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Coppicing and productivity of two indigenous tree species under different forest management regimes in Tanzania

Vincent G. Vyamana[a], Shabani A.O. Chamshama[b], Samora M. Andrew[b,*]

[a] P. O. Box 1349, Morogoro, Tanzania

[b] Department of Ecosystems and Conservation, College of Forestry, Wildlife and Tourism, Sokoine University of Agriculture, P.O. Box 3010 Chuo Kikuu, Morogoro, Tanzania

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ABSTRACT

There is a renewed interest to improve sustainable wood production from African savanna but our knowledge on management of individual tree species to optimize harvesting return times is limited. A factorial experiment was therefore established to assess the effects of stump diameter and height, and coppice thinning on growth and yield of *Albizia harveyi* Fourn (Ah) and *Albizia versicolor* Welw ex. Oliver. (Av) in Forest Reserve (FR) and the General Land (GL) at area in Morogoro region, Tanzania. Coppice diameter and height growth was significantly high in Av than Ah; and was highest in stumps cut at 30 cm or 90 cm regardless of tree species. Ah had significantly high average coppicing effectiveness (11.74 coppices per stump) than Av (4.18 coppices per stump) in the FR; but the variation was not significant in the GL. Coppice wood basic density was significantly high in Ah (446.04 ± 0.72 kg m^{-3}) than Av (400.52 ± 0.97 kg m^{-3}). Coppice wood biomass ranged from 3.08 ± 0.02 kg $stool^{-1}$ in Ah to 3.45 ± 0.03 kg $stool^{-1}$ in Av. Ah produced highest coppice wood biomass in medium diameter stumps cut at 30 cm (3.57 kg $stool^{-1}$) or 90 cm (3.76 kg $stool^{-1}$) and large stumps cut at 5 cm (4.55 kg $stool^{-1}$); and the least biomass in small stumps cut at 5 cm (1.26 kg $stool^{-1}$). For Av, highest coppice wood biomass values were 6.41 kg $stool^{-1}$ for medium diameter stumps cut at 90 cm and 6.20 kg $stool^{-1}$ for large stumps cut at 30 cm; and the least was 1.87 kg $stool^{-1}$ for small stumps cut at 5 cm. This paper concludes with discussion on the need for further studies on optimal canopy cover and wild fire control strategies under short-rotation coppice silvicultural system; and suitability of multipurpose indigenous trees for simultaneous on-farm production.

1. Introduction

Savanna ecosystem comprises tree-grass systems that are characterized by discontinuous trees canopy in a continuous xeromorphic and fire tolerant-shade intolerant grass layer. It is the most extensive ecosystem covering more than 50% and 20% of land surfaces of Africa and globally, respectively. Miombo woodlands of Southern Africa is part of the southern hemisphere of the African savanna (Sankaran et al., 2005; Osborne et al., 2018). In Tanzania and most Sub-Saharan African countries, the African savanna continues to be an important source of woodfuel for both urban and rural populations. Most African savanna tree species are preferred for woodfuel due to their high wood density and calorific value (Abbot and Lowore, 1999; Luoga et al., 2002). Besides, the African savanna is important for a myriad of goods and services that support livelihoods of millions of people (Campbell et al., 2007; Dewees et al., 2010). The total annual estimated monetary value of goods and services in the African savanna exceeds $9 billion (Ryan et al., 2016).

Sustainable utilization of the African savanna for woodfuel production is considered more environmentally friendly and socially acceptable than non-renewable energy sources, and/or short-rotation coppice plantations (Spinelli et al., 2017). According to Biilgen et al. (2007) and Kaygusuz (2009) among others, sustainable harvesting of woodfuel from natural forests results in less greenhouse gas emission than non-renewable energy sources; and is more socially acceptable than the previously promulgated short-rotation coppice plantations as the latter compete with food production. Nevertheless, unsustainable woodfuel harvesting is widespread and exerting enormous pressure on the natural forests in Tanzania and many other African countries where African savanna occurs.

Several studies have consistently alerted that the wood harvested for woodfuel from African savannas, besides other uses, exceeds

* Corresponding author.
E-mail address: smacrice@sua.ac.tz (S.M. Andrew).

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sustainable off-takes (Luoga et al., 2002; Manyanda et al., 2020). In Tanzania, wood harvested for woodfuel from the African savanna constitutes the largest share of total wood removals (Luoga et al., 2002). For example, woodfuel accounts for 69% of the annual wood deficit of 19 million m^3 reported in the most recent forest assessment in Tanzania (MNRT, 2015). This suggests the need to design improved strategies for sustainable production of woodfuel and wood products from the African savanna as a matter of urgency.

Most African savanna tree species regenerate and recover from disturbances mainly through coppices and root suckers due to deep and extensive lateral root system that facilitates access to adequate reserves of water and nutrients (Frost, 1996). Thus, most studies have demonstrated the potential of coppice rotation management of silvicultural systems for improved productivity and sustainable production of woodfuel and other wood products in the African savanna (Chidumayo, 2004; Syampungani et al., 2016a; Njoghomi et al., 2020). However, the knowledge on coppice management of individual tree species to optimize harvesting return times is limited (Luoga et al., 2004; Kaschula et al., 2005).

It is well established that coppicing and coppice growth are likely to be influenced by interaction of tree species, tree size; stump height and amount of sunlight reaching the stumps as influenced by canopy cover of remaining live trees (Chidumayo, 1997; Handavu et al., 2011; Syampungani et al., 2016a, b); and site characteristics such as soils and topography (Chidumayo, 2004; Sankaran et al., 2005; Goldenberg et al., 2020), among others. However, past studies have seldomly integrated these factors besides being small-scale and site-specific. Furthermore, some studies that assessed coppicing of African savanna tree species have inherent uncertainty regarding coppice age, and so growth rate cannot be inferred (Luoga et al., 2004). This hinders precise estimation of suitable rotation age, among others; which is one of important parameters needed to guide sustainable forest management planning.

In this paper findings from the experiment designed to test effects of stump diameter and height, and coppice thinning on growth and yield of *Albizia harveyi* Fourn (Ah) and *Albizia versicolor* Welw ex. Oliver. (Av) in Forest Reserve (FR) and General Land (GL) in Morogoro region, Tanzania is presented. The FR is characterized by stringent government restrictions on utilization but with sporadic illegal tree cutting; whereas GL is without any control with high levels of utilization including conversion to farmlands (Luoga et al., 2004). The study tree species are among the species preferred for woodfuel in Tanzania and other countries with African savanna ecosystems (Kaschula et al., 2005).

2. Methodology

2.1. Study area

The study was carried out at Kitulanghalo Forest Reserve (FR) (2452 ha) and surrounding open woodlands (13,500 ha) in General Land (GL) (6^{0}34″S–6^{0}45″S and 37^{0}53″E–38^{0}04″E) located at about 50 km east of Morogoro town and 150 km west of Dar-es-Salaam city. The FR and the GL are separated by Dar-es-Salaam-Morogoro highway (Fig. 1). The vegetation of the area comprises of savanna of open miombo woodland type dominated by trees of *Julbernardia globiflora* (Benth.) Troupin and *Combretum* spp. The climate of the area is tropical and sub-humid with bimodal rainfall. The rainfall ranges from 700 to 1000 mm per annum with an average of about 900 mm per annum. Rain-fed agriculture and charcoal production are the major economic activities for the inhabitants around the study area. The main crops grown are maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L. Moench) and garden peas (*Pisum sativum* L.).

2.2. Experimental design, management and data collection

A 5-way (2 × 2 × 3 × 3 × 2) factorial experiment with three replications was set up in woodlands within two different forest tenures i.e., FR and GL to examine the relationship between tree species, forest tenure, original stem size, cutting height and post-felling coppice thinning on coppice growth and yield of *A. harveyi* and *A. versicolor* (Table 1).

In the FR, 54 individual trees were randomly selected to include 18 trees from each of the three tree DBH size classes. On the contrary, there were no trees of large DBH class in the GL and in that case 36 individual trees were randomly selected to include 18 trees from medium and 18 from small DBH classes. For each DBH class and for each of the two study tree species, one third of the 18 sample trees (i.e., 6 trees), were cut at 0 cm (ground level), 30 and 90 cm from the ground, respectively, using a crosscut saw. After tree cutting, each individual stump was treated as a replicate. Thus, there were three replicates of stumps per each treatment combination (DBH class × cutting height × coppice thinning) per forest tenure. Two coppice thinning treatments (i.e., no thinning and thinning to leave two coppices), were then randomly assigned using a table of random numbers and compass bearing (1–360^0) to all stumps. Thinning treatments were applied when coppices reached 10 cm height, which was achieved four months after tree cutting. Subsequent coppice thinning was maintained at the same interval of four months. During the first coppice thinning operation, the two tallest coppices were left per thinned stump. Thereafter any coppices that re-sprouted were removed subsequently.

Assessments of coppice growth were done at the ages of 6, 12, 18 and 24 months. During each assessment, all surviving coppices were measured for basal diameter at 10 cm (D10) from the base of the coppice and total height. Height was measured to the nearest 0.01 m using a graduated pole while D10 was measured to the nearest 0.01 cm using a measuring caliper. The tally of height and D10 also gave the number of coppice stems per stump. Canopy cover was measured once during the last assessment. Four measurements of canopy cover were taken from the edge of each coppiced stump using a spherical densiometer. The average canopy cover of the four measurements was finally used in analysis.

To develop allometric equations, a total of 60 coppice shoots for each tree species including all diameter classes were randomly selected from each of the forest tenures during the last assessment. Before felling, each individual coppice was measured for diameters at 10 cm and 130 cm from the base, and total height. Felled coppices were portioned into stem wood, branches and leaves/twigs and sub-samples of each component dried in the laboratory at 70 °C to constant weight. In addition, subsamples for determination of wood basic density were taken following the procedure described by Nyadzi (2004), using 15 coppices for each species from each of FR and GL representing the three diameter classes (small, medium and large). For each of the 15 sampled coppices, three discs of about 4 cm thickness were taken from the 1.3 m mark, 1/3 and 2/3 of the total stem height. Each disc was inserted in the trough of fluted paper and immediately air dried for two months to prevent fungal growth.

Dry weight of coppices together with the respective diameters and heights were used to develop allometric equations for foliar biomass, wood biomass and total biomass. Four different models developed by Chamshama et al. (2004) were fitted into the collected data. The best models were selected based on the adjusted coefficients of determination (R^2), standard error of estimate (SEE) and F-ratio. The best prediction models were then used to derive the individual coppice and tree components (stem, wood, foliage and total) biomass using the tree growth data set collected over the entire study period. The estimated biomass was multiplied by respective correction factor (CF) to account for bias associated with logarithmic transformation. Determination of wood basic density (WBD) followed Nyadzi (2004). Fuelwood value index (FVI) was calculated as wood basic density (kg m^{-3}) divided by air dry moisture content (%), (Abbot and Lowore, 1999). For determination of WBD and computation of FVI wood samples were pooled from on-farm coppices, FR and GL at area, which had the same age.

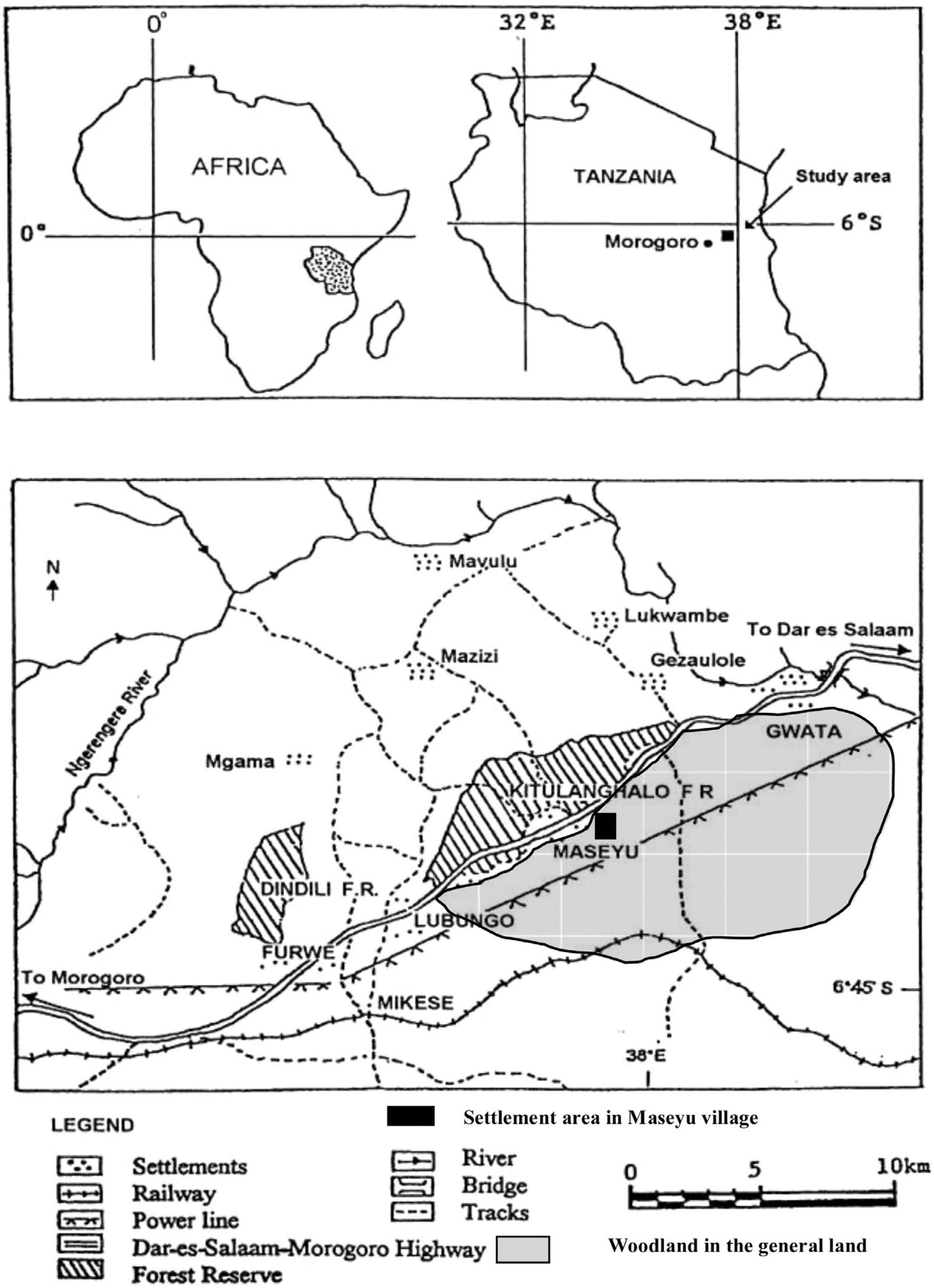

Fig. 1. Location of Forest Reserve and adjacent forest on the General Land in Morogoro, Tanzania. Modified from Luoga et al. (2002).

2.3. Data analyses

Prior to statistical analyses, data sets for all dependent variables were examined for parametric statistical assumptions of normality and constant variance as described by Zar (1996), using Shapiro–Wilk and Levene's tests, respectively (SAS Institute, 1999). Normality and constant variance tests showed that coppice mortality, stump survival and canopy cover data sets violated the requirements for normality and homoscedasticity and were therefore arcsine transformed to correct for the observed deviations. Nevertheless, only non-transformed data are presented in this work for clarity (Wallin et al., 2008). All statistical analyses were conducted at 5% level of significance. In all cases, analysis of variance (ANOVA) was done in two stages using the General Linear Model procedure of SAS at 5% level of statistical significance (SAS Institute, 1999). In the first stage, interactions effects that were not statistically significant were identified. In the second stage, all interactions identified as being not statistically significant were omitted from the model in order to increase precision of the model, and the analysis was repeated to get the final outputs.

Analysis of all the data was carried out as 5-way ($2 \times 2 \times 3 \times 3 \times 2$) factorial experiments. However, data set from the GL had missing data on treatment combination associated with large DBH size class, which did not exist during establishment of experiments. Replicate and replicate-by-treatment interaction(s) effects were treated as error terms in the model. After ANOVA, means separation for significant main treatment effects was done according to Duncan's Multiple Range Test (Gomez and Gomez, 1983). For significant treatment interactions, least square means were ranked according to Tukey's Studentized Range Test after appropriate sorting. In addition, Student's *t*-test was used to compare differences in canopy cover between FR and the GL. Pearson's

Table 1
Factorial treatment for in-situ coppice management experiment at Kitulanghalo Morogoro Tanzania.

Factor one	**Factor two**	**Factor three**	**Factor four**	**Factor five**
Two levels of study species	Two levels of forest tenure	Three levels of DBH classes	Three levels of tree cutting heights	Two levels of coppice thinning
A. harveyi (Ah)*A. versicolor* (Av)	Forest reserve (FR)	Large (DBH ≥20 cm)	5 cm i.e. ground level (C1)[a]	Coppices not thinned (TH_0)
	Forest on GeneralLand (GL)	Medium (11 ≤ DBH ≤ 20 cm)	30 cm above the ground (C2)	Coppices thinned to leave two coppice shoots (TH_1)
		Small (5 ≤ DBH ≤ 10 cm)	90 cm above the ground (C3)	

[a] It was not possible to cut trees exactly at the ground level given the type of equipment used i.e. two-man crosscut saw.

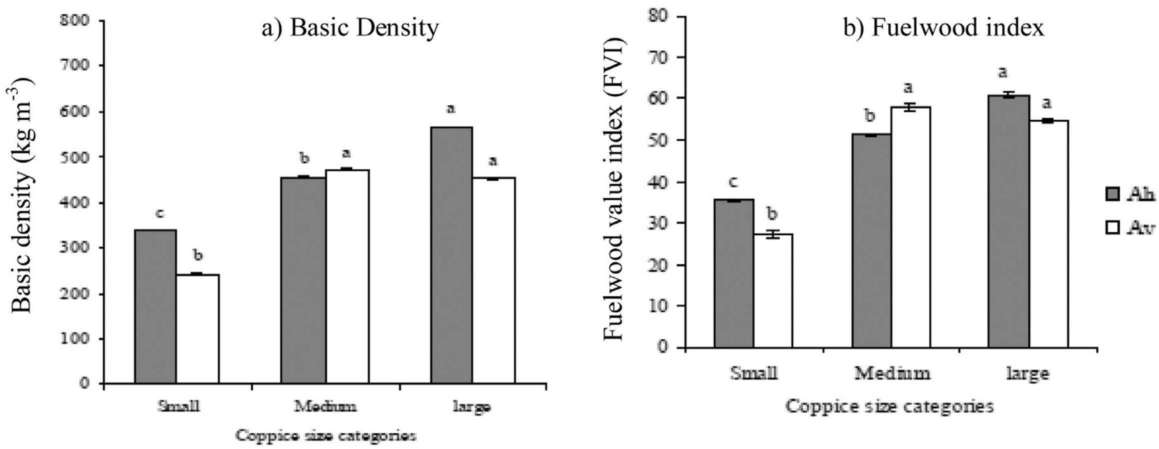

Fig. 2. Variation in coppice wood basic density (a) and fuel wood value index (b) in different diameter sizes classes of coppices of *A. harveyi* and *A. versicolor* pooled from on-farm, FR and GL at Kitulanghalo area in Morogoro, Tanzania.

Table 2
Variation in basic density and fuel-wood value index between coppices of *A. harveyi* and *A. versicolor* pooled from FR and GL at Kitulanghalo area in Morogoro, Tanzania

Tree species	Basic density (kg m^{-3})	Fuel wood value index (FVI)
A. harveyi	446.04a (0.72)[a]	48.33a (0.24)
A. versicolor	400.52b (0.97)	48.11a (0.35)
P>*F*-Ratio	0.0263	0.3298

[a] Means of six replicates followed by standard error in brackets. Within each column means marked by the same lower-case letters are not statistically different at 5% level of statistical significance according to Tukey's HSD test.

correlation coefficients were calculated between canopy cover and coppice yield.

3. Results

3.1. Wood basic density and fuel wood value index

Wood basic density (WBD) of 446.04 ± 0.72 kg m^{-3} recorded in *A. harveyi* was significantly ($p < 0.05$) higher than 400.52 ± 0.97 kg m^{-3} recorded in *A. versicolor* (Table 2). Nevertheless, the two species had very similar FVIs ($p > 0.05$). For both tree species, WBD and FVI for coppice wood increased significantly with stem size (Fig. 2).

3.2. Biomass equations

Table 3 shows best prediction models chosen to compute coppice biomass (kg $stool^{-1}$). All of the selected models were significant at $\alpha = 0.0001$. The common feature for most of the selected equations for biomass estimation was the use of D10 as independent variable (Table 3).

Table 3
Summary of selected allometric equations for estimating stem, branch, foliage and total biomass of coppices of *A. harveyi* and *A. versicolor* coppiced on FR and the GL at Kitulanghalo area in Morogoro, Tanzania.

Selected equations	R^2	SEE	CF
a) *A. harveyi*			
Ln (stem wood) = 1.3911744ln(D10) − 1.3490293	0.65	0.38	1.07
Ln (Branch wood) = 1.1869116ln(D10) + 0.659868915ln(Ht) − 5.5951851	0.63	0.43	1.10
Ln (Leaves and twigs) = 1.4151056ln(D10) − 1.982886	0.53	0.48	1.12
Ln (Whole stool) = 1.4098322ln(D10) − 0.6357853	0.68	0.36	1.07
b) *A. versicolor*			
Ln (Stem) = 1.2687252ln(D10) + 0.971329819ln(Ht) − 6.7463643	0.82	0.36	1.07
Ln (Branch) = 1.5594496ln(D10) − 2.0625399	0.62	0.54	1.16
Ln (Leaves and twigs) = 1.5183198(D10) − 1.993383	0.67	0.47	1.12
Ln (Whole stool) = 1.1893842ln(D10) + 0.93543542ln (Ht) − 5.687517	0.82	0.34	1.06

CF = Correction factor; SEE=Standard error of regression estimate and R^2= Coefficients of determination.

3.3. Coppice growth

Despite lack of consistent pattern over time, ANOVA revealed statistical significance ($p < 0.05$) for main effects as well as second and third order interactions of the factors with respect to coppice height and diameter growth at different ages (Fig. 3). *A. versicolor* recorded significantly ($p < 0.05$) highest values for both coppice height and diameter growth for the entire assessment period (Fig. 3a, b). Both coppice height and diameter growth were significantly ($p < 0.05$) highest in stumps of 90 cm height than the rest stump heights starting at the age of 1.5 years.

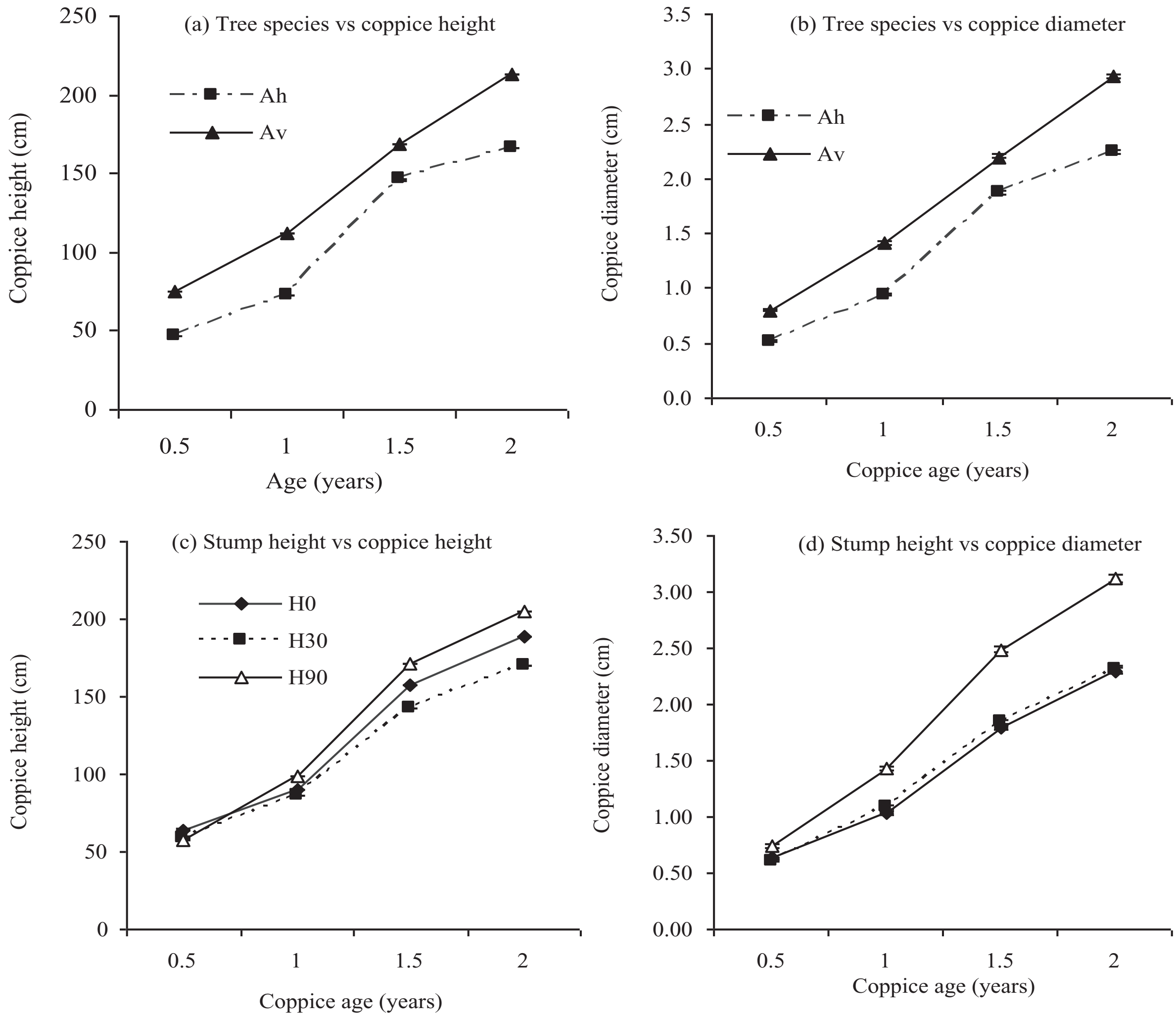

Fig. 3. The effects of tree species on coppice height (a) and diameter (b) development and stump height on coppice height (c) and diameter (d) development of *A. harveyi* and *A. versicolor* in the FR and GL at Kitulanghalo area, Morogoro Tanzania**.** Treatments were Ah = *Albizia harveyi,* Av = *Albizia versicolor,* H0 = stumps cut at the ground level, H30 = stumps cut 30 cm from the ground and H90 = stumps at 90 cm from the ground. Vertical bars indicate standard errors of means.

However, differences in coppice height growth among different stump diameters were not significant ($p > 0.05$) throughout the assessment period. For both coppice height and diameter growth, interaction of species and stump diameter growth were significant ($p < 0.05$) at the age of 0.5 year but not significant ($p > 0.05$) for the rest of the ages. Interaction of tree species, stump diameter and coppice thinning had significant ($p < 0.05$) effects on coppice diameter growth at the ages of 0.5 and 1 year but the effects were insignificant ($p > 05$) with respect to coppice height growth.

As was expected, the effect of coppice thinning on coppicing effectiveness was significant ($p < 0.05$) starting at the age of 1 year up to the end of assessment period; whereas the rest of the factors had no significant ($p > 0.05$) effects on coppicing effectiveness. Also, the interaction of site, tree species and coppice thinning had significant effects on coppicing effectiveness at the ages of 0.5, 1.5 years through the age of 2 years. The studied tree species varied in their coppicing effectiveness response to different thinning treatments in different sites. In the GL, coppicing effectiveness in *A. harveyi* was similar to *A. versicolor* regardless of the thinning treatments applied (Fig. 4). At the age of two years, coppicing effectiveness in *A. harveyi* not thinned was higher by 70% compared to thinned coppices of the same species, and by 11% compared to *A. versicolor* coppices in not thinned in the GL. *A. harveyi* coppices not thinned exhibited the highest coppicing effectiveness ($p < 0.05$) in the FR than in the GL, whereas the pattern remained virtually unchanged for *A. versicolor*. Within the FR, coppicing effectiveness of *A. harveyi* (11.74 coppices per stump) in coppices not thinned was higher by 181% compared to the coppices of *A. versicolor* not thinned (4.18 coppices per stump).

3.4. Coppice mortality

Site had significant ($p < 0.05$) effect on the final coppice mortality at the age of two years. However, the rest of the factors as well as interaction of the factors had no significant ($p > 0.05$) effects on coppice mortality. At the age of two years, mean coppice mortality of 34.85 ± 0.10% for coppices in the GL was higher by 217% compared to the mean coppice mortality of 10.98 ± 0.07% in the FR. These results indicate that bio-physical factors are harsher to coppice survival and growth in the GL but conducive in the FR. Fig. 5 shows causes of coppice mortality in the FR and GL. Frequencies of total dead coppices were 46 and 17 in the GL and FR, respectively. For the GL, wildfires and shifting cultivation caused 63% and 37% of the total mortality, respectively. Whereas in the FR, wildfires, gully erosion and termites accounted for 52%, 41% and 5.9% of the total mortality, respectively. Chi-square test of independence revealed significant association ($n = 63$; df = 3; $\chi^2 = 28.140$; $p = 0.000$) between forest site and causes of coppice mortality. Wildfire

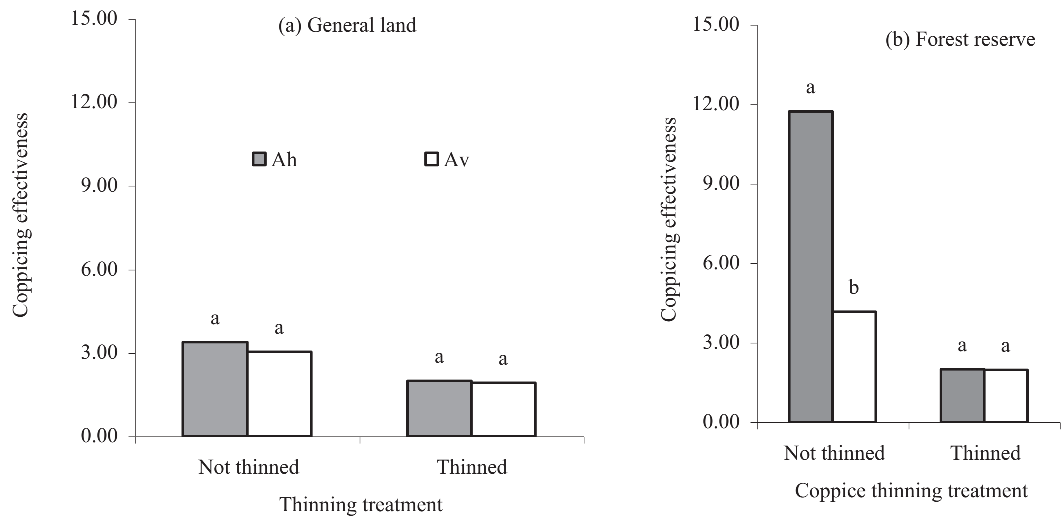

Fig. 4. The effects of coppice tree species and coppicing thinning treatment on coppicing effectiveness of *A. harveyi* and *A. versicolor* growing in the general (a) and forest reserve (b) at Kitulanghalo area in Morogoro, Tanzania**.** Treatments were Ah = *Albizia harveyi,* Av = *Albizia versicolor*, TH0 = Coppices not thinned, TH1 = Coppices thinned to leave two coppice stems per stool.

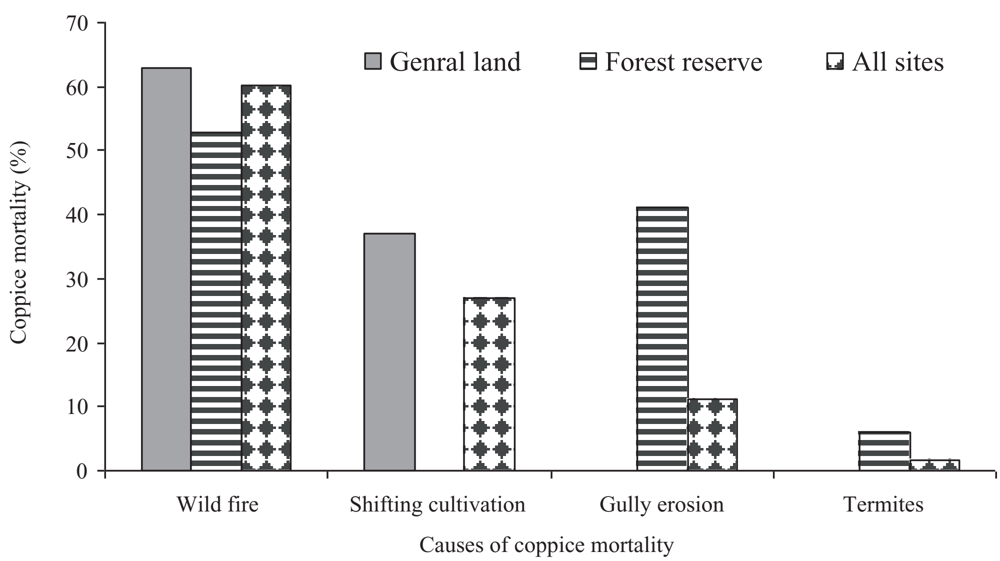

Fig. 5. Causes of coppice mortality in two years old coppices of *A. harveyi* and *A. versicolor* growing in the FR and GL at Kitulanghalo area in Morogoro, Tanzania.

was the major and common cause of coppice mortality in both the GL and FR. However, coppice mortality due to shifting cultivation and gully erosion were unique to the GL and the FR, respectively.

3.5. Biomass production

Results showed significant ($p < 0.05$) variation among the studied tree species in all coppice biomass components as well as coppice total wood mean annual increment (MAI), (Fig. 6). Regardless of the site, all coppice biomass components and total wood MAI were always higher in *A. versicolor* than in *A. harveyi*. At the age of two years, stem wood biomass ranged from 3.08 ± 0.02 kg stool^{-1} in *A. harveyi* to 3.45 ± 0.03 kg stool^{-1} in *A. versicolor*. Corresponding ranges were 1.08 ± 0.01 kg stool^{-1} to 2.29 ± 0.03 kg stool^{-1}, 1.62 ± 0.01 kg stool^{-1} to 2.35 ± 0.03 kg stool^{-1}, 6.19 ± 0.03 kg stool^{-1} to 7.25 ± 0.03 kg stool^{-1}, 4.07 ± 0.02 kg stool^{-1} to 5.75 ± 0.04 kg stool^{-1} and 2.02 ± 0.02 kg stool^{-1} year^{-1} to 2.87 ± 0.03 kg stool^{-1} year^{-1} for branch wood, foliage, whole stool, total wood biomass and MAI respectively.

Interaction of tree species, stump diameter and stump cutting height had significant ($p < 0.05$) effects on stem wood and total biomass production (Fig. 7a–d). However, the effects of the rest of the factors and interactions on both coppice biomass and MAI were not significant ($p >$ 0.05). For *A. harveyi*, wood biomass was similar for stumps cut at 30 cm (3.57 kg stool^{-1}) and stumps cut at 90 cm (3.76 kg stool^{-1}). The highest biomass was obtained in stumps cut at 5 cm from large DBH class trees (4.55 kg stool^{-1}) whereas the least wood biomass was recorded in stumps cut at 5 cm from small DBH class trees (1.26 kg stool^{-1}). For *A. versicolor*, wood biomass was similar and highest for stumps cut from medium DBH class trees at 90 cm (6.41 kg stool^{-1}) and stumps cut from large DBH class trees at 30 cm (6.20 kg stool^{-1}). Stumps cut from small DBH class trees at 5 cm (1.87 kg stool^{-1}) had the least wood biomass. A similar pattern was observed for total biomass in both studied tree species.

3.6. Canopy cover and its relationship with coppice biomass

Paired t-test showed significant differences of canopy cover between FR and the GL (paired $t_{45} = -3.532, p = 0.001$). Average canopy cover in

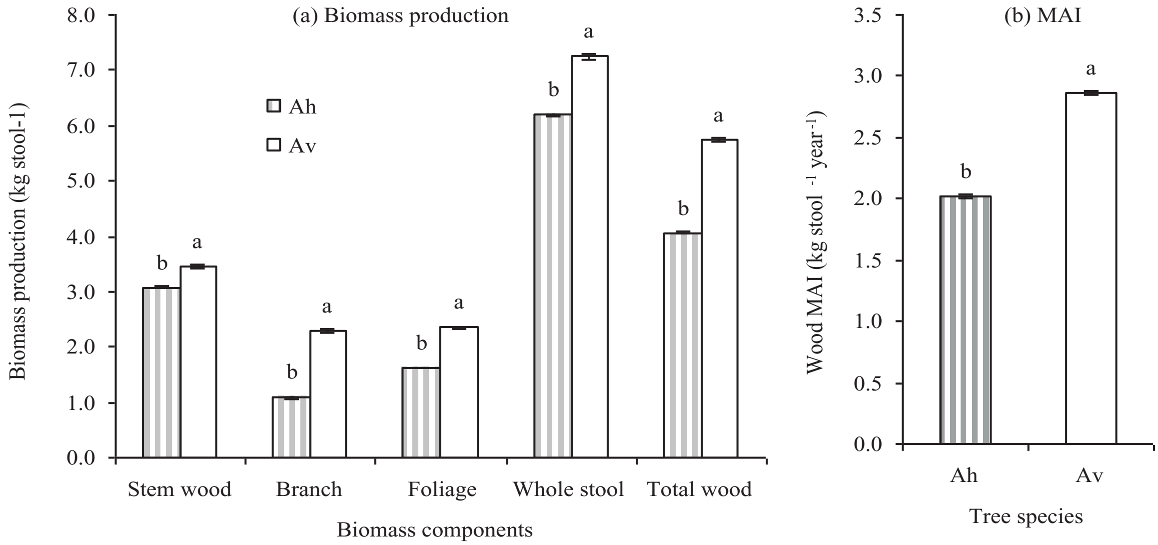

Fig. 6. Effects of coppiced tree species onbiomass production and (b) and MAI in two years old coppices of *A. harveyi* and *A. versicolor* growing in the native miombo woodlands in Kitulanghalo FR and adjacent GL at Kitulanghalo area in Morogoro, Tanzania. Data were pooled for both FR and the GL; Vertical bars indicate standard errors of means.

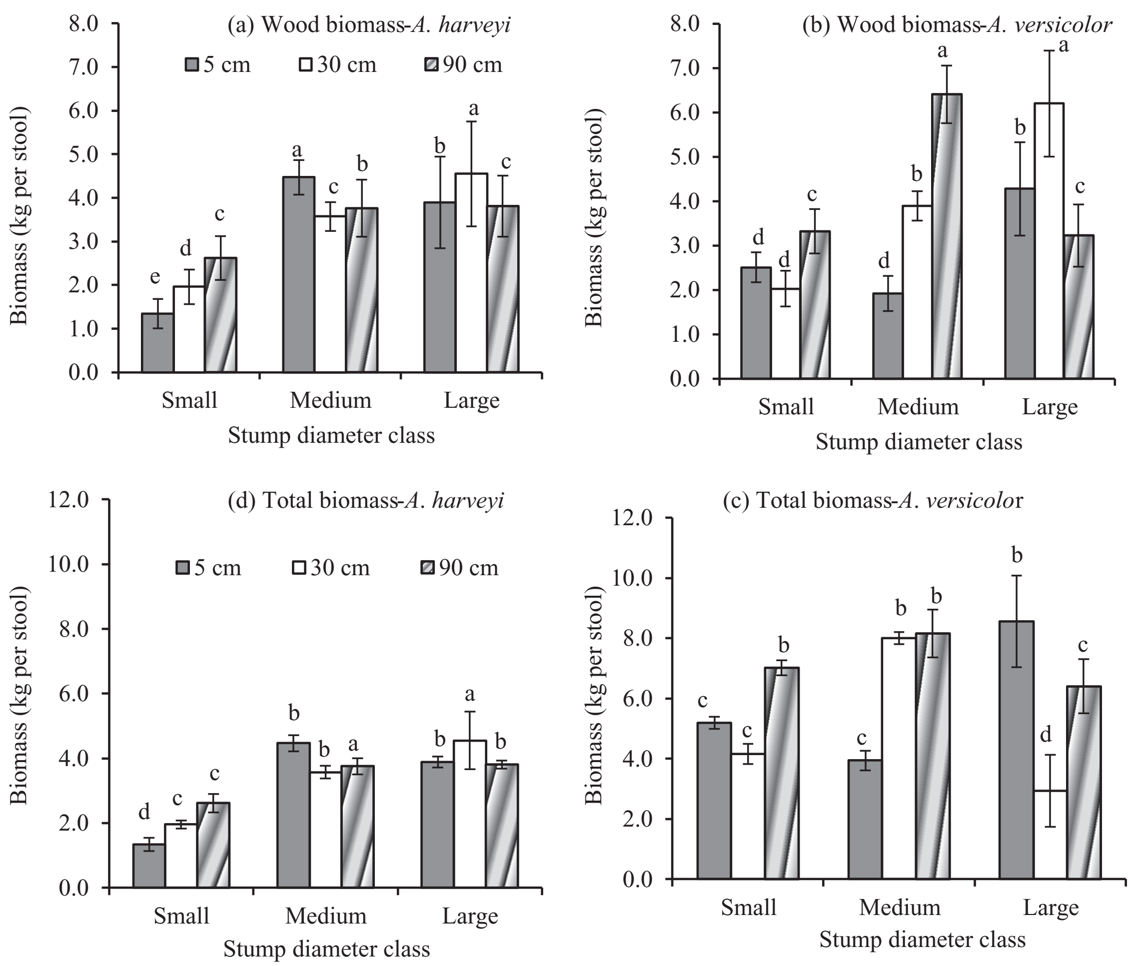

Fig. 7. Variation in coppice wood (a and b) and total biomass (c and d) for the interactions between tree species, stump diameter and stump heights for *A. harveyi* and *A. versicolor* coppices in the FR and GL at Kitulanghalo area in Morogoro, Tanzania. Data were pooled for both FR and the GL; Vertical bars indicate standard errors of means. For each figure, values represent least square means of treatment combination and those marked by the same letter within each tree species are not statistically significantly different at $\alpha = 0.005$ according to Tukey's HSD test.

Table 4
Pearson correlation coefficient for coppice biomass components and the canopy cover for *A. harveyi* and *A. versicolor* at Kitulanghalo area in Morogoro, Tanzania.

Coppice biomass component yield	N	Pearson's r (arcsine transformed canopy cover percent)	*P*-value
Stem wood biomass	124	−0.005	0.963
Branch wood biomass	132	−0.251	0.008
Total wood biomass	132	−0.122	0.204
Foliar biomass	132	−0.037	0.701

the FR was 37.41 ± 3.51%, which is higher compared to average canopy cover of 21.09 ± 3.17% in the GL. Table 4 shows correlations between yields of coppice biomass components and arcsine transformed canopy cover percent. As was expected, all biomass components were negatively correlated with canopy cover but were insignificant with exception of branch wood biomass. However, regression analyses between canopy cover with logarithmic and inverse transformed biomass components did not reveal any statistically significant non-linear relations between canopy cover and any of the biomass components.

4. Discussion

4.1. Wood basic density and fuelwood value index

WBD is one of the important wood characteristics that influences the quality of fuel. Tree species having wood with higher density are favored as source of fuel wood due to high energy content per unit volume and slow burning property (Goel and Behl, 1996). WBDs found in this study for two years old coppices (400–446 kg m^{-3}) are within the range reported in other studies from tropical Africa (Abbot and Lowore, 1999). This study found significant increase of WBD with increasing diameter of coppice stems. This pattern is probably due to the fact that coppices' diameter size categories could be associated with differences in age of individual coppices. Most likely the small coppice stems were younger compared to the large ones. Several studies have reported significant WBD increase with age (Githiomi and Kariuki, 2010; Lemenih and Bekele, 2004).

The FVI values found in this study are higher compared to values reported in most studies. Abbot and Lowore (1999) reported FVI ranging from 9.06 to 19.25, whereas Kimaro et al. (2009) reported values between 9 and 23. Studying wood from native forests of Brazil, Ramos et al. (2008) reported a wider range of FVI (5.5–30.9). The differences in the published FVI values and this study could also be due to differences in wood drying duration (Abbot and Lowore, 1999). Wood drying period used in this study was two months (approximately 8 weeks) as opposed to 5 weeks used for most species reported in other studies. Increased drying period could lead to loss of more moisture from the wood leading to high FVI, which was calculated using air-dry moisture content of wood as denominator. On the other hand, differences in FVI for the same species have also been reported by other authors in Uganda that was ascribed to the differences to site and methodological differences (Tabuti et al., 2003; Ojelel et al., 2015).

4.2. Biomass estimation models

Use of coppice basal diameter measured at 10 cm from the base as independent variable for estimation of coppice biomass in most of the fitted models in this study allows estimation of removed coppice biomass where coppices have been harvested and removed from the site (Chamshama et al., 2004). This is possible because in the study area, coppices and trees in general are harvested for firewood and simple construction purposes where they are cut at a height ranging from 15 cm to 56 cm (Luoga et al., 2004). In practice, use of diameter measured at 10 cm is more practical than 130 cm due to the multi-stemmed nature of re-growth miombo trees (Abbot and Lowore, 1999; Luoga et al., 2004). From utilization point of view, Shackleton (2001) found that harvestable coppice sizes were better described based on diameter measured at 10 to 30 cm as opposed to conventional forest inventory where tree diameter is measured at 130 cm.

4.3. Coppice growth, mortality and biomass production

The ranges for mean height growth of 170.27 ± 0.25 cm to 205.19 ± 0.25 cm (stumps cut at 90 cm) and mean diameter growth 2.31± 0.03 cm to 3.12 ± 0.03 cm at the age of 2 years for stump cut at 0–30 cm and 90 cm, respectively, are comparable to the range reported from other miombo coppice growth studies (Abbot and Lowore, 1999; Shackleton, 2001). Based on prescribed size limit of 5 cm basal diameter for miombo coppices frequently harvested for fuel wood and construction wood (Abbot and Lowore, 1999; Luoga et al., 2004; Neke et al., 2006), the studied species can be managed on a coppice rotation period of 5 years for production of firewood for stumps cut at 5–30 cm with possibility to reduce coppice rotation period to 3 years by cutting stumps at 90 cm from the ground.

The positive relationship between stump height versus coppice height and diameter growth found in this study could be attributed to the fact that increasing stump heights reduced the potential impacts of fire by raising the coppices above the threshold height at which the fire could be detrimental (Shackleton, 2001). However, the increased coppice growth with increasing stump height must be balanced against the loss of useful woody biomass that is left behind as stump (Shackleton, 2001). According to Shackleton (2001), stump height is the simplest and less labor-intensive parameter to manipulate compared to stump diameter and coppice thinning. Thus, the fact that in the present study both coppice thinning and stump diameter did not affect coppice growth means that the studied species are relatively easy to manage, at low cost under coppice rotation system, by manipulating stump height only.

High coppicing effectiveness recorded in the FR compared to the GL for *A. harveyi* is in sharp contrast with the study by Luoga et al. (2004) who reported high coppicing effectiveness in the GL than FR of the same area. The plausible explanation for this discrepancy could be differences in fire tolerance that varies with species (Chidumayo, 1988), which most likely confounded the site effects with respects to results by Luoga et al. (2004). According to Hoffmann et al. (2012, 2020), the probability of individual tree of specific species to be killed or its growth reversed by fire is influenced by five key factors: (1) the growth rate of trees, (2) fire intensity, (3) the time interval between fires, (4) the size necessary to become fire resistant and (5) fortuitous factors. These factors may vary between and within species and could interact with site or micro-site characteristics to determine the final outcome of a given fire event. Besides these factors, Hoffmann et al. (2020) concluded that most of the saplings and coppices that escape fire-trap in the savanna ecosystems do so by being just lucky (i.e., experiencing an occasional longer-than-average interval without fire or a below-average fire severity within a site where the fire event is recorded as severe). In this regard, more open canopy in the GL (Luoga et al., 2004) probably favored increased shade-intolerant grasses that accumulated to form fuel load leading to increased fire severity that was associated with high mortality in the GL (Nefabas and Gambiza, 2007; Hoffmann et al., 2012). It is possible that due to its relatively slow growth rate (Fig. 2), *A. harveyi* was more fire-sensitive and most of its coppices were killed by fire in the GL leading to lower coppicing effectiveness. In the present study, the effects of fire on coppicing effectiveness of *A. versicolor* could not be detected due to the fact that individual trees were systematically localized in areas that are likely to escape fire fortuitously such as valley bottom and rock outcrops and so most of the coppices escaped fire leading to relatively low mortality due to fire. This corresponds to a scenario where an individual trees escape fire by experiencing chance exposure to low fire severity described by Hoffmann et al. (2020). Similar lack of significant differences in coppice effectiveness between the FR and GL in the same study site and in the presence of frequent fire records were also reported by Luoga et al. (2004) for *Julbernadia globifora* (Benth.) and *Combretum molle* Engl. and Diels. However, the mechanisms involved to escape fire could be different from that of *A. versicolor* found in this study. Wildfires and shifting cultivation were recorded as the major cause of high coppice mortality in the GL which is in agreement with other studies that reported fire and tree cutting as the common anthropogenic disturbances in savanna biome (Luoga et al., 2000; Zida et al., 2007).

Literature on miombo coppice biomass production for comparison with the present study is limited or non-existing. Past studies on miombo coppices have focused on coppicing capacity and coppicing effectiveness for Tanzania miombo (Luoga et al., 2004), and coppice growth for Malawian (Shackleton, 2001) and Zambian (Abbot and Lowore, 1999) miombo woodlands. Given the importance of biomass energy for SSA (Horst and Hovorka, 2009) and the importance of miombo woodlands for fuel wood supply (Chidumayo et al., 1996), analysis of the potential fuel wood yield is imperative.

Coppice biomass production estimates are based on two indigenous tree species that are not dominant and should be confirmed or refuted by studies covering a range of dominant species. However, to the extent that these findings are representative of the situation in the entire miombo woodland at Kitulanghalo area and other areas in Tanzania, the data can provide a reliable estimate of coppice wood production. Based on MAI range of 2.02 to 2.87 kg stump^{-1} year^{-1} and a coppice rotation of 5 years, the estimated oven dry wood yield ranges from 10.1 to 14.35 kg stump^{-1}. According to Luoga et al. (2004) the stocking of coppicing stumps in the GL is 182 stumps ha^{-1}, which would yield oven dry wood biomass of 1.84 to 2.61 metric tons per hectare at a coppice rotation age of 5 years. Assuming a projected population size of 4640 people in 2000 around Kitulanghalo forest area (Luoga et al., 2000), average household size of 4.8 people per household and population growth rate of 2.2% (TNBS, 2009), and annual fuel wood consumption of 7 metric tons per household (Chidumayo et al., 1996); the entire population, projected at 7204 in 2020, would require an annual coupe of 4022 to 5715 ha of regrowth miombo for fuel wood. For sustainable supply of coppice wood for household consumption at a coppice rotation of 5 years a total miombo woodland area of 20,108 to 28,576 ha would be required. The available area of 2452 ha is lower than the required area by 820% to 1165% indicating that to fulfill household wood demand for the population in the area, cutting of new trees will have to continue unless on-farm wood sources are introduced. The foregoing analysis is consistent with findings by Luoga et al. (2000) who found that the overall annual wood removal of 6.38 exceeded MAI of 4.35 for the study area. At the national level, MNRT (2015) reported national annual wood deficit of about 19 million m^3 of which wood harvested for woodfuel contributes 69% of the deficit. Thus, promotion of on-farm wood production to meet the increasing wood demand in the area is imperative in order to reduce pressure on the native miombo woodland. Given the potential competition between on-farm woodfuel production and crops due to increasingly small land holdings, it is important that trees that are compatible with crops be introduced concurrently with a less competitive agroforestry systems such rotational woodlots (Nyadzi, 2004; Kimaro, 2009). The potential environmental challenges associated with exotic tree species such as invasiveness in the natural ecosystems and interference with local hydrology (Chanie et al., 2013); suggests for the need to promote on-farm planting of less competitive indigenous tree species for supplementary production of woodfuel.

4.4. Relationships between canopy and coppice biomass production

There are reasons to suspect a non-linear relationship between canopy cover and the yield of different biomass components. In particular, the effects of shading due to increase in canopy cover has a maximum upper bound, by default, because there may be some minimum threshold of canopy cover that must be reached before growth of coppices begin to respond to changes in canopy cover (Hoffmann et al., 2012). However, lack of significant regression relations between canopy cover with logarithmic and inverse transformed biomass components indicates that within the range of observations found in all the coppices, the relationship between canopy cover and biomass components is approximately linear. Analytically, this implies that results of the Pearson's *r* analysis in Table 4 accurately summarize the relationship for the whole range of canopy cover and the biomass components observed in this study (Gomez and Gomez, 1983).

Overall, there are limited studies on the effects of canopy cover on coppice biomass production for direct comparison with the present study. The negative correlations between canopy cover and coppice biomass yields of the studied species agrees with other coppice growth studies that reported improved coppice growth due to low canopy cover (Luoga et al., 2004; Neke et al., 2006). However, it appears that there is a threshold canopy cover below which further canopy opening is likely to have significant negative impacts on coppice growth and yields. This proposition is supported by a number of studies from miombo woodlands (Luoga et al., 2000) and savanna ecosystems (Riginos, 2009; Riginos et al., 2009), which reported increasing grass biomass with increasing canopy opening in these ecosystems. The increase in grass biomass due to excessive canopy gaps can reduce coppice growth through its competitive effects on coppices (Riginos, 2009) or intense wildfires as the grass provides potential fuel for burning in the miombo and savanna ecosystems (Riginos et al., 2009). However, the clear-cut optimum canopy cover for improved coppice growth needs further investigation.

5. Conclusions

This study has shown variation of coppice biomass yield as a function of stump diameter and height. Maximum wood biomass is attained in stumps cut at 90 cm, 30 cm to 90 cm and 5 cm above the ground for trees of small (5 ≤ DBH ≤ 10 cm), medium (11 ≤ DBH ≤ 20 cm) and large DBH size (DBH ≥20 cm) classes, respectively. Although the studied species are not the dominant miombo tree species, the high WBD and FVI recorded in this study justify suitability of the Africana savanna including miombo woodland to short rotation coppice silvicultural system for woodfuel production. On the basis of minimum diameter of 5 cm for trees harvested for fuelwood, the rotation period of 5 years would suffice to sustain the system at optimal stump heights for different DBH classes. Based on the findings from this study, growth and biomass production can be optimized by manipulating stump heights for different DBH classes. However, the increased coppice yield with increasing stump height observed in small and medium DBH size class trees must be further assessed on the basis of the potential loss of useful woody biomass left behind as stump. It is worth noting that wood yields from coppice managed on short rotation periods of 3 to 5 years cannot satisfy demand of the human population surrounding the studied miombo biome suggesting a need for on-farm wood production to reduce pressure on the savanna woodlands. This study has shown that fire and shifting cultivation are the major factors causing coppice mortality, particularly in the GL, thereby reducing overall coppice productivity. Thus, successful management of miombo woodlands under short rotation coppice system requires integration of appropriate strategies to control recurrent wildfires. Prescribed burning could be an ecologically and socially acceptable tool to minimize the effects of fire on miombo coppice growth and yield.

The negative correlation between canopy cover and coppice biomass production is an indication that selective cutting of trees such as adopting coppice with standard silvicultural system can enhance coppice growth than clear cutting system; although the optimum level of canopy opening needs further investigation. Long-term studies on patterns of coppice growth for a wide range of miombo tree species particularly those favored for firewood are necessary especially in response to repeated harvesting, canopy cover and fire dynamics.

Declaration of Competing Interest

None.

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