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Quantifying Emissions and Removals in Malawi's Forestry Sector: Activity Data and Emission Factor Analysis

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Abstract: This paper presents estimates of activity data, emission factors and emissions and removals for Malawi's three REDD+ activities: deforestation, forest degradation, and enhancement. Calculations are based on data from Malawi's National Forest Inventory (NFI) and plantation data for the reference period 2010 to 2020. Deforestation occurred at a rate of 11,565ha ± 1,067ha per year, representing a 0.66% annual change. Notably, deforestation was higher in non-protected areas (0.69%) than protected areas (0.66%). Forest degradation resulted in an annual loss of 14,192 ha, equivalent to 0.77% per annum, with 54% degradation occurring in protected areas, mainly within the dense canopy class (>60%). These protected areas had an area weighted carbon stock of 57.26 tC/ha while forests outside the protected areas had an average carbon stock of 45.03 tC/ha. The estimated annual emissions from deforestation and forest degradation were 1,008,600 and 543,511 tCO_2e/yr, respectively. Annual removal due to forest enhancement averaged 61,070 tCO_2e/yr. The mean net forest emissions for this reference period were 1,491,041 tCO_2e/yr. Malawi has the potential to enhance its forests and mitigate its emissions through industrial plantations while also abating forest and biodiversity loss through avoided deforestation and forest degradation. By using Collect Earth, a free and open-source platform, this analysis provides a model for emissions and removals assessments that are transparent, fully replicable, and cost-effective for governments.

Keywords: activity data; emission factor; deforestation; forest degradation; forest enhancement

1. Introduction

The forestry sector in Malawi serves as a cornerstone of environmental sustainability and social cohesion (Kambewa and Chiwaula, 2010). Currently, the country has total forest cover of approximately 2.36 million hectares, accounting for 25% of the country's land areas (DoF ,2019). The country's forests comprise both natural (22,281 sq km), predominantly characterized by Miombo woodland, and plantation forests (673 sq km), predominantly consisting of pine and *Eucalyptus* species. Malawi boasts 88 forest reserves, 5 national parks, 4 wildlife reserves and 3 nature sanctuaries, with natural forests also interspersed within private and community lands (DoF 2019).

With its rich array of ecosystems, spanning from woodlands to wetlands, Malawi's forests play a pivotal role in conserving biodiversity, sequestering carbon, managing watersheds, regulating water flow, recycling nutrients, and mitigating climate impacts (GoM, 2017). Notably, these forests are indispensable to both rural and urban communities, with over 80% of the population relying on forest resources for everyday cooking needs (World Bank Group, 2019; Ngwira and Watanabe, 2019).

Forests in Malawi provide a range of products, including timber, fuelwood, charcoal, and non-timber forest products (NTFPs) (Ngwira and Watanabe, 2019). Approximately 85% of Malawi's population resides in rural and marginalized areas, where around 80% of the population relies heavily on natural resources for their subsistence, income, and livelihoods (Munthali *et al*., 2019, World Bank 2022).

In recent decades, Malawi's forests have faced direct mounting pressures from activities such as illegal charcoal production, unsustainable firewood collection, agricultural expansion and unsustainable logging practices, with the main underlying drivers as population growth and poverty, resulting in high rates of deforestation and forest degradation, and diminished ecosystem services (Ngwira and Watanabe, 2019; DoF 2023; Skole *et al*., 2021). Malawi's forests are also vulnerable to climate change impacts, including increased frequency and severity of droughts and floods (World Bank 2022). As a result, monitoring these forests is essential to sustain livelihoods, local economies, and ecosystem services into the future.

Malawi, as a party to various Multilateral Environmental Agreements such as UNFCCC and UNCCD, has pledged to combat climate change through forest conservation and restoration initiatives. Specially, through the UNFCCC and REDD+ program, Malawi committed to reduce greenhouse gas emissions (GHGs) by 51% by 2040, primarily by addressing deforestation and forest degradation, while promoting sustainable forest management and carbon sequestration (Carbon Count, 2021). Notably, Malawi's current GHG emissions are among the lowest globally, both in an absolute term and per capita. However, under a business-as-usual (BAU) scenario, emissions are projected to triple by 2040, increasing from approximately 9 million tCO2e in 2017 to over 34 million tCO2e (Carbon Count, 2021).

Malawi is committed to monitoring national emissions levels and implementing climate action activities. To support this effort, the country recognizes the importance of establishing national Reference Emissions Levels (REL)/Reference Levels (RL) that align with international agreements, such as UNFCCC Paris Agreement. The Forest Reference Level (FRL) is a critical component of REDD+ readiness, besides the National REDD+ Strategy/Action Plan, National Forest Monitoring System (NFMS) and the Safeguards Information System, as guided by the UNFCCC (Paudel and Paudel, 2018). By establishing a robust FRL, through selection of its REDD+ activities, Malawi can ensure a credible and transparent framework for its REDD+ initiatives, supporting the country's efforts to mitigate climate change and promote sustainable development. FRL also serves as a benchmark to evaluate the effectiveness of policies and determine result-based payments for performance through both emission reduction activities and removals. Additionally, forest coverage and potential land use changes are of great interest to the National GHG inventories in Malawi.

Assessing carbon emissions in the forestry sector is crucial for mitigating climate change and fostering sustainable development. Forests play a vital role as carbon sinks, absorbing carbon dioxide from the atmosphere and mitigating its adverse effects on climate (World Bank 2022). By quantifying emissions, policymakers can identify drivers of emissions, formulate targeted mitigation strategies, and monitor progress toward emission reduction goals. Moreover, accurate assessments underscore the broader environmental, social, and economic benefits of sustainable forest management, including biodiversity conservation, ecosystem services provision, and livelihood support for forest-dependent communities. Robust assessments of emissions are required for evidence-based decision-making and transitioning toward a resilient and carbon-neutral future (Nesha, 2021).

REDD+ activities included in national FRLs may include deforestation, forest degradation, enhancement of forest carbon stocks, sustainable management of forests, and conservation of forest carbon stocks. However, a large proportion of national FRLs are much more limited (FAO, 2020a; Sandker et al., 2022). As of 2020, less than one third of countries (18 of 60 FRLs) included deforestation, degradation, and enhancements (FAO, 2020a). The costs of monitoring are a primary reason that countries limit their monitoring to only a subset of potential REDD+ activities (Sandker et al., 2022). By including the three activities of deforestation, degradation, and enhancements, Malawi's FRL is relatively ambitious by global standards, and it provides a replicable model for robust and cost-effective assessment.

This paper aims to present the revised FRL for Malawi, which were initially submitted to UNFCCC in 2019 (GoM 2019), addressing the recommendations of the UNFCCC technical assessment report (UNFCCC TAR 2021). The objective of this paper is to provide a comprehensive and more robust FRL, presenting activity data, emission factors and removals estimates for the forest sector under Malawi's REDD+ activities (deforestation, forest degradation, and enhancement) for the reference period 2010-2020, and demonstrating Malawi's commitment to transparent and accurate accounting of GHG emissions and removals. By doing so, this paper will serve as a basis for monitoring and reporting GHG emissions and removals, informing policy and decision-making on forest management and conservation, and supporting Malawi's efforts to achieve its REDD+ goals and contribute to global efforts to combat climate change.

The paper is organized into four sections. Section 1 provides an introduction to the topic. Section 2 describes the methods and methodology used, including details on emissions and removal factors, activity data, and the approaches employed for estimating GHG emissions and removals for all REDD+ activities for Malawi, thus, deforestation, forest degradation, and enhancement. Section 3 presents the results, showcasing the activity data, removals/emission factors and estimated emissions and removals for each REDD+ activity, as well as the overall FRL for Malawi. Finally, Section 4 concludes the paper by summarizing the key findings, discussing implications of the revised FRL, and outlining potential areas for future improvement.

2. Materials and Methods

2.1. Study Area

Malawi is a landlocked country in Southern Africa, shares borders with Zambia to the west, Tanzania to the north and northeast, and Mozambique to the south and southwest and covers 94,080 square kilometers of land areas. The country's subtropical climate, mainly influenced by the Lake Malawi, is characterized by three distinct seasons: a warm and wet season from November to April, a cool and dry season from May to August, and a hot and dry season from September to November. Malawi's forests, defined as having at least of 10% canopy cover and covering more than 0.5 hectares, consist of both natural and plantation forests predominantly featuring Miombo woodland ecosystems, a semi-arid tropical woodland (Skole *et al.*, 2021). The Miombo system covers 90% of the natural forest areas, with some dense evergreen forest located in the highlands. Pine and *Eucalyptus* are prevalent in plantation areas. The country's forests are predominantly found in the Northern, Central, and Southern Regions. With a population of approximately 20.6 million people, Malawi relies heavily on agriculture, forestry, and natural resources, with around 85% of the population living in rural areas (World Bank 2022).

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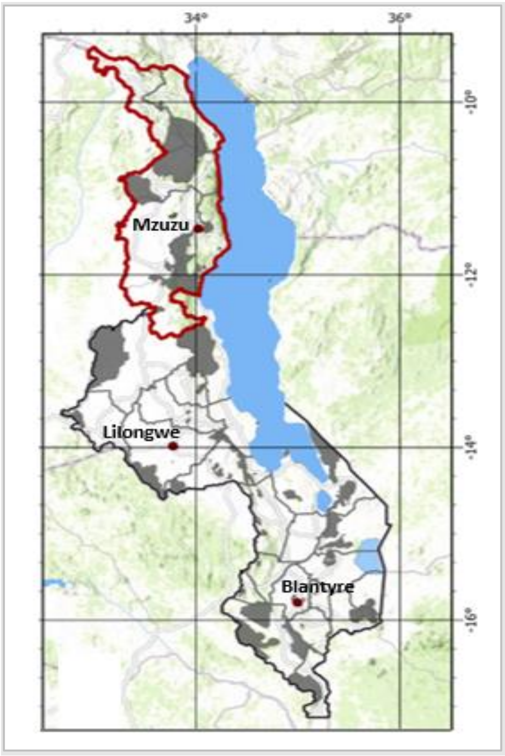

Figure 1. Map of Malawi protected areas and government plantations.

2.2. Development of Activity Data

Malawi's REDD+ program (2012-2019) aimed to maximize emission reductions through targeted measures and activities. These activities focused on lowering net emissions by reducing deforestation rates, minimizing forest degradation from unsustainable fuelwood harvesting, and enhancing carbon stocks through afforestation and reforestation. The program included three key activities: Reducing Emissions from Deforestation, defined as the conversion of forest to non-forest land uses; Reducing Emissions from Forest Degradation, which involves a reduction in canopy class while maintaining a minimum canopy cover of 10%; and Forest Enhancements, encompassing activities that increase carbon stocks within public and private plantations.

In contrast, two activities were excluded from the program. Sustainable Management of Forests, which involves the conversion of non-planted forest areas to planted forest areas, was not included due to operational capacity limitations and is instead considered under Forest Enhancements. Conservation of Carbon Stocks, referring to conservation activities that reduce emissions in naturally occurring forests, was also excluded due to a lack of clear definition and distinction within Malawi's forestry sector. However, both activities may be considered for inclusion in future monitoring as their scope and definition become more established.

2.2.1. Activity Data for Deforestation

Deforestation and forest degradation were estimated using a combined random sampling approach. This method involved visually interpreting plots to extrapolate the entire landscape's forest condition. The image interpretation was done using Google Earth images accessed via Collect Earth, a free and open-source system for remote sensing image analysis, with a 0.5 ha plot gridded into a 3x3 sub-grid configuration. Additionally, other image repositories, such as Bing Maps and Planet Imagery, were also considered to support the mapping process. The Collect Earth platform not only facilitates access to high-resolution imagery and streamlines the observation process, but it also offers flexible survey design and is easy to use (FAO, 2017). Collect Earth also promotes uniformity in identifying, interpreting, and annotating plots for reference data to categorize and monitor changes in land cover and land use (Saah et.al, 2019). This method proved advantageous

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over the traditional wall-to-wall mapping approach, which involves classifying every single pixel of land cover, making sampling more efficient and less resource-intensive despite requiring numerous analysts (Maniatis 2021).

Collect Earth's features, including pop-ups for error reminders and easy data exportation, ensured efficient assessment. Analysts underwent training to adhere to standard operating procedures, ensuring high-quality and reliable interpretation. Color, size, shape, texture, pattern, shadow, seasonality, context and cloud cover were thoroughly considered during the visual interpretation process. Overall, this sample-based approach provided comprehensive insights into deforestation and forest degradation dynamics, supporting effective conservation and management strategies in Malawi. Dozens of countries have used Collect Earth to account activity data for forest cover monitoring (CEO 2021).

The sampling frame, or area over which the random plots were generated, encompassed 2,459,000 hectares (25% of Malawi's land area), focusing on protected areas, forest reserves, and customary lands, while excluding timber and fuelwood plantations. The sample frame was developed using a land use land cover map developed by USGS in 2017, which was the most up to date land cover map available. Approximately 6,000 points were generated and 5,087 were evaluated to reach the precision threshold of at least 3,000 complete plots with usable imagery available for both 2010 and 2020, enabling analysis of deforestation activity data. If the image not available for specific year for certain plots, analysts were given the flexibility to use images with dates up to two years either before or after the nominal years, meaning that 2010 could include 2008-2012 and 2020 could include 2018-2022. Activity data for deforestation, expressed in units of hectares per year, were estimated by multiplying the period-adjusted proportion deforestation rate in the sample by the total area of the sample frame, as shown in equation 1.

Equation 1: Annual Rates of Deforestation in Hectares

$$AD = \frac{\hat{p}_{deforestation\ rate} \times A}{10}$$

Where:

AD	Activity Data deforestation (ha y^{-1})
A	Area of the sampling frame (ha)
$\hat{p}_{deforestation\ rate}$	Count of deforestation observations adjusted to account for differences in dates of source imagery

The percent deforestation was estimated by comparing the hectares of forest loss, which was calculated by multiplying the period-adjusted proportion of deforestation rate in the sample by the total area of the sample frame (Equation 1), to the circa-2010 forest extent observed in the sample (Equation 2). This comparison yielded the percentage of forest areas lost due to deforestation, providing a measure of the extent of deforestation in the sample area.

Equation 2: Forest Loss Expressed as a Percent of Initial Sampled Forest Area

$$deforestation\ \% = \frac{AD}{A \times \frac{N_{forest-time\ 1}}{N_{total}}}$$

Where:

Deforestation %	Percent of circa-time-one forest loss annually (% y^{-1})
AD	Activity Data for deforestation (ha y^{-1})
A	Area of the sampling frame (ha)
$N_{forest\text{-}time1}$	Count of observations showing forest land cover in time one
N_{total}	Total count of observations

2.2.2. Activity Data for Forest Degradation

The quantification of degradation activity data was collected concurrently with the deforestation data collection, as described above. Analysts used a Collect Earth survey, the same survey developed for deforestation assessment, to evaluate the landcover changes using freely available high resolution Google Earth images for circa 2010 (Time 1) and 2020 (Time 2). The same points generated for deforestation activity data assessment were used, including protected areas, and forests outside of protected areas. A mask was applied to exclude government and private timber or fuelwood plantations. Forest degradation was identified as a two-class reduction in canopy cover between the start and end of the reference period, as adopted by Zambia in their FRL (RoZ 2021). Each forested sample plot was assigned a canopy closure class for 2010 and 2020 with a transition from a higher canopy closure class to a lower-class indicating forest degradation. Analysts recorded canopy coverage within each plot for the following canopy coverage thresholds - sparse canopy closure (10%-15%), low canopy closure (15%-30%), moderate canopy closure (30%- 60%) and dense canopy closure (>60%). These canopy closure classes were derived from a fractional tree cover study in Malawi and complement the natural ecology and natural breaks in canopy (Skole 2021). Out of all analyzed plots, 3,301 plots were forest remaining forest, of which 277 points exhibited signs of degradation resulting from a change in canopy closure.

The rate of forest degradation transition was calculated using Equation 3, which divides the total count of degradation observations by the total number of observations to give the proportion of the sample that exhibits degradation.

Equation 3: Proportion of Degradation in the Sample

$$\hat{p}_{forest\ transition\ rate} = \frac{N_{adjusted-degradation}}{N_{adjusted-total}}$$

Where:

$\hat{p}_{forest\ transition}$	Proportion of the sample that exhibits degradation from time one-time two
$N_{adjusted\text{-}degradation}$	Count of degradation observations adjusted to account for differences in dates of source imagery
$N_{adjusted\text{-}total}$	Count of all observations

The area of each degradation transition was quantified, applying Equation 4. To estimate activity data for degradation in hectares per year, the period-adjusted proportion of degradation in the sample was multiplied by the total area of the sample frame, as shown in Equation 4.

Equation 4: Annual Rate of Degradation in Hectares.

$$AD = \frac{\hat{p}_{forest\ transition\ rate} \times A}{10}$$

Where:

AD	Activity data for deforestation (ha y^{-1})
A	Area of the sampling frame (ha)
$\hat{p}_{degradation}$	Count of degradation observations adjusted to account for differences in dates of source imagery

The percentage of forest transition from one higher level canopy closure to lower-level canopy closure was estimated using equation 5.

Equation 5: Forest transition expressed as a percent of initial sampled forest Area

$$Forest\ transition\ \% = \frac{AD}{A \times \frac{N_{forest-time\ 1}}{N_{total}}}$$

Where:

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Forest transition %	Percent of circa-time-one forest degradation annually (% y^{-1})
AD	Activity Data for forest transition (ha y^{-1})
A	Area of the sampling frame (ha)
$N_{forest\text{-}time1}$	Count of observations showing forest land cover in time one
N_{total}	Total count of observations

2.2.3. Activity Data for Enhancement

The forest carbon stock enhancement accounts for the total GHG removals generated by replanting non-forest areas within designated forest land. This includes all replanted timber and fuelwood plantations from 2010 to 2020. Any planting done outside of this reference period was excluded due to insufficient data and assumed to be negligible. Although the DoF is involved in forest restoration and planting activities outside of timber plantations - either directly or as a coordinator of NGO and community-based organizations-there is currently no systemized approach for monitoring the non-plantation-related enhancement of forest carbon stocks activities. Consequently, non-plantation restoration efforts have been omitted from the FRL. Plantation data was collected via a survey of each registered plantation manager. These managers oversee timber and fuelwood plantations established on lands managed by the government and private entities, including tobacco and tea estates. The survey template was designed to capture the best possible available data including years of plantation, species planted, planting density, the survival rate and areas planted in hectares.

2.3. Emission Factors

2.3.1. Emission Factors for Deforestation

The emission factor for deforestation was derived from the National Forest Inventory (NFI) data from 2018 to 2023. A total of 583 plots level data, 426 from protected areas and 157 from forest outside the protected areas (FOPA), were used to derive the emission factors. The inventory followed the DoF standard operating procedures (SOPs), which were developed and refined through several series of NFI events. National NFI synthesis presented forests data in two strata: protected areas and areas outside of protected areas, representing predominantly dense and less dense forests, respectively. These strata reported carbon stock for above and below-ground biomass. Malawi applies a T-shaped cluster design three nested plots for inventory purpose. Within each plot, the diameter at breast height (DBH), species and damage level of all live trees was recorded. The DBH measurements were taken in three plots of varying radii: 6 m (5-14.9 cm), 12 m (15-29.9 cm) and 20 m (DBH ≥ 30 cm).

Based on the trees inventoried in each plot, the forest carbon stocks were then calculated to determine the national emissions factors for tree carbon pools – aboveground and belowground. Aboveground biomass (AGB) and belowground biomass (BGB) were estimated using the country-specific allometric models (Equation 6), as developed by Kachamba *et al* (2016).

Equation 6: Above and Belowground Biomass Equation, from Kachamba et al. 2016.

$$AGB_t = 0.21691 * DBH^{2.318391}$$

$$BGB_t = 0.284615 * DBH^{1.992658}$$

Where:

BGBt	Belowground biomass of the tree *t*; kg dry mass (d.m.)
AGB_t	Aboveground biomass of the tree *t*; kg dry mass (d.m.)

Forest carbon stocks in the deadwood pool (standing and lying) were estimated by assuming dead biomass was equivalent to 1% of the total live biomass and litter biomass was equivalent to 1%

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of total live biomass1 following CDM look up tables for tropical forests which receive an annual precipitation of 1,000mm – 1,600mm per year. Forest soil carbon stocks were obtained from Henry *et al*. (2008).

The total live tree biomass was then converted to tons of carbon (C) multiplying by 0.47 t C t-1 dry biomass matter, which was then multiplied by the molecular weight ratio of CO_2 to C (i.e., 44/12) to convert to CO_2e, following IPCC 2006 Guidelines.

Deforestation emission factors were developed following the IPCC stock-difference approach (Equation 2.25 in the IPCC 2006 Guidelines, Volume 4), which estimates the difference between the pre-deforestation and post-deforestation carbon stocks for each stratum (Equation 7). The carbon stock in biomass prior to deforestation is subtracted from the carbon stock post deforestation, plus the change in soil carbon stock following deforestation (see Equation 7), the conversion factor of C to CO_2 e were applied to give a final result in units of tonnes of CO_2 e per ha. The post deforestation carbon stock in biomass was derived from the IPCC guidelines lookup tables based on the end land use. The tropical dry ecosystem type was applied because Malawi is generally dry for 5-8 months of the year. The post deforestation carbon stock for forests converted to grasslands is 8.7 tC/ha and the carbon stock for forests converted to croplands is 1.8 tC/ha (IPCC Guidelines 2006, chapters 6, Table 6.4 and Chapter 5, Table 5.9 respectively).

Equation 7: Deforestation Emission factor.

$$EFdef = (Cbio.pre - Cbio.post + \Delta SOC) * 44/12$$

Where:

EFdef Emission factor for deforestation, $tCO_2e\ ha^{-1}$

Cbio.pre Carbon stock in biomass, prior to deforestation (see Equation 8), $tC\ ha^{-1}$

Cbio.post Carbon stock in biomass, post-deforestation, $tC\ ha^{-1}$

ΔSOC Change in soil carbon stock following deforestation (see Equation 7), $t\text{-}C\ ha^{-1}$

44/12 Conversion factor from carbon to CO_2

The forest soil carbon stock (SOC.f) was obtained from Henry *et al*., 2008 (Table 6). At the recommendation of the technical assessment team of the initial FRL submission, a national average provided for Malawi was used rather than an average of an ecoregion. As suggested in IPCC 2006 guidelines, the relative stock change coefficients for forest land converted into grassland are 1, 0.97 and 1 for land use factor (FLU), management factor (FMG) and input factor (FI) respectively. Similarly, for forest land converted into cropland, the coefficients are 0.58, 1, and 0.96 for land use factor (FLU), management factor (FMG) and input factor (FI), respectively. Malawi's deforestation EF development assumed that cropland is characterized by long-term, full-tillage, and low to medium inputs (as described in Tables 5.5 and 5.9 of the IPCC 2006 Guidelines, Volume 4), whereas grassland is assumed to have a moderately degraded management (as described in Table 6.2 of the IPCC 2006 Guidelines, Volume 4).

Equation 8: Change in Soil Carbon Stock Following Deforestation

$$\Delta SOC = SOC.f * (1 - (FLU * FMG * FI))$$

Where:

ΔSOC Change in soil carbon stock following deforestation, $tC\ ha^{-1}$

SOC.f Forest soil carbon stock prior to deforestation, $tC\ ha^{-1}$

FLU Stock change factor for land-use, dimensionless

FMG Stock change factor for management regime, dimensionless

FI Stock change factor for input of organic matter, dimensionless

The deforestation emission factor is based on biomass carbon stock difference for above and below ground biomass (Equation 9), with the addition of soil emissions which are calculated separately (Equation 8). The carbon stock in aboveground biomass (C.AGB) and belowground

[1] https://cdm.unfccc.int/methodologies/ARmethodologies/tools/ar-am-tool-12-v3.0.pdf

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biomass (C.BGB) were calculated as the area-based aggregate from the NFI reports from 2018- 2023. The rest of the carbon stocks (i.e. deadwood and litter) were obtained following the IPCC guidelines.

Equation 9: Carbon Stock in Total Forest Biomass, Prior to Deforestation, used in Malawi's Deforestation EF.

$$Cbio.pre = C.AGB + C.BGB + C.DW + C.LIT$$

Where:

Cbio.pre	Carbon stock in forest biomass, prior to deforestation, tC ha^{-1}
C.AGB	Carbon stock in aboveground live tree biomass, tC ha^{-1}
C.BGB	Carbon stock in belowground live tree biomass, tC ha^{-1}
C.DW	Carbon stock in standing and lying deadwood pool, tC ha^{-1}
C.LIT	Carbon stock in litter, tC ha^{-1}

2.3.2. Emission Factor for Forest Degradation

Estimating emission factors from forest degradation poses a significant challenge due to various factors inherent in the dynamic nature of forests and the complexities involved in measuring and quantifying changes accurately. For emissions from forest degradation, aboveground biomass and below ground biomass pools are included. It is assumed that deadwood and litter pools would be insignificant due to anthropogenic pressures. In Malawi, estimating emission factors for forest degradation is particularly challenging due to the prevalence of anthropogenic activities such as illegal charcoal production, unsustainable firewood collection, forest fires, logging, and agricultural expansion. To address this challenge, emission factors were calculated using a robust method based on national inventory data collected from 2018-2023, comprising 583 total plots. The inventory teams assessed and recorded all canopy closure classes in the field, and the following steps were taken to account for activity data:

- Each of the 583 plots was assigned a canopy closure class based on field observations, categorizing them as sparse forest (10%-15%), low forest (15%-30%), moderate forest (30%-60%), or dense forest (60% and above).
- The area-weighted average of each canopy closure class was then calculated to ensure representative coverage
- Finally, emission factors were calculated by applying the change in canopy closure class (from initial to final) to each plot and multiplying it by the area of each transition, thereby accounting for the impact of forest degradation on carbon stocks.

Equation 10: Change in Carbon Stock EF for Degradation.

$$\Delta Cstock = Cstock_{time1} - Cstock_{time2}$$

Where:

$\Delta Cstock$	Change in carbon stock between canopy closure classes, tC ha^{-1}
$Cstock_{2010}$	Carbon stock in AGB and BGB at canopy closure class in 2010, tC ha^{-1}
$Cstock_{2020}$	Carbon stock in AGB and BGB at canopy closure class in 2020, tC ha^{-1}

2.3.3. Emission Factor for Forest Enhancement

The removal factors utilized in this study represent the carbon sequestration capacity of planted tree species in both governmental and private plantations in Malawi. Derived from empirical data, these factors estimate the amount of carbon dioxide removed from the atmosphere through the growth of specific tree species over time. Predominantly, *Eucalyptus* and pine species are documented in plantation records, and chosen for their suitability to local conditions. Table 1 outlines the proportions of plantation areas allocated to each species and their typical harvest cycles, providing essential data for estimating carbon accumulation rates. By incorporating species-specific information, this approach ensures accurate carbon accounting in Malawi's forestry sector, tailored to the characteristics of planted tree species and management practices. This comprehensive methodology enhances the reliability and precision of carbon sequestration assessments in plantation forests.

Table 1. Planted Species in Malawi and Rotation Cycles.

Species	Average % of National Plantation Area	Rotation Cycle (Years)
Eucalyptus spp.	41.15%	14
Pinus spp.	58.36%	30
Others spp.	0.48%	36

The removal factors used in this study were extracted from the Global CO_2 Removals Database (Bernal *et al*., 2018), specifically opting for values applied to tropical dry climates and corresponding to the tree species outlined in Table 2. The Global Removals Database was chosen over the IPCC defaults (2006 Guidelines and 2019 Refinement, Volume 4) due to its comprehensive and scientifically validated data on all three species of interest in Malawi. Notably, the IPCC (2019) does not provide removal rates for coniferous *Eucalyptus* species in tropical dry climates. In contrast, the Global CO_2 Removals Database, developed through a review of 335 scientific peer-reviewed manuscripts and published reports, offers a robust dataset with 1197 independent data points. Specifically, the database provides 32 data points for *Eucalyptus* and 28 data points for Pine species, ensuring a reliable basis for our removal factor calculations. Adhering to a conservative methodology, only above ground and below ground biomass pools are included as the other pools are not considered a significant source of additional removals (Pearson et al. 2005). The growth curves employed to derive removal factors for the three species categories encompassed in this investigation were selected to ensure alignment with empirical research and observed growth patterns (Bernal et al. 2018).

To derive an annual removal rate, the total aboveground biomass carbon stocks for each of these species were divided by the length of their rotation (listed in Table 1). The final removal factors applied for each species planted in forest plantations included in Malawi's REDD+ program assume that each year the committed sequestration for an entire rotation length is accounted for each year a new plantation area is planted. This entails taking the middle point of the maximum peak biomass at felling age. Table 2 summarizes the removal rates.

Table 2. Removal Factors (tC ha-1 yr -1 and tCO2e ha-1 yr-1) applied to estimate the enhancements reference level in Malawi.

Plantation Species	Tons of Total Biomass (C ha^{-1} yr^{-1})	Tons of Total Biomass (CO2e ha^{-1} yr^{-1})
Eucalyptus spp.	16.9 ± 1.4	61.8 ± 5.0
Pinus spp.	6.4 ± 0.5	23.5 ± 1.9
Conifer (Non-*pinus* spp.)	10.9 ± 0.1	39.8 ± 0.5

2.4. Uncertainty and Quality Assurance/Quality Control

The development of Emission Factors (EF) and Activity Data (AD) for deforestation and degradation followed rigorous protocols to ensure robust and reliable data collection and analysis. The EF were developed using data from the NFI, which adheres to SOPs developed by the Department of Forestry, Malawi. Similarly, the AD was estimated using the SOPs developed by the DoF, ensuring consistency and transparency in data collection and analysis. To ensure accurate imagery interpretations for AD calculations for deforestation and forest degradation, robust training activities were conducted. These training sessions included discussions on the rationale for assigning majority land cover and test points, enabling targeted improvements in guidance. Before each

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assessment, analysts underwent training to familiarize themselves with deforestation and degradation mapping SOPs and calibrate their interpretations, ensuring consistency across the group.

A multi-tiered QA/QC process was implemented to ensure consistent, accurate, and reliable imagery interpretations. Despite this, uncertainties still exist due to limitations in activity data and emission factors. These uncertainties were quantified at a 90% confidence interval, using the Monte Carlo procedure. The uncertainty was combined to estimate the overall uncertainty of the proposed FRL.

3. Results and Discussion

3.1. Deforestation: Activity Data and Emission Factor

The activity data for deforestation in protected areas and FOPA is presented in Table 4. Of the total number of points assessed, 247 points exhibited a conversion from forest area in Time 1 (2010) to non-forest area in Time 2 (2020). This translates to an annual deforestation rate of 11,565ha ± 1,067ha per year, equivalent to annual loss of 0.66% ± 0.03% of the total forest area nationally. From 2010 to 2020, forests in protected areas decreased by an annual rate of 7,035 ha, while forest outside the protected areas decreased by the annual rate of 4,192 ha, during the same period (Table 4).

This current estimated deforestation rate of 0.66% per annum is slightly higher than the 0.63% rate reported during the first FRL submission, which translated to 14,500 ha. Previously, the Government of Malawi had estimated a deforestation rate of 2.98% since the early 1990s (Malawi Forestry Policy, 2016). Various studies have been conducted over time using different approaches. For instance, Skole *et al*. (2021) employed fraction cover mapping, reporting a deforestation rate of 22,410 ha/yr. Similarly, Bone *et al*. (2016) assessed deforestation from 1972 to 2009, yielding a rate of 34,486 ha/yr. Kerr (2005), while reporting a deforestation rate of 2.4%, identified some of the underlying drivers to this deforestation as population increase that was reported as high as 3.1% per annum; and poverty with 80% of the population employed in subsistence agriculture. Despite these variations in these estimates, most of this deforestation is commonly and proximately attributed to excessive biomass extraction, agriculture expansion and flue-cured tobacco growing. World bank data[2] shows that population growth rate is persistently high at 2.6% and 72% of the population living on less than $2.15/day, replying in forests for their livelihood.

Deforestation predominantly occurred within forests having a canopy coverage exceeding 30%, with over 60% of the deforestation taking place in these areas. As shown in Table 3, the majority of the plots (3,301) remained as forested areas, while a notable 227 plots underwent a transition from non-forest to forest areas. This conversion can be attributed to restoration efforts within both customary forests and protected reserves (GoM, 2017).

Table 3. National transition.

Time 1	Time 2	Number of plots	Transition
Forest	Non-Forest	247	Forest- non-Forest
Forest	Forest	3,301	Forest- Forest
Non-Forest	Forest	227	Non-Forest- Forest
Non-forest	Non-Forest	1,312	Non-forest-non-forest
Total		5,087	

Notably, 85% of the deforestation points were converted to grassland, while 15% were attributed to cropland, accounting for the majority of land-use conversion. Within the protected areas, an average of 703 hectares of forest were converted to cropland, while 6,331 hectares were converted to

[2] https://www.worldbank.org/en/country/malawi/overview

grassland each year. Similarly, outside the protected areas, the annual conversion rates were 1,048 hectares to grassland and 3,144 hectares to cropland. Over a ten-year period, the cumulative conversion of forest to grassland and cropland was 94,755 hectares and 17,515 hectares, respectively. A study by Missanjo and Kadzuwa (2024) reported significantly higher conversion rates, with 220,800 hectares of forest land converted to cropland and 15,300 hectares to grassland between 2010 and 2022. These findings align with other studies that have linked deforestation to agricultural expansion, unsustainable fuelwood extraction, and charcoal production (Missanjo and Kadzuwa, 2024; Munthali *et al*., 2019). Study conducted in Dzalanyama Forest Reserve and Dedza also found that charcoal production, firewood production, infrastructure development, and agriculture expansion are major drivers of deforestation in the forest reserves and peripheral areas (Katumbi *et al*., 2017; Munthali *et al*., 2019).

Table 4. Deforestation rate in Malawi between 2010 and 2020.

Forest stratum	Total area (ha)	Deforestation	
		Annual change (ha)	Annual change (%)
Protected area	1,324,500	7035 ± 1215	0.66% ± 0.07%
Non protected area	1,134,500	4192 ± 1040	0.69% ± 0.07%
National	245,900	11,565 ± 1,067	0.66% ± 0.03%

Five major carbon pools were considered to estimate emission factors, as provisioned in the UNFCCC guidelines: Aboveground Biomass (ABG), Belowground Biomass (BGB), Leaf Litter, Deadwood, and Soil Organic Carbon (SOC). Using allometric equations from Kachamba *et al*. (2016), the National Forest Inventory (NFI) data collected between 2018 and 2023 were used to estimate ABG and BGB. As expected, carbon stock estimates for ABG and BGB differed between Reserve and FOPA areas. In the Reserve area, the average carbon stock per hectare (tC/ha) ranged from 46.46 tC/ha in 2023 to 67.73 tC/ha in 2021, with an area-weighted average of 57.26 tC/ha across the five inventory periods (Table 5). In contrast, the non-reserve area exhibited relatively stable carbon stock estimates, with an area-weighted average of 45.03 tC/ha. Notably, the average weighted biomass value of forests outside protected areas was 18% lower than those within protected areas, indicating some variation, although less than expected anecdotally. The differences in carbon stock estimates between Reserve and Non-Reserve areas can be attributed to differences in forest management practices and pressure on forest resources from the communities.

The CDM AR tool's default factor of 1% of total biomass was used to calculate the carbon stock for deadwood and leaf litter. This resulted in a carbon stock estimate of 0.57 tC/ha for both leaf litter and deadwood in Forest Reserves, and 0.45 tC/ha for both components in FOPA. As recommended by the technical assessment team during the initial FRL submission, the national average carbon stock value for Malawi, based on Henry *et al*. (2008), was used to calculate the SOC stock, with a national average carbon stock of 47 tC/ha.

Table 5. Stocks in forest carbon pools applied to develop Malawi's forest EF.

	Total Live Tree Carbon Stocks (AGB & BGB) (tC/ha)	Dead Wood Carbon Stocks (tC/ha)	Litter Carbon Stocks (tC/ha)	SOC (tC/ha)	Total Forest Carbon Stocks (tC/ha)
Forest Reserve	57.26	0.57	0.57	47.00	105.40
FOPA	45.03	0.45	0.45	47.00	92.93

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Source	NFI Data Collection	CDM AR-TOOL12	CDM AR-TOOL12	Henry et al. 2008	IPCC 2006 method

Deforestation emission factors were developed following the IPCC stock-difference approach (Equation 2.25 in the IPCC 2006 Guidelines, Volume 4). This approach estimates the difference between pre-deforestation and post-deforestation carbon stocks for each stratum (Equation 7). The carbon stock in biomass prior to deforestation is subtracted from the carbon stock post-deforestation, and then the change in soil carbon stock following deforestation is added. The resulting value is then converted to CO_2 equivalent (CO_2-e) using the appropriate conversion factor, yielding a result in units of tons of CO_2-e per hectare. The final deforestation emission factors for areas of Forest Reserve and FOPA converted into cropland are 133.92- and 112.42-tons CO_2-e/ha, respectively. Similarly, the deforestation emission factors for areas of Forest Reserve and FOPA converted into grassland are 88.09- and 66.59-tons CO_2-e/ha, respectively.

3.2. Degradation: Activity Data and Emission Factor

An analysis of 3,301 forest remaining forest plots revealed that 277 plots exhibited a change in canopy closure. The estimated annual degradation rate was 14,192 ha per year, equivalent to 0.77% ± 0.04%. Furthermore, the annual hectares of deforestation were calculated for each canopy closure class transition in both reserves and FOPA. As shown in Table 6, the activity data presents the area of forest degradation in hectares for Forest Reserve and FOPA across six canopy closure transition classes. Within the Forest Reserve, a total of 7,761 hectares were degraded, with the majority (1,938 hectares) attributed to Dense-Moderate canopy closure transition, followed by Moderate-Low (1,925 hectares). Similarly, FOPA experienced a total of 6,431 hectares of degradation, with the majority (2,886 hectares) under the Dense-Moderate canopy closure transition class, followed by Moderate-Sparse canopy closure transition (745 hectares). Notably, Forest Reserve exhibited a slightly higher total degraded area compared to FOPA, with approximately 55% of degradation occurring in protected areas. Thus, it suggests that human pressure, such as encroachment, logging, or other human activities, is still significant within the reserve, despite its protected status.

Table 6. Activity data for each transition.

Activity Data	Area Degradation Forest Reserve (ha)	Area Degradation FOPA (ha)
Dense- Moderate	1,938	2,886
Dense-Low	962	800
Dense- Sparse	719	440
Moderate-Low	1,925	652
Moderate-Sparse	1,168	745
Low-Sparse	1,049	908
Total	7,761	6,431

Degradation has 50 plus working definitions due to complexities in the causes, different forms and intensity of forest degradation (FAO, 2011; Wheeler *et al*., 2021). Forest degradation encompasses a wide range of processes and drivers, including selective logging, fire, and fragmentation, which can impact carbon stocks differently. These processes often occur over large spatial scales, making it challenging to accurately capture their full extent and impact. Furthermore, the rate and intensity of degradation can vary significantly across different forest types and regions, complicating estimation efforts. While canopy gaps are not always indicative of forest degradation, remote sensing is widely used to measure degradation (Duarte *et al*., 2020; Gao *et al*., 2020; Mitchell *et al*., 2017). Indicators such as patch number, fractal dimension, and area serve as proxies to monitor forest degradation. This study employed a reduction in canopy coverage or density as a proxy for forest degradation, which

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can be easily detected using high-resolution remote sensing tools. However, conventional remote sensing is ineffective in detecting forest degradation without complete canopy loss (Skole *et al*., 2021). The study acknowledges that the applied degradation approach is more sensitive to biomass loss, resulting in changes to canopy class.

Carbon stocks for different canopy closure classes were estimated using National Forest Inventory (NFI) data, revealing a positive correlation between canopy density and biomass. Unlike deforestation, only Above-Ground Biomass (AGB) and Below-Ground Biomass (BGB) were considered for forest degradation. As shown in Table 7, the average AGB and BGB increase significantly from sparse to denser canopy classes, indicating a higher carbon sequestration potential in denser forests. Specifically, the calculated total biomass for the densest canopy closure class is 86.44 tDM/ha, whereas the value for the sparsest canopy closure class is 44.28 tDM/ha (Table 7). The change in carbon stock due to forest degradation was calculated by accounting for the carbon stock at each canopy closure class in 2010 and 2020. Emission calculations were then performed by applying the change in initial forest canopy class to the final canopy closure class and multiplying it by the area of each transition.

Table 7. Carbon stock averages per canopy closure class.

Canopy Closure class	Dense	Moderate	Low	Sparse
	tDM/ha	tDM/ha	tDM/ha	tDM/ha
AGB & BGB (tC/ha)	86.44	64.42	46.12	44.28
Area Weighted Average t DM/ha	183.91	137.06	98.13	94.21

3.3. Forest Enhancement: Activity Data and Removal Rates

Forest plantations cover around 3% of the total forest area in Malawi (FAO 2020b). These plantations were established to meet domestic forest product demands and to restore environmental services while reducing pressure on the slow replenishing forest reserves. Forest plantations in the country continue to play a critical role in meeting Malawi's socio-economic, biodiversity, ecological, and climate needs. The country has focused on establishing and managing plantations of fast-growing species. Different species of *Eucalyptus* and Pinus are planted in Malawi, consisting of 41.15% and 58.36%, respectively, of the total planted area. From 2010 to 2020, a total of 7,027 hectares of *Eucalyptus* and 9,966 hectares of Pine species were planted, with an average annual plantation establishment of 1,552 hectares per year. The fluctuation in plantation areas in Malawi can be attributed to resource availability, environmental and climatic conditions, socio-economic factors, and disturbance, mainly fires, pests and diseases. However, due to government policies and initiatives aimed at restoring forest areas, we can expect an increasing trend in plantation areas in the coming years in Malawi.

Table 8 shows the average area of net plantation forest area established during the period 2010-2020.

Table 8. Average area of plantation forest established during 2010- 2020.

Year	Plantation Activity Data (ha)		
	Eucalyptus spp.	*Pinus* spp.	Other spp.
2010	543.4	647.5	0
2011	555.1	627.6	0
2012	188.6	1478.7	55.5
2013	228.6	1322.3	0
2014	662.2	781.2	0

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2015	560.0	669.7	0
2016	1080.3	1254.2	0.3
2017	793.7	1021.3	0
2018	746.3	527.9	0
2019	547.5	294.5	5
2020	1122.1	1341.2	21.9

3.4. Total Carbon Estimates

The final annual emissions from forest deforestation were 1,008,600 tCO_2e, with 671,590 tCO_2e attributed to forest reserves and 337,010 tCO_2e attributed to forests outside protected areas. Additionally, the total annual emissions from protected areas converting to grassland and cropland were 574,540 tCO_2e/year and 97,050 tCO_2e/year, respectively. Similarly, for FOPA, the total emissions from forest areas converting to grassland and cropland were 215,654 tCO_2e/year and 121,357 tCO_2e/year, respectively.

In terms of forest degradation, the final annual emissions were 543,511 tCO_2e, with 297,176 tCO_2e attributed to forest reserves and 246,335 tCO_2e to forests outside protected areas.The average annual removals from plantations in customary lands managed by Malawi's Government and private tobacco companies during the reference period (2010-2020) were 61,070 tCO_2e/yr. Removals fluctuated between 40,954 tCO_2e and 101,726 tCO_2e over the reference period (Table 9)

Table 9. Annual carbon emissions from three activities deforestation, forest degradation and enhancement.

Year	Deforestation emissions, tons CO_2e	Degradation emissions, tons CO_2e	Enhancements removals, tons CO_2e	Net Forest Emissions (tCO_2e /yr)
2010	1,008,600	543,511	-48,794	1,503,317
2011	1,008,600	543,511	-49,053	1,503,058
2012	1,008,600	543,511	-48,612	1,503,499
2013	1,008,600	543,511	-45,202	1,506,909
2014	1,008,600	543,511	-59,279	1,492,832
2015	1,008,600	543,511	-50,343	1,501,768
2016	1,008,600	543,511	-96,241	1,455,870
2017	1,008,600	543,511	-73,044	1,479,067
2018	1,008,600	543,511	-58,524	1,493,587
2019	1,008,600	543,511	-40,954	1,511,157
2020	1,008,600	543,511	-101,726	1,450,385
Annual average	1,008,600	543,511	-61,070	1,491,041

The nationwide net annual emission of carbon from all three REDD+ activities - deforestation, forest degradation, and forest enhancement - in Malawi between 2010 and 2020 was estimated to be 1,491,041 tCO_2e/year. This estimate is based on activity data and emissions factors for all three REDD+ activities, calculated for Malawi. Table 9 summarizes the annual carbon emissions related to these activities for the years 2010 to 2020, providing a comprehensive overview of the trends and patterns in forest carbon emissions. The emissions from deforestation and degradation were averaged over a

10-year period, resulting in a steady annual emission rate of 1,552,111 tCO_2e/year. However, the values for forest enhancement, which represent carbon sequestration, varied annually, ranging from 40,954 tCO_2e to 101,726 tCO_2e, with an annual average of 61,070 t CO_2e /year. Consequently, the net forest emissions, calculated by combining deforestation and degradation emissions and subtracting the enhancement figures, slightly fluctuated accordingly, with a minimum net emission of 1,450,385 tCO_2e/year and a maximum of 1,511,157 tCO_2e/year.

The total uncertainty of the net emissions was estimated to be 7.18% (at 90% confidence interval) using Monte Carlo analysis with bootstrapping. This was calculated by combining the individual uncertainties of deforestation, degradation, and enhancement reference levels, which were simulated 10,000 times to account for variability.

3.5. Study Limitations and Areas of Improvements

The current method of degradation detection used in Malawi's FRL development has a few limitations. Firstly, it only captures large-scale degradation events resulting in changes in canopy closure classes, neglecting sub-canopy degradation. This methodological constraint is acknowledged, and refining monitoring approaches is identified as a key area for future improvement. To address this, future efforts should focus on developing more sensitive degradation detection methods and establishing robust data verification protocols to ensure accurate and consistent data collection. Furthermore, data collection for forest enhancement activities could be strengthened by the addition of verification measures, which would help to enhance the validity and reliability of the data. The inconsistent use of data reporting templates among plantation forests and the absence of measures to verify reported data could have an impact on the data quality. Addressing these limitations is crucial for enhancing the robustness and reliability of Malawi's FRL development. By improving degradation detection methods and data collection protocols, Malawi can ensure a more accurate and comprehensive accounting of its forest resources, ultimately supporting more effective forest management and conservation efforts.

4. Conclusions

The revisions to Malawi's FRL, as documented in this paper, address the recommendations made in the UNFCCC technical assessment report (UNFCCC TAR 2021) and have resulted in a more comprehensive and more robust assessment of Malawi's GHG emissions and removals. By including the three activities of deforestation, degradation, and forest carbon stock enhancement, Malawi's FRL is among the more comprehensive of FRLs globally. While cost constraints are a primary reason that limits the ability of lower-income countries to complete comprehensive FRLs, the assessment process in Malawi provides a potential model for other countries. Part of the reason that Malawi was able to complete an FRL that was both comprehensive and cost-effective was the because the open-source and free platform Collect Earth was used. Collect Earth also has the advantage of providing a replicable and transparent workflow that can be revisited and verified by future analysts.

This study analyzed emission factors and activity data for three REDD+ activities: deforestation, forest degradation, and enhancement. The results indicate that deforestation and degradation occur at annual rates of 0.66% and 0.47%, respectively, while efforts to restore forest areas through planting have been made. Malawi has demonstrated a significant commitment to enhancing its Forest Reference Level (FRL) submission through incremental improvements. The analysis reveals that, on average, deforestation and forest degradation emitted 1,008,600 tCO_2e and 543,511 tCO_2e, respectively, between 2010 and 2020, while forest enhancements through plantation management sequestered 61,070 tCO_2e annually during the same period. The combined reference level for these REDD+ activities total 1,491,041 tCO_2e y-1, providing a baseline for monitoring and reporting forest-related emissions and removals. Building upon the initial submission, the current FRL methods incorporate notable improvements aligned with the UNFCCC technical assessment report, ensuring a more robust and transparent FRL submission.

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