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RESEARCH ARTICLE

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Excessive pruning and limited regeneration: Are *Faidherbia albida* parklands heading for extinction in the Central Rift Valley of Ethiopia?

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Abstract

Scattered *Faidherbia albida* trees provide multiple ecological and production benefits across the Sahel. The intensive management and use of this important tree may impede its regeneration. Regeneration bottlenecks were explored and population dynamics modelled. On experimental plots in which seed of *F. albida* was sown, exposure to the first 2 months of dry season resulted in a quarter of seedling mortality. Exposure to season-long free grazing and browsing caused significantly greater seedling mortality. Results from monitoring 100 permanent plots scattered over the landscape showed that adult population density was 4.2 ± 0.3 (mean ± *SE*) trees ha^{-1} and dominated by old age classes. Sixty percent of the total population were older than 30 years. The mean density for juveniles was 1.4 ± 0.2 (mean ± *SE*) individuals ha^{-1}. The annual rates of decline were 1.2%, 51.3%, and 63.2% for adults, seedlings, and saplings, respectively. Our model predicted that the *F. albida* population will start to decline within 1–2 decades to eventually fall below 1 tree ha^{-1} within 60 years under current management. The model highlighted that the limited seed source, caused by excessive pruning, was the main constraint for recruitment. Appropriate land management policy to ensure adequate seed production would avert current trends in decline of *F. albida* population.

KEYWORDS

agrobiodiversity, climate change, farmer-managed natural regeneration, farmland degradation, winter thorn

1 | INTRODUCTION

Parkland agroforestry systems dominated by scattered *Faidherbia albida* (Delile. A. Chev) trees are common across the Sudano-Sahelian zone of sub-Saharan Africa (SSA). These parklands provide multiple ecosystem services in these fragile regions, which are susceptible to degradation (Mbow, Brandt, Ouedraogo, Leeuw, & Marshall, 2015). *F. albida* improves soil fertility by fixing atmospheric nitrogen (Giller, 2001), recycling nutrients from deep soil horizons (Canham, Froend, Stock, & Davies, 2012), and reducing soil erosion (Van Noordwijk, Lawson, Hairiah, & Wilson, 2015). As a result, soil organic matter (Gelaw, Singh, & Lal, 2014) and exchangeable cations (Umar, Aune, & Lungu, 2013) accumulate under its canopy. *F. albida* parklands improve soil moisture availability through increased infiltration (Sileshi, 2016) and reduced evaporation from the soil surface (Bayala & Ouedraogo, 2008). Bayala, Sanou, Teklehaimanot, Kalinganire, and Ouédraogo (2014) reported that parklands reduce the risk of climate change to smallholders in SSA through microclimate regulation. The trees also buffer crops against extreme heat and provide an affordable climate-smart production option (Sida, Baudron, Kim, & Giller, 2018). Various other studies reported that trees maintained in croplands sustain cereal yields (Bayala & Ouedraogo, 2008; Mokgolodi, Setshogo, Shi, Liu, & Ma, 2011; Sida et al., 2018; Sileshi, 2016) and improve household food and nutritional security (Akinnifesi, Ajayi, Sileshi, Chirwa, & Chianu, 2011; Mokgolodi et al., 2011). Ludwig, Kroon, Berendse, and Prins (2004) suggested that *F. albida* parklands in savannah ecosystems play a significant role in understorey microclimate amelioration.

F. albida was originally found scattered within natural woodland and grassland vegetation on seasonally waterlogged patches along riverbanks (Breitenbach, 1963), whereas its population is currently limited to scattered stands in farmlands where farmers deliberately maintain it. In the tree-scarce landscapes of the Rift Valley of Ethiopia, where millions of smallholder farmers maintain *F. albida* on crop and pasture fields, this species can be considered a keystone species as its contribution to ecosystem functioning is disproportionally large relative to its abundance (Manning, Fischer, & Lindenmayer, 2006; Mills, Soulé, & Doak, 1993). Sileshi (2016) found that the presence of *F. albida* trees tended to increase cropping systems diversity and crop yields in SSA, improving food security in the region (Mokgolodi et al., 2011).

There are indications that the Sahelian parklands are becoming degraded (Mbow et al., 2015). *F. albida* is rarely planted, although farmers might assist its natural regeneration. Farmer-managed natural regeneration (FMNR) has widely been advocated to promote regreening of the Sahel (Sendzimir, Reij, & Magnuszewski, 2011). According to Noulekoun, Birhane, Chude, and Zenebe (2017), *F. albida* density in Northern Ethiopia varied depending on environmental factors such as elevation and stone cover, and human activities such as harvesting for fodder. Thus, it was expected that the intensive pruning in *F. albida* practised in the Central Rift Valley of Ethiopia may result in limited seed production, reducing seedling recruitment. High dry season seedling mortality, ploughing, free grazing, and browsing may further limit juvenile survival. Similar to the effect of wild ungulates on the survival of woody seedlings in natural savannahs (Moe, Rutina, Hytteborn, & Toit, 2009), browsing from domestic animals during the free grazing season may threaten seedling survival on-farm (Marcora, Renison, País-Bosch, Cabido, & Tecco, 2013). Because of the importance of *F. albida* in environmental sustainability and soil health of the region, its conservation requires comprehensive assessment of the current status and trends in its population. This study aimed to (a) explore the current population status, (b) identify major regeneration bottlenecks, and (c) model future trends in population under different management scenarios.

2 | MATERIALS AND METHODS

2.1 | Study area

The study was located in the Central Rift Valley of Ethiopia (8.509°N, 39.071°E), at an elevation of 1,665 m above sea level within the Sudano-Sahelian zone (Figure 1). The climate is semiarid with average annual rainfall of 700 mm year^{-1}, which falls mainly between June and October (Regional Government of Oromia [RSO], 2003). The long-term mean minimum daily temperature is 24 °C, and the mean

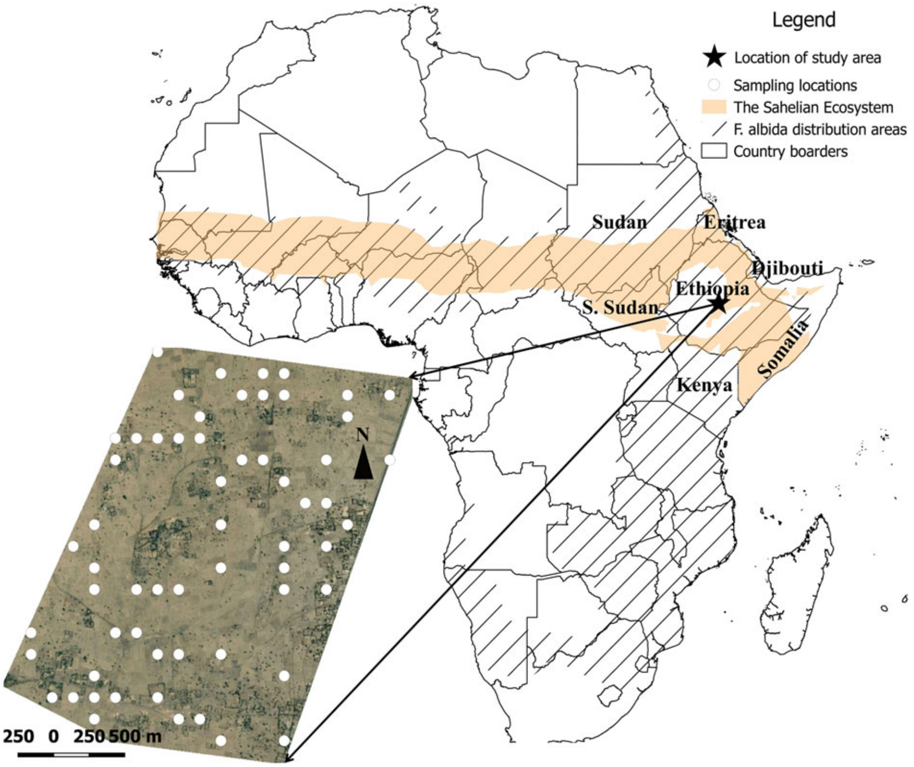

FIGURE 1 Map showing the location of the study area in relation to the Sahelian ecosystem and major distribution areas for *Faidherbia albida*. The dots on the aerial photo of the study area (bottom left) show the sampling locations [Colour figure can be viewed at wileyonlinelibrary.com]

maximum daily temperature is 31 °C (Kassie et al., 2013). Andosol is the dominant soil type (RSO, 2003). Sparsely distributed *F. albida* (Delile. A. Chev) is the main agroforestry species in wheat (*Triticum aestivum* L. var *aestivum*) and *tef* (*Eragrostis tef* [Zucc]) Trotter) fields. The smallholder farming system is characterized by integration of trees, crops, and livestock (Sida et al., 2013). Grazing is limited to pasture lands during the rainy season to avoid crop damage. After harvest, livestock roam freely in agricultural fields (referred to as free grazing and browsing in the rest of the text). Farmers keep cattle, sheep, goats, and donkeys. Camels also migrate from distant pastoral areas during the dry season and browse on trees.

2.2 | Seed production and germination

To quantify seed production, eight *F. albida* trees with a diameter at breast height (DBH = 1.3 m) ranging from 16 to 77 cm were randomly selected (Experiment 1). These included three unpruned, three partially pruned, and two completely pruned trees (Figure 2). A tree was considered completely pruned if all of its branches had been removed at least once during the last 6 years, partially pruned if some of its branches had been left unpruned during the last 6 years, and unpruned if it had not been pruned during the last 6 years. This was based on the observation from the trees in our sample that tree branches did not produce seeds during the 6 years of regeneration following pruning. We confirmed this by group discussions and key informant interviews. Randomized branch sampling was used to quantify seed production per tree (Chirici et al., 2014). Germination tests (Experiment 2) were conducted with healthy seeds following Koech et al. (2014). Seeds were treated by mechanical scarification with metal clippers to allow imbibition (Teketay, 1996). Experiment 2 was conducted to estimate germination rates for model parameterization. Results are provided in Table S1.

2.3 | Seedling emergence and survival

A field experiment was conducted to measure rates of seedling emergence and survival in a two-factor split-plot design with a fully factorial treatment (Experiment 3). Two blocks of land were marked (12 × 20 m) within farmers' fields. One of the blocks was fenced using wooden poles, whereas the other was left open to free grazing and browsing. The fences were tightened with lines of barbed wire and dry thorny shrubs for extra protection. Each block was further divided into two plots (6 × 20 m). One of the plots was ploughed and the other left unploughed. Four small subplots (4 × 4 m) were marked within each plot. Treated *F. albida* seeds were sown in each of the small sub-plots. The treatments were no ploughing–open grazing, no ploughing–exclosure, ploughing–open grazing, and ploughing–exclosure. Plots exposed to ploughing treatment were oxen ploughed four times following local practice. The experiment was conducted over two seasons (2014 and 2015). Seedling survival was recorded at (a) 2 weeks after planting, (b) 2 months after the end of rainy season, and (c) the end of the dry season. Seedling survival data were analysed using a generalized linear mixed model with a repeated measures design using R (R Core Team, 2015). In the model (equation below), exclosure (i.e., fenced vs. open-grazed) was treated as main plot factor. Ploughing (i.e., ploughed vs. unploughed) was used as subplot factor.

$$Y_{ij} = \alpha + \beta GR_i + \gamma TL_j + \lambda\left(GR_i \times TL_j\right) + R,$$

where Y_{ij} is seedling survival at different periods, GR_i is the ith grazing exposure, TL_j is the jth tillage treatment, and α, β, and λ represent regression coefficients for the main and interaction effects. R is the residual of the regression. As survival data were either count or proportions, a Poisson distribution was used. Although the two seasons varied in terms of the total amount of rainfall (728 and 578 mm year^{-1}, for 2014 and 2015, respectively), it did not cause differences in seedling and sapling survival rates between the seasons. Thus, it was excluded from the analysis.

2.4 | Tree survival and natural regeneration

Other mechanisms of regeneration were explored by marking 100 permanent plots within farmers' fields for two seasons (2014 and 2015; Experiment 4). QGIS mapping tool (Westra, 2014) was used to generate geographic grids of 150 × 150 m overlaying the whole study landscape (i.e., covering a total area 562.5 ha). A total of 237 grid points were created across the focus landscape, out of which we selected 100 systematically randomized plots (i.e., covering a sampling area of 78.5 ha). Circular sampling plots with radii of 50 m at the centre of the selected grids were marked. No experimental manipulation was made on the plots in order to represent seedling emergence, survival, and population dynamics under farmers' management. All *F. albida* trees (adults, saplings, seedlings) rooted within the plots were investigated over two seasons (2014 and 2015). The criteria used to classify individuals into seedlings, saplings, and adult were based on

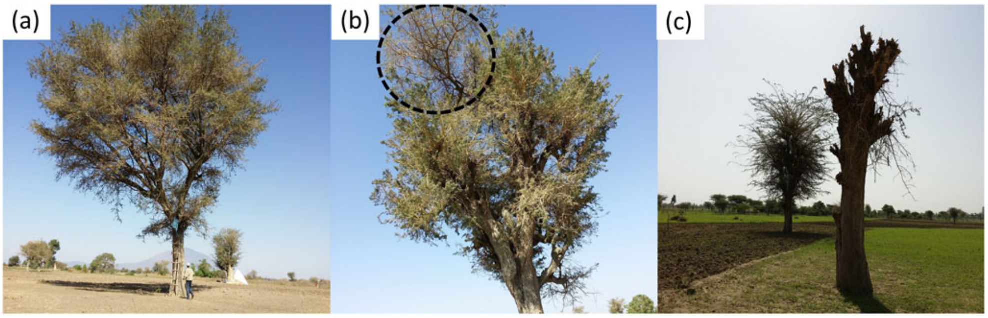

FIGURE 2 *Faidherbia albida* trees (a) unpruned within the last 6 years, (b) partially pruned within the last 3 years (part of the branch encircled at the top of the canopy was unpruned over the last 6 years, whereas the lower part was pruned 4 years ago), and (c) completely pruned recently (the tree in the background of (c) was pruned 3 years previously and did not produce any seed) [Colour figure can be viewed at wileyonlinelibrary.com]

Groenendijk, Eshete, Sterck, Zuidema, and Bongers (2012). Accordingly, trees with diameter at stem base, called ‘diameter at stump height (DSH = 0.3 m)’ of 0–2.0 cm and height of 0–2.6 cm were considered seedlings. Trees with DSH of 2–4 cm and height of <150 cm were considered saplings, whereas larger trees were considered adults. Root suckers, which were similar to seedlings except that they emerged from the root of an adult tree, were also investigated. We use the term ‘juveniles’ in the rest of the paper to refer jointly to seedlings, root suckers, and saplings. Data were recorded (a) at the end of the cropping season, (b) 2 months after the end of rainy season, (c) at the end of dry season, and (d) after the completion of seedbed preparation for planting crops, which involved intensive ploughing. Data from the first sampling period were assumed to represent survival under limited exposure to dry period, no pressure from free grazing and browsing, and without ploughing disturbance; data from the second sampling period to represent survival under some exposure to dry period, exposure to pressure from free grazing and browsing, and no ploughing disturbance; data from the third sampling period to represent survival under exposure to season-long dry period and exposure to free grazing and browsing; and data from the fourth sampling period to represent survival after intensive ploughing disturbance, in addition to season-long exposure to free grazing and browsing and exposure to season-long dry period.

In addition, questionnaires were administered to 60 randomly selected households to investigate whether farmers assist regeneration of new individuals, how they use tree prunings, and the main reasons for current management. The results of this household survey were used to inform rate variations in scenario modelling and were not presented separately.

2.5 | Growth ring formation and tree age

Discs from six purposively selected *F. albida* trees, from varying DBH ranges, were analysed to verify formation of incremental growth rings. A standard dendrochronological method was used for sample preparation and description of growth ring boundaries (Tolera, Sass-Klaassen, Eshete, Bongers, & Sterck, 2013). Although Gourlay (1995) reported that *F. albida* did not show distinct growth rings, our samples showed the presence of marginal parenchyma bands verifying the formation of growth rings. This is most likely due to strong seasonality in the climate, as evidenced by cross dating and a correlation between ring width and climate data.

Following the verification of growth ring boundaries, wood cores were collected from 60 trees at 0.3 m above soil surface. Core samples were collected from opposite directions, giving a total of 120 core samples (Experiment 5). The wood cores were collected purposively from different diameter classes representing the population. Growth rings were counted to estimate the age of sampled trees. For all adults rooted in the plots (described above), trunk height, DBH, and DSH were measured. An allometric regression equation relating tree age to DBH was developed, and used to predict ages of all trees within the plots.

2.6 | Modelling population and regeneration status of *F. albida*

The population dynamics of *F. albida* was modelled using the SIMILE (version 6.7; Muetzelfeldt & Massheder, 2003) package. SIMILE is a dynamic modelling environment that allows a two-phase approach to model construction. The first phase involves drawing of visual diagrams as compartments (stocks and levels) whose values are governed by in-flows and out-flows. The second phase involves adding quantitative information in the form of rates and equations. Under the current practice, intensive pruning of branches limited seed production (Figure 2c). Under increased seed production scenario, trees were left unpruned for at least 6 years (Figure 2a) or underwent partial pruning (Figure 2b) to allow some seed production. The model assumed natural regeneration to be a dynamic process where new individuals are recruited into the mature population, compensating the losses due to mortality. Factors affecting seedling and sapling mortality rates were the main focus. Figure 3 represents the model architecture in SIMILE, whereas Figure S1 shows our conceptual approach involving three interrelated submodules.

Measured, derived, and assumed values of variables used in the equations of the model were presented in Table S1. Population drivers in this model were assumed to affect the transition from seeds to adults, and the adult population change depended on natural mortality or removal by farmers. Model estimated output from two season's data in Experiment 5 was used to initialize the natural adult mortality. Eulers' integration—a time-step integration function—was used to transport individuals from younger to older adult population age class (Figure S1). In the model, 112 years was used as a rotation age limit, which was a recorded maximum age from Experiment 5. Rates as inputs for this function were measured mortality rates within each age group and time needed to the next class. Implications of current management practices (especially FMNR) under different scenarios were explored. Seed production scenarios of current practice and increased seed production were considered. The interlinkage among the experiments is summarized in Figure 4.

3 | RESULTS

3.1 | Current population status, seed production, and seedling survival

The mean density of adult *F. albida* was 4.2 trees ha^{-1}. The mean density for juveniles was 1.4 individuals ha^{-1}. The annual rates of decline, calculated as the ratio of the change in population between the end of wet season (i.e., when regeneration is maximum) and the end of dry season (i.e., when mortality is maximum) to the population at the beginning, were 1.2%, 51.3%, and 63.2% for adults, seedlings, and saplings, respectively.

Faidherbia albida trees did not produce any seed within 6 years of complete pruning (Table 1). Trees that were never pruned within the last 6 years produced the largest amount of seeds (4,355 ± 1,786, mean ± *SD*) followed by trees that underwent partial pruning within this period (2,416 ± 1,818, mean ± *SD*). Immediately after emergence, seedling survival was affected by exposure to neither free grazing and browsing nor ploughing (Table 2). The trend did not change within the first 2 months of the dry period, when more than 75% of the emerged seedlings survived. After 10 months (i.e., at the end of dry season), exposure to free grazing and browsing started to show a significant negative effect on seedling survival. After this period, seedlings on

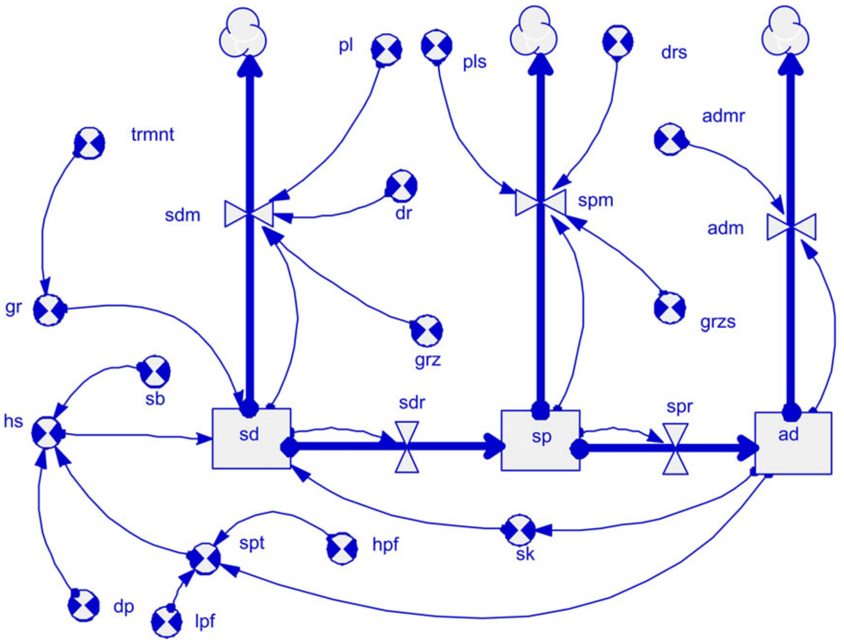

FIGURE 3 Model components for quantitative modelling of the population and regeneration status of *Faidherbia albida*. spt = seed production per tree, hpf = high pruning frequency, lpf = low pruning frequency, dp = disease and pest attack on seeds, hs = healthy seeds, sb = seeds from seed bank, gr = germination rate, trmnt = seed treatment, sd = seedling population, sdm = seedling mortality, pl = ploughing impact on seedlings, dr = drought impact on seedlings, grz = grazing impact on seedlings, sk = seedlings from root suckers, sdr = seedling survival in time, sp = sapling population, spm = sapling mortality, pls = ploughing impact on saplings, drs = drought impact on saplings, grzs = grazing impact on saplings, spr = sapling survival in time, ad = adult population, adm = adult mortality, admr = adult mortality rate [Colour figure can be viewed at wileyonlinelibrary.com]

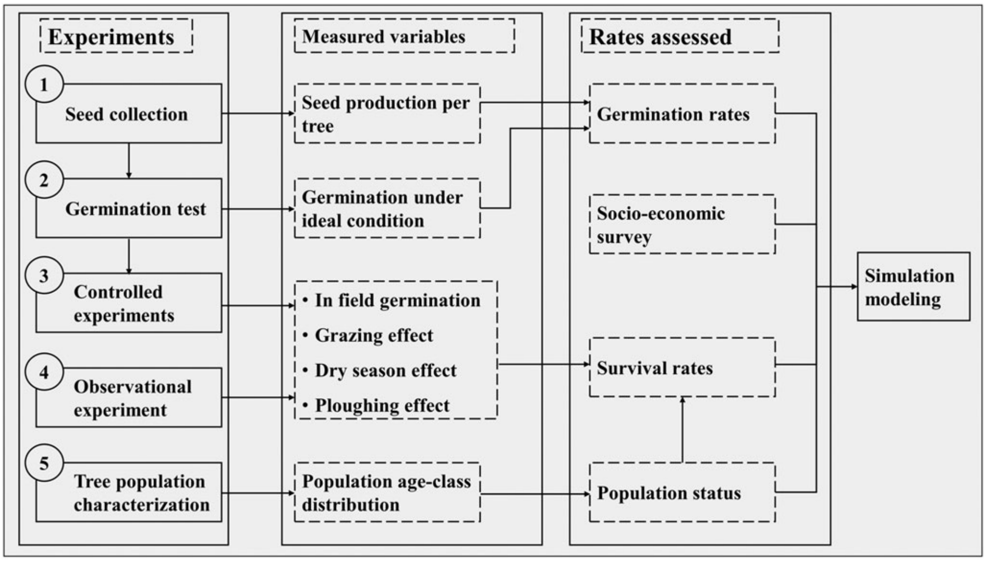

FIGURE 4 Flowchart summarizing the experiments carried out and their linkages

TABLE 1 Stage-wise population density, amount of seeds produced under different pruning regimes, and allometric characteristics of *Faidherbia albida*

	Stage-wise population density (*n* = 256)				Amount of seed produced (*n* = 8)		Biometric parameters (*n* = 256)			
Values	Adults (ha^{-1})	Saplings (ha^{-1})	Seedlings (ha^{-1})	Suckers (ha^{-1})	PP (tree^{-1})	NP (tree^{-1})	DBH (cm)	DSH (cm)	Height (m)	Age (years)
Max	36.9	9.8	12.7	10.2	3,478	5,190	103.5	118.0	20.0	110
Mean	4.2	0.3	1.9	0.4	2,416	4,355	29.5	32.2	6.0	42.7
Min	0.0	0.0	0.0	0.0	1,869	3,620	5.0	6.0	1.8	11.0
SD	6.1	1.4	3.2	1.4	1,818	1,786	18.0	20.0	3.1	19.6

Note. Trees that underwent complete pruning within the last 6 years did not produce any seed (zero seeds tree^{-1}) and were not included in this table. PP = partial pruning; NP = no pruning; DBH = diameter at breast height; DSH = diameter at stump height.

exclosed plots were 48% more likely to survive than seedlings on open-grazed and browsed plots (Table 2). On exclosed plots, 32.3% of the seedlings survived after the full dry season. On open-grazed and browsed plots, the survival was only 21% (i.e., seedling survival was about 53% greater on exclosed plots compared with open plots), indicating that free grazing and browsing significantly reduced survival

TABLE 2 Summary of the results of GLMM for explaining the effect of exclosure and tillage treatments on seedling survival in *Faidherbia albida* at different periods

Effects	Estimate	*SD*	*Z* value	*p* value
Two weeks after emergence				
Intercept	0.43	0.06	7.63	**<.001**
Grazing (exclosed)	0.04	0.08	0.48	.632
Tillage (unploughed)	0.10	0.08	1.22	.223
Grazing × Tillage	−0.05	0.11	−0.42	.671
Two months after the start of the dry season				
Intercept	0.43	0.06	7.4	**<.001**
Grazing (exclosed)	−0.01	0.08	−0.04	.967
Tillage (unploughed)	0.03	0.08	0.37	.713
Grazing × Tillage	−0.02	0.12	−0.17	.864
End of dry the season				
Intercept	0.32	0.10	3.20	**<.010**
Grazing (exclosed)	0.48	0.13	3.71	**<.001**
Tillage (unploughed)	0.06	0.14	0.42	.673
Grazing × Tillage	−0.07	0.18	−0.36	.715

Note. Seedling survival at 2 weeks after emergence, 2 months after the start of the dry season, and at the end of dry season. GLMM = generalized linear mixed model.

when maintained for longer than 10 months. By contrast, ploughing had no significant impact on seedling survival within this period.

3.2 | Tree age distribution and allometric relationships

Tree age was predicted by DBH (Figure 5). Age was exponentially related to DBH and had a mean bias of −1.0 ± 0.6% (mean ± *SE*), computed as bias = ([age calculated-age measured]/age measured) × 100%. Figure 6 presents the DBH class (a) and age class (b) distribution for the population, computed using the regression equation in Figure 5, using DBH alone. Figure 6b shows that the majority of trees (60% of the total population) were older than 30 years. Only 49% of the population is younger than the current average age of 41 years. The maximum age recorded from the current study area was 112 years, although less than 5% survived beyond 75 years. There were hardly any adult trees younger than 10 years, and only 14% of the trees were younger than 25 years, indicating little recruitment happened within the last 2–3 decades.

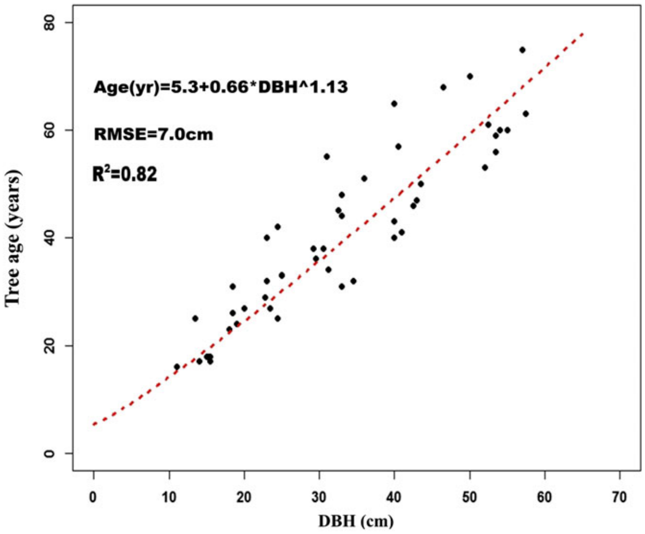

FIGURE 5 Relationship between tree age and diameter at breast height (DBH) for *Faidherbia albida* in Mojo, Ethiopia. Broken line represents the fitted regression line [Colour figure can be viewed at wileyonlinelibrary.com]

3.3 | Simulating *F. albida* population dynamics

Under current tree management, pruning intensity was the most important factor affecting the future population status (Figure 7). The current practice of pruning trees completely every 2–3 years (Figure 7a–c) limits seed production (Table 1). If the current trend continues (Figure 7a–c), the tree population will start to decline within one to two decades, depending on seedling and sapling survival rates. It will eventually fall below 1 tree ha^{-1} within the next 60 years. With management practices that lower both seedling and sapling mortality rates (Figure 7c), tree density could increase to 6.9 trees ha^{-1} in the next decade. However, that increase would only delay the on-set of population decline, which would fall below the base level within a little over two decades (Figure 7c).

Although there was a clear decline in tree densities for all scenarios under current management (Figure 7a–c), the rate of decline was more sensitive to seedling mortality than to sapling mortality. For example, increasing sapling survival by 50% with the current practice (Figure 7a–c) resulted in less than a 5% increase in tree density. By contrast, increase in seedling survival rate by the same rate resulted in an increase in tree density of more than 15% after 60 years.

4 | DISCUSSION

4.1 | Early mortality of *F. albida* seedlings in the dry season

More than a quarter of emerged seedlings did not survive the first 2 months of dry season, regardless of exclosure and ploughing treatments (Table 2). In other studies, such early seedling mortality has

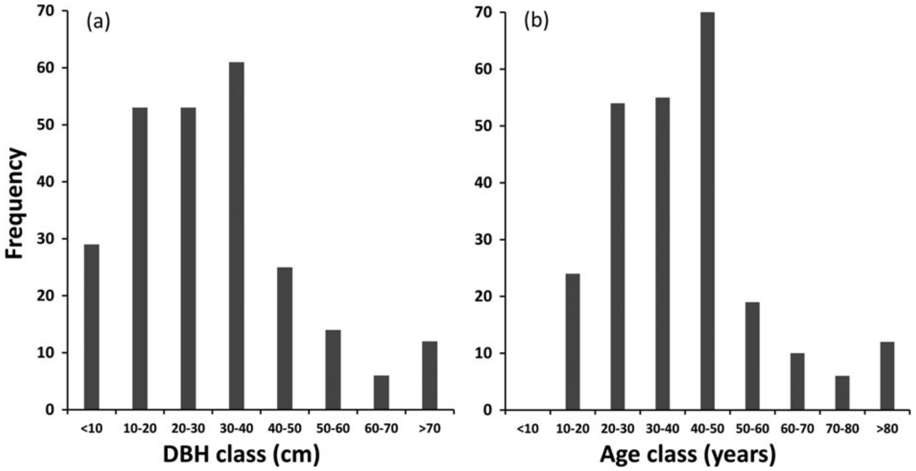

FIGURE 6 Measured diameter at breast height (DBH) class (a) and predicted age class (b) for *Faidherbia albida* population in Mojo, Ethiopia

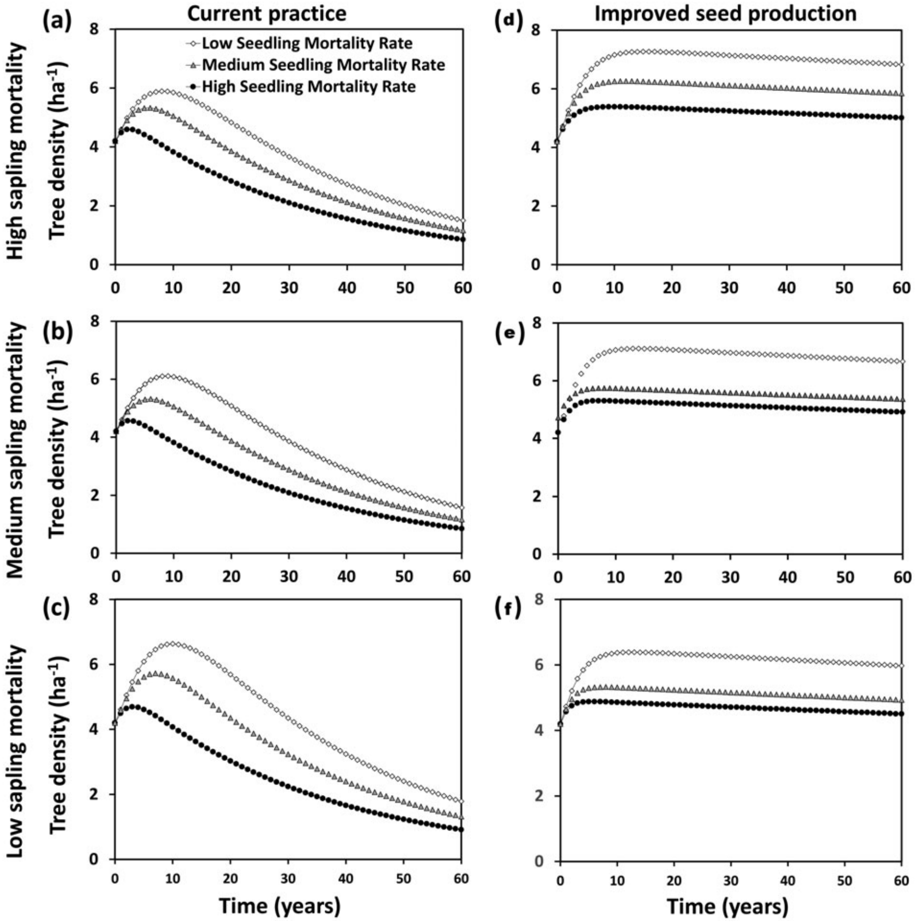

FIGURE 7 Simulated population status of *Faidherbia albida* for different seedling mortality rates and under low (a & d), medium (b & e), and high (c & f) sapling survival rates for the current management (a–c) and under improved seed production (d–f). Low, medium, and high survival rates were 0.2, 0.5, and 0.8, respectively. The difference in input between 'current practice' and 'improved seed production' is only the amount of seeds produced per tree

been attributed to moisture limitation starting from early in the season in *F. albida* (Stave, Oba, Eriksen, Nordal, & Stenseth, 2005), seed predation by invertebrates of *Acacia* spp. in the East African savannah (Shaw, Keesing, & Ostfeld, 2002), and seed predation of *Acacia* spp. by rodents in a cattle–wildlife system in Kenya (Goheen, Keesing, Allan, Ogada, & Ostfeld, 2004). In our experiment, a third of the seedlings survived in the exclosure 10 months after sowing, compared with only 21% in the open plots. Exclusion from free grazing and browsing improved seedling survival significantly (seedling survival was about 53% higher on exclosed plots compared with open plots). However, the seedling mortality in exclosed plots was still high (i.e., a third of the total seedlings), indicating that damage by factors other than free grazing and browsing contributed to seedling mortality. This result contrasts with those of Moe et al. (2009) who found much higher *F. albida* seedling survival in exclosures in Chobe National Park in northern Botswana. They reported seedling survival rates as high as 78% in plots where grazing and browsing herbivores were excluded, compared with only 32% survival in open plots subjected to grazing and browsing. The detrimental effect of open grazing on seedling survival has been established for different tree species, under varying management and environmental conditions. For example, grazing reduced seedling survival in woody patches of *Ekebergia capensis* and *Olea europaea* in Northern Ethiopia, where exclusion of livestock improved seedling survival in these species (Wassie, Sterck, Teketay, & Bongers, 2009). As a result, exclosures have been a strong focus of land management policy in Ethiopia (Baudron, Mamo, Tirfessa, & Argaw, 2015) and in other parts of the world (Marcora et al., 2013; Pulido, García, Obrador, & Moreno, 2010; Tyler, Davis, & Mahall, 2008).

Surprisingly, we found no significant effect on seedling survival of ploughing. Although we did not find any studies in the literature that quantified the effect of tillage on seedling survival of on-farm species, we expected tillage to damage newly emerging seedlings. For example, Pulido et al. (2010) found that tillage reduced seedling survival of oak in the Mediterranean savannah, and Baer and Groninger (2004) reported that tillage reduced seedling survival in *Fraxinus pennsylvanica*. We hypothesize that this negligible effect is due to two main reasons. First, the *Maresha* ploughing implement, which forms V-shaped furrows leaving untilled land between two consecutive furrows (Temesgen, Rockstrom, Savenije, Hoogmoed, & Alemu, 2008), may impose minimum damage to seedlings, unlike the moldboard plough, which inverts the soil. Second, *F. albida* seedlings develop early belowground growth that exceeds its aboveground development (Van Noordwijk et al., 2015), making it resistant to uprooting during tillage.

4.2 | *Faidherbia albida* tree age was exponentially related to its DBH

Understanding population structure and pattern enables the design of appropriate parkland tree management (Pulido, Díaz, & de Trucios, 2001), whereas methods to assess population age distribution are complex and costly (Tolera et al., 2013). Regression equations have rarely been used to estimate population age-class distributions from simple allometric measurements for parkland species. We found a good fit for a regression curve relating DBH to tree ages. This corroborates the findings of several studies that reported DBH as a good estimator of age in savannah species (Gebrekirstos, Mitlöhner, Teketay, & Worbes, 2008; Mbow, Chhin, Sambou, & Skole, 2013). The combination of the three parameters (trunk height, DBH, and DSH) predicted tree ages with only a slightly improved accuracy (R^2 = .83, p < .001, RMSE = 6.6). Our results indicated that allometric approaches can also be used to estimate tree age structure accurately for *F. albida*, which is a species with reverse phenology, concurring with the expectation of Gebrekirstos, Beedy, Sileshi, and Neufeldt (2014).

4.3 | The current population of *F. albida* is sparse and declining

In addition to low overall population density, the ratio of juveniles to adults of *F. albida* was very low—about 0.3 young individuals for every adult. A low juvenile to adult ratio is a manifestation of a population facing an extremely high risk of juvenile mortality (Gonzalez, Tucker, & Sy, 2012). Although the rate of adult mortality rate was not high in *F. albida*, new recruitment was very limited, making population decline inevitable (Lykke, 1998).

From our study, the maximum age of *F. albida* was 112 years (Table 1 and Figure 6b), agreeing with previous findings that reported a maximum age of 100 years from *F. albida* populations across the Sahel, including samples from Ethiopia (Barnes & Fagg, 2003). *F. albida* trees as old as 150 years had been reported from southern Africa (Wood, 1989). A small juvenile population, such as found in this study, is characteristic of fast-growing species with an even population growth and high survival rate (Lykke, 1998). By contrast, *F. albida* is not a fast-growing species and showed uneven population growth and a high risk of mortality (Figures 5 and 7). A special case where small juvenile population may not necessarily indicate population decline occurs for long-lived parkland species with very low mortality, such as baobab (*Adansonia digitata*; Venter & Witkowski, 2010). However, *F. albida* is comparatively short lived. In thriving populations, the size-class distribution graph (Figure 6) normally follows an 'inverted-J' shape—a large number of individuals with younger size classes and small number of older individuals (Tolera et al., 2013). A bell-shaped population distribution, similar to Figure 6b, indicates a declining population (Pulido et al., 2001), except where the juvenile survival rate is very high. As juvenile survival for *F. albida* is extremely low, the bell-shaped population distribution (Figure 6) clearly indicated that its population is declining. On the other hand, Prins and van der Jeugd (1993) showed that such bell-shaped population distribution for trees in natural savannah ecosystems may not necessarily be a sign of limited recruitment that could lead to population decline, because seedling recruitment for these species may occur within narrow time windows, during episodes of particularly favourable environmental conditions. However, the influence of particularly favourable episodes for recruitment is less likely in intensively managed parkland systems.

We observed few individuals of *F. albida* had been established after the last 35 years (Figure 6b). The population distribution of trees older than 40–50 years followed the 'inverse-J' shape characteristic of a thriving population, hinting that population decline started about half a century ago. A study from the same area reported that adult *F. albida* was 4.7 trees ha^{-1} (Poschen, 1986). We found 4.2 trees ha^{-1}, indicating that only a minor decline (about 11%) had occurred over the last three decades. By contrast, population modelling predicted a rate of population decline of 27% over the forthcoming three decades—much faster than observed over the corresponding period in the past. Thus, the fast population decline appears to be a relatively recent phenomenon, which is likely to intensify in the future. Similar population declines were reported for parkland trees within human dominated landscapes in the Sahel

(Venter & Witkowski, 2010) and North Ethiopian savannah (Tolera et al., 2013). Although the causes of population decline ranged from ungulate browsing (Moe et al., 2009) to suspected climate change (Gonzalez et al., 2012), the decline of tree populations within agricultural landscapes has long become a hot discussion topic in environmental conservation (Sendzimir et al., 2011). As reported by Bernardi, Holmgren, Arim, and Scheffer (2016) for South America, climate change could affect tree regeneration negatively, and the population decline of *F. albida* in the study area could be worst under climate change scenarios.

4.4 | Limited recruitment due to lack of seed source causes population decline in *F. albida*

Both our direct observations and the population modelling pointed to a population decline in *F. albida*. However, disentangling the main factors driving this decline requires a dynamic modelling approach (Muetzelfeldt & Massheder, 2003). Although seedling and sapling mortality affected the rate of population decline (Figure 7), lack of seed appeared to be the most threatening factor for population decline. Several previous studies have reported free grazing and browsing, and low dry season survival as common bottlenecks for parkland tree regeneration in contrasting ecosystems (Pulido et al., 2010; Stave et al., 2005; Venter & Witkowski, 2010). Although our model confirmed the impact of dry season survival and free grazing and browsing on survival, it underlined low seed production as the most important bottleneck. Although improved seedling and sapling survival through management practices, such as fencing, may increase the population in the short term, lack of *F. albida* seed is the most important constraint for recruitment (Figure 7d–f). Even under high sapling and seedling mortality rates (Figure 7d), the population can be maintained at its current level only if seed availability is improved. Minor changes in tree management can improve seed availability but require collective action. Policies that promote FMNR could assist to increase seed production. For example, leaving some unpruned trees across the landscape or leaving a few branches unpruned would result in increased seed production. Although individual farmers can protect and manage trees, the effectiveness of such an approach was highly dependent on whether village communities organize and develop by-laws for managing trees (Garrity et al., 2010). Pasture rotation, where animals are excluded for some years, can lead to the regeneration of trees sufficiently large to survive browsing. In addition, Baudron et al. (2015) demonstrated that farmland exclosure can be an effective conservation and sustainable intensification pathway in the Central Rift Valley of Ethiopia. On the other hand, other factors such as seed dormancy (Barnes & Fagg, 2003), seed herbivory (Shaw et al., 2002), and diseases and pests (Moe et al., 2009) may constrain seed availability as reported from other regions, in addition to pruning practices. Farmers remove branches to use for fencing and fuelwood. A payment for ecosystem services scheme that compensates farmers for the foregone value of fencing and fuel materials could ensure seed multiplication and prevent tree population decline. Such policies have been successfully implemented elsewhere to influence farmers' practices (Smith et al., 2013).

5 | CONCLUSIONS

Unless seed production is increased—by decreasing pruning frequency and/or intensity—the density of *F. albida* will start to fall within a decade. Within season survival of *F. albida* seedlings was affected by dry season browsing and drought but not by ploughing. Even if current tree and regeneration management practices were changed to improve recruitment, the population is still predicted to decline to a critical density of less than a tree per hectare within half a century from now, if seed production is not improved. Policies that encourage farmers to change their pruning frequency and/or intensity would ensure seed production and could avert the decline in the population of this important tree.

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Additional Supporting Information may be found online in the supporting information tab for this article.

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