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Research Article

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Determinants of Above Ground Biomass Accumulation in Awuria Dry Afromontane Forest, Ethiopia

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Abstract

Tree spacing significantly influences its morphology, biomass accumulation, and productivity. The objective of this study was to understand factors determining the above ground biomass accumulation of selected focal trees in Awuria forest. Afrocarpus falcatus (Thunb.) C.N.Page and Juniperus procera Hochst. ex Endl. are the two most dominant tree species found in Awuria forest, hence considered as focal trees in the forest. Thirty six systematic 20 meter by 20 meter (400 m2) sized plots were established to collect data on focal and their four nearest neighbor trees. Species name, neighbor tree distance from focal tree, and DBH of focal and the four nearest neighbor trees were recorded during data collection. The biomass of each focal tree was estimated using Chave et. al. allometric equation. Mean distance, and the mean DBH of neighbor trees were determined through descriptive statistics. The competition index was analyzed using Hegyi's competition index formula. Competition index and mean neighbor DBH showed strong potential to determine above ground biomass of the selected focal trees. Generalized additive model was used to fit the above ground biomass of the focal tree. Competition index, mean neighbor distance, and mean neighbor tree DBH were fitted as independent and potential variables in determining the above ground biomass in GAM mode. The optimum tree spacing for *A.falcatus* and *J.procera* were 1 and 1.8 meters, respectively.

Keywords: Focal Trees; Restoration; Competition Index; Mean Distance; Optimum Distance.

INTRODUCTION

Ethiopia is endowed with diverse landscape types, which have given rise to different agro ecological zones and vegetation formations. Among the different vegetation formations that the country has, Dry Afromontane Forests (DAFs) is the one, which is located between 1500–3000 meters above sea level elevation in the highlands. It covers an area of nearly 50% of the country's forest resources [1].The flagship woody plant species found in this vegetation formation include *Afrocarpus falcatus*, *Juniperus procera, Hagenia abyssinica* and *Olea europaea subsp. cuspidata*. DAFs play an important role by providing both direct income and supporting the farming activities of local people living in and around the forest. Non-timber forest products like honey and bee wax, medicinal plants, and wild fruits are among the long list of them. The importance of DAFs for fuel wood and construction wood is immense. The importances of DAFs for fodder are a key ingredient for the country's economically vital livestock production.

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Beyond to their direct benefits, DAFs have deep relation with the society of the local community where DAFs are presented. Because of their role as a safety net benefit for the poor part of the society by providing them off farm income during non-farming period. They are the source of genetic material for traditional medicine that passed through generation to generation. The importance of DAFs are not limited to only providing economic and social benefits, but also protect the environment by sequestering carbon, protecting watersheds and water bodies and protecting the top productive soil from different types of soil erosion.

Despite of all these economic, social, and environmental benefits, DAFs are challenged by different human induced factors such as deforestation by farmland expansion and illegal cutting to fulfill the construction and fuel wood demand of the people, degradation by free grazing, and climate. Due to these factors most of DAFs are under severer degradation status.

Forest restoration has become a national priority in Ethiopia as the country faces accelerating land degradation, declining forest cover, and increasing pressure on natural ecosystems. Over the past two decades, the Ethiopian government has launched ambitious restoration programs which includes Green Legacy initiative, signing to restore 15 million hectare of landscapes in 2016 as part of African Forest Landscape Restoration Initiative (AFR 100) [2], Great Green Wall for Sub-Saharan Initiative (GGWSSI) to protect and restore the potential of production of ecologically fragile areas through ecosystem management [3], development of Climate Resilient Green Economy (CRGE) strategy of Ethiopia [4], in order to protecting and reforest for economic

and ecosystem service including as carbon stocks (increased greenhouse gas sequestration in forestry), and large-scale landscape restoration commitments under the Bonn Challenge, aiming [3], to restore millions of hectares of degraded land [5,6].

In the restoration programs, restoring degraded forests with native tree species gets higher attentions than the exotic species. Restoration success heavily depends on the performance of indigenous species, which are better adapted to local climatic and edaphic conditions [7]. Currently, connect to the current high demand of native tree species for restoration of degraded forest requires evidence based restoration program. Among these evidences, optimum tree spacing is the one that needed to be required in the country. On the other hand, biotic factors like tree size [8], and competition index have effect on biomass and growth of individual tree. Small trees grow slowly in closed-canopy forests, because they are suppressed and shaded by canopy trees [9]. Therefore, the nearest neighbor trees are critical indicators for forest structure and spatial heterogeneity [10,11]. Domestication of native tree species and their integration into restoration initiatives are increasingly recognized as a vital strategy for reversing forest degradation in Ethiopia's highlands. Even though there are many environmental factors that influnce individual tree growth neighborhood interactions greatly shape the stand structure [12,13]. Nearest neighbor trees are critical indicators of forest structure and spatial heterogeneity at the stand level. The immediate neighborhood of trees reveals individual contributions to heterogeneity within forest stands [14].This variability can be con specific or hetero specific [15,16].

Tree spacing was done by Amanuel S [17], in Ethiopia, but it was specific to plantation forest. These authors explained that spacing had great role in higher AGB accumulation and growth. However, information on optimum tree spacing for AGB and growth for native tree species for degraded natural DAF was lacking.

With this background and justification the general objective of this study was to provide evidence based information on the determinants of above ground biomass accumulation of the selected focal trees species in Awuria DAF. The specific objectives were;

- To determine the natural spacing patterns of focal tree species in Awuria DAF.
- To determine the effects of tree spacing, competition index, and neighbor tree DBH on focal tree above ground biomass accumulation.
- To determine the optimal focal tree spacing to provide evidence based recommendation for domestication and restoration of degraded landscape.

MATERIALS AND METHODS

Description of The Study Area

The study was conducted in Cheha district of Gurage Zone, Central Ethiopia Region. The town of the district, Emdbir, is located at 188 km south of Addis Ababa. The geographical location of the study area extends from 8°00'18.9" to 8°15'28.53"N latitude and 37°35'46.48" to 38°03'59.59"E longitude at an elevation ranging from 1900 to 3000 meters above sea level (m.a.s.l.), and classified under the highland and midland agro-climatic zone (Figure 1). It has a total area of 57,313.85 hectare of which 40,190 hectare is cultivated and 102 hectare is forest land. The average annual rain fall of the area is about 1268.04 mm and the average maximum and minimum temperature in the study area is 24.97°C and 10.69°C, respectively.

Source: [18]

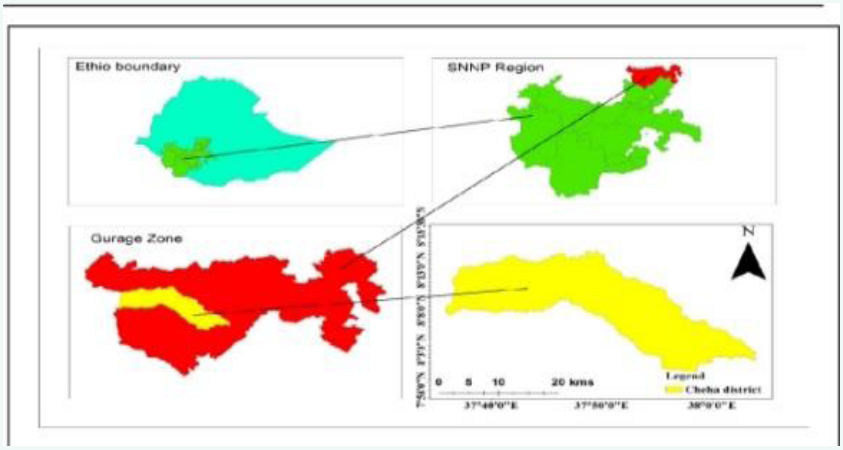


Figure 1: Map of Ethiopia showing the study area

Data Collection

A focal tree is an individual tree selected for assessment of its biomass and competition, whose condition and development may be influenced by the presence, size, and spatial arrangement of neighboring trees. Focal trees are selected based on their timber value and dominance during forest inventory. In the current study, all individuals of *A.falcatus* and *J.procera* whose DBH was ≥ 2.5 cm were selected as focal trees based on their dominance in the forest inside 20 meter by 20 meter quadrat. DBH distributions at 10 cm intervals were considered to distribute individual focal trees across the diameter classes. In each DBH class focal trees were determined proportionally. Whereas, a neighbor tree is an individual tree surrounding a focal tree and having the potential to influence it through competition for growing space, light, water, nutrients, and other resources. Four the nearest trees that surrounded the focal tree and whose DBH is ≥ 2.5 cm were considered as neighboring trees (Figure 2). Four transect lines 50 meters apart each other were laid down and nine plots in each transect line were established at 50 meter interval. A total of thirty six 20 meter by 20 meter (400 m^2) sample plots were systematically established for data collection. Tree parameters and environmental data were collected. Tree parameters include species name, DBH, height, and neighbor distance of the four nearest individual trees and focal trees were recorded. Whereas, environmental data such as GPS coordinate, elevation, aspect, and slope were recorded using GPS and Vertex IV.

Data Analysis

The collected data were encoded in to Microsoft excel file. The data were cleaned and checked for its liability for running formal analysis. After data management the following equations were used to determine mean neighbor distance (MS), Competition index (CI), mean neighbor DBH (MNDBH), and above ground biomass (AGB), respectively.

$$MS = (1/k) \sum S \quad \text{equation 1}$$

Where MS= mean distance, S = neighbor tree distance from focal tree, k = number of neighbor trees

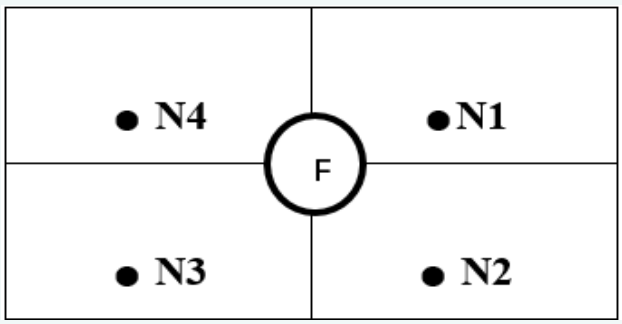


Figure 2: The diagrammatical representation of focal and four nearest trees in the forest.

A mean neighbor DBH (MNDBH) was the summing up of the DBH of the 4 neighbor trees and dividing the sum by 4 (number of neighboring trees).

$$MNDBH = (1/k) \sum DBH \quad \text{equation 2}$$

Where MNDBH= mean DBH of neighboring trees, k = number of neighbor trees

Hegyi's competition index (**CI**) was calculated using the following equation (equation 3):

$$CI_i = \Sigma (DBH_j / DBH_i) / MS \quad \text{equation 3}$$

Where: DBH_i **=** The DBH of the focal tree,

DBH_j = The DBH of the neighboring trees. This index provides a size and distance-weighted measure of competition pressure of the four neighbor trees on the focal tree.

Above ground biomass (AGB) of individual trees was estimated using the moist-tropical allometric equation developed by Chave J [19] (equation 4):

$$AGB = 0.0673 \times (\rho D^2 H)^{0.976} \quad \text{Equation 4}$$

Where ***D*** is the DBH (cm), ***H*** is total tree height (m), and ***ρ*** is species-specific wood density (g cm^{-3}). Wood density values were obtained from the Global Wood Density Database [20] or Ethiopian species-specific studies when available.

Regression and competition analysis

Generalized additive model (GAM) was fitted to understood the influence of mean distance (MS), competition index (CI), and mean neighbor DBH (MNDBH) on above ground biomass (AGB) accumulation using;

AGB=gam (Biomass ~ s (CI) +s (MNDBH) +s (MS) ..... *equation 5*

Where: ***AGB*** = above ground biomass of the focal tree

- *MS = mean spacing distance*
- *CI* = Hegyi's competition index
- *MNDBH* = mean neighboring trees diameter

R software version 4.5.3 and Rstudio were used for running descriptive statistics, model fitting, graphics, biomass prediction, and determining the optimum tree spacing. In addition to basic R syntax, special R software packages like "mgcv" for model fit and biomass prediction and "ggplot2" for graphics were used.

The predicted maximum AGB was obtained by predicting the value of AGB obtained from GAM model by considering CI and MNDBH as constant. Predicted biomass = predict (AGB, data = data) ---------- equation 6

The optimum distance was determined using the following equation;

Optimal distance = data$MS[which.max(data$Predicted biomass)] ---------- equation 7

RESULTS

Afrocarpus falcatus and *Juniperus procera* are the two most dominant canopy tree species in Awuria forest. These two dominant species showed similar population structure in the forest with dome shaped population structure. More number of individuals of these species in the forest was presented at DBH class between 40 and 60 centimeters. In the lower DBH class (DBH ≤ 50 cm), individual trees of *A.falcatus* were more in number than *J.procera* and it became vice versa in the higher DBH class (DBH class > 50 cm) (Figure 3).

Mean Distance

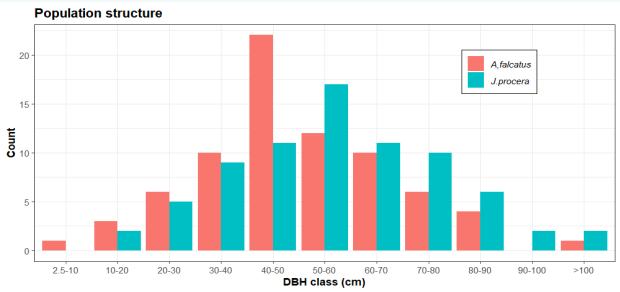


Figure 3: The population structure of the two dominant tree species in Awuria forest

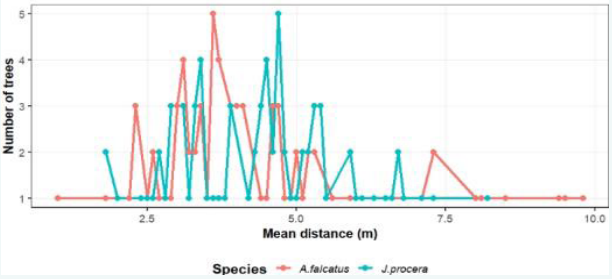


Figure 4: The showed mean distance pattern of the two dominant tree species in Awuria forest.

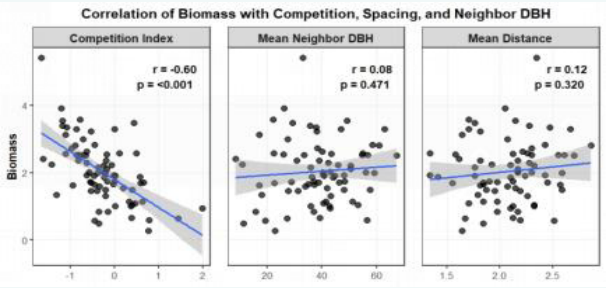


Figure 5: The correlation between above ground biomass and ecological variables of *J.procera*

The mean neighboring distance pattern of the two focal tree species with their neighboring individuals showed a little bit different distribution in the forest. That means *J.procera* showed wider spacing than that of *A.falcatus*. More individual numbers of *A.falcatus* and *J.procera* had mean neighboring distance of 2 and 3 meters, respectively. It was understood from the spacing pattern of the two focal trees, *J.procera* requires wider spacing than *A.falcatus* in the studied forest (Figure 4).

It was understood that *J.procera* had higher AGB than that of *A.falcatus* in the forest. But both of them had the same mean neighbor distance in the forest. *A.falcatus* was more susceptible for competition than *J.procera.* Tree parameter statistics indicated that *J.procera* better out perform in the forest than that of *A.falcatus* (Table 1).

CI had significant (<0.001) negative correlation (r = -0.6) effect on the AGB of *J.procera* focal tree species. Mean distance (r = 0.08) and MN_DBH (r = 0.12) showed weak positive correlation with AGB for *J.procera* (Figure 5).

In the case of *A.falcatus*, CI and MS showed significant (p<0.05)

Table 1: The descriptive statistics of the two dominant tree species in Awuria Forest

Species	Parameters	Min	Mean	Median	Max
A.falcatus	DBH (cm)	10	50.4±18.74	48.4	115
	MS (m)	1	4.4±1.83	3.9	9.8
	CI	0.26	1.4±1.28	1	9.5
	Biomass (t)	0	3.8±3.0	3.1	18
J.procera	DBH (cm)	13	57.3±23.03	55	146
	MS (m)	1.8	4.4±1.38	4.5	8.2
	CI	0.2	1±0.97	0.7	7.3
	Biomass (t)	0.1	5±4.5	3.7	29.3

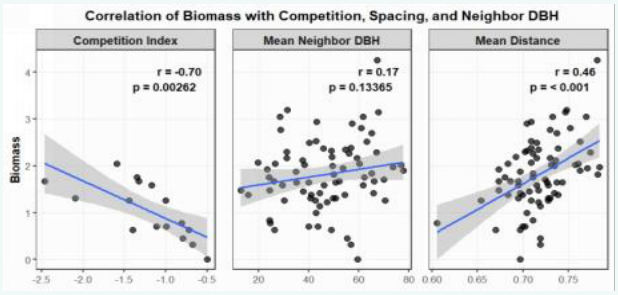


Figure 6: The correlation between above ground biomass and ecological variables of A.*falcatus*

correlation with AGB. But MN_DBH showed insignificant (p-value > 0.05) and weak positive correlation (r = 0.17) with AGB for *A.falcatus* (Figure 6).

General Additive Model (GAM)

The GAM results revealed that there was a significant nonlinear relationship between AGB accumulation and all the three explanatory variables in *A.falcatus.* MS showed a significant nonlinear relationship with AGB (efd = 4.478, F = 2.980, and p = 0.0158). CI exhibited highly significant nonlinear relationship with AGB (efd = 3.778, F = 33.445, and p < 0.001), indicating strong association between CI and AGB accumulation. MNDBH also showed a significant nonlinear relationship between AGB accumulation AGB (efd = 4.716, F = 9.109, and p < 0.001). Generally, the model explained 80.9 % of the deviance in AGB accumulation, with an adjusted R^2 of 0.768, indicating that the three explanatory variables collectively determined a substantial proportion of AGB variation in the forest for *A.falcatus* tree (Table 2).

The mixed effects of variables were fitted in to the GAM in order to understand the AGB predicting potential of the focal tree *A.falcatus.* Three of the fitted variables had significant prediction potential for this focal tree species. The best fitted mathematical equation including the model intercept was given to in the following (equation 8).

AGB = 1.81565 + 3.778 (CI) + 4.716 (MNDBH) + 4.478 (MS) ---------- *Equation 8*

Where; AGB = above ground biomass, CI = competition index, MNDBH = mean neighbor DBH, and MS = mean neighbor tree distance from focal tree,

The GAM model result exhibited that there was a significant relationship between AGB and the three explanatory variables. MS showed a significant approximately linear relationship with AGB of *J.procera* tree (edf = 1.000, F = 11.946, p = 0.000986). CI revealed a significant nonlinear relationship with AGB (edf = 5.158, F = 17.629, p < 0.001), this indicated that the relationship between AGB and CI varied along the competition gradient. MNDBH also showed a significant nonlinear relationship with AGB (edf = 4.639, F = 7.547, p < 0.001). Overall, GAM explained 67.2 % of the deviance in AGB, with an adjusted R^2 value of 0.616, indicating the explanatory variables collectively accounted a substantial proportion of AGB variation (Table 3).

The best fitted mathematical equation for AGB of *J.procera* was described in the following equation (equation 9)

AGB = 2.03946 + 5.158 (CI) + 4.639 (MNDBH) + 1.000 (MS) ---------- *Equation 9*

The smooth combined effect of the fitted variables on AGB indicated that how each variable affect the biomass of a focal tree while other variables take as constant. The AGB of *A.falcatus* was high at low CI values. DBH showed direct quadratic positive relation with AGB. CI and MS showed a nonlinear effect, with biomass decreasing with increasing values of CI and MS (Figure 7).

Table 2: Summary statistics of GAM for *A.falcatus*

Variables	edf	Ref.df	F	p-value
s(CI)	3.778	4.617	33.445	2e-16 ***
s(MNDBH)	4.716	5.734	9.109	1.08e-06 ***
s(MS)	4.478	5.421	2.980	0.0158 *
Adjusted R^2	0.768			
Deviance explained	80.9 %			
GCV	0.15931			
Scale est.	0.12963			
n	75			

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 3: Summary statistics of GAM for *J.procera*

Variables	edf	Ref.df	F	p-value
s(MS)	1.000	1.000	11.946	0.000986***
s(CI)	5.158	6.288	17.629	< 2e-16 ***
s(MNDBH)	4.639	5.711	7.547	6.45e-06 ***
R-sq.(adj)				0.616
Deviance explained				67.2 %
GCV				0.39219
Scale est.				0.3305
n				75

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

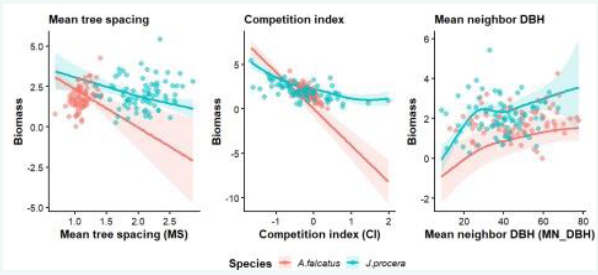


Figure 7: the combined correlation between AGB and the fitted variables in GAM for the focal tree species

Intra Specific and Inter Specific Competition

The mean competition index of *J.procera* with other species was greater than the mean competition index within itself. This implied that the CI of *J.procera* with itself becomes less than the competition of this focal tree species with others (Table 4).

The mean competition index of A.falcatus with other species was less than the mean competition index within itself. This implied that the competition of this species become strong with itself (table 5). This implied that the CI of *J.procera* with itself becomes less than the competition of this focal tree species with others (Table 5). The mean competition index of *A.falcatus* with other species was less than the mean competition index within itself (Table 5).

Determining Optimum Tree Spacing

Optimum distance for *A.falcatus* was 1 meter with maximum optimum spacing of 1.94 meters. The optimum spacing for trees varied with different environmental and tree related factors.

Table 4: The intra specific and inter specific competition level of the focal tree *J.procera*

Statistics	Intra specific CI	Inter specific CI	Total CI
Minimum	0.0000	0.0000	0.1905
Mean	0.2816	0.6957	0.9773
Maximum	1.7006	7.2655	7.2655

Table 5: The Intra specific and inter specific competition of *A.falcatus*

Statistics	Intra specific CI	Inter specific CI	Total CI
Minimum	0.0000	0.0000	0.2634
Mean	1.1398	0.21442	1.3542
Maximum	9.5586	1.35902	9.5586

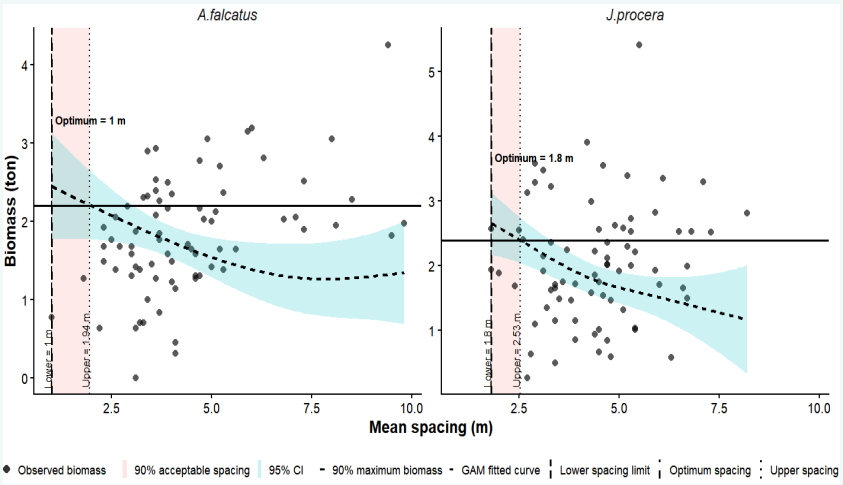


Figure 8: The optimums mean neighbor distance

Whereas, that of *J.procera* had optimum distance was 1.8 meter with maximum optimum spacing of 2.53 meters (Figure 8).

DISCUSSIONS

J.procera needs wider spacing than that of *A.falcatus*. This might be related to the prevalent natural characteristic of the two species. This means that *A.falcatus* is shade lover and *J.procera* is light lover tree species in their nature. This is in line with the research findings of Maame Esi Hammond [21]. The predicted optimum tree spacing (MS) for optimum AGB accumulation could be evidence for their natural characteristics. This natural spacing pattern reflects typical Afromontane forest structure, where regeneration occurs under mixed canopy conditions and spacing is shaped by microsite availability, disturbance history, and species-specific growth strategies. Similar natural spacing ranges have been reported for Afromontane conifers in other Ethiopian highland forests [22,23].

The mean biomass and DBH of *J.procera* was higher than that of *A.falcatus* in the forest. This difference might be driven from the susceptibility of *A.falcatus* for resource competition in the environment than *J.procera*. The results in the current study confirmed that the competition of A.falcatus became lower with increasing heterogeneity in the forest and vice versa for J.procera. In addition, a tree's own size and age are often the most important factors in determining its growth, and this can modify how it responds to its neighbors [8] CI of *A.falcatus* is higher than *J.procera*. At the local scale tree interactions neighboring individuals often experience intense intra specific and inter specific competition [24].

The linear correlation indicated that AGB moderately (p = 0.320) increased with increasing the MS for *J.procera*. Some research finding [25,26], reported that wider spacing exhibit higher growth rates and greater crown expansion compared with those in dense stands.

Biotic factors include initial size or age, genotype, competition [27], influence a rate of tree growth within a forest. Competition can be inter specific (between different species) or intra specific (between individuals of the same species) [28]. The presence of many neighbors, especially those of similar size, can significantly increase competition. The impact can be positive or negative depending on factors like species identity, stand structure, and environmental conditions [29]. For example Zhang J [16], reported that closer spacing led to higher AGB h^{-1} at early growth stages, whereas wider spacing produced larger stem diameters. Competition for light, water, and nutrients can reduce growth, while a more diverse stand with complementary resource use can enhance productivity and stability. The total basal area of neighbors can have a slight negative effect on a focal tree's growth. Neighbors engage in competition for growth resources, and the division of growth among individual parts helps to maintain an appropriate balance between their sizes [30].

In mixed forest, the distribution of trees was regularly spaced between 3-5 meters. When the space was greater than 5 meters tree densities were lower and hence the competition. Weak competitive thinning occurred among more densely packed small trees. The density of neighboring trees did not decline with increasing focal tree size at either the community level and DBH was not a good estimator of the implied competitive influence of a tree [31]. The current research finding showed that MS has comparatively weak positive effect on AGB in *J.procera* is strongly supported by existing research [22-26]. Although increased spacing improves access to light, water, and below ground resources, its influence is often overshadowed by the much stronger effects of CI and Neighbor DBH [32,33].

The non-linear response suggests that biomass gains are strongest at low to moderate spacing, after which the effect plateaus mirroring spacing trials where growth benefits diminish once competition is sufficiently reduced. The highly significant effect of CI (p < 2e-16) indicates that biomass declines sharply under increasing competitive pressure. The strong negative effect of CI on AGB was similarly reported by Alemu A [22,23]. The significant effect of MN_DBH (p < 0.001) highlights the role of size asymmetry in competitive interactions. Larger neighbors exert stronger suppressive effects, reducing AGB [26]. The current smooth term effects of CI and MN_DBH on AGB were highly significant (p < 0.05) for both focal trees, indicating a strong, non-linear suppressive effect of competition on biomass supported by Alemu A [22-33].

The current study evidenced that intra and inter specific competition is species specific. *J.procera* experienced higher intra specific interaction than *A.falcatus*. Therefore, neighborhood interaction is not only arisen from resource, but also from intra and interspecific interactions [15-24] and it can be also density dependent. At the determined optimum mean distance, *A.falcatus* stored predicted mean AGB of 2.6 tons per tree. This model based determined optimum mean distance for *A.falcatus* was 2.46 meter lower than the observed mean distance. For *J.procera* from the determined optimum mean distance the predicted mean AGB was 2.42 tons per tree. This determined optimum mean distance for *was* 1.87 meter lower than the observed mean distance. This implied that the resource in the forest has potential to support more density than the density currently found in the forest. It was reported by Amanuel S [17], closer spacing in plantation forest favored higher AGB. Similarly Hammann L [34], reported that closer mean distance significantly produced higher AGB per hectare at early growth stages, while wider spacing produced larger stem diameters.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Two focal trees were selected to determine the effects of different variables on AGB and determine optimum mean distance to achieve optimum AGB production. In the lower DBH class (DBH ≤ 50 cm), individual trees of *A.falcatus* were more in

number than *J.procera* and it became vice versa in the higher DBH class (DBH class > 50 cm). It was understood from the spacing pattern of the two focal trees, *J.procera* requires wider spacing than *A.falcatus* in the studied forest. Tree parameter statistics indicated that *J.procera* better out perform in the forest than that of *A.falcatus*. Three independent variables (CI, MS, and MN_DBH) were fitted in GAM in order to understand their effects on AGB. It was understood that CI and MN_DBH had strongly significant effect on AGB prediction. MS showed less, but significant effect on AGB accumulation. The current study evidenced that *J.procera* experienced higher intraspecific interaction than *A.falcatus*. According the result, the forest can support more density of the focal trees than the current density of the focal trees, because the focal trees were distributed in wider mean distance than the optimum.

RECOMMENDATIONS

The collective effects of the three explanatory variables (CI, MNDBH, and MS) played an important role in determining optimum AGB accumulation. Therefore, their combined effects should be considered in any future forest management planning. Understanding the intra specific and inter specific interaction of species was also an important factor that affect optimum AGB accumulation that should be considered in any degraded forest restoration program. The determined optimum MS in this research should be adopted for the two focal trees in similar ecological condition with the current forest for any restoration activity to gain optimum AGB accumulation. Finally, this results based recommendations were given without considering the edaphic factors in the forest, therefore further research should be needed to robust the evidence and adopt the result confidentially for restoration activity of the studied native focal trees.

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