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Estimation of Long-Term Above-Ground Biomass, Carbon Stocks and Carbon Dioxide Equivalent Lost Due to Deforestation in Mapfungautsi Forest, Zimbabwe

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***Abstract*— *Tropical forests play an important role of storing significant quantities of carbon, both, aboveground and belowground. However, deforestation activities for various purposes, among them, agriculture and settlement, have continued to remove unknown quantities of biomass and carbon stocks across tropical forests of Africa. This study was conducted to estimate aboveground tree biomass (AGB), carbon stocks (AGCS) and carbon dioxide equivalent (CO_2 e) among three vegetation cover types (wooded land, bushland and grassland) found in Mapfungautsi forest and to quantify the long-term estimated total AGB, AGCS and CO_2 e lost due to deforestation activities in the forest (between the year 2000 and 2020). Data collection was conducted using remote sensing imagery, field measurements and an allometric equation. A total of 22 plots, each measuring 50m x50m were established across the three vegetation cover types where tree height, diameter at breast height, number of stems/ha and regeneration were measured. The collected data was analysed using EViews Version 10 software. Wooded land generally had the highest values across all the four tree growth variables followed by bushland and grassland. The average estimated AGB stored were 50.78t/ha, 14.7t/ha and 8.2 t/ha for wooded land, bushland and grassland respectively. From the 10632ha cleared over 20 years, losses amounting to an estimated mean total AGB, AGCS and CO_2 e of 387669.53t, 182205.09t and 668692.69t respectively were observed. We conclude that quantifying and raising awareness about the lost AGB, AGCS and CO_2 e among stakeholders will lead to the implementation of remedial action to replenish the lost biomass and carbon stocks.*

Keywords*— *Aboveground biomass, agriculture, carbon stocks, deforestation, Mapfungautsi forest, trees

I. INTRODUCTION

Tropical forests store significant quantities of carbon in their wood, leaves and roots through a process called carbon sequestration. The carbon stored in the tree trunk, branches and leaves is known as the aboveground carbon and it also include deadwood found on the ground surface. The estimation of biomass and carbon stocked in forests is essential in evaluating productivity, carbon cycles and the impact of forest trees on the reduction of carbon emission and global climate change [1]. Biomass and carbon stocks estimates take into account stem dimensions, wood density, tree height and crown morphology in different vegetation cover types [2].

Thus any remote sensing approach for biomass estimation is also dependent upon field measurements of tree growth variables [3].

Anthropogenic activities like illegal timber logging, rapid agricultural intensification, overgrazing, browsing, and repeated wildfires, and to some extent, environmental and climatic dynamics have all contributed to the significant decline of forest biomass resources in Africa [4 - 6].

Estimates by FAO indicate that countries in the tropics lost their forest cover due to anthropogenic activities by as much 24 million ha between 1999 and 2000 [7]. Deforestation activities including clearing of forested land for agriculture and other activities contributed to an estimation of one third of the total anthropogenic emissions of carbon in the past 150 years [8]. In a study by [9] conducted in Mapfungautsi forest, Zimbabwe to determine the extent of deforestation over two decades (2000-2020) it was found that agriculture was the single most impactful factor responsible for deforestation and about 19.2% of the forest had been cleared. It was observed that, of the cleared forest, the most affected vegetation cover type was the wooded grassland (84%) followed by bushland (31%) and wooded land (10%) [9]. Despite the important findings on factors responsible for deforestation and the extent of deforestation in Mapfungautsi forest, the study by [9] did not estimate or quantify the aboveground biomass (AGB), aboveground carbon stocks (AGCS) and the carbon dioxide equivalent (CO_2 e) lost during the 20-year period. Consequently, the study could not present and enlighten the local people in and around Mapfungautsi forest of the far-reaching consequences of deforestation on other global catastrophes like climate change and subsequent challenges like threats to food production and livelihood systems of the majority of the small-scale farming community. It is for these reasons that this study was conducted in Mapfungautsi forest, as a follow-up, to estimate the long-term AGB, AGCS and CO_2 e lost in the three vegetation cover types in Mapfungautsi forest (wooded land, bushland and wooded grassland). The stratification of vegetation cover types in Mapfungautsi forest was necessitated by the potential differences in vegetation densities; biomass and carbon stocks. The wooded land is dominated by *Baikiaea plurijuga, Julbernadia globiflora and Brachystegia spiciformis, and Burkea africana* and this covers 75% of the forest area while the bushland covers 10% of the forest area and has a variety of species to *parinari curatelifollia*, *Pseudolachnostylis maproneifolia* and also *miombo*. The wooded grassland has some *terminalia* species, acacia *fleckii, piliostigma thonningii* and others. These three metrics (AGB, AGCS and CO_2 e) are important in establishing the climate change mitigation potential of the trees in the study area.

Beyond the above-mentioned reasons or research gaps, monitoring and quantifying of existing biomass and carbon stocks as well as reporting of deforestation and forest degradation are required in order to enter the carbon credit markets and are also encouraged in the implementation of the REDD+ initiative. It is therefore important to monitor vegetation gains and losses in order to estimate the quantities of emissions resulting from deforestation. Thus, this study specifically aimed to compare tree growth variables, stored AGB, AGCS and CO_2 e among the three vegetation cover types and to estimate the total AGB, AGCS and CO_2 e lost due to deforestation activities in Mapfungautsi forest between the year 2000 and 2020.

This paper proceeds as follows. Section 2 is the Materials and Methods which describe the biophysical and socio-economic attributes of the study area, Mapfungautsi forest. Further, the section describes the experimental design, data collection procedures and allometric equations adopted to estimate current AGB, AGCS and CO_2 e for the three vegetation cover types as well as to quantify the long-term estimated AGB, AGCS and CO_2 e lost due to deforestation. Lastly, Section 2 explains how the gathered data was analysed. Section 3 is the Results, which details findings on the measured four tree growth variables and the estimated AGB, AGCS and CO_2 e for the three vegetation cover types. The penultimate section, Section 4, is the discussion of the results and how they compare to findings from similar studies. The final section offers some concluding remarks.

II. MATERIALS AND METHODS

2.1 Study area

The study was conducted in Mapfungautsi forest situated in Gokwe South district, in the Midlands province of Zimbabwe. The northern boundary of the forest is Sengwa River from Bomba Business centre to the east up to Nkayi road (Fig. 1). Mapfungautsi forest lies within agro-ecological regions III and IV which are characterized by low to average annual rainfall ranging from 450mm to 850mm and mean temperatures ranging from 18^0 C to 24^0 C [9].

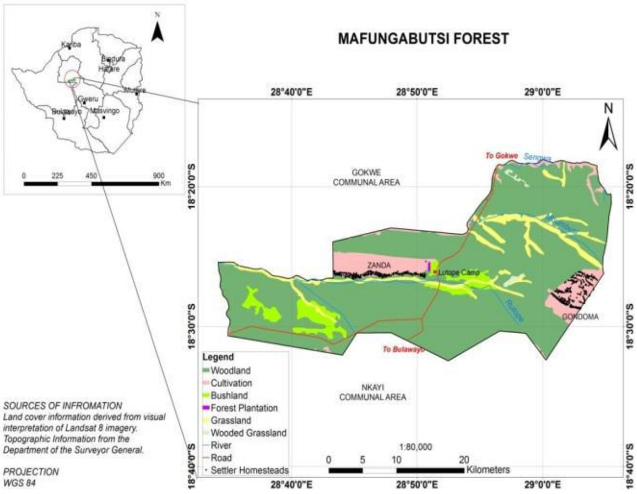

Fig.1. Map of the study area (Source: [9])

The forest is dominated by the Zambezi teak *Baikiaea plurijuga*, *Pterocarpus angolensis*, *Brachystegia spiciformis* and *Julbernadia globiflora* on the Kalahari sand ridges and slopes, and *Terminalia* species on the lowlands/furrows [9]. Essentially, Mapfungautsi forest is three-stratum and mature in undisturbed portions, with *Baikiaea plurijuga*, *Brachystegia spiciformis*, *Julbernadia globiflora*, *ricinodendron rautanenii* forming the canopy. The middle layer is comprised of some middle aged trees of the same species. The bottom layer comprise of grasses, regenerating saplings of the same species of the middle and upper layers.

Initially, Mapfungautsi was a designated protected forest with some utilization of timber and non-timber resources in the 1980s and 90s [9]. However, the introduction of human settlements soon after the year 2000 altered this land use system to include agricultural and related activities. The agricultural system mainly practiced was the slash and burn which has accelerated vegetation loss in the past two decades [9].

2.2 Sampling procedures and experimental design

Mapfungautsi forest was stratified into three major vegetation cover types namely; wooded land, bushland and wooded grassland (Fig. 2). In each of the three vegetation cover types, sample plots measuring 50 m x 50 m were allocated and marked on a base map (Fig. 2). Accessibility of the plot sites was considered when coming up with the final number of plots to be sampled in each vegetation strata.

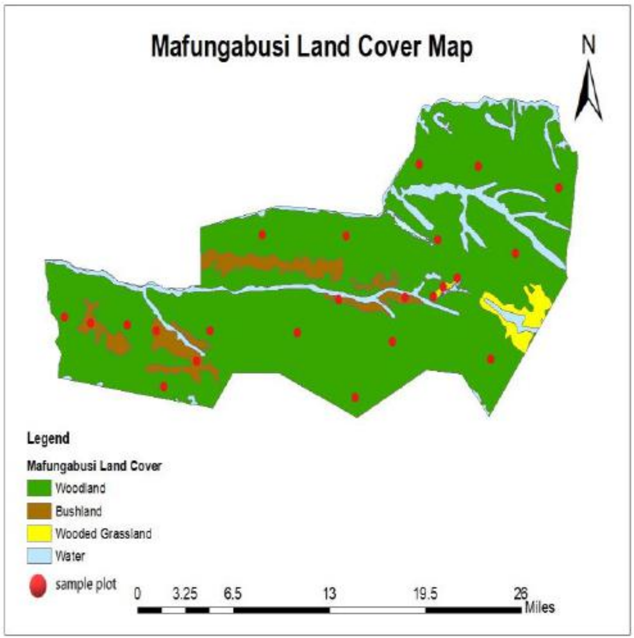

Fig. 2. Sample plots in each of the three vegetation cover type in Mapfungautsi Forest

Resultantly a total of 22 plots across the forest were established, with the majority of these falling under the wooded land, followed by bushland and wooded grassland (Table 1). These plots were within walking distances from fire lines for easy accessibility. Distances between plots differed for each vegetation cover type due total coverage of each cover type. As such, it was 8 km in the wooded land, 5 km in the bushland and 1.5 km in the wooded grassland. After finalizing the plot sites on the base map, coordinates for each plot boundaries were recorded and used for the actual identification and demarcation of plots in the field. Marking of trees on the plot boundaries was done using an axe.

Table 1. Distribution of sample plots across three vegetation cover types in Mafungautsi Forest

Vegetation cover type	Area covered in the year 2000 (Ha)	Number of plots
Wooded land	69295	14
Bushland	5724	5
Wooded grassland	2463	3
Total Plots		**22**

2.3 Data collection

2.3.1 Tree growth measurements

The measurements taken and recorded from each sample plot (50 m x 50 m) were the tree diameter at breast height (DBH), tree height (H), regeneration and number of stems. The undergrowth or saplings with a diameter less than 2 cm were only counted and recorded. A diameter tape and a measuring calliper were used to measure tree DBH while a clinometer-based Vertex instrument was used to measure the tree H. The species name of each tree was also recorded.

2.3.2 Determination of above ground tree biomass (AGB)

There are two methods of estimating AGB namely: destructive (tree harvesting) and non-destructive. While the destructive method is more accurate, it has numerous disadvantages including being time consuming, labour intensive and involves tree felling, which is not desirable to environmentalists and local communities [1, 10]. This leaves the non-destructive methods as the most suitable for ecosystems with rare or protected forests like Mapfungautsi, or tree species, where, harvesting of such species is not practical, feasible or allowed. One such non-destructive method is the application of allometric equations. Tree H and DBH are among the most important predictors of tree AGB [1, 10].

The tree growth measurements taken in each plot were used as input in the allometric equation to determine AGB. The following allometric equation was adopted and applied to determine the AGB (in tonnes/ha) of Mapfungautsi forest:

$$\text{Biomass} = 0.1936 * (DBH^2 * 3.141592654 / 4)^{1.1654} \quad (1)$$

Where DBH is the diameter at breast height

The AGB for each vegetation cover type was calculated and used to estimate the above ground carbon stock (AGCS).

2.3.3 Estimation of AGCS

The AGCS was estimated using the following equation: 47% of the AGB is carbon:

$$AGCS = AGB * 0.47 \quad (2)$$

Where 0.47 is a constant

The equation is based on the conversion of biomass to carbon since the 47% of biomass value carbon [11, 12].

2.3.4 Estimation of carbon dioxide equivalent (CO_2 e)

The estimation of CO_2 e is very important in evaluating the climate change mitigation potential of the trees in the study area. The following equation was used to estimate CO_2 e:

$$CO_2\,e = AGCS * 3.67 \quad [13] \quad (3)$$

Where 3.67 is a constant

2.3.4 Approximation of long-term AGB, AGCS and CO_2 e lost through deforestation in Mapfungautsi forest

Satellite images (from the years 2000, 2010 and 2020) and forest cover maps for Mapfungautsi forest were used to determine the extent of deforestation for 20 years (2000 – 2020). The extent of deforestation was measured at 10-year intervals. Deforested areas for each of the three vegetation cover stratum were identified and measured using the ArcGIS version 10.3.1. These deforested areas in each vegetation cover stratum were then multiplied by the corresponding current AGCS (t/ha) and CO_2 e to approximate the total AGCS and CO_2 e lost over the last two decades (2000 - 2020) respectively.

2.4 Data Analysis

All the data obtained from field measurements and estimated from the adopted allometric equation were subjected to statistical analysis using EViews Version 10 software.

III. RESULTS

3.1 Tree growth variables in Mapfungautsi forest

Four tree growth variables measured in each of the 22 total plots under the three vegetation cover types (wooded land, bushland, and wooded grassland) are summarized in Table 2.

Table 2. Summary statistics of tree growth variables in Mapfungautsi Forest

Variable	Veg Cover Type	Mean	Std Dev	Minimum	Median	Maximum
DBH (cm/tree)	Wooded land	11.92	2.75	8.4	11.55	16.7
	Bushland	7.2	0.71	6.4	7.5	8
	Grassland	5.63	0.49	5.3	5.4	6.2
Height (m/tree)	Wooded land	9.11	2.19	6.2	8.25	13.6
	Bushland	5.7	0.54	4.9	5.7	6.4
	Grassland	4.3	0.44	3.8	4.5	4.6
Stems (No./ha)	Wooded land	1212.71	180.74	947	1200	1504
	Bushland	878.2	119.68	733	884	1054
	Grassland	290.67	71.06	218	294	360
Regeneration	Wooded land	1716.36	1228.11	109	1825.5	3607
	Bushland	1598.8	993.12	208	1564	2977
	Grassland	593.67	462.59	267	391	1123

Wooded land generally had the highest values across all the four variables (DBH, H, stems/ha and regeneration), followed by bushland with grassland having the lowest (Table 2). On average, wooded land trees had a height of 9.11 metres compared to 5.7 metres and 4.3 metres for bushland and grassland respectively. Similarly, the average DBH were 11.9 cm, 7.2 cm and 5.63 cm for wooded land, bushland and grassland respectively. The notable difference from the three vegetation cover types was that grassland had a significantly narrower range than bushland and wooded land across all the four tree growth variables. For example grassland height ranged from 3.8 to 4.6 metres while bushland ranged from 4.9 to 6.4 metres and wooded land ranged from 6.2 metres to 13.6 metres. Conversely, the greatest spread range was observed for wooded land across all the measured tree variables

Table 3. Summary statistics for estimated AGB, AGC and CO_2 e in Mapfungautsi Forest

Variable	Veg Cover Type	Mean	Std Dev	Minimum	Median	Maximum
AGB (t/ha)	Wooded land	50.78	27.43	20.84	43.79	103.41
	Bushland	14.73	3.31	11.06	16	18.6
	Grassland	8.28	1.73	7.13	7.44	10.27
AGCS (t/ha)	Wooded land	23.67	12.89	9.8	20.58	48.6
	Bushland	6.92	1.56	5.2	7.52	8.74
	Grassland	3.89	0.81	3.35	3.5	4.83
CO_2 e (t/ha)	Wooded land	87.58	47.31	35.97	75.53	178.36
	Bushland	25.40	5.71	19.08	27.60	32.08
	Grassland	14.29	2.99	12.29	12.85	17.73

3.2 Estimated AGB, AGC and CO_2 e in Mapfungautsi forest

Estimated average AGB, AGC and CO_2 e in Mapfungautsi forest shown in Table 3, indicates that wooded land store had the most biomass and carbon stocks followed by bushland and grassland. The average estimated AGB were 50.78 t/ha, 14.7 t/ha and 8.28 t/ha for wooded land, bushland and grassland respectively. The same trend is noted for the AGCS and CO_2 e.

3.3 Estimated AGB, AGCS and CO_2 e lost due to deforestation in Mapfungautsi forest over 20 years

Deforestation has taken place in Mapfungautsi forest across the three vegetation cover types. In terms of percentages, grassland had the highest proportion affected by deforestation activities (84%) followed by bushland (31.1%) and wooded land (9.8%). However, in terms of total forest area cleared, wooded land had the highest (6780 ha) compared to grassland (2071 ha) and bushland (1781 ha) after 20 years (2000 to 2020). Consequently, the estimated total AGB lost in Mapfungautsi forest was 387669.53 tonnes with wooded land contributing 88.8%, bushland – 6.8% and grassland contributing the remaining 4.4%. A similar trend was also observed for both the AGCS and CO_2 e. The estimated mean total AGCS and CO_2 e lost in Mapfungautsi forest from the year 2000 up to the year 2020 are 182205.09 tonnes and 668692.69 tonnes respectively (Table 4).

Table 4. Estimated AGB, AGCS and CO_2 e lost due to deforestation in Mapfungautsi forest over two decades

Veg Cover Type	Forest CoverArea (ha) in the year 2000	Area cleared (ha) from the year 2000 up to 2020	Total mean AGB lost (t) from 2000 to 2020	Total mean AGCS lost (t) from 2000 to 2020	Total mean CO_2 e lost (t) from 2000 to 2020
Wooded land	69295	6780	344288.4	161815.55	593863.07
Bushland	5724	1781	26234.13	12330.04	45251.25
Grassland	2463	2071	17147.88	8059.5	29578.37
Grand Total	774824	10632	387669.53	182205.09	668692.69

IV. DISCUSSION

The study found that, of the three vegetation cover types, wooded land had the highest observed values for all the four measured tree growth variables: H, DBH, stems/ha and regeneration. Conversely, grassland had the least observed values across all the four tree growth variables. The reason for this could be that the the wooded land is dominated by *Baikiaea plurijuga, Julbernadia globiflora and Brachystegia spiciformis, and Burkea Africana*, which are generally characterised by big-sized trees with big-diameters compared to bushland and grassland. Bushland has a less dense forest structure dominated by species such as terminalia species, *parinari curatelifolia, diplorynchus condylocarpon, pseudolachnostylis maproneifolia. Julbernardia globiflora and Brachystegia spiciformis*, which are usually medium to big trees but are generally sparse as compared to teak and miombo woodlands. The grassland occupied part of the vleis in Mapfungautsi forest and are composed of *terminalia sericea piliostigma thonningii, acacia fleckii, dichrostachys cinerea* and *acacia karoo* which are generally much smaller than wooded land and bushland. These findings are consistent with findings from local studies like [14], on a study to quantify the carbon stock baseline for Ngamo and Sikumi forest reserves, and elsewhere in Africa, by [1, 15, 16].

Consistent with the measured tree growth variables, wooded land stored the most AGB, AGC and CO_2 e followed by bushland and grassland. As noted by [15 – 18] large-stem diameter and large trees make a disproportionately greater contribution to the AGB of tropical forests. The estimated average AGB were 50.78 t/ha, 14.7 t/ha and 8.28 t/ha for wooded land, bushland and grassland respectively. The corresponding estimated maximum AGB values were 103.41 t/ha, 18.6 t/ha and 10.27 t/ha. Similar AGB values were observed by [14, 15].

A total of 10632 ha of Mapfungautsi forest area was cleared due to deforestation activities over 20 years (2000 – 2020) with the wooded land contributing the highest (6780 ha) followed by grassland (2071 ha) and bushland (1781). However, in terms of the proportion affected by deforestation activities, grassland was the most affected (84%) followed by bushland (31.1%) and lastly wooded land (9.8%). This is consistent with findings by [9] and [15] who found grasslands to be characterised by persistent fires, clearing for settlement and agricultural activities. Consequently, the estimated mean total AGB lost in Mapfungautsi forest was 387669.53 tonnes with wooded land contributing 88.8%, bushland – 6.8% and grassland contributing the remaining 4.4%. The removal of large trees in wooded land which store the most biomass and carbon stocks is responsible for the wooded land having the greatest proportion of AGB, AGCS and CO_2 e lost. The main anthropogenic factors responsible for deforestation are for agricultural purposes, timber logging, firewood and settlement [4, 9, 19, 20].

Observed AGCS and CO_2 e values followed a similar trend like that of AGB. On average, the estimated total AGCS and CO_2 e lost in Mapfungautsi forest from the year 2000 up to the year 2020 are 182205.09 tonnes and 668692.69 tonnes respectively. These figures represent, on average, what was lost in Mapfungautsi forest from the year 2000 up to the year 2020 as a result of the action of man. It can be argued that most of the people responsible for the deforestation may not even be aware of the far-reaching effects of their actions [5]. As such, it figures that, lasting solutions to reduce deforestation and the resulting loss of AGB and AGCS must be developed holistically by involving all stakeholders including: farmers clearing the forest for cropland; government and local traditional leaders who were reported to be parcelling land for political expediency and settlement purposes; timber logging companies; firewood and timber poachers; relevant government ministries and departments like Forestry Commission and the Environmental Management Agency; and the community at large [9, 21]. Such genuine engagement is critical in developing sustainable solutions [22]. The engagement allows for all concerned to be enlightened on the far-reaching effects and impacts of deforestation and other unsustainable land management practices on green house gases emissions (CO_2 e), climate change and land degradation, all of which drastically affect farm productivity and thereby food security and livelihoods. As noted by [5] and [23], communities have shown a willingness to participate and act accordingly when their livelihoods are threatened. In this case, they are most likely going to be ready to do everything possible to arrest deforestation and even plant trees to replenish the lost AGB and AGCS.

V. CONCLUSION

Vegetation cover type is a major determinate of AGB, AGCS and CO_2 e stored. Wooded land had the highest values of the four measured tree growth variables (H, DBH, number of stems/ha and regeneration) as well as the estimated average AGB, AGCS and CO_2 e. Bushland vegetation cover type was second, with grassland recording the lowest values across board. The study found that deforestation activities for various purposes in Mapfungautsi forest over a 20-year period have resulted in significant clearance of forest area and significant losses in AGB, AGCS and CO_2 e, with the majority of these losses being recorded in the wooded land vegetation cover type. This implies that, to ensure accurate estimation of AGB, AGCS and CO_2 e lost due to deforestation activities, both vegetation cover type and total cleared forest area must be considered. Total cleared forest area alone cannot be taken as proxy for indicating AGB and AGCS lost. By actually quantifying the average AGB, AGCS and CO_2 e lost, this study added value to previously conducted researches done in Mapfungautsi forest (for example [9]), as stakeholders can now be able to visualise the depth and the breath of the damning effects of deforestation on the environment and their livelihoods. This entails that appropriate remedies like planting suitable tree species to replenish the biomass and carbon stocks lost due to deforestation can be easily implemented. The study has shown that wooded land trees species characterised by large-stem diameters and tall trees have a greater potential for mitigating climate change than bushland and grassland. Beyond the numerous advantages and applications of this paper, there were a few limitations which need to be improved on in future similar studies. For example, the study estimated the AGB, AGCS and CO_2 e lost in each of the three vegetation cover types found in Mapfungautsi forest, in retrospect. This may have compromised on the accuracy of the actual biomass and carbon stocks lost in Mapfungautsi forest over 20 years. Despite this limitation, the study is still useful as a starting point in implementing systems that report deforestation activities, gains and losses in biomass and carbon stocks as required by the REDD+ framework and carbon credit systems.

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