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Productivity of Smallholder Eucalyptus globulus Woodlots and Effects of Spacing and Tending Operations in Guna Begimeder District, South Gondar Zone, Ethiopia

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Abstract

The productivity of smallholder Eucalyptus globulus woodlots depends on stand density, spacing, site condition, seedling quality and silvicultural management. This paper evaluated the productivity of five-year-old smallholder E. globulus woodlots and examined the effects of spacing and tending operations on volume production in Guna Begimeder District, Ethiopia. Sixty representative five-year-old plots were inventoried from Ata, Arega Didem and Denkuara kebeles. Diameter at breast height and height were measured, and volume was calculated using $V = \pi/4 \times dbh^2 \times h \times f$ with form factor $f = 0.4$. The original analysis used descriptive statistics and one-way ANOVA; this strengthened version additionally used R to calculate derived productivity indicators and generate publication-quality figures from reported summary statistics. Mean volume was 301.144 $m^3\ ha^{-1}$ in Denkuara, 299.65 $m^3\ ha^{-1}$ in Arega Didem and 71.75 $m^3\ ha^{-1}$ in Ata. Ata had the highest tree density but the lowest volume, demonstrating that high stem number alone does not guarantee high productivity. Spacing and integrated tending operations strongly influenced volume. The results show that appropriate spacing, thinning, weeding, pitting, fencing and pruning are essential for improving smallholder eucalyptus productivity.

Keywords: *Eucalyptus globulus; woodlot productivity; R analysis; spacing; tending operations; basal area; smallholder plantation*

1. Introduction

Smallholder *eucalyptus* plantations are important sources of construction wood, poles, fuelwood and household income in the Ethiopian highlands. However, productivity is highly variable because stand growth is influenced by site quality, planting density, seedling quality, rotation age, coppice condition and tending operations (Latifah et al., 2014; Fentahun Ayene, 2019; Estegenet Emiru, 2018). Although *Eucalyptus globulus* has high growth potential, poor stand management can produce dense woodlots with small-diameter stems and low merchantable volume. Spacing is one of the most important silvicultural factors affecting *eucalyptus* productivity. International studies show that planting density influences diameter growth, biomass allocation and stand structure. Bernardo et al. (1998) reported that eucalyptus trees planted at wider spacing showed greater individual diameter growth, while Soares et al. (2016) demonstrated that stand structure and competition can reduce productivity in eucalyptus plantations. These findings are relevant to Ethiopian smallholders because farmers often use narrow spacing to maximize the number of stems on limited land, even though excessive density may intensify competition for light, moisture and nutrients. Tending operations are equally important for plantation productivity. Weeding reduces early competition, beating up maintains stocking, thinning redistributes growth to better stems, pruning improves stem quality, fencing protects seedlings and coppice shoots, and coppice management improves regeneration after harvesting. Similar studies in South Achefer and Lay Gayint found that management intensity affected eucalyptus woodlot performance and that better-managed stands produced better growth outcomes (Fentahun Ayene, 2019; Estegenet Emiru, 2018). General plantation-management literature also emphasizes that sustainable yield depends on establishment quality, protection and stand regulation (Chamshama and Nwonwu, 2004; Oballa and Muchiri, 2010). In Guna Begimeder, farmers plant *Eucalyptus globulus* under smallholder conditions where land shortage, market demand, labour availability and management knowledge interact. A productivity study is therefore needed to determine whether high stem density actually translates into high volume and whether spacing and tending operations explain productivity differences among kebeles. By combining reported inventory results with R-generated figures and derived indicators, this paper provides a stronger basis for interpreting productivity patterns and for recommending practical management improvements.

1.1 Objectives

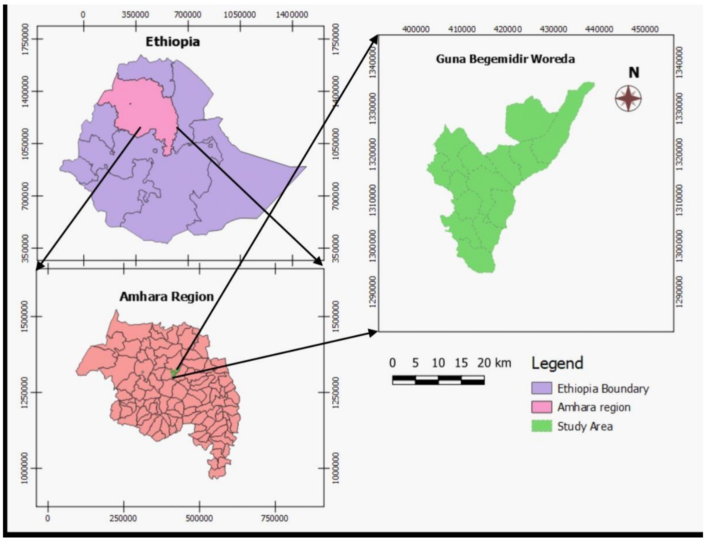
This paper integrates its objectives within the introduction because the productivity problem follows directly from how smallholder woodlots are established and managed. The first objective is to estimate stand density, basal area, average tree volume and volume per hectare of five-year-old Eucalyptus globulus woodlots in selected kebeles of Guna Begimeder District. This objective provides the quantitative basis for comparing productivity among Ata, Arega Didem and Denkuara.

The second objective is to evaluate the effects of spacing and tending-operation intensity on woodlot productivity. Spacing and tending operations are treated as key management variables because they influence competition, diameter growth, stem quality, survival, basal area development and final volume production. The paper therefore links inventory-based productivity estimates with management categories in order to identify practical options for improving smallholder *eucalyptus* productivity.

2. Materials and Methods

2.1 Study Area and Sampling

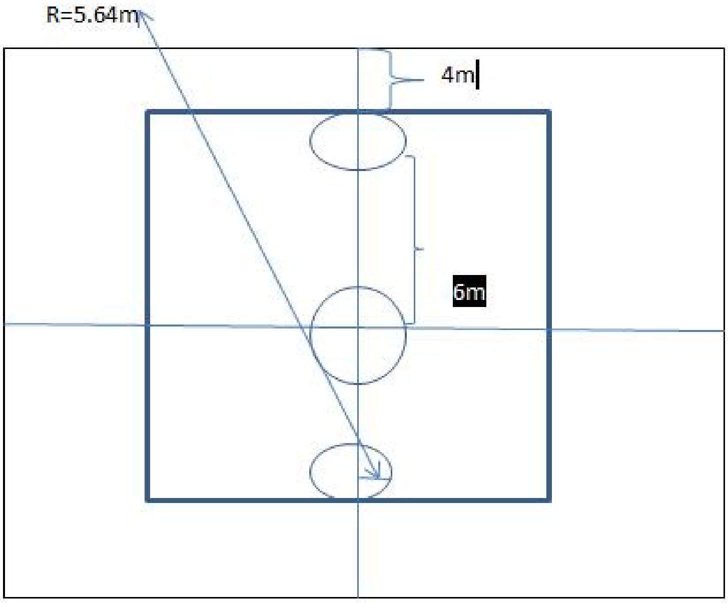
The productivity study was conducted in Ata, Arega Didem and Denkuara kebeles of Guna Begimeder District. A total of 60 representative five-year-old E. globulus plots were inventoried, with 20 plots from each kebele.



Paper 2 Figure 1. Study area map showing the location of the sampled kebeles in Guna Begimeder District.

2.2 Woodlot Inventory

Two perpendicular lines were established in each woodlot to reduce border effects, and three circular plots with radius 5.64 m were laid along the lines. Diameter at breast height and tree height were measured, and volume was calculated using $V = \pi/4 \times dbh^2 \times h \times f$, where $f = 0.4$.



Paper 2 Figure 2. Circular plot layout used for woodlot inventory measurements of diameter, height, density, basal area and volume.

2.3 Data Analysis

The original study used descriptive statistics and one-way ANOVA. R version 4.5.0 was also used to reproduce reported summary results and compute derived productivity indicators. Derived indicators included volume per 1000 trees and basal area per 1000 trees. Raw plot-level data were not supplied; therefore, ANOVA could not be re-estimated, but the reported p-values and means were presented transparently.

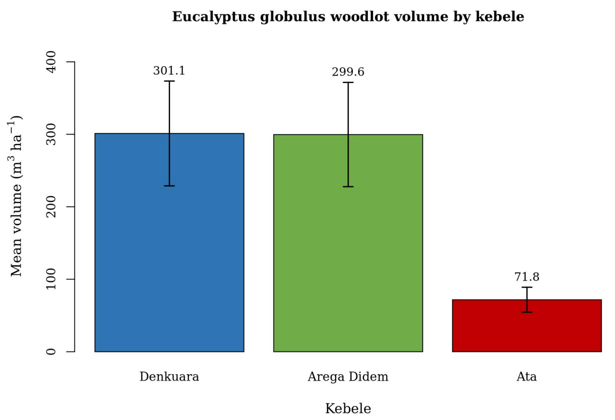
3. Results

3.1 Productivity by Kebele

Volume varied strongly among kebeles. Denkuara had the highest mean volume per hectare (301.144 m^3 ha^{-1}), followed by Arega Didem (299.65 m^3 ha^{-1}), while Ata recorded the lowest volume (71.75 m^3 ha^{-1}). Ata had the highest stem density (6255 trees ha^{-1}), but its basal area and volume were lowest, showing that excessive density without appropriate tending can suppress growth.

Table 1. Average stand density, basal area and volume per hectare of Eucalyptus globulus woodlots by kebele.

Variable	Denkuara	Arega Didem	Ata
Average number of trees ha⁻¹	3105 ± 754.2	3150 ± 765.5	6255 ± 1557.56
Average basal area ha⁻¹	59.77 ± 14.34	58.843 ± 14.12	15.69 ± 3.77
Average volume per tree (m³)	0.09 ± 0.022	0.095 ± 0.023	0.011 ± 0.0026
Average volume ha⁻¹ (m³)	301.144 ± 72.3	299.65 ± 71.92	71.75 ± 17.22



Paper 2 Figure 3. R-generated mean volume per hectare by kebele with reported error values.

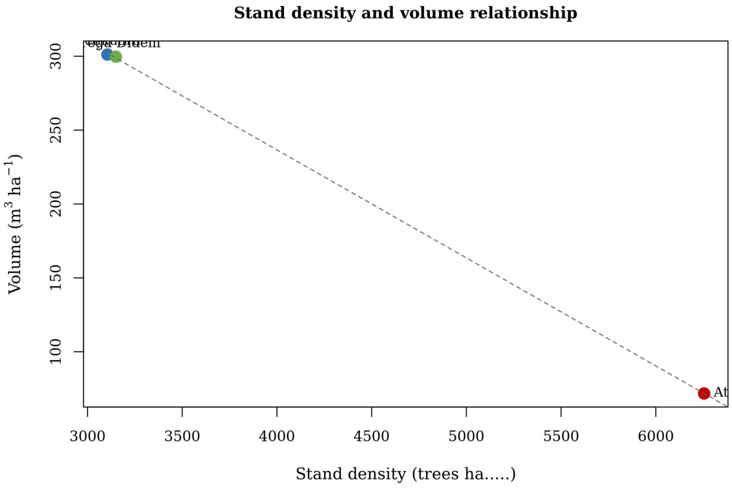


Figure 4. R-generated relationship between stand density and volume, showing that higher density did not imply higher productivity.

Table 2. R-derived productivity indicators based on reported summary statistics.

Kebele	Trees ha⁻¹	Volume ha⁻¹	Volume per 1000 trees	Basal area ha⁻¹	Basal area per 1000 trees
Denkuara	3105.0	301.14	96.99	59.77	19.25
Arega Didem	3150.0	299.65	95.13	58.84	18.68
Ata	6255.0	71.75	11.47	15.69	2.51

3.2 Effect of Spacing

Spacing significantly influenced productivity. Mean volume increased from 40.64 m³ ha⁻¹ under 0.25–0.5 m spacing to 255.40 m³ ha⁻¹ under 1–1.5 m spacing. The result confirms that extremely narrow spacing can reduce volume because of competition for light, water and nutrients.

Table 3. Effect of spacing category on Eucalyptus globulus woodlot productivity.

Spacing category	Mean volume ($m^3\ ha^{-1}$)	Pr > F
0.25–0.5 m	40.64	0.0001
0.5–1 m	156.80	
1–1.5 m	255.40	
>1.5 m	219.70	

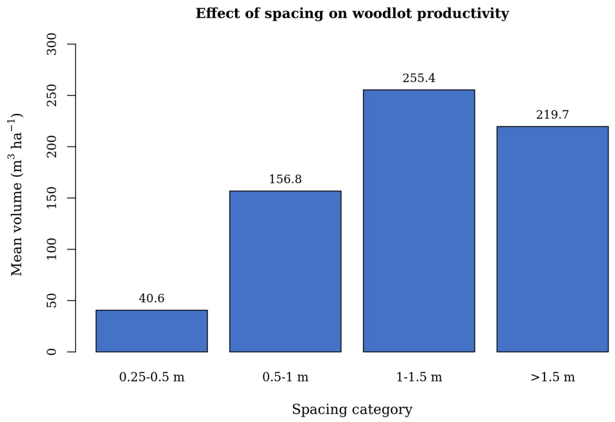


Figure 5. R-generated effect of spacing on Eucalyptus globulus woodlot productivity.

3.3 Effect of Tending Operations

Integrated tending operations increased productivity. Woodlots receiving only weeding and pitting preparation produced 63.10 $m^3\ ha^{-1}$, while those receiving thinning, weeding, pitting preparation, fencing and pruning produced 235.90 $m^3\ ha^{-1}$. The result shows that combined tending packages are more effective than minimal management.

Table 4. Effect of different tending-operation combinations on Eucalyptus globulus woodlot productivity.

No.	Management activity	Mean volume ($m^3\ ha^{-1}$)	P-value	Significance
1	Weeding and pitting preparation	63.10	0.183266	Not significant
2	Thinning, weeding and pitting preparation	146.44	0.174363	Not significant
3	Thinning, weeding, pitting preparation, fencing and pruning	235.90	0.0013832	Highly significant
4	Thinning, weeding, pitting preparation and fencing	227.10	0.0101334	Highly significant

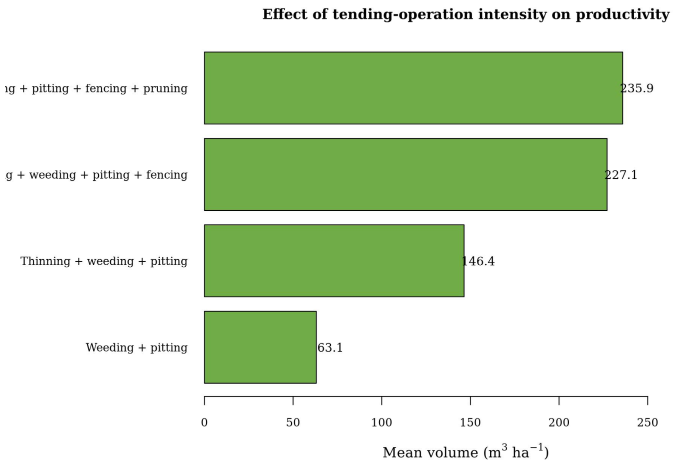


Figure 6. R-generated effect of tending-operation intensity on productivity.

4. Discussion

4.1 Productivity Variation and the Stand-Density Paradox

The first objective of the productivity paper was to estimate stand density, basal area and volume of five-year-old *Eucalyptus globulus* woodlots. The results show a clear productivity contrast among kebeles. Denkuara and Arega Didem recorded high volumes, while Ata had the highest number of stems per hectare but the lowest volume. This is a central scientific finding because it challenges the common assumption that more trees per hectare automatically result in higher productivity. In forestry, stand density must be interpreted together with diameter growth, basal area and merchantable volume.

The Ata result is consistent with competition theory and with *eucalyptus* spacing research. Bernardo et al. (1998) found that spacing affected growth and biomass distribution in *eucalyptus* plantations, with wider spacing improving individual tree diameter growth. Soares et al. (2016) also showed that stand structure and competition influence productivity in Brazilian *eucalyptus* stands. Although these studies were conducted outside Ethiopia, the biological principle is relevant: excessive density increases competition for light, water and nutrients and can reduce individual stem growth.

The finding also agrees with Ethiopian studies by Fentahun Ayene (2019) and Estegenet Emiru (2018), which reported that *eucalyptus* productivity varied with management conditions, spacing and stand structure. Therefore, the Guna Begimeder result should be interpreted as part of a wider pattern: eucalyptus can be highly productive under smallholder conditions, but productivity depends on how stand density is regulated and how management practices are applied.

4.2 Spacing Effects Compared with Similar Eucalyptus Studies

The spacing result shows that 1–1.5 m spacing produced the highest mean volume among the observed spacing classes, whereas very narrow spacing produced the lowest volume. This is consistent with Bernardo et al. (1998), who demonstrated that individual trees respond to wider spacing with greater diameter growth. It is also consistent with Oballa and Muchiri (2010), who recommend that eucalyptus spacing should depend on site conditions and product objectives.

In Ethiopia, farmers often use narrow spacing because land is scarce and because they expect more stems to produce more income. Similar reasoning was reported by Fentahun Ayene (2019) in South Achefer. However, the present study shows that narrow spacing may reduce volume when competition becomes excessive. The practical message is that spacing should be linked to the intended product. Close spacing may be acceptable for short-rotation fuelwood, but pole and construction-wood production require enough growing space for diameter development.

Latifah et al. (2014) emphasized that eucalyptus yield is affected by site quality, spacing, genotype and management. The current study supports this view by demonstrating that spacing is a measurable management factor affecting productivity. Because the study used five-year-old stands, the results are particularly relevant for short-rotation smallholder *eucalyptus* systems, where early competition can strongly affect final harvest size and quality.

4.3 Tending Operations and Integrated Silvicultural Management

The tending-operation results show that integrated management packages produced higher volumes than minimal management. Woodlots receiving thinning, weeding, pitting preparation, fencing and pruning had substantially higher volume than woodlots receiving only weeding and pitting preparation. This supports the silvicultural principle that productivity is improved by reducing competition, improving site conditions, protecting seedlings and coppice shoots, and improving stem form.

This finding agrees with Fentahun Ayene (2019), who reported that tending operations improved eucalyptus woodlot performance in South Achefer, and with Estegenet Emiru (2018), who observed productivity differences between management systems in Lay Gayint. It also supports broader plantation-management literature such as Chamshama and Nwonwu (2004), which emphasizes that sustainable plantation productivity depends on proper establishment, protection and stand management.

Thinning deserves special attention because farmers often see thinned stems as immediate products for fuelwood, fencing or sale. However, thinning also has a long-term productivity role because it reallocates growing resources to the remaining stems. Pruning improves stem quality, fencing protects against livestock damage, and weeding reduces early competition. The high productivity under combined tending shows that these practices should be promoted as a package rather than as isolated recommendations.

4.4 Coppicing, Rotation and Product-Objective Considerations

Although the productivity paper focuses on five-year-old stands, its findings should be interpreted in relation to coppice and rotation management. *Eucalyptus* is attractive to smallholders because it coppices and can be harvested repeatedly without replanting. However, repeated coppicing can reduce stump vigour if shoots are not managed and old stumps are not replaced. Liz Hamilton (2000) and Miranda et al. (2015) show that coppice quality and growth can vary across rotations, supporting farmers' observation that productivity declines after several coppicing cycles.

Product objective is also important. Farmers may harvest eucalyptus for fuelwood, poles, rails, construction material or sale to merchants. Oballa and Muchiri (2010) note that different products require different rotation lengths and stand management. Therefore, productivity should not be evaluated only as total volume per hectare; quality, diameter class, product type and market value should also be considered in future research.

4.5 Contribution of R-Based Analysis to Publication Quality

The R-enhanced analysis strengthens the paper in three ways. First, R-generated figures make the productivity patterns more visible, especially the contrast between high density and low volume in Ata. Second, R-derived indicators such as volume per 1000 trees provide an additional interpretation of stand efficiency. Third, reproducible analysis improves transparency because readers can see which summary data were used to generate figures and derived indicators.

However, the R analysis is appropriately limited to summary statistics because raw plot-level and household-level data were not supplied. Full re-estimation of ANOVA, regression diagnostics, residual plots, effect sizes and yield models would require raw observations. Stating this limitation improves the scientific credibility of the paper and prevents overclaiming.

4.6 Limitations and Future Research

The main implication is that extension services should discourage the simple idea that more stems per hectare always mean higher productivity. Instead, farmers should be trained to evaluate productivity through diameter growth, basal area, volume, product quality and market value. This message is consistent with the findings of Bernardo et al. (1998), Soares et al. (2016), Fentahun Ayene (2019) and Estegenet Emiru (2018).

The study is limited to five-year-old stands in three kebeles and relies on reported summary statistics for the R-enhanced analysis. Future studies should include raw plot-level data, site index, soil properties, slope, seed source, management history, market prices, rotation number and coppice age. Such data would allow stronger statistical modelling of productivity and profitability. Despite these limitations, the paper adequately addresses both objectives and provides a strong evidence-based message for improving smallholder eucalyptus productivity.

5. Conclusion and Recommendations

The productivity objective and the management-effect objective were both addressed. Denkuara and Arega Didem had much higher volume than Ata, despite Ata having more stems per hectare. Spacing and integrated tending operations strongly influenced productivity. R-based visualization strengthened the interpretation and made the productivity message clearer for publication and extension use.

- Promote objective-based spacing, especially avoiding excessively narrow spacing where pole and construction wood are desired.
- Encourage integrated tending packages including thinning, weeding, pitting preparation, fencing and pruning.
- Train farmers to use basal area, diameter growth and volume rather than stem count alone as productivity indicators.
- Collect raw plot-level data in future studies so that full ANOVA, regression diagnostics and yield modelling can be conducted in R. Declarations

Ethics approval and consent to participate: The study involved household interviews and woodlot inventory. Respondents were informed about the study purpose before interview.

Consent for publication: The authors consent to publication of the manuscript and associated non-identifiable information.

Competing interests: The authors declare no competing interests.

Availability of data and materials: Datasets are available from the corresponding author upon reasonable request. R outputs generated from

summary tables are included as reproducibility products.

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Authors' contributions: Gashaw Getaneh contributed to data collection, analysis, interpretation and writing. Yohannis G/Mariam, Asmamaw Alemu and Berhanu Debela contributed to review, editing and scientific strengthening of the manuscripts

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