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Review

Carbon Stocks in Miombo Woodlands: Evidence from over 50 Years

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Abstract: Miombo woodlands are extensive dry forest ecosystems in central and southern Africa covering $\approx$2.7 million km^2. Despite their vast expanse and global importance for carbon storage, the long-term carbon stocks and dynamics have been poorly researched. The objective of this paper was to present and summarize the evidence gathered on aboveground carbon (AGC) and soil organic carbon (SOC) stocks of miombo woodlands from the 1960s to mid-2018 through a literature review. We reviewed the data to find out to what extent aboveground carbon and soil organic carbon stocks are found in miombo woodlands and further investigated if are there differences in carbon stocks based on woodland categories (old-growth, disturbed and re-growth). A review protocol was used to identify 56 publications from which quantitative data on AGC and SOC stocks were extracted. We found that the mean AGC in old-growth miombo (45.8 $\pm$ 17.8 Mg C ha^{-1}), disturbed miombo (26.7 $\pm$ 15 Mg C ha^{-1}), and regrowth miombo (18.8 $\pm$ 16.8 Mg C ha^{-1}) differed significantly. Data on rainfall, stand age, and land-use suggested that the variability in aboveground carbon is site-specific, relating to climatic and geographic conditions as well as land-use history. SOC stocks in both old-growth and re-growth miombo were found to vary widely. It must be noted these soil data are provided only for information; they inconsistently refer to varying soil depths and are thus difficult to interpret. The wide range reported suggests a need for further studies which are much more systematic in method and reporting. Other limitations of the dataset include the lack of systematic sampling and lack of data in some countries, viz. Angola and Democratic Republic of the Congo.

Keywords: miombo; dry forests; biomass; aboveground; soil organic carbon

1. Introduction

Forests are important terrestrial ecosystems and act as carbon sinks with up to 2.4 $\pm$ 0.4 Pg C year^{-1} carbon sequestered globally over the last two decades [1]. Despite their numerous benefits, trends in global forest cover show a rapid loss of forests due to land-use conversion and degradation. These trends have resulted in a loss of 11 Pg of global carbon stocks in the past 25 years alone [2], with net emissions arising from tropical land-use change estimated at 1.3 $\pm$ 0.7 Pg C year^{-1} [1]. While the changes occurring in carbon stocks of tropical moist forests are well documented, the changes occurring in the carbon stocks of tropical dry forests, such as the African miombo woodlands, remain poorly quantified and understood. To address this gap, this review synthesized the current data available on above and below-ground carbon stocks in the miombo woodlands to aid effective policy development to better manage these valuable, but diminishing, ecosystems.

Miombo woodlands are seasonal tropical dry forests found in parts of south and central Africa and extend over Angola, the Democratic Republic of Congo, Malawi, Mozambique, Tanzania, Zambia, and Zimbabwe [3]. They are the most extensive dry-forest

woodlands in all of Africa, covering over 2.7 million km^2 [4]. These woodlands are recognized as an ecoregion (a large area of land or water having characteristic species and environmental conditions that are biologically different from other regions) [5]. Miombo woodlands are the largest of 21 ecoregions in sub-Saharan Africa and part of the WWF's (World Wildlife Fund) Global 200 most-important ecoregions [5]. The landscape of these woodlands is dominated by trees of the genera *Brachystegia, Julbernardia,* and/or *Isoberlinia,* all belonging to the legume family Fabaceae (subfamily Caesalpinioideae) [4].

Miombo woodlands can be broadly categorized into old-growth, disturbed, and re-growth. Old-growth woodlands (OG) are relatively mature woodlands with little indication that they were intensively used or logged. However, due to the long history of human use (charcoal production, logging, gathering of fuelwood, and shifting cultivation) as well as natural causes such as wildlife damage and fire, many areas of woodlands are disturbed. Hence, this is included as a category by itself in this review. Re-growth woodlands (RG) refer to naturally regenerating woodlands following the clearing of mature woodlands for agriculture or other purposes [6]. Since the Caesalpinoid species do not die out after clearing and regenerate easily from existing root systems [5], it is common to find these woodlands in various stages of regrowth. Re-growth woodlands contribute to carbon sequestration [5] with wood C stock increments of 0.4 to 0.9 t C ha^{-1} year^{-1} having been reported [7]. Young miombo stands were found to sequester carbon at an even higher rate of 1.2 to 3.4 t C ha^{-1} year^{-1} [8].

Rainfall varies significantly in the ecoregion and the woodlands are often characterized as either dry or wet [9] based on the mean annual precipitation (MAP); MAP ranges between 629 and 1600 mm were reported in the reviewed literature. Dry miombo refers to areas receiving less than 1000 mm of rainfall annually with *Brachystegia spiciformis, B. boehmii,* and *Julbernardia globiflora* as the dominant tree species, while wet miombo areas receive more than 1000 mm of rainfall per year with a comparatively richer floristic composition of *Brachystegia floribunda, B. glaberrima, B. longifolia, B. wangermeeana, Julbernardia paniculata, Isoberlinia angolensis,* and *Marquesia macroura* [4]. Elevation also varies in the region: study sites reported an elevation range of 316 to 2080 m above sea level.

The objective of this paper was to present and summarize the evidence gathered on aboveground carbon (AGC) and soil organic carbon (SOC) stocks in miombo woodlands from the 1960s to mid-2018. Further, we investigated if there were differences in AGC stocks between the categories of old-growth, disturbed and re-growth woodlands. We also included two case studies in (I) Kataba Forest Reserve (FR) in the Western Province of Zambia and (II) Kitulangalo Forest Reserve in the Morogoro region of Tanzania.

2. Materials and Methods

2.1. Literature Review and Data Extraction

The aim of this paper was to review evidence on the above- and belowground carbon stocks of miombo woodlands spanning six decades (1960s to mid-2018). To be included in the review, studies had to show two main criteria. First, the study site(s) were in miombo woodlands through the presence of tree species of the genera *Brachystegia, Julbernardia* and *Isoberlinia*; and second, the study had to present quantitative data for AGC and/or SOC pools. Literature was reviewed following the systematic review protocol by Syampungani et al. [10]. This follows a previous systematic review protocol and systematic review methods described by CIFOR's Evidence-Based Forestry (EBF) initiative [11,12]. However, we emphasize that the present paper was not based on a 'pure' systematic review. Specifically, the intention of this paper was to provide a summarized assessment of carbon data for miombo based on the available literature, screened to the best of our knowledge, but falling short of the standard set by EBF (and other systematic review) criteria. In a 'pure' systematic review, the references are gathered through a pre-defined search strategy including the time period [13]. Here, we deviated from the confines of a strict review and added these 'additional' references to the annotated bibliography following the same protocol described above.

Following full text screening (Figure 1), critical appraisal criteria were applied, which included study length and duration, relevance of the study area/population (e.g., presence of relevant woodland species), exposures, (e.g., activities which affect aboveground carbon (AGC) and/or soil organic carbon (SOC) such as wood extraction for fuel and charcoal) comparators (e.g., control plots included in study design or before-and-after intervention comparison of study sites), and outcomes (e.g., quantitative data on above and below-ground carbon) [10]. For the appraisal rating, each study was given a score of 1 = yes, 0.5 = unclear and 0 = no for each criterion described above. The values in each row were summed up to obtain an overall rating for each study in the list. The overall rating was categorized as 13–14 = high, 9–12.5 = medium, 6–8.5 = low and 0–5.5 = very low. All studies with low and very low rating were excluded (See TABLE S1–Study validity, included in the supplementary material). Further, the replicability of methods, clarity and replicability of the analysis, and if the results were logically derived and whether confounding factors were also included in assessing the study validity. Additional context-based social and site information were also recorded (such as historical information of the study area, ecological context, site characteristics such as climate, soil, seasonality, and site vegetation) to further appraise studies.
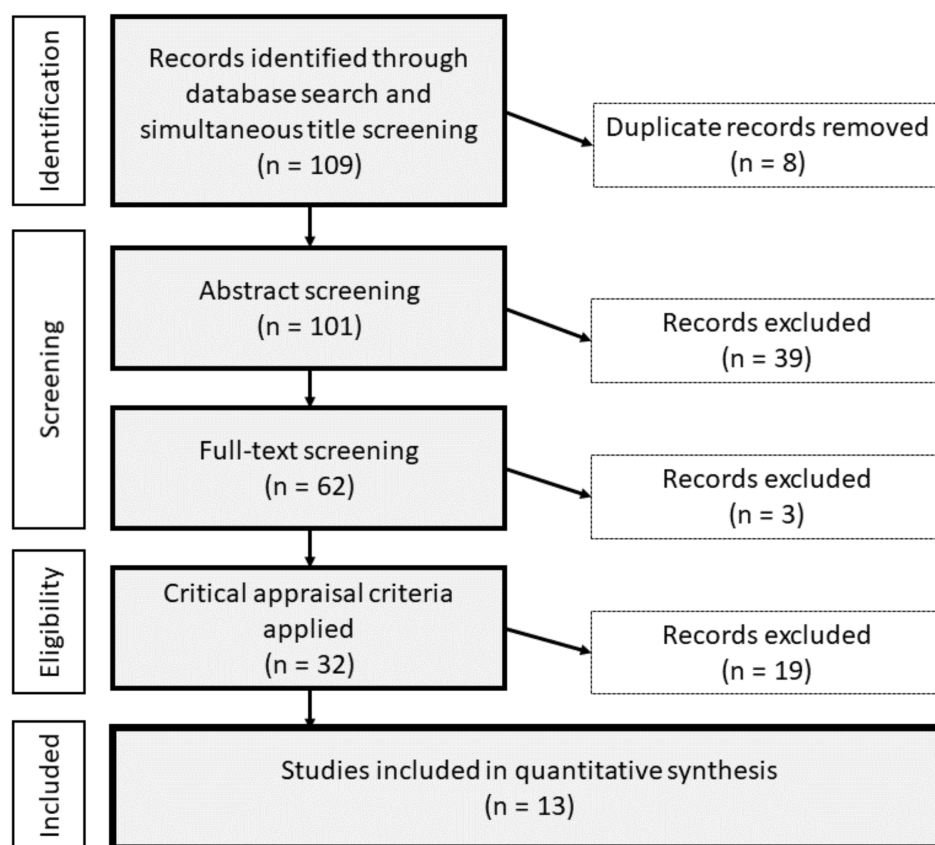

Figure 1. Steps outlining the systematic review process. Source: graph by the authors.

After applying the above criteria to the dataset, 13 papers were finally selected and data on wood biomass, carbon stocks, and SOC stocks were extracted into an Excel file. Data were mainly reported as basal area (m^2 ha^{-1}), biomass (Mg ha^{-1}), and aboveground carbon stocks (Mg C ha^{-1}). Other information such as country of study, location, age of study sites, year(s) during which data was collected, geographical coordinates, elevation, MAP, and miombo type were included in the database. In addition, bibliographic information such as author, year of publication, reference, and study type was recorded.

Data from the 13 studies were collated with data from 38 quantitative studies from the recently published systematic map by Gumbo et al. [14] for this review. It must be noted

that a few references from [14] were excluded due to unverifiable data. The final dataset contained a total of 52 quantitative studies of the best available evidence on the AGC and SOC stocks of miombo woodlands. Thus, while the systematic map [14] also describes values for aboveground carbon in old-growth miombo woodland, the present study was based on a revised and completed dataset and provided a more in-depth analysis which included estimates for regrowth miombo and SOC pools. By providing a summary of published carbon data as they are currently available, we hope to prompt further, more systematic research into questions regarding the study and documentation of land use, management, and carbon stocks in the miombo woodlands. We also hope this review provides a better basis for calculating forest reference levels for such as the UNFCCC (United Nations Framework Convention on Climate Change).

The countries covered in the literature sweep were Malawi, Mozambique, Tanzania, Zambia, and Zimbabwe. No data were found for Angola and the Democratic Republic of Congo. Most studies in the dataset were from Tanzania (36%), followed by Zambia (28%) and Zimbabwe (17%). The quantitative studies included are from 1966 to mid-2018 with the majority (67%) published in the 2010s. A total of 227 observations for AGC stocks were recorded into the database with 33, 81, and 113 observations for the cover types old-growth, disturbed, and re-growth, respectively.

2.2. Aboveground Carbon Stocks in Trees

Data on woody biomass and carbon stocks were recorded into a database. When only basal area estimates were provided, these were converted to biomass using the equation from [15]:

$$AGB = 0.702 \times BA_{bh} - 281.484, \tag{1}$$

where AGB is aboveground wood biomass in kg ha^{-1}, BA_{bh} is basal area at breast height (1.3 m aboveground ground) in cm^2. Basal area data at stump height (BA_{sh}), measured between 15 and 30 cm above ground, were converted to its equivalent at breast height following the equation from [16]:

$$BA_{bh} = -0.0019 + 0.71 \times BA_{sh}, \tag{2}$$

Biomass data calculated from Equation (1) were then converted into Mg ha^{-1} by multiplying with 0.001. A carbon conversion factor of 0.47 [17] was used to estimate carbon stocks.

2.3. Soil Carbon Stocks

In the assessed literature (Supplementary material: Table S2), soil data were estimated at various depths ranging from 2.5 to 150 cm and often presented as stratified by soil layers or horizons. However, some studies provided information only on pooled-soil organic carbon (SOC) stocks, i.e., for the entire sampling depth considered in the study design rather than stratified by layers [18,19]. For these studies, only the total SOC stocks were recorded in the database. It is important to note that not all studies published error/variation estimates. Data on sampling depth and SOC stocks were extracted from the selected literature. For estimating SOC stocks (Mg C ha^{-1}) from SOC%, the equation from [20] was used:

$$SOC = SOC\% \times BD \times SD, \tag{3}$$

where SOC%, soil organic carbon; BD, bulk density, g cm^{-3}; SD, soil depth, cm. Not all studies reported bulk density (BD) values. For miombo woodlands, soil bulk density (to a depth of 20 cm) was found in the range of 1.2 to 1.4 g cm^{-3} [7,21] and an average value of 1.3 g cm^{-3} was used for estimating SOC stocks whenever BD values were not reported. When only soil organic matter (SOM)% data were reported [22], they were converted to SOC% using the equation from [23]:

$$SOC\% = SOM\% \times 0.50, \tag{4}$$

2.4. Statistical Analysis

A preliminary analysis on the distribution of the aboveground carbon (AGC) stocks using the Shapiro-Wilk normality test showed that the data did not conform to a normal distribution. Non-parametric tests Mann-Whitney (M-W) and Kruskal-Wallis (K-W) ANOVA were used to test for significant differences between AGC groups based on factors such as woodland category, conservation status, rainfall, stand age, and land-use change. When results were significant at the 0.05 level, pairwise comparisons of each pair of groups were performed using the M-W test with Bonferroni correction to test which pairs of groups were significantly different to each other. All descriptive and comparative statistics were computed using RStudio version 1.3.959.

All data were categorized into old-growth ($n = 33$), disturbed ($n = 81$), and re-growth ($n = 113$) categories. We also sub-categorized re-growth data into 'mature' re-growth ($\geq$30 years) and 'young' re-growth (<30 years). Here, old-growth woodlands refer to those described in the literature as primary, undisturbed, or mature woodlands. Disturbed miombo have varying levels of disturbance caused by anthropogenic activities (charcoal production, logging, fuelwood gathering, shifting cultivation) or due to wildlife damage (elephants) and fire. Re-growth sites are on previously clear-cut sites. A K-W ANOVA was used to test for differences among these categories with respect to AGC. Additionally, AGC stocks were grouped into four categories: old-growth ($n = 33$), disturbed ($n = 81$), re-growth $\geq$30 years ($n = 21$), and re-growth <30 years ($n = 78$). Differences in C stocks for each category in the aboveground pool were estimated using the K-W test.

3. Results

3.1. Aboveground Carbon Stocks in Trees

AGC in old-growth miombo ranged from 11.55 to 107.25 Mg ha^{-1} and from 1.48 to 75.42 Mg ha^{-1} in disturbed miombo. In re-growth miombo, the range was from 0.09 to 77.07 Mg ha^{-1}. Significant differences in AGC were observed between all three woodland categories (M-W: $p < 0.001$). All categories of miombo woodlands showed large variation in the AGC stocks (Table 1).

Table 1. Aboveground carbon stocks in miombo woodlands.

Woodland Category	Summary Statistics					
	n	**Mean**	**SD**	**Min**	**Median**	**Max**
Old-growth Miombo	33	45.75	17.6	11.55	44.7	107.24
Disturbed Miombo	81	26.71	15.0	1.48	21.6	75.42
Re-growth Miombo	113	18.76	16.8	0.09	13.6	77.07

n, sample size; SD, standard deviation.

Aboveground carbon differed significantly between all three woodland categories (K-W ANOVA: $p < 0.001$) (Figure 2).

When comparing AGC stocks in old-growth, disturbed, mature re-growth ($\geq$30 years), and young re-growth (<30 years), results were significant at the 0.05 level (K-W ANOVA: $p < 0.001$). Pairwise comparisons showed that old-growth and mature re-growth as well as disturbed and mature re-growth woodlands did not differ significantly ($p = 0.238$ and $p = 0.074$ respectively). All other pairs differed significantly ($p < 0.001$) (Figure 3).

In the next two sections, we explore the characteristics of the miombo AGC data further in two case studies. Case study I considers variation between sites and within sites. Case study II considers biomass growth over time.
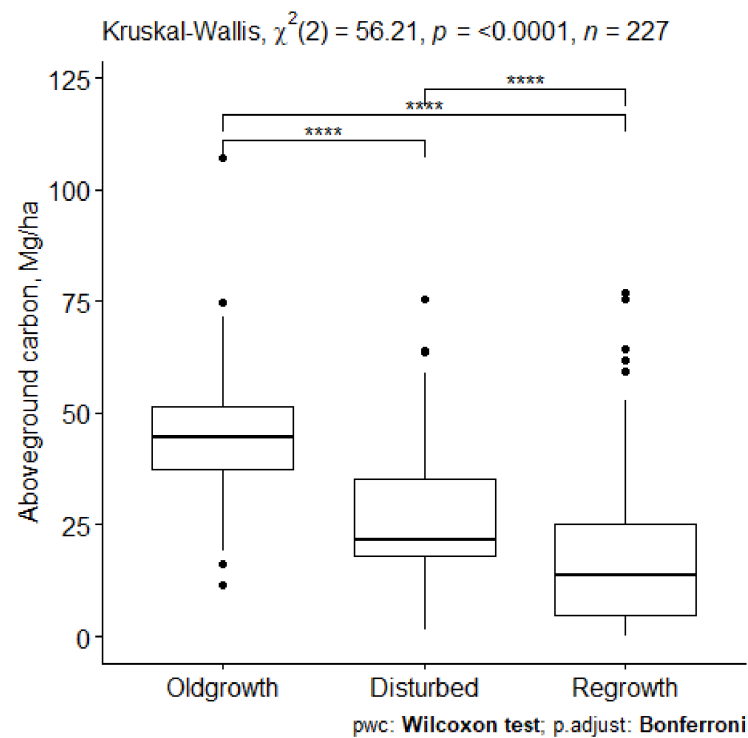
Kruskal-Wallis, $\chi^2(2) = 56.21$, $p = <0.0001$, $n = 227$

Figure 2. Aboveground carbon stocks in old-growth, disturbed and re-growth woodlands. Statis-tical significances are indicated: *p*-value < 0.001 '***'. Source: Graph by the authors.

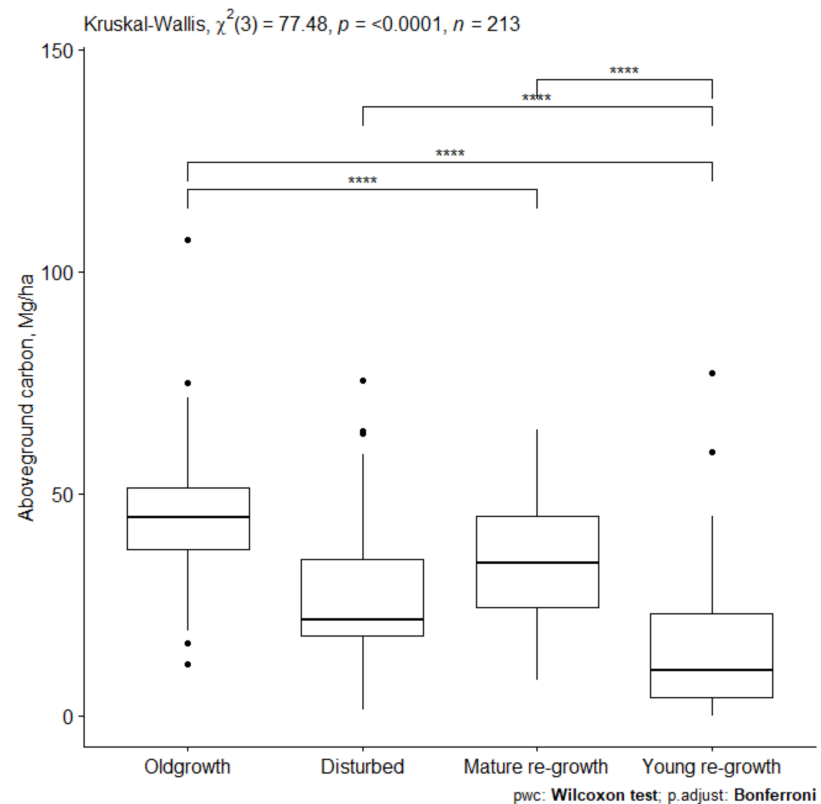Kruskal-Wallis, $\chi^2(3) = 77.48$, $p = <0.0001$, $n = 213$

Figure 3. Comparison of old-growth, disturbed, mature re-growth (>30 years), and young re-growth (<30 years). Statistical significances are indicated: *p*-value < 0.001 '***'. Source: Graph by the authors.

3.1.1. Case Study I: Miombo Biomass in Old-Growth Sites

This case study data set is from [24], but more detailed information about the site is found in [25]. The site is a miombo woodland within the Kataba Forest Reserve (FR) in the Western Province of Zambia. Some extractive activities were permitted in the reserve [24]. Four plots of 50 × 50 m and numbered one to four were established to follow a degradation gradient from highly disturbed (1; cf. Figure 4), via slightly disturbed (two and three; forest edge effects), to undisturbed (four; in the core area of a forest reserve established in 1973). AGB was measured in 100 subplots of 5 × 5 m per plots, resulting in a 100% sampling coverage. It is not clear when the plots were sampled, but assuming it was closely before the publication year of 2011, the reserve had had more than 30 years to recover and, consequently, plot four showed no signs of disturbance. However, disturbance from forest edge effects was high in plots two and three; plot one, outside of the reserve, had been strongly degraded by logging and charcoal production during the three years prior to their study, with few trees remaining, but some shrubs and grasses were recovering in the area. All plots were on Arenosols, but they differed in height, tree density, and species composition [24,25].
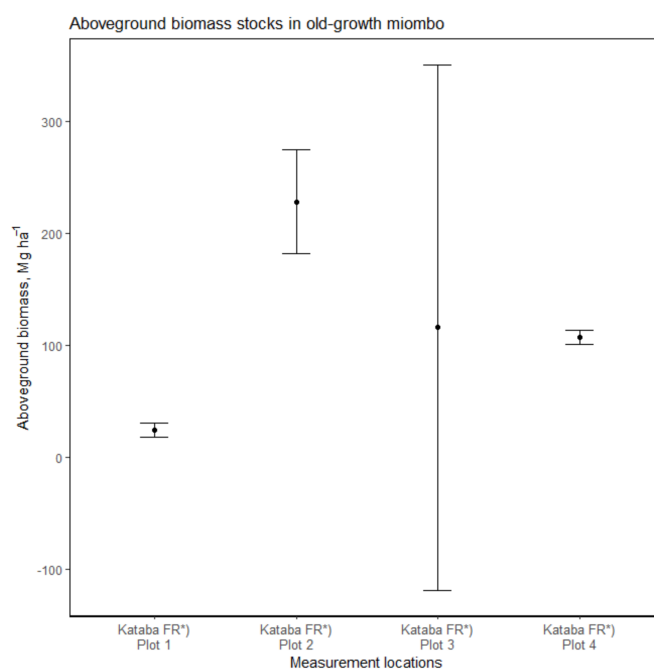

Figure 4. Old-growth AGB data for cases selected for case study I in Kataba Forest Reserve, Zambia (data from [24], ordered by increasing standard deviation). The forest is characterized by a projected canopy cover of nearly 70% [26] and is commonly described as a "woodland" [25]. Source: Graph by the authors based on data in [25].

ABG estimates vary between 38.0 and 228.2 Mg ha^{-1}, a difference by a factor of 6. They were low in the highly disturbed plot (1: 24.5 Mg ha^{-1}), high to very high in the two disturbed plots (2: 228.2 Mg ha^{-1}; 3: 116.0 Mg ha^{-1}), and high in the undisturbed plot (four: 107.6 Mg ha^{-1}). Thus, one disturbed plot (two) had very high biomass, which was one of the highest values recorded in our study.

Variability in these plots also differed dramatically. The variability in one disturbed plots (two: standard deviation ±234.3) was so large that it wrapped around that of all other plots (between ±6.3 and ±46.5). As the same method was used across all four plots, the variation must be an intrinsic characteristic of each site. For example, plot one had 48 trees left, while site four had 364 trees (above 2 cm dbh), a difference by a factor of 8, which could explain the different AGB. The variance across the subplots in the disturbed plots was high, suggesting the disturbance was selective (taking out single trees).

Our conclusions are that (1) it is possible but difficult to find a non-disturbed miombo plot even in reserves; (2) miombo forests characteristics differ greatly, resulting in varied AGBs, making it hard to come up with unequivocal numbers for miombo AGB for climate models; and (3) AGB varies dramatically depending on site characteristics, disturbance levels, and time since recovery. Insufficient documentation of the intensity of disturbances renders it difficult to assess its role in AGB from such studies. Better, more practical, and uniformly applied miombo classification according to vegetation type, rainfall, soil type, height, slope, disturbance, and etc. will be needed to be able to distinguish various types of miombo biomass reliably across the region.

3.1.2. Case Study II: Biomass Increments in Old-Growth Miombo in Morogoro, Tanzania

Several studies in the database provide longitudinal data on old-growth miombo woodlands from the Kitulangalo Forest Reserve in the Morogoro region of Tanzania. In 1985, the area was established as a reserve with restrictions on wood harvest which, in 1995, was completely protected from any extractive activities [27]. Eight permanent sampling plots were established and measured for biomass density in 1977 by Kielland-Lund [28]. Another study repeated the biomass measurements at the same sites over a period of 15 years [29] (Figure 5). These observations are cited in [27]. Note the case study is in biomass units, not carbon.
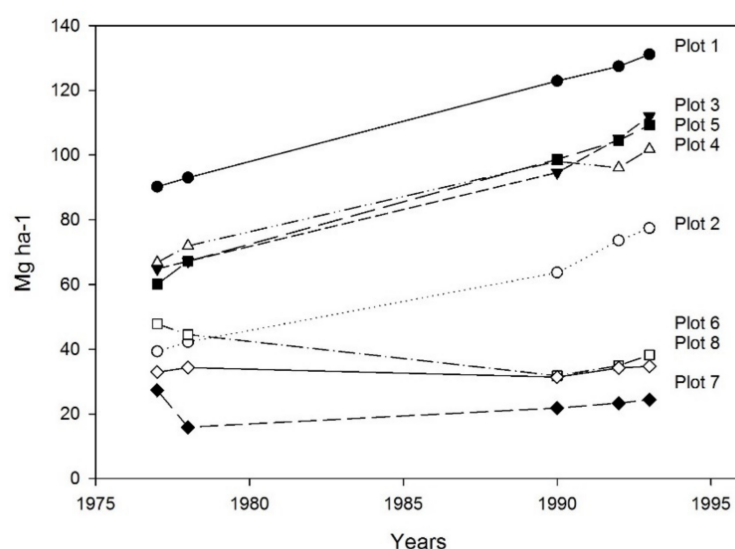

Figure 5. Variation in old-growth biomass as measured in eight sites in Kitulango Forest Reserve, Tanzania over a period of 15 years. Source: Graph by the authors based on data in [27].

Considering the 15-year period, the plots one, three, five, four, and two showed relative linear aboveground increments of between 2.1 and 2.9 Mg ha^{-1}, while the three remaining plots showed stagnant or declining biomass (-0.7 to 0.1 Mg ha^{-1}) (Figure 5). The plots one, three, five, four, and two (following their ranking in Figure 2), which showed an increase in biomass at the end of the period, had higher biomass levels in 1977 (39–90 Mg ha^{-1}). In comparison, plots six, eight, and seven started out with lower biomass levels (22–46 Mg ha^{-1}) and the levels remained stagnant or even declined at the end of the 15-year period. This case study illustrates (1) that even in miombo sites in the same areas biomass and growth rates can vary widely, and (2) that the growth rates depend on the initial biomass and may reflect different site-specific conditions.

3.2. Soil Organic Carbon Stocks

The SOC stocks of old-growth and disturbed miombo were reported at varying sampling depths (Table 2). Soil carbon data in re-growth miombo were reported from ages 1 to 30 years since abandonment of the previous land use, i.e., either as fallow land following

cultivation or following clearing for other purposes with a minimum of 10.73 Mg C ha^{-1} and a maximum of 52.2 Mg C ha^{-1}.

Table 2. Soil organic carbon stocks for old-growth and disturbed miombo woodlands [18,19,22,24,30–41]. Note: Data in the same columns are from one or more of the given sources.

Depth cm	Soil C Mg/ha	Depth cm	Soil C Mg/ha	Depth cm	Soil C Mg/ha	Depth cm	Soil C Mg/ha	Depth cm	Soil C Mg/ha	Depth cm	Soil C Mg/ha
0–5	8.75	0–15	28.47	0–16	19.40	0–20	54.10	0–25	25.00	0–30	14.51
0–5	12.10	0–15	45.63			0–20	30.90			0–30	14.33
		0–15	16.19			0–20	36.50			0–30	13.70
		0–15	15.41			0–20	21.06			0–30	14.66
		0–15	14.63			0–20	21.32			0–30	34.52
		0–15	18.35			0–20	47.32			0–30	46.80
						0–20	28.90			0–30	27.11
										0–30	28.08
										0–30	20.20
										0–30	40.10
										0–30	29.25
										0–30	43.88
0–35	55.70	0–40	45.30	0–45	45.60	0–50	87.00	0–60	134.60	0–100	72.47
						0–50	76.30	0–60	33.90	0–150	82.52
						0–50	34.90	0–60	80.10		
								0–60	71.80		

There is a need to emphasize, however, the limitations of interpreting these data due to the variation in the soil depths. Other factors such as variation in the edaphic and climatic conditions, or differences in spatial and temporal dimensions of the data, further contribute to the limitations. Although SOC stocks in re-growth are reported at varying ages of natural regeneration, the high variability in the data (Table 3) and the fact that these were reported at differing depths prevents further analyses, such as looking at variation in SOC with age and/or exploring time trends. Similarly, it is difficult to interpret the SOC data in re-growth miombo woodlands due to these differences and the changing but mostly unknown site histories.

Table 3. Soil organic carbon stocks in re-growth miombo woodlands at various stages of recovery ranging from 1 to 30 years since abandonment [7,22,31,42,43].

Depth cm	Age Year	Soil C Mg/ha	Depth cm	Age year	Soil C Mg/ha	Depth cm	Age Year	Soil C Mg/ha	Depth cm	Age Year	Soil C Mg/ha
0–15	1	20.38	0–20	16	32.76	0–30	1	24.18	0–150	M	52.2
0–15	1	20.30	0–20	16	26.26	0–30	1	42.32			
0–15	1	19.70				0–30	2	13.85			
0–15	1	14.70				0–30	2	18.72			
0–15	1	13.00				0–30	5	23.99			
0–15	2	20.87				0–30	5	35.10			
0–15	2	19.17				0–30	6	25.55			
0–15	2	21.26				0–30	6	10.73			
0–15	2	15.91				0–30	7	19.50			
0–15	2	13.82				0–30	13	24.77			
0–15	3	21.22				0–30	19	29.45			
0–15	3	20.21				0–30	20	34.32			
0–15	4	19.85				0–30	25	24.57			
0–15	20	20.50				0–30	1–30	45.20			
0–15	20	22.50									

M, data not reported.

4. Discussion

Miombo woodlands across the region are found in various stages of disturbance from human activities, such as selective wood harvesting for charcoal production and fuelwood collection, leading to changes in wood species structure and diversity. It seems difficult to find completely undisturbed miombo woodlands and, hence, to establish reference biomass/ACG data for natural vegetation. Often, the extractive activities modify the ecosystem to an extent that makes it vulnerable to further degradation. The results suggested that conversion of old-growth miombo has consequences for carbon storage with a significantly lower range of carbon stocks found in re-growth miombo.

Data for AGC in old-growth miombo had a much higher mean (45.6 Mg ha^{-1}) than in disturbed (26.7 Mg C ha^{-1}) and re-growth (18.8 Mg C ha^{-1}) miombo. However, large variation was observed in all three groups, which suggests that other factors such as rainfall, species composition, and variable growth conditions [44] also influence carbon storage. Data suggest that more mature re-growth stands (age >30 years) have comparable AGC stocks to old-growth and disturbed stands, which seems to indicate that woodland recovery is taking place with respect to woody biomass. Chidumayo (1991) showed that a minimum of 30 years is required for naturally regenerating miombo to reach woody biomass levels comparable to that of pre-disturbance levels [45]. This matches recovery information found in a global meta-study [46].

SOC presents a lesser-studied but important carbon pool in the miombo ecoregion. Studies show that the SOC stocks in miombo forests account for significant amounts of total C stored in the ecosystem, storing up to 50–80% of total C [9,30]. Woollen et al. (2012) [39] observed that soil C stocks in miombo woodland vary significantly over short distances of 14–26 m, which may explain the large variability we observed in SOC stocks. Therefore, we hypothesize, concurring with Gibbs et al., (2007) [47], that in general soil C stocks in miombo woodland are more stable than those in aboveground biomass which are directly impacted by woodland degradation. The ranges for re-growth and cropland SOC stocks indicate that the two datasets cover a similar range of underlying variability. This could be explained by the similar age range that the data cover, i.e., between 0–30 years, and most of the data in the re-growth cover type fall under the post-cultivation category. Hence, prior to abandonment, most re-growth areas were cultivated. Thus, the similarity in variability of SOC stocks of the two cover types may be attributed the similar land-use management histories. The minimum SOC stock in old-growth miombo also falls under a similar range as re-growth and cropland, but old-growth miombo stores up to 2.5 times more C on the upper end of the scale.

Forest conservation strategies such as national parks and forest reserves appear ineffective in stemming forest cover loss with no significant differences found between these two categories and open areas which are not formally protected from encroachment. Muposhi et al. [34] studied the effects of anthropogenic disturbances on the edges of protected areas along a disturbance gradient with increasing distance from the edge of the park boundary to inside to the park. They found that these disturbances significantly affected wood plant density and height, which is likely to affect the carbon storage of these woodlands. Therefore, there is an urgent need to manage these boundary areas which act as a buffer between communities living outside these protected areas and the protected areas themselves. Introducing buffer zones and extractive reserves to limit encroachment and degradation of woodlands in these protected areas are some potential possibilities for woodland management.

This review demonstrated the limited information available for the biomass and carbon stocks in aboveground carbon and SOC pools for the miombo ecoregion in earlier decades. It is only in the last decade (2010s) that the evidence base has considerably expanded, accounting for nearly 70% of the studies in this review. The regional coverage has, however, not changed and is restricted to the countries of Malawi, Mozambique, Tanzania, Zambia, and Zimbabwe, while no data are available for Angola and the Democratic Republic of Congo.

Most of our data were extracted from chronosequence studies that used space for time ("false time series") and therefore may have spatial confounding factors that may have affected the analytical results [48]. Further, the sampling designs and the resultant data used may not have met the standard sampling protocols to enable data analysis using parametric statistical tests. Therefore, we used non-parametric tests to compare the effects of protection and other comparators on carbon stocks and fluxes.

5. Conclusions

Despite the ecological and social importance of miombo woodlands, the carbon stocks of these ecosystems remain poorly assessed and documented, which limits the scope of any analysis. The variability in aboveground carbon data reported points to stand characteristics and age, environmental effects, and disturbance, but these factors are not consistently recorded across the studies. Root carbon data are missing and could only be inferred from conversion factors, which is not optimal. SOC stocks cannot be reliably computed because different studies sampled widely different soil depths, often pooling the data. More systematic miombo site classifications and clearly defined disturbance parameters should be used more uniformly in further miombo assessments. Establishing permanent sampling plots with systematic records of environmental parameters and disturbance regimes and levels would be needed to assess the time trends in carbon stocks in these woodlands. Moreover, future studies should include sites in the miombo woodlands of Angola and the Democratic Republic of Congo, whose ecosystems and carbon dynamics are absent in the available literature.

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