8.2.2 Removal Factors for Natural Forests, Afforestation and Reforestation and Plantations

Removals factors within Fiji are in the early stages of investigation and were difficult to find for the FRL calculations. Below presents a description of the process to select/generate removal factors with national relevance from available data. A more detailed description of the calculation methods and applied uncertainty to these factors can be found in Annex 8.3 and 12.1 respectively.

Removal factors for natural forests

Removals occur on areas that have been logged. In logged Natural Forest carbon stock gains are assumed to be slightly higher than carbon stock losses and it is assumed that carbon stocks will not fully recover until the next harvest.

Data on net carbon stock gains after logging in Natural Forest within Fiji have not yet been assessed nationally. For the FRL, data were taken from a limited data set available from the REDD+ pilot site at Nakavu.

The estimated net carbon gain (AGB and BGB) was reported as $0.99 \text{ tC ha}^{-1} \text{ yr}^{-1}$ (Mussong; personal communication; unpublished data). These data currently represent the only data on carbon growth in logged Natural Forest currently available in Fiji. Estimates of variance for carbon stock gains in logged Natural Forest are not available and therefore the uncertainty applied to this emissions factor was set as large in the Monte Carlo simulations (refer to Annex 12.1).

In the future, assessments of regrowth following logging should also be derived for other parts of the REDD+ Accounting Area, e.g., Vanua Levu and Taveuni. The Nakavu site is located in the lower wet area of Viti Levu and increments may be different in more drier areas and areas not located in lowland forest (i.e., 600 m above sea level [a.s.l.]). The PSP data (see Appendix B.1) could not be used for the estimation of C stock gains in Natural Forest due to limitations in data procurement procedures.

Removal Factors for afforestation and reforestation

Mean annual carbon increments on areas of afforestation/reforestation (A/R) of natural forest species have not yet been rigorously assessed in Fiji. For the FRL, data on the mean annual increment (MAI) provided by Fiji Harwood Corporation Limited (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, noting that the MAI provided by FHCL refers to volume increments, i.e., MAIV, and not to C increments.

As the species planted (or naturally regenerated) historically was not known on these identified A/R lands, selection of an appropriate MAIC was challenging. To avoid the risk of underestimating removals from AR for the FRL, the average MAIV over all species reported by FHCL was computed; excluding the MAI from mixed hardwood stands. The value of MAIV used for the FRL was $3.71 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.

Combining this MAIV with a biomass expansion factor of 1.1 (from Table 4.5 in IPCC 2006 Vol.

4, Chap. 4) a root shoot ratio of 0.37 (IPCC, 2006, Vol. 4; Chap. 4; Tab. 4.4) and carbon fraction of 0.47, the mean annual increment in carbon was calculated to be $2.63 \text{ tC ha}^{-1} \text{ yr}^{-1}$.

Removal factors for plantations

Removals from Forest Plantations were estimated based on the MAI reported for Hard-and Softwood Plantations.

Hardwood Plantations

Annual increments of wood volume in Hardwood Plantations were estimated based on data on mean annual volume increments, MAIV_{HW} . Removals were estimated based on data on

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. Table 2 lists increments of tree species managed by FHCL. As FHCL did not report areas planted by species and year, a weighted average of the $MAIV_{HW}$ was calculated using the data from Table 2. Weights were computed by dividing the stocking of a species, A_{HW} in Table 2, by the total of A_{HW} . The average $MAIV_{HW}$ was found to be $5.85 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. Growth functions that would allow to derive current annual increments, CAIV, or the MAIV at different plantation ages were not available from FHCL.

Volume increments were converted to increments of AGB by multiplying the volume by a biomass conversion and expansion factor for increment (BCEFI) of $1.1 \text{ tB (m}^3 \text{)}$. The value was taken from IPCC [2006, Vol. 4, Chap. 4, Tab. 4.5; humid tropical natural forests; growing stock level 21-40 $\text{m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$] and the root:shoot ratio from IPCC, 2006, Vol.4, Chap. 4, Tab. 4.4 then to carbon by multiplying by biomass:carbon default conversion factor (0.47). The resulting mean annual carbon increment was calculated, as outlined below, to be $4.14 \text{ tC ha}^{-1} \text{ yr}^{-1}$.

Total carbon increment, including above- and belowground was estimated from mean annual increment values provided by Fiji Hardwood Corporation Limited (FHCL) as follows:

$$MAIAGB_{HW} = \overline{MAIV}_{HW} \times BCEF_{HW,I} = 5.85 \times 1.1 = 6.435$$

Where;

$MAIAGB_{HW}$ = mean annual AGB increment in hardwood plantations; $\text{tB ha}^{-1} \text{ yr}^{-1}$

$\overline{MAIV}_{HW}$ = average mean annual volume increment in hardwood plantations; $\text{m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$;

calculated as a weighted mean estimate as $5.85 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$

$BCEF_{HW,I}$ = biomass conversion and expansion factor for increment for humid tropical natural forest; growing stock level 21-40 $\text{m}^3 \text{ ha}^{-1}$; $\text{tB (m}^3 \text{)}^{-1}$

Total carbon increment, including above- and belowground was estimated by:

$$MAIC_{HW} = [MAIAG_{HW} \times (1 + R_{wl})] \times \eta_{CF} = [6.435 \times 1.37 \times 0.47] = 4.14$$

Where;

$MAIC_{HW}$ = mean annual carbon increment in hardwood plantations; $\text{tB ha}^{-1} \text{ yr}^{-1}$

$MAIAG_{HW}$ = mean annual increment $\text{tB ha}^{-1} \text{ yr}^{-1}$

R_{wl} = root-to-shoot ration for tropical rainforest taken from IPCC, 2006, Vol.4, Chap. 4, Tab. 4.4; dimensionless

η_{CF} = biomass to carbon conversion factor; tC (tB)^{-1}

Table 2: Estimated mean annual volume increments in Hardwood Plantations expected cut volumes, and stocking area in 2017. The data were provided by the Fiji Hardwood Corporation Limited (FHCL). CC: cutting cycle length (rotation) in years.

Species	$MAIV_{HW}$ [$\text{m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$]	CC [yrs]	Cut volume [$\text{m}^3 \text{ ha}^{-1}$]	A_{HW} [ha]
Mahogany	6.30	37	220	48801
Mixed hardwoods	2.00	35	70	3634
Cadamba	5.00	35	180	1263
Cordia	1.40	35	50	940
Maesopsis	2.90	35	100	912
Pine	7.10	27	180	532
Dakua Makadre	3.00	60	180	241
Eucalyptus	7.50	25	150	161
Yemini	4.00	60	100	46
Kauvula	1.70	50	100	33
Teak	4.00	30	120	2

Softwood Plantations

The mean annual biomass increment in softwood plantations, $MAIB_{SW}$ was taken from Waterloo [1994]) which reported mean annual biomass increment for pine plantations in Fiji to be $10 \text{ tB ha}^{-1}\text{yr}^{-1}$ which includes both above- and belowground biomass. This was converted to carbon increment, MAIC, by a simple multiplication of the default biomass:carbon conversation factor (0.47). The resulting mean annual carbon increment was calculation to be: $4.7 \text{ tC ha}^{-1} \text{ yr}^{-1}$.

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