Wonegizi REDD+ Project: Baseline Carbon Stock Report 2019

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Executive Summary

The design and implementation of the REDD+ project in Wonegizi to VCS/CCBS requires activity data and emission factors for the project site or the broader landscape in which the project is located. Working with implementing partners, FFI established forest and post-deforestation sampling plots in 2013 and 2019 and gathered biomass data for estimation of plant carbon density and development of emission factors.

Two field expeditions were conducted in 2013 and 2019 to establish 70 forest and 42 post-deforestation sampling plots in the Wonegizi REDD+ pilot project in Liberia and gather biomass data to develop emission factors (EFs). Several methods and techniques were used to gather biomass data: tree carbon pools were estimated in the forest areas following VM0007 Modules CP-AB and CP-S, VCS methodology modules BL-UP and X-STR and FFI's Standard Operating Procedures (SOPs) for collecting biomass; estimation of belowground biomass (CS Module VMD 0001 v1-1); estimation of lying dead wood using the methodology of Harmon and Sexton (1964; VM0002, equation 7 in CP-D; measuring standing dead wood using equation; and calculation of tree biomass using allometric equation 7 (Chave et al., 2014; VCS Module VCS VMD 0001). Carbon content of tree and non-tree biomass was estimated by multiplying biomass by an IPCC default value (0.47), while carbon was converted to CO2-e by multiplying it by the ratio – 44/12.

During the initial fieldwork, the forest was stratified into three categories: primary forest, secondary forest and post-deforestation sites. Above- and belowground biomass, and dead wood biomass, differed significantly across pools. Aboveground living biomass accounted for almost 80% of tree carbon fraction. However, above- and belowground together accounted for 95% of the total tree biomass. Mean aboveground biomass values for primary forests, unstrafified forests, secondary forests, post-deforestation were 157, 151, 129 and 18.16 t ha^{-1}, respectively. The second largest pool is belowground biomass, which was estimated using the Root:Shoot Ratio of 0.24. The mean aboveground biomass stock in unstratified forests (191 tC ha^{-1}) is lower than mean estimates for Landscape 1 (277 tC ha^{-1}) and Landscape 2 (336t ha^{-1}) possibly due to differences in measurement techniques, forest management histories, climatic and edaphic conditions, and the FREL used a carbon conversion factor 0.49, while this study used 0.47.

The aboveground biomass in post-deforestation land use systems is the largest fraction of tree biomass carbon. The stock (18 tC ha^{-1}) in this study is within the estimated range (22-95 tC ha^{-1}). This study shows that as the fallow increases, aboveground tree biomass also increases signifying forest recovery. The mean belowground biomass carbon stocks in unstratified forests (30 tC ha^{-1}) in this study is lower than values reported for intact forests in Landscapes 1 (61 tC ha^{-1}) and 2 (76 tC ha^{-1}), but it is comparable to stocks in secondary forests (27 and 30 tC ha^{-1}, respectively).

The primary forest had the highest EF (626.7 tCO_2-e ha^{-1}) while the secondary forest had the lowest value (447.36 tCO_2-e ha^{-1}). However, the unstratified forest EF was calculated because aggregated data for two data collection expeditions (2013 & 2019) showed that carbon stocks were not significantly different across strata after aggregation of data. The study concluded that there was no justification for stratifying forests. The project decided to use the EF value for unstratified forests in all its calculations of emissions.

The aboveground stocks in unstratified forests (557 tCO2 ha^{-1}) is lower than stocks reported for the Gola National Park (GRNP) North (578 tCO_2 ha^{-1}) and South stratum (629 tCO2 ha^{-1}), but the value for the primary forest (578 tCO2 ha^{-1}) in this study is the same as the value for GRNP South. The stocks in intact forest in Landscape 2 (955 tCO_2 ha^{-1}) and Landscape 1 (755 tCO_2 ha^{-1}) were greater than the values for the intact forests for this study.

Total carbon stocks in intact forests and non-stratified forests were 1.9 and 2.3 times greater in forests than in secondary forests in Landscapes 1 & 2, respectively. However, total carbon values and EF factors for intact and secondary forests in Landscape 2 were higher than those for Landscape 1. All forested strata had significantly higher biomass carbon stocks than post-deforestation sites. Total carbon stocks in forests were 4.3 – 6.8 times greater in forest than in crop-fallow ecosystems in Landscape 1, while forested sites in Landscape 2 had 4.4 – 10 times more stocks than deforested areas.

This carbon assessment activity produced carbon data that will be used in calculating the project baseline and contribute to the forest and post-deforestation database. Both the carbon stocks and emission factors provide a useful benchmark for further studies. Extra work is needed to monitor carbon stock changes and update the EFs and additional data is gathered.

Introduction to the Wonegizi REDD+ project

North western Liberia contains the largest remaining tracts of Upper Guinean Forest, the original ecosystem that covered this area and which spreads across the whole of West Africa. The Wonegizi forest (Figure. 1), covering an area of approximately 37,987.9 hectares in northern Liberia, forms a critical link in the transboundary Guinean rainforest corridor which connects the forests of Sierra Leone through Liberia to Guinea. The Wonegizi forests, and the trans-boundary forest complex of which it is a part, provides habitat for a range of globally important and threatened species and holds large stocks of carbon in plant biomass and the soil.

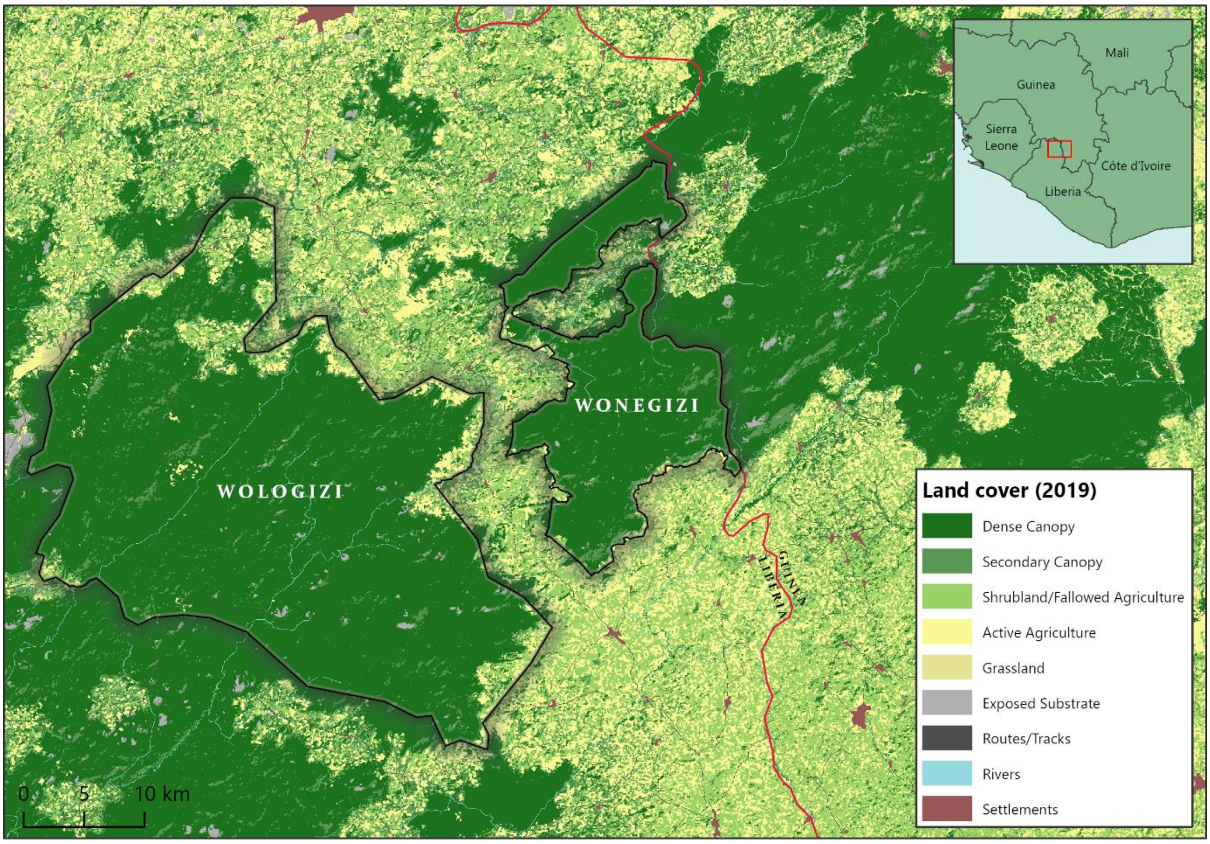

Figure 1. The location of the REDD+ project area in the Wonegizi Proposed Protected Area

Like much of rural Liberia, the communities surrounding the Wonegizi forest suffer from extreme poverty and are dependent on this forest for food, water and land. The rapidly increasing population of communities that have resettled in this landscape after the civil war poses a significant threat of forest conversion due to slash-and-burn agriculture, and forest degradation due to extraction of wood for fuel and charcoal. These drivers of deforestation and forest degradation have contributed to significant biodiversity loss and greenhouse gas emissions to the atmosphere. Liberia, like any other country experiencing high rates of deforestation and forest degradation, is determined to reduce emissions from these activities and enhance biodiversity and ecosystem services in compliance with the Paris Agreement and requirements for Nationally Determined Contributions (NDCs). In view of this, Liberia implemented REDD+ Readiness (Warsaw Framework) using the Forest Carbon Partnership

Facility funding and decided to implement a pilot REDD+ project in compliance with its National REDD+ Strategy.

An initial Norad-funded REDD+ pilot project was implemented from 2011 – 2015 to reduce deforestation through community-based agriculture, establishment of a co-managed Protected Area with effective enforcement and supporting rural livelihoods using results-based payments to conserve forests and implement community development projects. This will also include establishment of an equitable Benefit-Sharing Mechanism (BSM). The pilot REDD+ project is recognized as part of Liberia's effort to operationalise the Liberia National REDD+ Strategy. Fauna & Flora International (FFI)'s Norad-funded project, "Driving national and international REDD+ policy consensus and realization of community rights, through integrated REDD+ implementation and community-based forest and agricultural resource management frameworks in Liberia, (2016-2020)" is a continuation of an initial NORAD grant-funded project. The Wonegizi REDD+ Project is being developing to the Voluntary Carbon Standard (VCS), the most widely used global voluntary carbon certification standard in the Agriculture, Forestry and Other Land Use (AFOLU) sector, and specifically to VCS Methodology VM0007 for Avoiding Unplanned Deforestation. VCS projects generate revenue by issuing Verified Carbon Units, VCUs (colloquially termed 'carbon credits', with each credit representing 1 tonne of CO2 equivalent), which are sold on international markets. VCUs are calculated by estimating the quantity of carbon emissions reduced (emissions reductions) due to the projects' activities. Calculation of emission reductions from avoided deforestation requires that accurate measurements of carbon from both the forest and post-deforestation landscapes (i.e. farmland and fallow land). However, the design and implementation of the REDD+ project in Wonegizi to VCS/CCBS requires activity data and emission factors for the project site or the broader landscape in which the programme/project is located. Working with implementing partners, FFI established forest and post-deforestation sampling plots in 2013 and 2019 and gathered biomass data for estimation of plant carbon density and development of emission factors.

Background to the Field Work

Data on carbon density of forests in Wonegizi project area are scarce. But the project needed these data to develop emission factors (EFs) for development of a baseline and project scenarios. EFs are coefficients for conversion of activity data (i.e. number of ha of Wonegizi forest converted to non-forest) to emissions. They state the amount of GHG emissions (expressed as tonnes of carbon dioxide equivalent; CO_2e) released into the atmosphere by the conversion of 1 hectare of forest to non-forest. Non-forest land in this case is fallow land, as the conversion of forest to land managed under a crop-fallow cycle through slash-and-burn deforestation is the primary driver of land-use change in the Wonegizi landscape.

For the REDD+ project, EFs combined with estimates of annual deforestation rates determined through the historic analyses of land-use change are the critical data for calculating the baseline emissions scenario; i.e. what would happen in the absence of the REDD+ project. Similarly, the EF states exactly how many GHG emissions are prevented from entering the atmosphere if the forest is conserved.

To allow the calculation of EFs with accuracy, the Wonegizi REDD+ project conducted a series of fieldwork surveys to measure the carbon within the main carbon pools in the forest and non-forest sampling plots in and surrounding the Wonegizi PPA. The report therefore provides an overview of the sampling strategy employed by the carbon surveys, and methodologies and techniques used in the field to measure the individual carbon pools, the calculations used to estimate carbon stocks per pool, and estimates of forest carbon stocks for both the Wonegizi forest and Post-Deforestation landscapes. The EFs are calculated directly from these data.

The structure of the report is as follows:

Section 1: Outlines the processes, fieldwork, data and data analyses conducted to estimate the above-ground biomass (AGB) within the Project Area. This includes the sampling approach taken, the number of forest plots, the methodology and data collected during the fieldwork and calculations used to estimate AGB, as well as subsidiary analyses and fieldwork, such as the validation of the allometric equation used and estimation of species wood densities.

Section 2: Outlines the fieldwork and data analyses conducted to estimate the above-ground biomass (AGB) for the Post-Deforestation landscape. This includes the sampling approach taken, the number of plots established, the methodology and data collected during the fieldwork campaigns and calculations used to estimate AGB, and associated work such as calculating the wet-to-dry ratio.

Section 3: Quality Assurance and Quality Control: The quality assurance and quality control measures employed to reduce the uncertainties associated with data collection and analysis. It provides sources of relevant tools and techniques needed to improve the quality of data and products of field studies undertaken in the Wonegizi project area.

Section 4: Emission factors for Conversion of Forests: This section explains how emission factors (EFs) were developed from carbon stocks. It further compares the carbon values in this study with results from other field studies undertaken within and outside Landscape 1.

Section 5: Discussion and Conclusion: This section interprets and discusses the results of the biomass data collected from forest and post-deforestation sampling plots in the Wonegizi REDD+ project area. It also draws conclusions on the questions addressed by the carbon assessment.

Section 6: References: A list of literature cited in the document is provided in this section.

Section 1: Estimation of forest carbon stocks in Above-Ground Biomass

1.1 Sampling Strategy

The sampling strategy for the Wonegizi REDD+ Project was informed by the results of a pilot carbon assessment of AGB in the WPPA conducted in 2013 (FFI 2013). The goal of this survey was to provide an initial estimate of forest carbon for the development of the REDD+ project and to determine whether forest carbon was stratified either by elevation (lowland versus sub-montane forest habitats) or disturbance history (primary versus secondary forest). This seven week survey established 48 paired cluster plots of 14m radius in five different localities within the WPPA, providing access to all four forest types, within which all trees with DBH ≥5 cm were identified and measured. A 2x2 m subplot located at the cluster-plot centre was established to measure non-woody vegetation biomass. This survey showed that secondary forests had lower biomass (used interchangeably with carbon given that carbon is approximately 50% of biomass) than primary forest, and there was no difference in biomass between sub-montane and lowland forest areas within the PPA (FFI, *unpublished*).

The VCS methodology modules BL-UP and X-STR require that forests within the Project Area are stratified by carbon stock values. Based on the results of the 2013 survey, the 2017 carbon survey stratified the plots to be established into primary and secondary forest plots on the basis of:

(a) A 2013 land cover classification (RSS GmbH, 2013); and
(b) A significant difference in carbon stored in primary and secondary plots observed in the 48 plots established in 2013 (elevation and other environmental factors were insignificant).

1.2 Survey design

A stratified random survey design was applied for the survey design, with randomised plot locations generated using an ArcGIS Sampling Design Tool extension (NOAA 2017).

A 3km grid was overlaid over the Wonegizi PPA project area, in total 63 grid squares. The randomised grid square selection script selected 30 of these 63 grid squares at random, and the subsequent analysis was carried out on those 30.

The following areas were excluded from the forest carbon survey sampling design:

- Non forest areas and forest fragments (defined as < approximately 2 ha – a 1km buffer around these was created and excluded).
- DTM-derived areas of steep slopes ≥65%,
- Any areas within the Wonegizi PPA above 900m elevation, as these were considered at low risk of deforestation,
- Areas identified as dangerous and/or inaccessible by local staff were excluded.

A total of 70 plots were subsequently (section 1.3) located within both primary (35 plots) and secondary forest (35 plots) (Fig. 2):

ArcMap Document Name: Wonegizi_Sampling_Strategy_Map_20191114

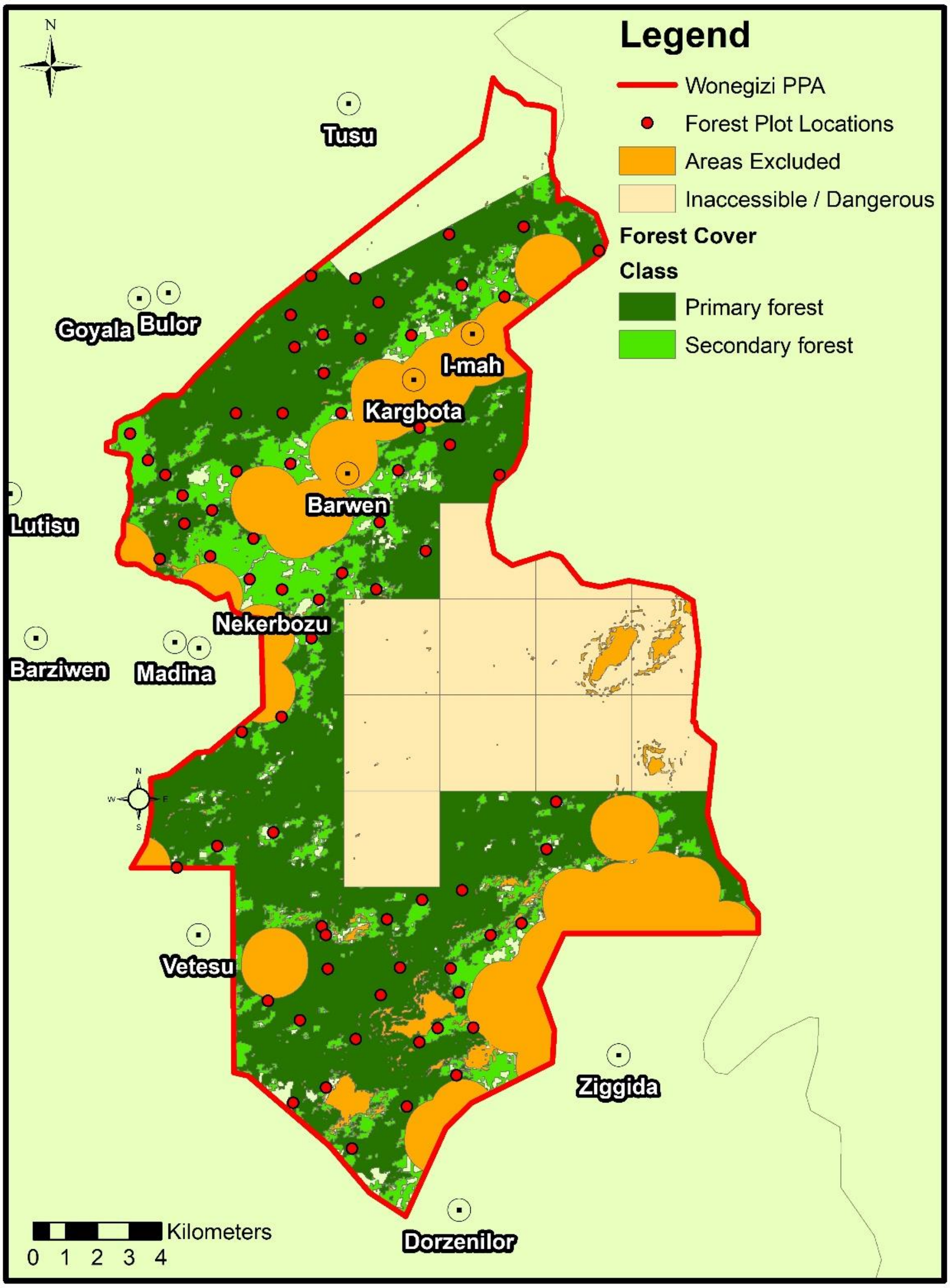

Figure 2: Biomass sampling plots in forest and post-deforestation plots in Wonegizi project area in Liberia

1.3 Number of plots

The number of plots required was estimated using the Winrock Terrestrial Sampling Calculator, with a target precision level of 15% at the 95% confidence interval.

Originally the number of plots forecast were based on the mean and standard deviation for above ground biomass for two forest strata measured in the 2013 survey data, and a substantial number extra to ensure that the number of plots established met VSC requirements should the mean and standard deviation in the 2017 survey differ substantially to the 2013 survey. This was later adjusted with survey data collated throughout the campaign in 2017 as well as updated 2017 forest strata maps, and until such point that the target precision level was met. A total of 70 plots were subsequently (section 1.3) located within both primary (35 plots) and secondary forest (35 plots).

It should be noted that between the completion of the RSS consultancy in 2013 and the commissioning of the Remote Sensing consultancy of Winrock International in 2017, FFI convened a working group of stakeholders, which developed a new definition of forest for use in Liberia. The 2016 forest definition did not distinguish between primary and secondary forest, but instead broke down forests into two classes based on percentage canopy cover: forests with canopy cover 30-80%, and forests with >80% canopy cover. (The Forest definition is: area > 1 ha, canopy cover ≥30%, minimum height at maturity of 5 m)

A subsequent remote sensing consultancy was conducted by Winrock International to develop historic land cover classifications for the VCS project, to determine the spatial boundaries of the REDD+ project and estimate baseline rates of deforestation. This consultancy used the 2016 forest definition rather than the classification into primary and secondary as per the 2013 consultancy performed by RSS. The plots were therefore located randomly according to the 2013 land cover classification not the 2017 land cover classification. In addition, the Government of Liberia's FREL uses 'intact' forest, 'secondary' and 'non-forest'.

The 2017 carbon survey was planned in advance of the completion of the 2017 remote sensing consultancy by Winrock International. Consequently, the number of forest plots was calculated using the Winrock Plot Calculator using the preliminary data on forest carbon collected in the 2013 carbon survey of the Wonegizi PPA. The sampling strategy for forest carbon therefore stratified the Wonegizi forest into two strata (as per the remote sensing consultancy conducted by RSS in 2014), representing a pre-stratification (VMD0016, page 5) into 'primary' and 'secondary' forest, on the a priori expectation that primary forest locations would have higher biomasses than secondary forest locations.

Results from the 2019 biomass assessment in Wonegizi REDD+ project area showed that differences in above and belowground biomass carbon stocks were not significant across the forest strata (primary vs secondary forest). Based on current estimates of ABG + St Dev (t DM ha^{-1}) for 70 forest sampling plots derived from the Winrock Plot Calculator. With 26,700 ha of forests in the project area within the Wonegizi harmonized Protected Area (VCS/PA) treated as a single stratum, carbon values calculated with 15% uncertainty at 95% confidence interval, 36 plots were required. The study concluded that the number of plots established meets the VCS uncertainty.

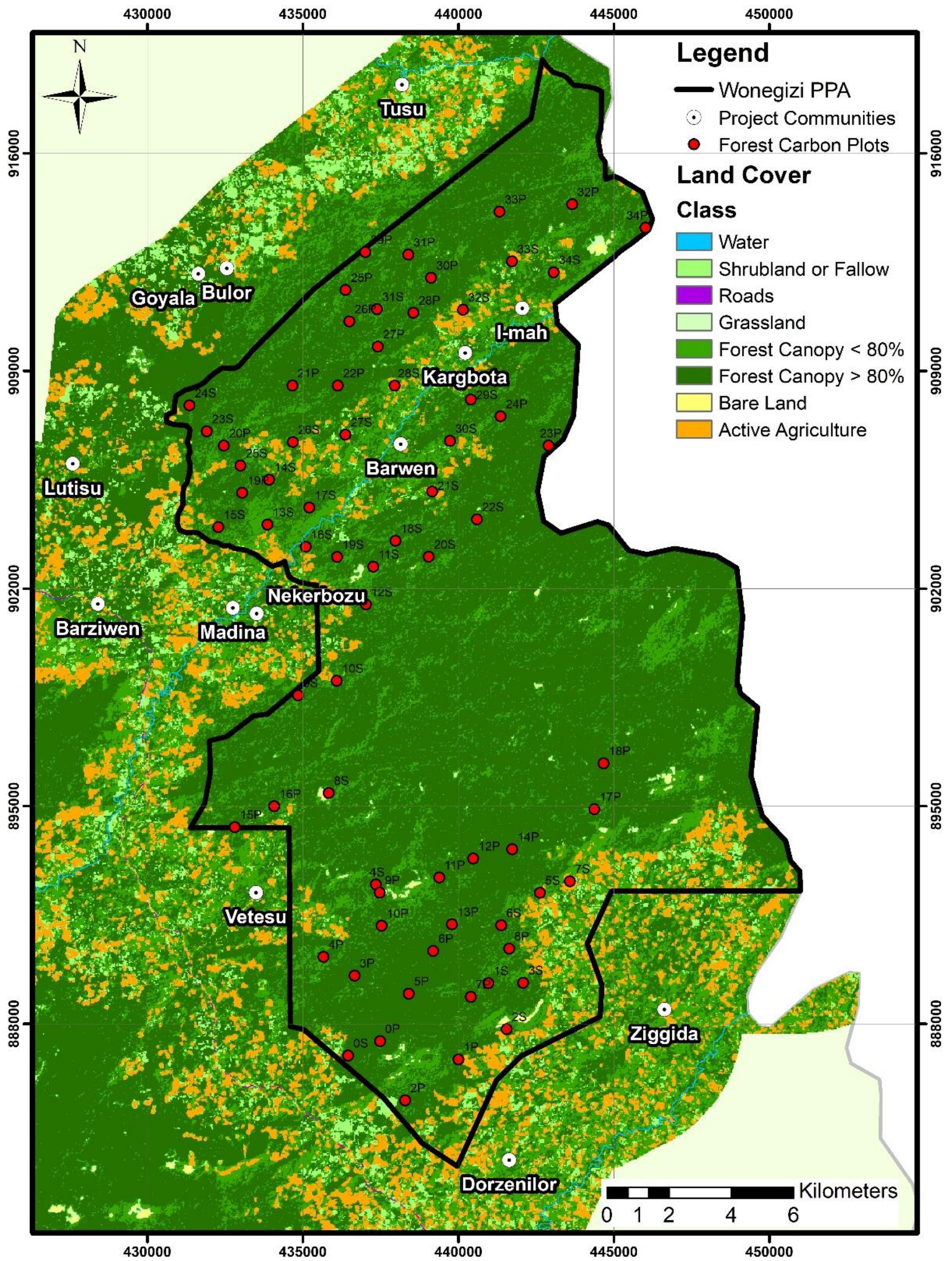

Figure 3. Seventy randomly located forest carbon plots established in 2017 and 2019 using Winrock International's 2017 land cover classification (Brown & Ling, 2018).

It was originally planned that a carbon team would be assembled and trained on FFI's Standard Operating Procedures (SOPs) for Measuring Above-Ground Biomass (henceforth 'the SOP') before conducting the entire forest carbon survey in 2017. However, for logistical reasons only 46 out of 70 plots were sampled during the field campaign, and these were not randomly located throughout the WPPA. A further carbon survey was required in 2019 to measure forest AGB in the 24 unsampled plots from 2017.

1.2 Carbon Pools Measured

The following carbon pools were measured in the forest carbon surveys:

- Above-ground Live Tree Biomass (AGB)
- Lying Deadwood
- Standing Deadwood

Below-Ground Biomass (BGB) is difficult and time consuming to measure, and can be readily estimated using default root-to-shoot ratios and therefore this carbon pool was not measured. The litter and non-tree woody biomass pools were considered insignificant, based on the results of the 2013 carbon survey, which estimated non-woody biomass in 2x2 m sub-plots (FFI 2013). Soil carbon was conservatively excluded, as this pool is expected to increase in the project scenario.

1.3 Establishment of Forest Inventory Plots

The forest carbon surveys employed single fixed area plots, with the plot centre point located at the predetermined sample locations generated through the sampling strategy (outlined in section 1.1). Plot centres were permanently marked using a 30 cm iron rod hammered into the ground.

1.4 Measurement Protocols

All protocols for establishing the plot and measuring the selected carbon pools are contained with the FFI Standard Operating Procedures for Measuring Above-Ground Biomass (hereafter 'the SOPs'). The sections below provide summary information on protocols, for ease of interpreting biomass calculations in section 1.5; for additional informational refer to the SOP.

1.5 Above-Ground Biomass

Above-Ground Biomass (AGB) estimates for each plot are calculated as the summed AGBs for all individual trees within a plot, with tree biomasses estimated using allometric equations (see section 2.1) from stem Diameters at Breast Height (DBH, 1.3 m above ground). Each plot consisted of three circular subplots: subplot A – radius 6 m; subplot B – 14 m; subplot C – 20 m. All trees with a DBH ≥ 5 cm, ≥15 cm and ≥30 cm were measured and identified to species in subplots A, B and C respectively. All measurements were made with DBH tapes in centimetres to 1 decimal place.

For consistent measurement of DBH between, trees the SOPs followed best-practice guidelines (Walker et al. 2016 & 2018):

- A tree pole of 1.3 m length was used to determine the DBH measurement point on each tree trunk.
- DBH was always measured on the up-side of a slope.
- Where trees were leaning, the point of measurement was located 1.3 m on the underside of the lean, and the DBH tape was used perpendicular to the angle of the lean

- For trees with buttress roots, the DBH was measured at 1.3m if the buttress roots were less than 1.3 m high, and 30 cm above the top of the buttress when the buttresses were >1.3 m high
- For trees with stilt roots, the DBH was measured at 1.3 m if the stilt roots were less than 1.3 m high, and 30 cm above the top of the stilts and where the tree trunk becomes regular in form when the stilt roots were >1.3 m high
- For trees with multiple stems, if the fork was located equal to OR less than 30 cm below 1.3 m the DBH was measured below the fork. Where the fork started more than 30 cm below 1.3 m the DBH of each tree stem was measured separately at 1.3 m
- If trees had a deformity at 1.3 m, the DBH was measured 30 cm above the deformity
- For trees with extremely high buttresses which preventing measurement in the normal way, the two-stick method was used (see the SOPs)

Trees were marked using crayon or chalk after measurement to avoid double counting. Tree measurement was conducted on a subplot by subplot basis (i.e. starting with A and finishing with C), and to reduce the probability of the team missing individual trees each subplot started from a compass bearing North and moved clockwise through the subplot.

1.6 Lying Deadwood

Lying deadwood was sampled along a 100 m transect running North to South through the plot centre (i.e. 50 m North and 50 m South). All lying deadwood with diameter ≥6 cm was recorded along this transect. A machete test was used to estimate dead wood density class in three categories: ‘hard’, ‘medium’ and ‘soft’ (also termed ‘sound’, ‘intermediate’ and ‘rotten’; FFI SOPs; CP-D, page 6). The dead wood density for each of these classes was estimated from field collected samples (see the FFI SOP for Measuring Dead Wood Density).

1.7 Standing Deadwood

Standing deadwood was sampled in the subplots, using the same DBH cut-offs as for live trees. Two classes of standing deadwood were used:

- Class 1: dead trees that look identical to live trees other than lacking leaves
- Class 2: all other dead trees ranging from tree snags (dead boles only) to dead trees including branches (differentiated from Class 1 trees by a lack of fine twigs and small branches)

For class 1 trees only the DBH was measured. For class 2 trees the diameter at the base of the tree and height to top of tree bole was measured in addition to DBH.

1.8 Tree height

The 2019 forest carbon survey collected data on tree bole heights. This data was collected in order to validate the allometric equation to be used in estimating plot biomass, as required by VCS module VMD0001 (CP-AB). Tree bole height was defined as the height of the tree to the first canopy forming branch. Bole heights were estimated using a Suunto clinometer. Approximately three trees with DBH ≥20 cm per plot were measured.

1.9 Additional measurements

During the establishment of each plot the following parameters were measured and recorded:

- New GPS coordinate (if plot was relocated)
- Elevation (using GPS altimeter)
- Slope using a clinometer
- Habitat type (e.g. primary or secondary forest, swamp, signs of natural disturbance)
- Water or geological features (e.g. streams, rocky outcrops etc.)
- Percentage Canopy Cover (using a GRS Densitometer, 2019 survey only)
- Indications of human disturbance (tree stumps, shotgun cartridges, snares, old camps)
- Any wildlife from tracks, spore, visual sightings, vocalizations etc.

1.10 Equipment

The carbon survey team were equipped with the following equipment for plot establishment and measurement of carbon pools:

- 2m & 5m diameter tapes
- 50m measuring tapes
- 1.3 Tree measuring pole
- Hagloff DME
- Garmin GPSs
- Camera
- Compass
- Suunto clinometers
- Cutlass
- Data collection sheets / stationary / waterproof wallets
- Copy of FFI SOPs and tree species list (2019 only)
- Flagging tape, multiple colours
- Chalk / crayon for marking trees
- Metal rod
- Maps
- GRS Densitometer (2019 only)
- Olympus binoculars (10x50)
- First aid kit and mobile phones

2 Allometric Equation

It is not possible to measure the biomass of a tree first-hand without cutting it into sections and summing the weight of all sections. Naturally this kills the tree. Allometric equations are therefore used. Allometric equations estimate the total tree biomass from (typically a combination) easily measured characteristics of tree form, such as DBH, height and wood density and mass without requiring each individual to be destructively harvested.

2.1 Selection of Allometric Equation

Equation 7 from Chave et al. (2014) was selected as the allometric equation for estimating tree biomass (kg d.m. tree^{-1}) from DBH measurements. A thorough literature search and search through the GlobAllomeTree database (http://www.globallometree.org/) returned no national species or forest type equations, nor equations developed for the Upper Guinean Forest Ecoregion, and consequently this pan-tropical allometric equation was selected. The equation is shown below:

$$AGB_{est} = \exp[-1.803 - 0.976E + 0.976\ln(\rho) + 2.673\ln(D) - 0.0299[ln(D)^2]$$

Where:

AGB_{est} = Estimate of tree biomass (kg dry matter tree^{-1})
E = Environmental coefficient
p = species wood density (g/cm^3)
D = Diameter at Breast Height (DBH, cm)

Despite the guidance in VCS Module VMD0001 (CP-AB) that local or national allometric equations should be preferred over pan-tropical ones, pan-tropical allometric equations are increasingly preferred over locally derived allometric equations for estimating tree biomass in the scientific literature (Chave et al 2014). Increasing evidence from pan-tropical analyses of forest AGB incorporating data from thousands of plots (and millions of trees) is that the use of local allometries reduces the error by such a small margin compared to globally applicable allometries as to make their use significant, and in some cases in fact can introduce additional error into the AGB estimate. Whilst the Chave et al. (2014) equation does not explicitly consider local DBH:height relationships, it includes a variable '*E*', an environmental parameter that represents the effects of climate on tree growth and forest structure (e.g. canopy height). The mean *E* value for the WPPA was calculated as -0.11754.

Furthermore, this equation is recommended as being best suited to Liberia's forests within the Upper Guinean Forest Ecoregion in the Development of Liberia's REDD+ Reference Level (Winrock International, 2016; Liberia FREL, p. 30). Use of this pan-tropical equation is consequently in line with emerging national carbon accounts and facilitates the nesting of the Wonegizi REDD+ project with the developing jurisdictional REDD+ frameworks in Liberia.

2.2 Validation of Allometric Equation

VCS Module VMD0001 (CP-AB) requires that the selected allometric equation is validated to ensure that it is representative of the forest type or community composition present, and does not therefore systematically overestimate AGB. The allometric equation chosen was validated using option 1, Limited Measurements (VMD0001v1.1 page 14), using the tree bole height data collected from forest plots established during 2019 (see section 1.7). This compares tree biomasses as calculated using the allometric equation to tree biomasses estimated independently from first principles using the bole volume and biomass expansion factors. If the allometric equation selected does not systematically generate higher estimates of tree biomass compared to the biomasses calculated from first principles then it can be used.

Data on a total of 66 trees with DBH ≥20 cm were used. Tree DBHs were converted to Basal Areas (m^2) using the equation:

$$\text{BA}\ (m^2) = \frac{\pi \times DBH^2}{40{,}000}$$

Trunk Basal Areas were then converted to volumes (m^3) by multiplying tree BA by bole height. Trunk volumes were converted to biomass (kg dry matter) through multiplication with species wood densities (see section 3). Finally, the total tree biomass was estimated by applying a Biomass Expansion Factor (BEF) using the following BEFs specified in VCS Module VMD0001v1.1 (CP-AB):

- For trees with DBH 20-40 cm: 1.38

- For trees with DBH 40-80 cm: 1.33
- For trees with DBH ≥80 cm: 1.25

2.3 Results of Allometric Equation Validation

Tree biomass estimates calculated using trunk volumes and BEFs were compared to estimates of trees biomass calculated using the Chave et al. 2014 equation. However, to generate a curve using the allometric equation (VMD0001v1.1 page 14), the mean wood density of all species-specific and genus level wood densities (0.607 g/cm^3) was used as opposed to species specific wood densities (Fig. 3).

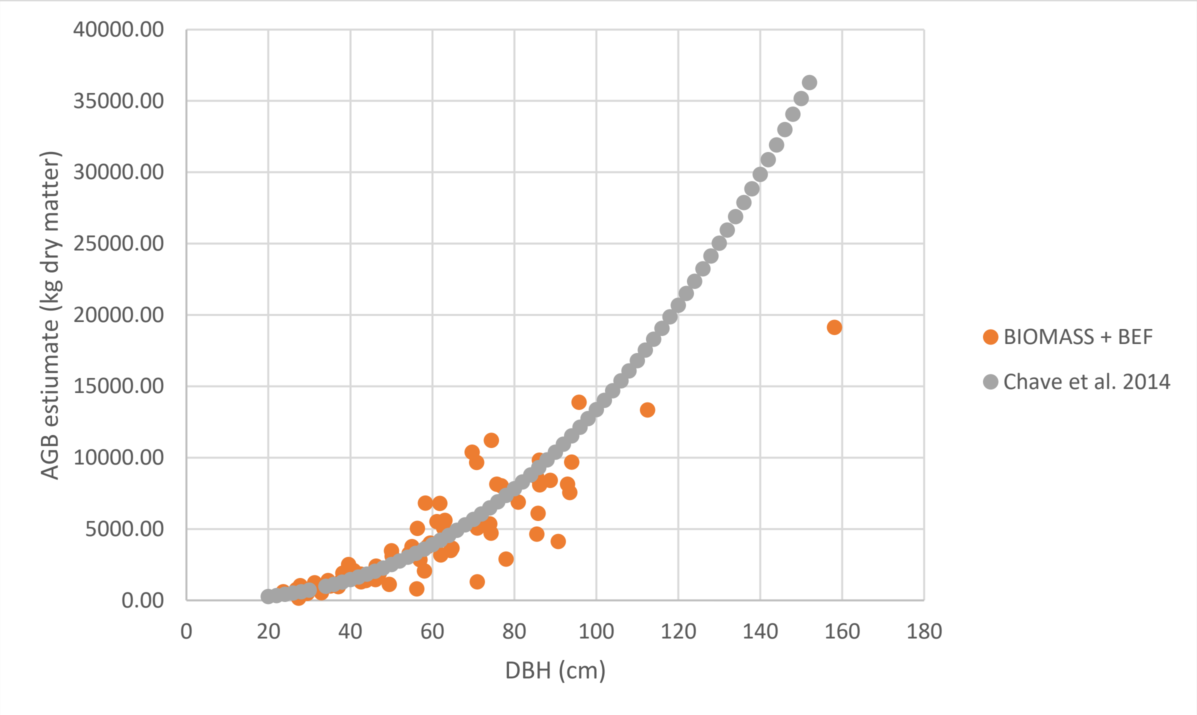

Figure 3: Estimates of tree biomass calculated from trunk biomasses and BEF versus estimates using the Chave et al. 2014 allometric equation (wood density of 0.607 g/cm^3). The Chave et al. 2014 estimates are represented by the grey curve.

Estimates of tree biomass calculated using trunk volumes and BEFs fall either side of the curve generated using the Chave et al. 2014 allometric equation (45.5% of estimates were greater and 54.5% lower than the allometric equation estimates for the same DBH) and therefore the Chave et al. 2014 allometric equation can be used.

Nevertheless, as an additional check, estimates of tree biomass calculated using trunk volumes and BEFs were compared against estimates of biomass generated using the Chave et al. 2014 equation using species-specific wood densities as opposed to a dataset mean (Figure X).

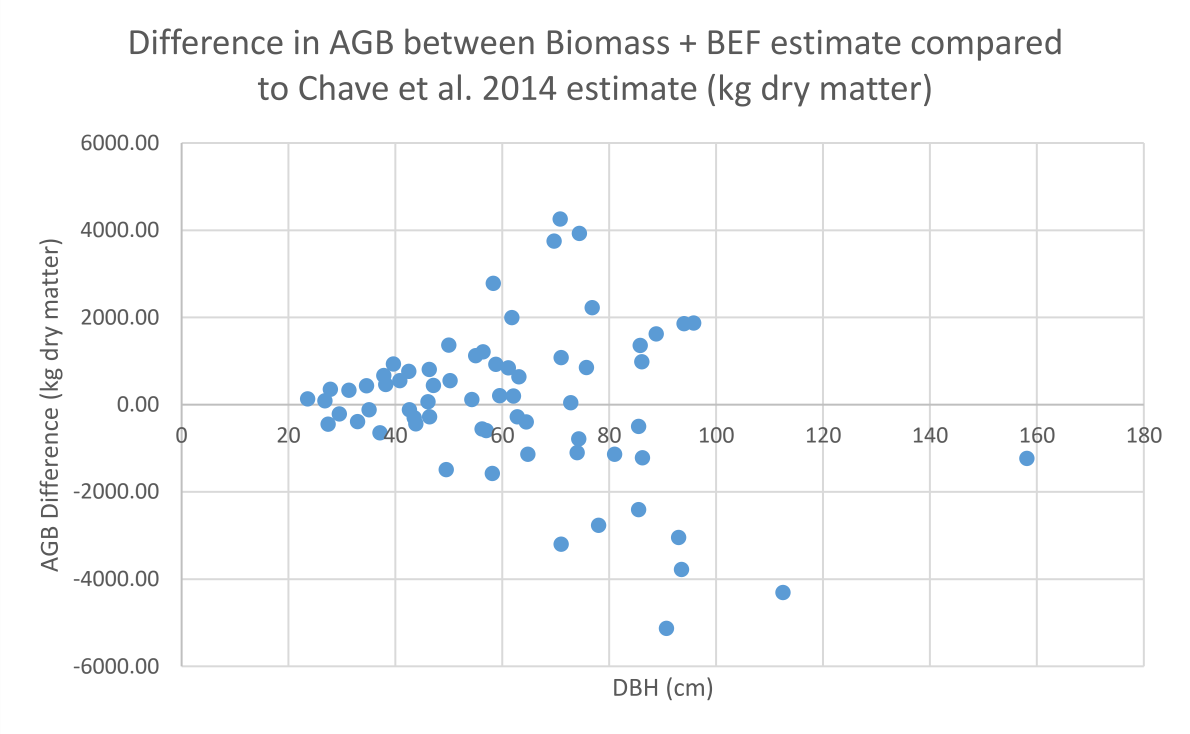

Figure 4. Differences in AGB estimated from trunk biomass and BEF versus estimate using the Chave et al. 2014 allometric equation (using species-specific wood densities). The Chave et al. 2014 estimates are represented by the horizontal line of value 0. Points above the line represent instances where the trunk biomass and BEF estimate is greater than the Chave et al. 2014 estimate and vice versa.

Again, estimates of tree biomass calculated using trunk volumes and BEFs fall either side of the values generated using the Chave et al. 2014 allometric equation (56.1% of estimates were greater and 43.9% lower than the allometric equation estimates for the same DBH) providing additional comfort that the Chave et al. (2014) allometric equation does not consistently over-estimate tree biomass and is suitable for the forest type present in the WPPA.

The Chave et al. 2014 equation has been validated as suitable for the estimation of tree biomass for the Wonegizi REDD+ project.

3. Species Wood Densities

Tropical tree species vary widely in their wood density, a trait that is highly correlated to species life-histories. Wood density has been observed, after tree DBH, to be the most important predictor of tree AGB (Chave et al. 2005), and therefore the inclusion of this trait and the use of accurate species-specific wood densities where possible greatly improves the accuracy of allometric equations in estimating AGB. The allometric equation selected (see above) therefore includes species wood density as an explanatory variable.

Species wood densities were obtained from the Global Wood Density Database (GWDD; Zanne et al. 2009). Many species had multiple wood density values obtained from different studies. In such cases the species mean wood density was used (50.9% of species recorded).

Conversely, for species without entries in the GWDD the mean genus level wood density was used if available (37.4% of species recorded), as wood density is a highly conserved trait within genera (Chave et al. 2006). Where neither species of genus wood density was available the mean wood density of 0.609 g/cm^3 was used (11.7% of species recorded), as wood density is less phylogenetically conserved at the family level (Chave et al. 2006).

2.4 Calculation of Tree Biomass

Above-Ground Biomass

Individual tree AGBs were estimated from the stem DBH and species wood densities using equation 7 of Chave et al. (2014). Wood densities applied followed the taxonomic hierarchy described in section 3 'Wood Densities'. An environmental '*E*' parameter of -0.11754 was used. Individual stem AGBs were summed to calculate total plot AGB in tonnes of dry matter (t DM) using equation 1 of module CP-AB:

$$C_{AB\_tree,sp,i} = \sum_{j}^{S} \sum_{l=1}^{N_{j,sp,i}} f_j(X,Y\ldots) * CF_j$$

Where:

$C_{AB\_tree,sp,i}$	= Carbon stock in aboveground biomass of trees in plot *sp* in stratum *i*; t C
CF_j	= Carbon fraction of biomass for species group *j*; t C t^{-1} d.m.
fj(X,Y..)	= Aboveground biomass of trees based on allometric equation for species group *j* based on measured tree variable(s); t. d.m. tree^{-1}
i	= *1, 2, 3, …M* strata
j	= *1, 2, 3 … S* tree species
l	= *1, 2, 3, … Nj,sp,i* sequence number of individual trees of species group *j* in sample plot *sp* in stratum *i*

Due to the topographic heterogeneity of the Project Area within the Wonegizi PPA, the 70 forest carbon plots were established on slopes ranging from 1% to 43% (mean 18.7%). A slope correction was therefore applied to account for this variation in actual plot radius on a horizontal plane (Walker et al. 2018):

$$Sloped\_Radius = \frac{Nest\_Radius}{Cos\theta}$$

Where:

Sloped_Radius	= Length of radius (m) on slope that corresponds to horizontal radius
Nest_Radius	= Length of radius agreed upon in flat terrain (m)
Cosθ	= Cosine of the slope angle

After slope correction the mean radius of nested plot C for the 70 forest inventory plots was 19.58 m. Plots areas (ha) were calculated from the corrected plot radii using the area of circle. The mean area of the nested plot C for the 70 forest inventory plots was 0.123 ha. Plot AGB were converted to carbon stocks per stratum using equation 2 of module CP-AB:

$$C_{AB\_tree,i} = \sum_{sp=1}^{P_i} \frac{C_{AB\_tree,sp,i}}{A_{sp,i}} * \frac{44}{12}$$

Where:

$C_{AB\_tree,i}$	= Mean aboveground biomass carbon stock in stratum *i*; t CO_2-e ha^{-1}
$C_{AB\_tree,sp,i,t}$	= Aboveground biomass carbon stock of trees in sample plot sp. of stratum *i* , t C
A_{spi}	= Area of sample plot sp in stratum *i*; ha
sp	= *1, 2, 3 … Pi* sample plots in stratum *i*
i	= *1, 2, 3 … M* strata
44/12	= Ratio of molecular weight of CO_2 to carbon, t CO_2-e t C^{-1}

Below-Ground Biomass

Below-Ground Biomass (BGB; t d.m. ha^{-1}) was conservatively calculated from the plot AGB using a root-to-shoot ratio of 0.24 for Tropical Rainforests as per parameter R in VCS Module VMD0001v1.1 (page 17). This calculation followed equation 5 of module CP-AB:

$$C_{BB\_tree,sp,i} = R * C_{AB\_tree,sp,i}$$

Where:

$C_{BB\_tree,sp,i}$	= Belowground tree biomass carbon stock of trees in plot *sp*, in stratum *i*; t C
$C_{AB\_tree,sp,i}$	= Aboveground tree biomass carbon stock of trees in plot *sp*, in stratum *i*; t C
R	= Root to shoot ratio; t root d.m. t^{-1} shoot d.m.
i	= *1, 2, 3, …M* strata

Plot estimates of BGB were converted to stratum level estimates of total carbon (CO_2e) by applying equation 6 of module CP-AB:

$$C_{BB\_tree,i} = \sum_{sp=1}^{P_i} \frac{C_{BB\_tree\_sp,i}}{A_{sp,i}} * \frac{44}{12}$$

Where:

$C_{BB\_tree,i}$	= Mean belowground tree biomass carbon stock in stratum *i*; t CO_2-e ha^{-1}
$C_{BB\_tree\_sp,i}$	= Mean belowground tree biomass carbon stock of trees in plot sp, in stratum *i*; t C
$A_{sp,i}$	= Area of sample plot *sp* in stratum *i*; ha
sp	= 1, 2, 3 … *Pi* sample plots in stratum *i*
i	= 1, 2, 3 … *M* strata
44/12	= Ratio of molecular weight of CO2 to carbon, t CO2-e t C-1

Lying Dead Wood
All lying dead wood with a diameter ≥6 cm was measured on the transect. However, only dead wood with a diameter ≥10 cm were analysed as per the methodology of Harmon & Sexton 1996 (VMD0002).

The volume of lying dead wood per unit area (m^3 ha^{-1}) was estimated for each density class (hard/medium/soft) following the modified Van Wagner (1964; VMD0002) equation (equation 7 in CP-D):

$$V_{LDWdc,i} = \frac{\pi^2 * \left(\sum_{n=1}^{N} Dia_{dc,n,i}^{\ 2} \right)}{8 * L}$$

Where:

V_{LDWi}	Volume of lying dead wood per unit area in density class *dc* in stratum *i*; m^3 ha^{-1}
$Dia_{n,i,t}$	Diameter of piece *n* of dead wood along the transect in stratum *i*; cm
n	1, 2, 3, … *N* sequence number of wood pieces in density class *dc* intersecting the transect
L	Length of the transect; 100 m
dc	dead wood density class – sound (1), intermediate (2), and rotten (3); dimensionless
i	1, 2, 3, … *M* strata in the project scenario

The mean wood density estimates for the three dead wood density classes ('sound', 'intermediate', 'rotten') were not calculated the machete studies were done. According to module CP-D, if projects cannot find forest type default values for dead wood in the three dead wood density classes then project specific values should be developed from field sampling. Although the project has used the approach within CDM tool AR-TOOL12 for calculating dead wood density (dead wood density reduction factors), it has not been clear whether Verra recognizes this methodology. Despite efforts to seek Verra's position on the use of this tool, they have not confirmed the CDM tool is counts as literature at the same level as the IPCC Reports.

Lying wood volume was converted to biomass using equation 8 in module CP-D:

$$B_{LDWi} = \sum_{dc=1}^{3} V_{LDWdc,i} * D_{DWdc}$$

Where:

B_{LDWi}	Biomass of lying dead wood per unit area in stratum *i*; d.m. ha^{-1}
$V_{LDWdc,i}$	Volume of lying dead wood per unit area in density class *dc* in stratum *i*; m^3 ha^{-1}
D_{DWdc}	Mean wood density of dead wood in the density class (*dc*) – sound (1), intermediate (2), and rotten (3); t d.m. m-3
dc	dead wood density class – sound (1), intermediate (2), and rotten (3); dimensionless
i	1, 2, 3, … *M* strata

NOTE: Due to concerns on the quality of the field collected dead wood density data from 2017, for lying deadwood we use the default wood density reduction factors for 'sound', 'intermediate' and 'rotten' classes as per the CDM A/R Methodological Tool "Estimation of carbon stocks and change in carbon stocks in dead wood and litter in A/R CDM project activities"; 6.1.1.4.24. The mean wood density for the tree species observed in forest plots is multiplied by the wood density reduction factors. These are:

- Sound (/ hard) wood – 1 (i.e. no reduction)
- Intermediate (/medium) wood – 0.8
- Rotten (/soft) – 0.45

Standing Dead Wood

The same slope corrections were applied for estimating standing deadwood biomasses as per live tree AGB per plot. The biomass of dead standing trees in class 1 was calculated using the same biomass allometric equation as for live trees (see equations X). However, as standing dead trees were not identified to species (lack of leaf and other characteristics etc.), the mean wood density for live trees was used. For standing dead trees class 2, the biomass was calculated using the mean wood density and the volume calculated as a cone, given that the diameter at the top of the bole was not measured.

The bole height of standing dead trees in class 2 was measured, however the diameter at the top of the bole was not measured. Equation 1 from module CP-D, which treats each tree as being conical, was therefore used to estimate the biomass:

$$B_{SDWl,sp,i} = \frac{1}{3} * \pi * \left(\frac{BDia_{SDWl,sp,i}}{200} \right)^2 * H_{SDWl,sp,i} * D_{DWdc}$$

Where:

$B_{SDWl,sp,l}$	Biomass of standing dead tree *l* from sample plot/point *sp* in stratum *i*; t d.m.
$BDia_{SDWl,sp,i}$	Basal diameter of standing dead tree *l* from sample plot/point *sp* in stratum *i*; cm
$H_{SDWl,sp,i}$	Height of standing dead tree *l* from sample plot/point *sp* in stratum *i*; m
$D_{DW,dc}$	Mean wood density of dead wood in the density class (dc) – sound (1), intermediate (2), and rotten (3); t d.m. m^3
sp	1, 2, 3, … *Pi* sample plots/points in stratum *i*
i	1, 2, 3, … *M* strata in the project scenario

Note that the machete test was not used on standing dead trees. Instead, following the guidance of Walker et al. (2012/2018) standing dead trees were assumed to be 'sound' and consequently the mean wood density of lying deadwood in the 'sound' wood density class was used for estimating the biomass of standing dead wood.

The tree bole height measured in 2017 was of poor quality as the team consistently failed to record whether the angle to the base of the tree was positive or negative (the SOP requires measurements of tree height to be made from an upslope position in the first instance, and therefore measurements should *a priori* be negative). The data sheets therefore record positive angles to both the top of the bole and to the base of the tree, leading to extremely low estimates of bole height (as the total tree height is calculated as bole height above the horizontal – bole height below the horizontal). The study assumed everything was negative unless height was physically measured.

The total standing dead wood per plot was calculated using equation 3 of module CP-D:

$$B_{SDWsp,i} = \sum_{l=1}^{N_{sp,i}} B_{SDWl,sp,i}$$

Where:

$B_{SDWsp,i}$	Biomass of standing dead wood in sample plot *sp* in stratum *i*; t d.m.
$B_{SDWl,sp,i}$	Biomass of standing dead tree *l* in sample plot *sp* in stratum *i*; t d.m.
sp	1, 2, 3, … *Pi* sample plots in stratum *i*
i	1, 2, 3, … *M* strata
$N_{sp,i}$	Number of standing dead trees in sample plot *sp* of stratum *i*
l	1, 2, 3, … *Ni,sp,t* standing dead trees in sample plot *sp* of stratum *i*

Subsequently the mean standing dead wood for each stratum was calculated following equation 4 of CP-D:

$$B_{SDWi} = \frac{1}{A_{sp,i}} * \sum_{sp=1}^{P_i} B_{SDWsp,i}$$

Where:

B_{SDWi}	Mean biomass of standing dead wood in stratum *i*; t d.m. ha^{-1}
$B_{SDWsp,i}$	Biomass of standing dead wood in sample plot *sp* in stratum *i*; t d.m.
A_{spi}	Total area of all sample plots in stratum *i*; ha
sp	1, 2, 3, … *Pi* sample plots in stratum *i*
i	1, 2, 3, … *M* strata

Total Dead Wood

Estimates of lying dead wood biomass and standing dead wood biomass were converted to a mean carbon stock per stratum (in CO_2e) by applying equation 9 of module CP-D:

$$C_{DWi} = \left(\left(B_{SDWi} + B_{LDWi} \right) * CF_{DW} \right) * \frac{44}{12}$$

Where:

C_{DWi}	Mean carbon stock of dead wood in stratum *i*; t CO_2-e ha^{-1}
B_{SDWi}	Biomass of standing dead wood in stratum *i*; t d.m. ha^{-1}
B_{LDWi}	Biomass of lying dead wood in stratum *i*; t d.m. ha^{-1}
C_{FDW}	Carbon fraction of dry matter in dead wood; t C t^{-1} d.m.
i	1, 2, 3, … *M* strata
44/12	Ratio of molecular weight of CO_2 to carbon, t CO_2-e t C^{-1}

5. Results of the field biomass C assessments

Mean estimates of aboveground tree biomass carbon stocks in, and carbon dioxide emissions from, stratified and unstratified forests in the Wonegizi forest project area in Liberia are presented in Table 1. Mean aboveground carbon stocks in stratified and unstratified forests were significantly greater than those calculated for other carbon pools However, stocks in aboveground biomass differed across strata in the order: primary forest (158 tC ha^{-1}) > unstratified forest (152 tC ha^{-1}) > secondary forest (129 tC ha^{-1}). Carbon dioxide emissions from destruction of above- and ground biomass in stratified and unstratified forests were significantly higher than those from other pools. They followed the same trend as carbon stocks because they are a product of carbon stocks and the carbon to CO_2 conversion factor (3.67; the ratio of molecular weight of CO_2 to carbon).

Table 1: Carbon stocks (tC ha^{-1}) and carbon dioxide (tCO_2-e ha^{-1}) emissions in stratified and unstratified Wonegizi forest project area in Liberia

Carbon pool	Primary forest		Secondary forest		Unstratified	
	Carbons stocks (tC ha^{-1})	Emissions (tCO_2 e ha^{-1})	Carbons stocks (tC ha^{-1})	Emissions (tCO_2 e ha^{-1})	Carbons stocks (tC ha^{-1})	Emissions (tCO_2 e ha^{-1})
AGB	157.58	577.78	129.05	473.17	151.95	557.16
BGB	31.52	115.56	25.81	94.63	30.39	111.43
SDWB	4.29	15.60	4.23	15.85	4.29	15.72
LDWB	4.01	14.70	5.80	21.28	4.91	17.99
Total	197.30	723.64	164.98	604.93	191.54	702.31

Legend: AGB – Aboveground Biomass; BGB – Belowground Biomass; SDW – Standing Dead Wood Biomass; LDWB – Lying Dead Wood Biomass.

Identification of Forest Strata

The 70 forest inventory plot locations were pre-stratified, with a random distribution of 35 plots in both ‘primary’ and ‘secondary’ forest strata as identified by a land cover classification dated 2019. Due to a change in the forest definition between 2013 and 2016, subsequent land cover classifications positioned these plots on forest with ≥80% canopy cover, and 30-80% canopy cover. Analysis of the both the AGB (AGB) and total carbon (sum of all pools, tC/ha) observed no significant difference in carbon stocks between the two forest strata identified *ex ante*, either in the original form of primary versus secondary forest, or between canopy cover ≥80% versus 30-80% (See Table 1).

Secondly, although a large number of plots were observed to have carbon stocks ≥20% more than the mean, and ≤20% of the mean, no clear, observable strata (i.e. clustering of plots with higher or lower carbon stocks) were observed when the data was plotted onto a map of forest cover within the VCS Project Area (Figure X). Consequently, the pre-stratification distinction between ‘primary’ and ‘secondary’ plots was abandoned, and *ex post* stratification applied; *i.e.* the forest is considered composed of a single forest strata. This is considered a highly conservation measure.

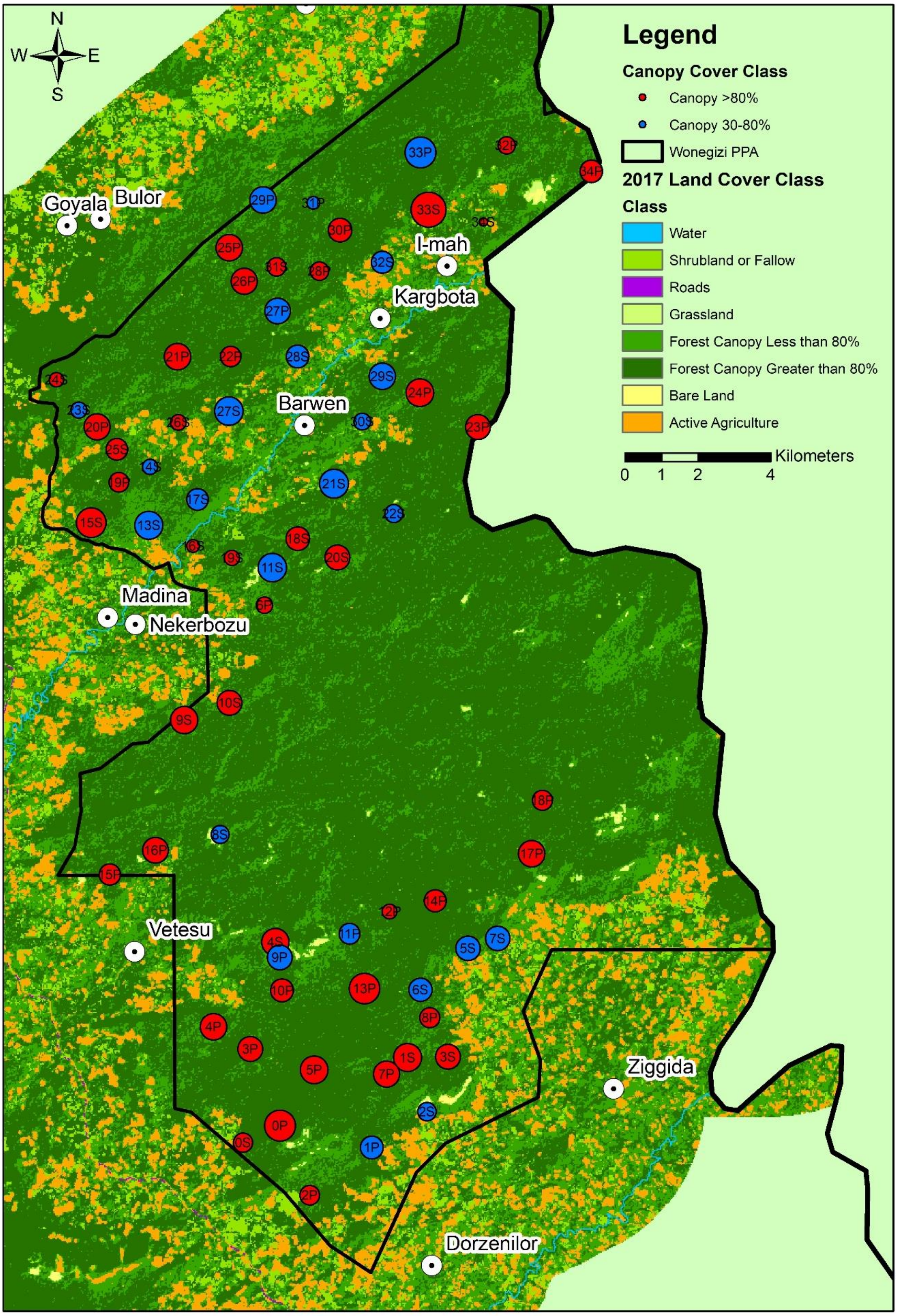
N
W
E
S
Legend
Canopy Cover Class
Canopy >80%
Canopy 30-80%
Wonegizi PPA
2017 Land Cover Class
Class
Water
Shrubland or Fallow
Roads
Grassland
Forest Canopy Less than 80%
Forest Canopy Greater than 80%
Bare Land
Active Agriculture
Kilometers
0 1 2 4
Goyala
Bulor
I-mah
Kargbota
Barwen
Madina
Nekerbozu
Vetesu
Ziggida
Dorzenilor

Figure 5. Mapped locations of each of the 70 forest carbon plots established in 2017/2019, aggregated by pre-stratification classes of 'Primary' (red) and 'Secondary' (blue) forest. Size of points is equal to the square root of the total plot carbon (tC ha^{-1}), allowing for visual identification of cluster points into strata. No clear strata are evident in this post-stratification.

Based on the above observations the Wonegizi REDD+ project does not recognize any distinct forest strata within the Wonegizi forest Project Area, and for carbon accounting purposes the mean forest above- and belowground tree biomass carbon stock is 192 tC ha^{-1} unless VCS rejects the CDM Methodology as a credible source of information for estimation of dead wood biomass and carbon stocks.

Section 2: Estimation of Post-Deforestation Carbon Stocks

The term 'post-deforestation' means after deforestation. In reference to REDD+ methodologies it relates to the land uses that occur after conversion of forest to non-forest; surrounding the WPPA, and Lofa County more generally, this is predominantly subsistence agriculture in a crop-fallow cycle, following slash-and-burn deforestation (Witkowski et al 2012a, Bulte et al., 2013). A study in Gola forest area showed that the farming process begins with brushing early in the year. Then the trees are felled, and the land is burned in March or April (Witkowski et al 2012a, Bulte et al 2013). Traditional practices involve the clearing of forests to make way for 1-2 years of crop plantations followed by an average of 7.5 years fallow time in the reference region, in the Leakage Belt, the average fallow period is 7 years (Witkowski et al. 2012a). Therefore the post deforestation strata is considered crop-fallow.

The 2017 carbon survey focused solely on the establishment of inventory plots to measure forest carbon. VCS Methodology VM0007 allows for the use of secondary data sources for estimating carbon in the post-deforestation landscape. However, review of the scientific and grey literature in early 2019 highlighted that there were very few estimates of carbon in the post-deforestation in the literature for Liberia or West-African landscapes with similar land-use change dynamics to Wonegizi. It was therefore decided to conduct a survey of AGB / Carbon in the Post-Deforestation Landscape surrounding the WPPA in 2019.

Sampling Strategy

Deforestation in and around the Wonegizi PPA is driven almost entirely by conversion to agriculture managed under a shifting agriculture regime where the deforested land is cultivated for 2-4 years before being left to fallow for 6-10 years before being converted to farmland again. Measuring carbon in the 'post-deforestation' landscape therefore requires the establishment of inventory plots in the fallow lands (locally termed 'young bush').

Aboveground biomass in post-deforestation sampling plots was estimated using a methodology described in section 4.2.2 of VM0007. As the crop-fallow post-deforestation land use is a cyclical land use system the time-weighted average of carbon stocks was used. Above-ground biomass in tree and non-tree woody biomass increases with increasing fallow age and thus the carbon stock of fallows >6 years was expected to be greater than fallows of <3 years. Consequently, the fallows were stratified into three classes (0-3 year old, 3-6 years old, and 6-10 years old). The mean AGB for the three fallow age classes was therefore used as the post-deforestation AGB for carbon stocks. Land under active agriculture (i.e. vegetable or rice cultivation) were excluded from the time-weighted average of carbon stocks in the post-deforestation landscape. This was considered both conservative (as they have very low woody biomass) and ethical (given that we did not want to perform destructive harvests in communities that suffer on average 2-3 ‘hungry months’ per year).

Number of Plots

Forty-two (42) carbon plots were established in the Post-Deforestation landscape, following the FFI SOP for Measuring Above-Ground Biomass in the ‘Post-deforestation’ Landscape. The number of plots required was estimated using the Winrock International Sample Plot Calculator. As there were no good estimates for AGB in fallow systems in Liberia the mean biomass / carbon estimates and standard deviations for each of the three fallow age classes was calculated from the estimates of fallow (Klop et al. 2012). The Sample Plot Calculator functions on the basis that strata covering the largest areas and with higher biomasses should be sampled more than strata covering smaller areas with lower biomasses (as they are more material to down-stream calculations of emissions reductions) and therefore the means for the three fallow ages calculated from Klop et al. (2012) were used . With no detailed information on the relative areas of land covered by the three fallow classes, they were given equal areas in the calculator. The calculator was observed to be insensitive to area after an area input of approximately 1000 hectares (where the area is held constant across all three fallow age classes). The Sample Plot Calculator determined that 42 post-deforestation plots were required, with greater sampling of the older (6-10 years) than younger (0-3 years) fallows.

Due to time constraints and logistics, it was not considered feasible to establish plots in each of the 13 REDD+ Project communities. Instead, seven plots (2 fallows 0-3 years old, 2 fallows 3-6 years old, and 3 fallows 6-10 years) were established in six towns, randomly chosen from the 13 towns in advance of the carbon survey a series of random numbers generated in Microsoft excel.

Plot establishment

The methodology for establishing carbon plots in the post-deforestation landscape followed the SOP for forest carbon plots, however, there were some differences in the protocols, and these were outlined in an Annex to the main forest plot SOPs (the ‘Post-deforestation SOPs’; see references). The main difference with regard to the establishment of post-deforestation plots is that unlike the forest carbon plots, which were established at predetermined GPS coordinates, post-deforestation plots were located in fallow land opportunistically after visiting fallow lands of different ages and assessing the areas to determine whether it met the criteria listed in the Post-deforestation SOP. The carbon team navigated to fallows within the age classes given above with the aid of a local community member familiar with the town’s land-use history. A post-deforestation plot was established if the fallow land was of a homogeneous fallow class for at least 25 m in each direction from the plot centre point, and it showed no other signs of disturbance.

Carbon Pools measured

At each post-deforestation plot the following carbon pools were measured:

- Above-ground Tree Biomass (AGB)
- Lying Deadwood
- Standing Deadwood
- Non-tree Woody Biomass (NTWB)

Below-Ground Biomass (BGB) is difficult and time consuming to measure, and can be readily estimated using default root-to-shoot ratios and therefore this carbon pool was not measured.

The litter pool was considered insignificant. Soil carbon was conservatively excluded, as this pool is expected to increase in the project scenario.

Equipment

The team were equipped with the same equipment for the post-deforestation survey as for the forest carbon survey, with the addition of equipment required to measure NTWB in clip plots. This additional equipment included:

- Clip plot frame, composed of 4 tubes of PVC piping with 4 corner pieces
- Vegetation / pruning clippers
- Hand saw
- Cotton bags
- Plastic bucket with handle
- 22 kg, 5 kg and 300 g hanging scales

Measurement Protocols

All protocols for establishing the plot and measuring the selected carbon pools are contained with the FFI Standard Operating Procedures for Measuring Above-Ground Biomass (hereafter 'the SOPs').

Above-Ground Live Tree Biomass

Above-Ground Live Tree Biomass was measured as per the methodology for AGB in the forest carbon plots (section 2.4).

Palms, represented by a single species (*Elaeis guineensis*, the African oil palm), were included in this carbon pool in the post-deforestation plots. Despite not being 'true' trees, they were the most abundant 'trees' (DBH ≥ 5 cm) in the post-deforestation plots and therefore were conservatively included in the estimates of AGB. Due to weak relationships between DBH and palm biomass the majority of palm species specific allometric equations include stem height as an explanatory variable (Goodman et al., 2013). The carbon survey team were trained in 2019 to measure the stem height of palms as well as DBH, however, due to human error this was not included in the post-deforestation SOP and standardized data sheets and palm stem height was inconsistently measured (height measurements were made for 64.6% of palms).

Below-Ground Biomass

Below-Ground Biomass (BGB; t d.m. ha^{-1}) was conservatively calculated from the plot AGB using a root-to-shoot ratio of 0.20 for Tropical Rainforests (as the mean AGB across post-deforestation plots in all fallow age classes was <125 tC/ha) as per parameter R in VCS Module VMD0001v1.1 (page 17).

Lying deadwood

This carbon pool was measured following the same methodology for forest carbon plots (section 2.4).

Standing deadwood

This carbon pool was measured following the same methodology for forest carbon plots (section 2.4).

Non-tree Woody Biomass

Non-Tree Woody Biomass (NTWB) includes trees < 5 cm DBH, all shrubs, and all other non-herbaceous live vegetation. NTWB was measured as per the FFI SOP for Measuring Above-

Ground Biomass in the 'Post-deforestation' Landscape (2019), using 50 cm x 50 cm square clip plots, located 10 m along transects North, East, South and West from the plot centre point. All NTWB growing in the clip plot was destructively harvested at stem base and fresh weight measured in the field. A sub-sample of destructively harvested vegetation from the four clip-plots was taken, fresh weight weighed, and then sent to the laboratory for drying until a constant weight at 70°C (Walker et al. 2018). From this data the wet-to-dry ratio for NTWB was calculated.

Calculations of Oil Palm Biomass

Palm AGB

A total of 48 palm trees (*Elaeis guineensis*) were recorded. Data on stem height was available for 31 of these trees. The scientific literature on palm allometries observes that there is a weak relationship between stem diameter and stem height in palm species (Goodman et al. 2013). Allometric equations which include stem height correlate better with palm AGBs (i.e. have higher R^2 values) and lower residual standard errors (Goodman et al. 2013). Consequently the allometric equation of Khasanah et al. (2015; R^2 = 0.9155) was used to estimate palm AGB:

$$y = 0.1839 \times \ Palm\ Height^{0.766}$$

Where:
y = Palm AGB in tonnes of dry matter (Mg)
Palm height = Palm stem height (to lowest frond) in m

Rather than use a separate allometric equation (using DBH only) to estimate the biomass of the 17 palms trees without stem height data, the mean AGB calculated using the Khasanah et al. (2015) allometric equation for palms in 5 cm DBH size class brackets was used as per Table 2.

Table 2. Mean AGB (t. dry matter) of palm trees in 5 cm DBH size class brackets.

DBH Class	Count	Mean AGB (t d.m.)
20 - 25	1	1.05
25 - 30	3	1.505
30 - 35	12	1.440
35 - 40	9	1.491
>40	5	1.571

Above-Ground Live Tree Biomass

Individual tree AGB values were estimated from the stem DBH and species wood densities using equation 7 of Chave et al. (2014). Wood densities applied followed the taxonomic hierarchy described in section 3 'Wood Densities'. An environmental '*E*' parameter of -0.11754 was used. Individual stem AGBs, including palm trees (estimated as per the previous section) were summed to calculate total plot AGB in tonnes of dry matter (t d.m.) using equation 1 of module CP-AB:

$$C_{AB\_tree,sp,i} = \sum_{j}^{S} \sum_{l=1}^{N_{j,sp,i}} f_j(X,Y...) * CF_j$$

Where:

$C_{AB\_tree,sp,i}$	= Carbon stock in aboveground biomass of trees in plot *sp* in stratum *i*; t C
CF_j	= Carbon fraction of biomass for species group *j*; t C t^{-1} d.m.
fj(X,Y..)	= Aboveground biomass of trees based on allometric equation for species group *j* based on measured tree variable(s); t. d.m. $tree^{-1}$
i	= *1, 2, 3, …M* strata
j	= *1, 2, 3 … S* tree species
l	= *1, 2, 3, … Nj,sp,i* sequence number of individual trees of species group *j* in sample plot *sp* in stratum *i*

A slope correction was therefore applied to account for this variation in actual plot radius on a horizontal plane (Walker et al. 2018):

$$Sloped\_Radius = \frac{Nest\_Radius}{Cos\theta}$$

Where:

Sloped_Radius	= Length of radius (m) on slope that corresponds to horizontal radius
Nest_Radius	= Length of radius agreed upon in flat terrain (m)
Cosθ	= Cosine of the slope angle

Plot AGBs were converted to carbon stocks per stratum using equation 2 of module CP-AB:

$$C_{AB\_tree,i} = \sum_{sp=1}^{P_i} \frac{C_{AB\_tree,sp,i}}{A_{sp,i}} * \frac{44}{12}$$

Where:

$C_{AB\_tree,i}$	= Mean aboveground biomass carbon stock in stratum *i*; t CO_2-e ha^{-1}
$C_{AB\_tree,sp,i,t}$	= Aboveground biomass carbon stock of trees in sample plot *sp* of stratum *i* , t C
A_{spi}	= Area of sample plot *sp* in stratum *i*; ha
sp	= *1, 2, 3 … Pi* sample plots in stratum *i*
i	= *1, 2, 3 … M* strata
44/12	= Ratio of molecular weight of CO_2 to carbon, t CO_2-e t C^{-1}

Below-Ground Biomass

This carbon pool was calculated following the methodology for forest carbon plots (section 4), except that a root-to-shoot ratio of 0.2 was used as opposed to 0.24 (as per module CP-D), due to a mean AGB of <125 tC/ha in the post-deforestation landscape.

Lying deadwood

This carbon pool was calculated following the methodology for forest carbon plots (section 4), except that the CDM tool and wood density factors were also used to calculate lying deadwood.

Standing deadwood
This carbon pool was calculated following the methodology for forest carbon plots (section 4), excepting that the mean wood value used was the mean wood density for the living wood density class measured in the post-deforestation landscape (Section 4).

Non-tree Woody Biomass
The mean wet-to-dry ratio across all post-deforestation plots was 0.335. The Non-tree Woody Biomass measured in the four clip plots was summed and multiplied by 10,000 (the summed area of the four clip plots = $1m^2$), then multiplied by the wet-to-dry ratio (0.335) to give the dry NTWB per hectare. This was multiplied by the carbon fraction (0.47) and 44/12 to estimate NTWB in tCO_2e.

There were significant differences in above- and belowground biomass and their CO2 equivalents across carbon pools and post-deforestation periods (Table 3). Aboveground biomass had significantly larger quantities of carbon stocks than other pools. Largest quantities of aboveground tree biomass carbon stocks (28 tC ha^{-1}) were found in 6-10 year post-deforestation plots, with estimated carbon dioxide emissions of 104 tCO_2-e ha^{-1}.While above and below ground biomass, and deadwood biomass, increased with increasing duration of the post-deforestation crop-fallow cycle, non-tree woody biomass declined with increasing duration of the cycle. With increasing duration of the cycle regrowth of the tree species contributes to the system's biomass increment. However, this phase was characterised by limited natural tree mortality.

Table 3: Carbon stocks (tC ha^{-1}) and carbon dioxide (tCO_2-e ha^{-1}) emissions in post-deforestation plots in Wonegizi forest project area in Liberia

Carbon pool	Post-deforestation period						No strata	
	0 – 3 years		3 – 6 years		6 – 10 years			
	Carbons stocks (tC ha^{-1})	Emissions (tCO_2 e ha^{-1})	Carbons stocks (tC ha^{-1})	Emissions (tCO_2 e ha^{-1})	Carbons stocks (tC ha^{-1})	Emissions (tCO_2 e ha^{-1})	Carbons stocks (tC ha^{-1})	Emissions (tCO_2 e ha^{-1})
AGB	8.21	30.11	13.90	50.98	28.44	104.30	18.16	66.60
BGB	1.64	6.02	2.78	10.20	5.69	20.86	3.63	13.32
NTWB	2.77	10.17	1.48	5.43	0.97	3.57	1.65	6.63
SDWB	1.37	4.98	1.41	5.18	1.89	6.93	1.55	5.70
LDB	5.82	21.38	1.70	6.23	2.22	8.14	3.09	11.32
Total	19.81	72.63	21.78	78.01	39.22	143.79	28.68	102.96

Legend: AGB – Aboveground Biomass; BGB – Belowground Biomass; SDW – Standing Dead Wood Biomass; LDWB – Lying Dead Wood Biomass; NTWB – Non-Tree Woody Biomass

Section 3: Quality Assurance and Quality Control

Team Competency and Training
To ensure team competency in establishing forest and post-deforestation sampling plots and measuring biomass, all staff participating in field studies attended a SOP training. The team leader and botanist was very familiar with the flora of Wonegizi, having lead the carbon survey in 2013, 2017 and 2019. The use of the same botanists in both the 2017 and 2019 surveys further ensured consistency in randomization and establishment of sampling plots. All carbon team members, irrespective of their previous experience and expertise, were required to

attend training on FFI's SOPs for the measurement of terrestrial carbon. Though developed by FFI, SOPs were based on industry best practices. All training was led by FFI's Forest Carbon Specialist in person.

Training (including in use of equipment, theory)

Daily records of training attendance were kept and only people who attended all training sessions participated in the carbon surveys. All team members, irrespective of their position in the team and expected duties during the actual survey, were trained on all aspects of plot establishment and measurement to ensure the survey progress would not be delayed should individual team members become unavailable due to unforeseen circumstances (injury / illness etc.). All training courses included the establishment of measurement of practice plots and measurement of plant biomass in sampling plots. This hands-on training consisted of theory and field practical sessions, allowing the team to use relevant methods and equipment in the field. The major topics covered in this training included:

- The theory of REDD+;
- FFI SOPs for Measuring Above Ground Biomass;
- Use of survey equipment;
- Establishment of carbon plots;
- Measurement of forest carbon pools;
- FFI SOPs for Measuring Above-Ground Biomass in the 'Post-deforestation' Landscape; and
- Establishment and measurement of forest and post-deforestation carbon plots

Data Quality

A number of procedures and actions were implemented to ensure high quality data was collected during the surveys.

During the survey:

- The carbon team carried a copy of the SOPs with them in the field at all times in a waterproof zip-lock document wallet, to ensure the FFI SOPs could be followed in any cases of uncertainty.
- The 2019 carbon survey team were provided with a laminated species list with taxonomic spellings corrected against the World Flora Online (http://www.worldfloraonline.org/) and The Plant List (http://www.theplantlist.org/) to reduce transcription error
- Standardized data entry sheets were used (and presented during the training courses). Data sheets can be observed in the SOPs.
- The carbon survey team were equipped with a 'Rite in the Rain'® waterproof notebook to ensure that data was not lost or that spellings etc. were not distorted should they need to collect data in the field for a limited period of time under heavy rain.
- Data was recorded by a single person for all plots, to reduce transcription errors due to poor legibility of data recorded.

A number of quality control measures were put in place. Due to lack of access to internet and computing facilities, all data entry into a standardized excel workbook was completed by FFI UK staff, after all datasheets had been scanned to PDF, and saved on FFI's internal Microsoft SharePoint server. All original datasheets are stored in a waterproof plastic box in an air conditioned room at FFI Liberia's Monrovia office. Importantly, all data transcription into

Microsoft excel was checked by a second person to ensure that no transcription mistakes were made.

Quality Control
Tree DBHs were re-measured in a total of 10 forest carbon plots (14.3%) by an independent team. DBH measurements were made by FFI's Technical Specialist – Forestry and Forest Carbon, with data recorded by FFI's Wonegizi REDD+ Officer.

Measurement Error

Measurement error was calculated using a blind check of data from 10 plots re-measured by an independent team for quality control purposes. Measurement error was calculated using the equation (Walker et al. 2018):

$$Measurement\ Error\ (\%) = \left| \frac{(tC/ha\ of measured\ plot - tC/ha\ \ of\ remeasured\ plot)}{tC/ha\ of\ remeasured\ plot} \times 100 \right|$$

The resulting mean measurement error (on 10 plots) was 0.2%, which is below the 10% requirement (Walker et al. 2018).

Re-measurements of post-deforestation carbon plots for quality control purposes were not made. The reasons for this were two-fold. The mean number of trees per post-deforestation plot was much lower than for forest plots, and the mean DBH was far smaller. The carbon stored in this pool is therefore far lower than for the forest carbon plots (Table 2), and secondly, the survey of the post-deforestation carbon plots was made after the forest carbon plots, and by the exact same team. As the forest carbon plots passed the QC check it was considered that trees in the post-deforestation plots would be measured with the same diligence and accuracy, and further that there was a far lower probability of tree exclusion or double counting due to the substantially lower number of tree individuals per plot. Secondly, estimates of Non-Tree Woody Biomass (NTWB) are made through the destructive harvest of vegetation in clip plots. Destructive harvests from clip plots cannot be replicated at a later date as they are destructive.

Section 4: Emissions Factor for conversion

Table 4 presents estimated emission factors (EFs) based on calculated forest and post-deforestation carbon dioxide emissions. Emission factors are based on the difference of the carbon stock factors depending on the previous pre- and post-deforestation land use specifically for deforestation and degradation (IPCC 2006 guidelines, equation 2.15 and 2.16). The conversion from carbon stocks to CO2 emissions is facilitated through the molecular weight conversion factor (44/12). Table 4 provides an overview of how the emissions factors for each of the classes was calculated.

Table 4: Carbon emissions (tCO2 ha^{-1}) from different strata in the Wonegizi project area in Liberia

Carbon pools	Carbon dioxide emissions from forest and post-deforestation plots (tCO_2-e ha^{-1})			
	Forest	Unstratified forest	Secondary forest	Post-deforestation
AGB	577.78	557.16	413.17	66.60

BGB	115.56	111.43	94.03	13.32
SDWB	15.68	15.72	15.85	5.70
LDWB	14.70	17.99	21.28	11.32
Total	723.64	702.3	544.33	96.94

Legend: AGB – Aboveground Biomass; BGB – Belowground Biomass; SDW – Standing Dead Wood Biomass; LDWB – Lying Dead Wood Biomass.

Emissions from loss of above- and belowground live tree biomass in unstratified forest constitute a significantly the larger fraction (95%) of total emissions from tree biomass, but emissions from aboveground biomass alone account for almost 80% of total emissions. There are significant differences between emission factors across carbon pools. The aboveground carbon pool is 490 tCO_2-e ha^{-1} is the highest emission factor, followed by belowground pool (100 tCO_2-e ha^{-1}). Dead wood biomass pools have comparatively lower EFs compared to living tree biomass carbon pools.

Emission factors for different strata in the Wonegizi REDD+ project are presented in Table 5. The primary forest had the highest EF (626.7 tCO_2-e ha^{-1}) while the secondary forest had the lowest value (447.36 tCO_2-e ha^{-1}). The unstratified forest EF was calculated because aggregated data for two data collection expeditions (2013 & 2019) showed that carbon stocks were not significantly different across strata after aggregation of data. The study concluded that there was no justification for stratifying forests. The project decided to use the EF value for unstratified forests in all its calculations of emissions.

Table 5: Emission factors for different strata in Wonegizi REDD+ project area in Liberia

	Carbon stocks (tCO_2 ha^{-1})		
Strata	Before deforestation	Post-deforestation	Emission Factor (tCO_2-e ha^{-1})
Primary Forest	723.64	96.94	626.70
Non-stratified forest	702.3	96.94	606.36
Secondary forest	544.33	96.94	447.36

Table 6 shows total biomass - above- and belowground, and deadwood biomass (tCO_2 ha^{-1}) - and EFs for strata in the Wonegizi REDD+ project area and Landscape 1 in Liberia. Total carbon stocks in intact forests and non-stratified forests were 1.9 and 2.3 times greater in forests than in secondary forests in Landscapes 1 & 2, respectively. However, total carbon values and EF factors for intact and secondary forests in Landscape 2 were higher than those for Landscape 1. But, all forested strata had significantly higher biomass carbon stocks than post-deforestation sites. Total carbon stocks in forests were 4.3 – 6.8 times greater in forest than in crop-fallow ecosystems in Landscape 1, while forested sites in Landscape 2 had 4.4 – 10 times more stocks than deforested areas.

Table 6: Carbon stocks and emission factors of strata in the Wonegizi REDD+ project area and Landscape 1 (Liberia FREL, 2020) in Liberia

Source	Strata	Total biomass (tC ha^{-1})	Emission Factor (tCO_2 ha^{-1})	Reference
Liberia FREL[a]	Intact forest	277.29	867.86	Liberia FREL (2020
(Landscape 1)	Secondary forest	142.76	374.76	Liberia FREL (2020)
	Non-forest	40.72		Liberia FREL (2020)
Liberia FREL	Intact forest	336.43	1113.38	Liberia FREL (2020)

(Landscape 2)	Secondary forest	144.52	409.71	Liberia FREL (2020)
	Non-forest	32.78		Liberia FREL (2020)
FFI Wonegizi REDD+ Project	Non-stratified forest	191.44	605.03	FFI (2019)
	Non-forest	26.43		FFI (2019)

[a]Adapted from Tables 12 & 13 (p. 38)of the Liberia FREL (2020).

Section 5: Discussion and Conclusion

The above- and belowground tree biomass carbon stocks differed across carbon pools and post-deforestation periods. Aboveground biomass represents the largest fraction of total tree biomass carbon stocks. Harvesting aboveground tree biomass exports significant carbon stocks from the forest or any tree-based ecosystem. Any activity that avoids or reduces deforestation or forest degradation should essentially target this carbon pool. The mean aboveground biomass stocks in unstratified forests (191 tC ha^{-1}) is lower than mean estimates for Landscape 1 (277 tC ha $^{-1}$) and Landscape 2 (336t ha^{-1}) possibly due to differences in measurement techniques, forest management histories, and climatic and edaphic conditions. In addition, the FREL calculations used the IPCC default biomass to carbon conversion factor 0.49, while this study used 0.47. These factors collectively could contribute for large variations in carbon estimations, especially working at landscape level.

The aboveground biomass in post-deforestation land use systems is the largest fraction of tree biomass carbon. The stock (18tC ha^{-1}) in this study is within the estimated range (22-95 tC ha^{-1}). This study shows that as the fallow increased, aboveground tree biomass also increased signifying forest recovery. While above and below ground biomass, and deadwood biomass, increased with increasing duration of the post-deforestation crop-fallow cycle, non-tree woody biomass declined with increasing duration of the cycle. This could be attributed to low natural tree mortality during early stages of forest recovery.

The mean belowground biomass carbon stocks in unstratified forests (30 tC ha^{-1}) in this study were lower than values reported for intact forests in Landscapes 1 (61 tC ha^{-1}) and 2 (76 tC ha^{-1}), but they are comparable to stocks in secondary forests (27 and 30 tC ha^{-1}, respectively). The variance in the stocks could partially be explained by differences in measurement of stocks. Belowground measurements for the Liberian FREL were estimated using an allometric model according to Cairns et al. (1997) in Mokany et al. (2006). Dead wood biomass pools have comparatively lower EFs compared to living tree biomass carbon pools.

Emissions from loss of above- and belowground live tree biomass in unstratified forest constitute a significantly larger fraction (95%) of total emissions from tree biomass, but emissions from aboveground biomass alone account for almost 80% of total emissions. Estimation of impacts of forest conversion using carbon stocks is largely influenced by the dominant aboveground biomass carbon pool.

The primary forest had the highest EF (626.7 tCO_2-e ha^{-1}) while the secondary forest had the lowest (447.36 tCO_2-e ha^{-1}). However, the unstratified forest EF was calculated because aggregated data for two data collection expeditions (2013 & 2019) showed that carbon stocks were not significantly different across strata. The study concluded that there was no justification for stratifying forests. The project decided to use the EF value for unstratified forests in all its calculations of emissions.

The aboveground stocks for the unstratified (557 tCO2 ha^{-1}) were lower than stocks reported for the Gola National Park (GRNP) North (578 tCO_2 ha^{-1}) and South stratum (629 tCO2 ha^{-1}), but the value for the primary forest (578 tCO2 ha^{-1}) in this study is the same as the value for GRNP South. The stocks in intact forest in Landscape 2 (955 tCO_2 ha^{-1}) and Landscape 1 (755 tCO_2 ha^{-1}) were greater than the values for the intact forests for this study. The disparities in stocks are probably due to sampling procedures and differences in scale of the studies.

Total carbon stocks in intact forests and non-stratified forests were 1.9 and 2.3 times greater in primary forests than in secondary forests in Landscapes 1 & 2, respectively. However, total carbon values and EF factors for intact and secondary forests in Landscape 2 were higher than those for Landscape 1. All forested strata had significantly higher biomass carbon stocks than post-deforestation sites. Total carbon stocks in forests were 4.3 – 6.8 times greater in forest than in crop-fallow ecosystems in Landscape 1, while forested sites in Landscape 2 had 4.4 – 10 times more stocks than deforested areas.

Despite the progress made in gathering carbon data and developing EFs, there were some challenges in establishing plots and gathering data. While the aggregated data suggested that there were no significant differences across strata, lack of strata was probably due to the placement of plots based on data collected by RSS, which differed from the land cover classification by Winrock International. In addition, there were some constraints in the placement of plots in what were initially classified as primary and secondary forests. This task could as well result in loss of some plots that were relocated. There is need to explore, in the long-term, the possibility of establishing additional plots in the forest to ensure areas that were originally inaccessible and that could affect the proportionality of location of plots are equally covered. This would further assess whether these adjustments to the project would create distinct strata.

Between 2013 and 2016, the definition of the forest was modified by FFI's stakeholders and the project had to develop this definition, which is based on canopy cover: <30% - post-deforestation; 30-80% - secondary forest; and >80% - primary forest. The study recommends that the definition should be evaluate to ascertain whether there is scope to revert to the original one.

This carbon assessment activity produced carbon data that will be used in calculating a baseline and contribute to the forest and post-deforestation database. Both the carbon stocks and emission factors provide a useful benchmark for further studies. Extra work is needed to monitor carbon stock changes and update the EFs as additional data is gathered.

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