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Genetic Considerations for Species Choice and Seed Procurement in Ethiopia's Forest Restoration Initiatives

Nigussu Begashaw Abate[1*], Tesfaye Abebe[1]

[1]*School of Plant and Horticultural Sciences, College of Agriculture, Hawassa University, P. O. Box 5, Hawassa, Ethiopia*

Abstract

Global commitments to large-scale tree planting and forest restoration are increasing to help restore degraded ecosystems. Ethiopia has pledged to restore 22 million hectares of degraded land, undertaking massive forest restoration campaigns under the umbrella of the "Green Legacy Initiative," with billions of tree seedlings reportedly planted annually. Genetic and ecological research underscores that using native tree species with high genetic diversity is essential for restoration success. This study assessed the consideration of genetic principles in species choice and seed procurement in Ethiopia's restoration initiatives. Data was collected from surveys with seed vendors and nurseries, as well as secondary data from tree seed centers within the national tree seed network. The findings indicated that genetic considerations in species choice and seed procurement are often overlooked in current large-scale restoration practices. Species selection is mainly dominated by a few exotics—Grevillea robusta, *Eucalyptus camaldulensis*, *Acacia decurrens*, and *Cupressus lusitanica*—leaving native species underrepresented. Moreover, seed collection practices frequently disregard guidelines critical for preserving genetic diversity. Notably, 84% of seed collectors source from any available tree, 87% of nurseries receive seeds without passport data, 97% of seed collectors do not consider a minimum number of mother trees for a single collection event, and 88% ignore the required distances between selected mother trees, risking inbred seed collection. These gaps threaten the evolutionary resilience and adaptive capacity of planted seedlings, impacting the long-term success of restoration efforts. To improve outcomes, EFD and other relevant authorities leading the restoration initiatives should devise policies that promote native species use and enforce genetic standards in seed procurement.

Key words: forest restoration, germplasm, genetic diversity, seed procurement, tree nurseries, tree seed

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***Corresponding author's address:** Nigussu Begashaw Abate, Email: nigussu@hu.edu.et; nigussub@yahoo.com

Authors: Tesfaye Abebe: tesfayeabebe165@gmail.com

INTRODUCTION

Deforestation, land degradation, climate change, desertification, and biodiversity loss continue to pose significant challenges to ecosystems worldwide. One widely adopted strategy to mitigate these environmental crises is forest ecosystem restoration. This imperative action has spurred large-scale tree planting initiatives and ambitious global reforestation commitments (Broadhurst et al., 2008; Thomas et al., 2014; Lamb, 2018; Fagan et al., 2020). Notable examples include the Green Wall of China, spanning 4,500 km and covering 35 million hectares since its inception in 1978, and the Great Green Wall of Africa, which aims to plant a 7,775 km-long tree belt across the Sahel. Initiatives such as the Bonn Challenge and the African Forest Landscape Restoration (AFR100) aim to restore 350 million hectares of degraded land globally, 100 million hectares of which are in Africa, by 2030 (Bozzano et al., 2014; Pistorius et al., 2017; Verdone and Seidl, 2017). To further inspire and accelerate these global restoration initiatives, the United Nations (UN) has designated 2021–2030 as the UN Decade on Ecosystem Restoration (https://www.decadeonrestoration.org/), followed by the World Economic Forum's 1 Trillion Trees Initiative in support of the UN's goals (Aronson et al., 2020). However, many reforestation projects around the globe have faced limited success, often due to mismatches between planting material and site conditions, poor genetic quality of planting stock, and inadequate management practices (Thomas et al., 2014; Méndez-Toribio et al., 2021).

In Ethiopia, deforestation has been a persistent challenge, dating back to 500 BC (Darbyshire et al., 2003) and re-intensifying since the 16th century (Pohjonen & Pukkala, 1990). Natural forest cover continues to decline (Reusing, 2000; Dessie & Kleman, 2007; Demissie et al., 2017; Etefa et al., 2018), with recent losses confirmed by the FAO (2020). A rapidly growing population exceeding 120 million has intensified pressures on forests, driven by agricultural expansion and wood extraction for household energy (Stebek, 2008; Kindu et al., 2015), resulting in land degradation, erosion, biodiversity loss, and forest fragmentation (Kassa et al., 2017; Mengist et al., 2022). Efforts to combat deforestation began in the 1890s with the introduction of eucalyptus species and expanded in the 1970s with large-scale plantations of fast-growing exotic species of Eucalyptus, Cupressus, and Pinus (Ayana et al., 2013; Lemenih & Kassa, 2014). Recent approaches such as the "climate-resilient green economy strategy" aim to double forest cover by 2025 and cut greenhouse gas emissions by 50% by 2030 (FDRE, 2011; MEFCC, 2018). Ethiopia has also pledged to restore 22 million hectares of degraded land through global programs like the Bonn Challenge and AFR100 (Pistorius et al., 2017; Kassa et al., 2022). Massive tree-planting campaigns, including the "Green Legacy Initiative," are central to these efforts, with billions of tree seedlings reportedly planted annually to restore degraded landscapes (Fikreyesus et al., 2022; Kassa et al., 2022).

While plantations of exotic species in Ethiopia have supported fuelwood and timber supplies, their role in ecosystem restoration remains questionable. Exotics often underperform in maintaining soil quality (Lemenih et al., 2004; Demessie et al., 2012), water-use efficiency (Gindaba et al., 2004, 2005), biodiversity (Abiyu et al., 2011), and pest resistance (Demeke, 2018). Some of them are even becoming invasive (Shiferaw et al., 2004, 2019). Whether exotic species still dominate large-scale planting efforts or if native species are now prioritized remains unclear. Restoration success also depends on the genetic quality of germplasm, which is crucial for resilient and self-sustaining populations capable of adapting to environmental challenges (Broadhurst et al., 2008; Thomas et al., 2014). The extent to which tree seed collections in Ethiopia follow established guidelines, such as those from the World Agroforestry Centre, ICRAF (Kindt et al., 2006), and the Royal Botanical Gardens, Kew (2003), which recommend sampling from at least 30 widely spaced trees to avoid inbreeding, is largely unstudied. A few available studies highlight gaps in the tree seed system and the overlooking of guidelines, with collections often relying on limited mother trees or fragmented populations, leading to reduced genetic diversity (Dedefo et al., 2016; Mehari et al., 2024). As many tree species are naturally outbreeding and carry a genetic load of deleterious recessive alleles (Lowe et al., 2005; Broadhurst & Boshier, 2014), seed collection from isolated trees often results in inbred progeny with slower growth, higher susceptibility to stresses, and reduced resilience (White et al., 2007; Tata et al., 2023). This jeopardizes long-term sustainability as today's plantations often serve as future seed sources. Ensuring genetically diverse germplasm is thus essential for restoration initiatives to yield viable, self-sustaining, and resilient landscapes.

Formal evaluations of the large-scale tree planting campaigns are rare, yet anecdotal reports suggest that seedling survival rates are low, with some estimates indicating that less than 40% of seedlings survive beyond the initial establishment phase (ENA, 2019). A recent study in Tigrai, northern Ethiopia, reported a survival rate of only 53% for planted seedlings, with overall plantation success deemed unsatisfactory (Berhe et al., 2024). However, even these short-term survival rates may not accurately predict long-term restoration outcomes. Effective landscape restoration requires establishment of initial seedling which is accompanied by long-term indicators such as growth, maturation, and reproductive capacity (Le et al., 2011; Bozzano et al., 2014; Thomas et al., 2014). Ethiopia's 10-year national forest development program document (MEFCC, 2018) acknowledges that "… billions of seedlings are planted each year in the country but hardly grow to become a forest." While poor site conditions and inadequate silvicultural management are often blamed for these failures (MEFCC, 2018; Magaju et al., 2020), the role of genetic quality of the germplasm in planting success remains largely overlooked.

This study aims to assess the extent to which genetic considerations are factored into tree species selection and seed procurement for ongoing forest restoration initiatives in Ethiopia. The results will have substantial practical implications for restoration authorities and practitioners, informing future efforts to enhance the genetic quality of planting material and improve the long-term sustainability of restoration projects.

MATERIALS AND METHODS

Data Sources and Types

Both primary and secondary data were utilized in this study (Table 1). Primary data were collected through a survey of 24 tree nurseries and 23 seed suppliers or vendors (Figure 1). The nurseries and vendors were identified in consultation with the former South Nations, Nationalities, and Peoples Region (SNNPR) Forest and Environment Bureau, the SNNPR Tree Seed Center, and the SNNPR REDD+ Coordination Office. At the time of sampling, the region had not yet been divided; however, since it has been split into four new regions, with the sampled districts now fall within three of them—Sidama, South Ethiopia, and Central Ethiopia. Initially, 14 active tree seed cooperatives, organized by the SNNPR Tree Seed Center and distributed across 11 districts (woredas), were identified and included in the survey.

Private seed vendors, as well as public tree nurseries operating in these districts, were also included in the survey. Since no formal registry of private seed vendors existed, a snowball sampling approach was used to identify them. Additionally, five tree nurseries managed by the regional REDD+ Coordination Office were incorporated into the survey. Once the nurseries and seed vendors were identified, data were gathered through interviews with nursery foremen, cooperative leaders, and individual seed vendors using semi-structured questionnaire. Key informant interviews were also conducted with the heads of the regional Tree Seed Center and the REDD+ Coordination Office.

Secondary data were sourced from the Telegram page of the Ethiopian Tree Seed Network (https://t.me/Ethiopian_TSN). These data comprised monthly seed availability reports from three tree seed centers that regularly posted seed balance updates between January 2020 and August 2022. These centers were the Ethiopian Environment and Forest Research Institute (EEFRI) in Addis Ababa, the Dimma Tree Seed Center in Sebeta (Oromia Region), and the Bahir Dar Tree Seed Center (Amhara Region).

Table 1. Survey entities used as data sources for this study

Survey entities	Data type	Source	No. of entries
National tree seed network			3
EEFRI	secondary	https://t.me/Ethiopian_TSN	
Dimma tree seed center	secondary	https://t.me/Ethiopian_TSN	
Bahirdar tree seed center	secondary	https://t.me/Ethiopian_TSN	
Nurseries			
Government/public	primary	own survey	17
NGO/project	primary	own survey	5
Private	primary	own survey	2
Seed suppliers/ vendors			
Cooperatives	primary	own survey	14
Private	primary	own survey	9

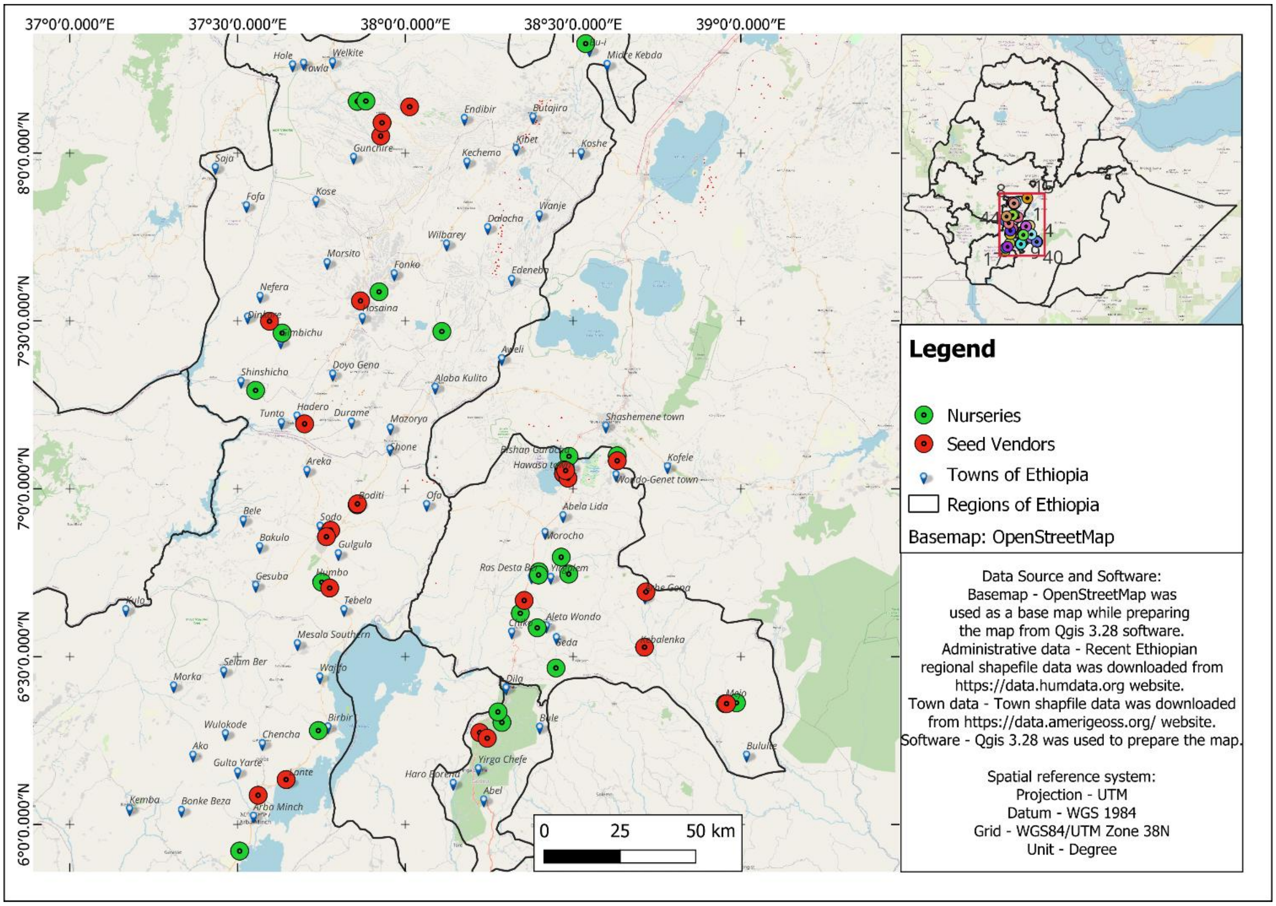

Figure 1. Map showing the locations of surveyed tree nurseries and seed vendors

Data Analysis

The survey data were coded and initially entered into MS Excel. After organizing the data, it was imported into the R statistical software for further analysis and visualization. Most analyses involved summarizing the data using the *dplyr* package (Wickham et al., 2023), followed by graphical visualization with the *ggplot2* package (Wickham, 2016). Additional R packages employed included *xlsx (*Dragulescu & Arendt, 2020) for importing Excel files and *patchwork* (Pedersen, 2024) for combining multiple plots. The results were presented as tables and graphs.

RESULTS AND DISCUSSION

Composition and Ranking of Tree Species Distributed by Vendors and Raised in Nurseries

Figure 2A presents the average seed quantity reported per species in a single monthly entry from the three seed centers. The data reveals that exotic species dominate the largest seed stocks, with the top six species all being exotics. Only two native species, *Cordia africana* and *Olea africana*, make it into the top ten. A larger average seed quantity may reflect either frequent restocking or a large initial acquisition that remains in stock without significant distribution. This dynamic is further explored in Figure 3, where Figure 3A shows the frequency with which species were reported as available, and Figure 3B tracks seed quantity trends over a 32-month period for the 12 most commonly reported species. *Sesbania aculeata*, for example, ranked highest in seed quantity (Figure 2A), but was not frequently reported, ranking 26th in frequency (Figure 3A). Figure 3B reveals that *S. aculeata* was acquired in bulk in May 2020, remained stable in stock until March 2021, and was fully distributed by May 2021, with no further significant reports thereafter. In contrast, species like *Acacia decurrens*, *Eucalyptus camaldulensis*, and *Cupressus lusitanica* exhibited periodic fluctuations, indicating more frequent acquisitions and distributions over the entire period.

In Figure 2B, seed availability is ranked by the estimated number of seeds per species, further highlighting the dominance of exotic species over native ones. The number of seeds, which develop into potential seedlings in nurseries, is disproportionately higher for exotics. This dominance is even more evident in Figure 2B, where native species are nearly invisible when plotted on the same scale as the exotics. The disparity can be attributed to the finer seeds of exotic species, which yield significantly more seeds per kilogram compared to native species. For instance, exotic species like *Eucalyptus camaldulensis* (1,887,507 seeds/kg), *Eucalyptus saligna* (2,101,282 seeds/kg), and *Cupressus lusitanica* (156,739 seeds/kg) far outnumber the native species *Cordia africana* (6,141 seeds/kg) and *Olea africana* (10,020 seeds/kg), despite these natives being reported in relatively higher quantities in Figure 2A.

Figure 2C breaks down the average amount of seed reported for each species by the three seed centers. Exotic species are clearly dominant in both the Bahirdar and Dimma seed centers, while the Ethiopian Environment and Forest Research Institute (EEFRI) center reported a relatively higher presence of native species. The Bahirdar and Dimma centers also reported higher seed quantities for most of the species compared to EEFRI. Notably, *Acacia decurrens*, *Susbania aculeata*, and *Leucaena leucocephala* have the highest seed quantities at Bahirdar, Dimma, and EEFRI, respectively.

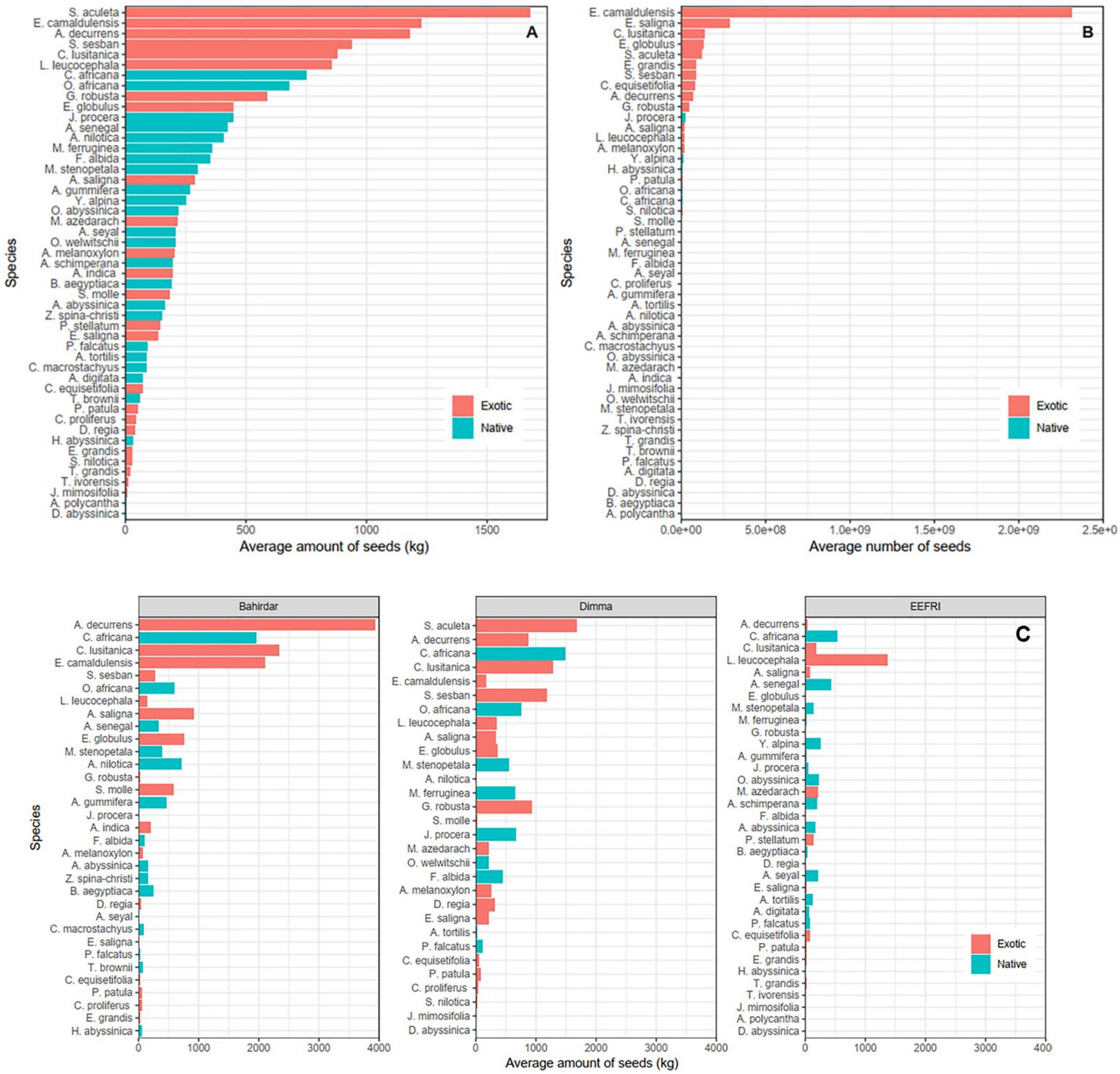

Figure 2. Tree seed availability per species reported by three centers of the national tree seed network of Ethiopia. A) Total amount of seed (in kg) for each species, averaged across all monthly reports.; B) Estimated average number of seeds per species, derived from the average seed amounts reported in A; C) Average seed amounts (in kg) reported by each center (Bahir Dar, Dimma, and EFFRI) for each species. Species are categorized as either exotic (shaded red) or native (shaded blue)

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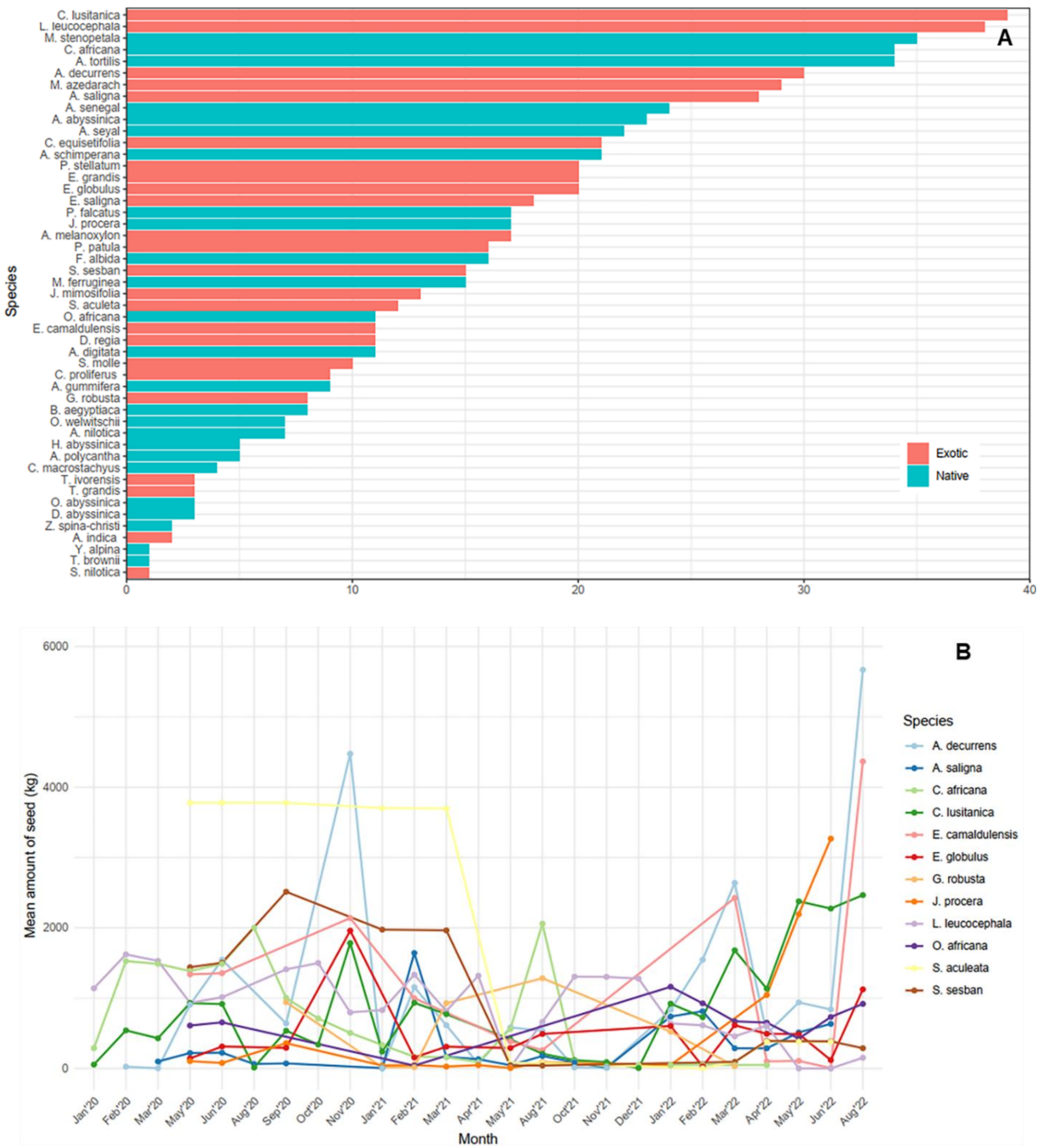

Figure 3. Commonality of Species in the Tree Seed Balance Report. A) The frequency of each species reported in the seed balance by the three seed centers; B) The trend of 12 common species reported over a 32-month period.

Lastly, Figure 4 presents the species preference rankings based on primary survey data from tree nurseries and seed vendors in southern Ethiopia. *Grevillea robusta* ranked first in terms of the volume of seeds and seedlings distributed, followed by *Cupressus lusitanica*, both of which are exotic species. Among the native species, *Cordia africana* and *Afrocarpus gracilior* were relatively preferred, but the gap between them and the exotics—particularly *G. robusta*—was substantial. Overall, the results from both primary and secondary data sources indicated that exotic species dominated germplasm distribution for tree planting activities in Ethiopia.

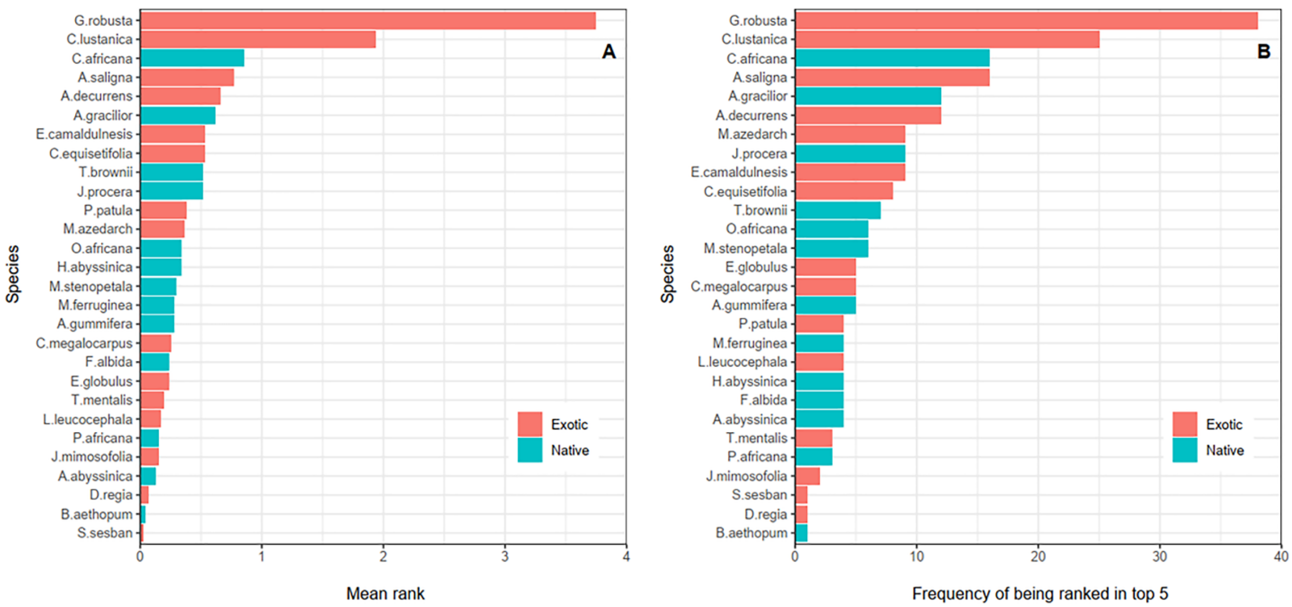

Figure 4. Rank of species preference based on surveyed nurseries and seed vendors. A) Mean rank (on a scale of 1 to 5, with 5 being the highest) for each species, with unranked species scored as 0 in the calculation.; B) The frequency of each species being ranked among the top 5.

Seed Procurement Practices by Nurseries and Seed Vendors

Figures 5, 6 and 7 illustrate the tree seed procurement practices of nurseries and seed vendors. Half of the nurseries surveyed fully outsource their seed requirements, while an additional 46% combine outsourcing with their own seed collection (Figure 5A). This means that 96% of the nurseries rely on some form of outsourced seed to meet their production needs. When outsourcing, 52% of nurseries acquire seed through an open bidding process, 22% purchase directly from local vendors, and another 22% use a combination of both methods (Figure 5B). Among the seed vendors, 65% are cooperatives whose members participate in seed collection, whereas 26% of vendors fully outsource their seed supply, purchasing seeds only after winning bids to provide nurseries (Figure 7B). Regarding seed populations, 84% of seed collectors utilize any available tree or population as a seed source, 10% focus exclusively on natural forests, and only 3% each collect seeds from designated seed production areas and plantations or provenances (Figure 6A). Moreover, only 59% of seed collectors select mother trees based on phenotypic superiority, while the remaining 41% collect from any tree as long as it is seeding (Figure 6B).

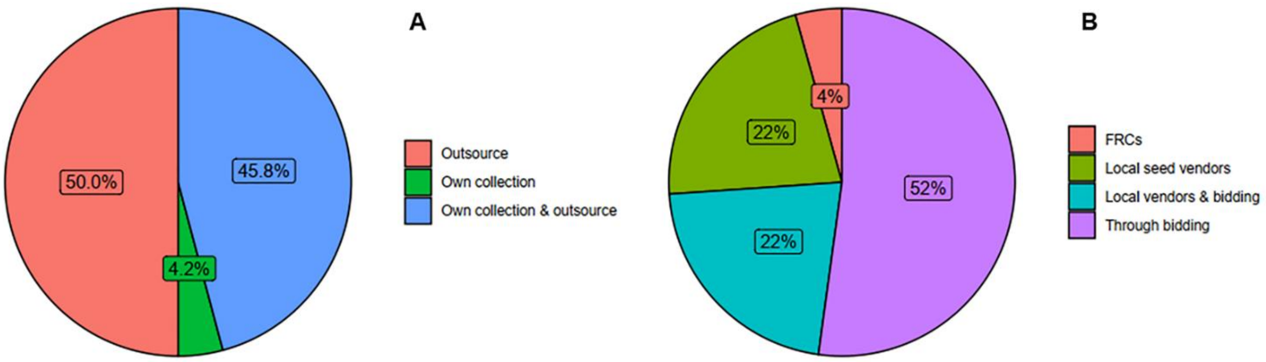

Figure 5. Tree seed procurement approaches by the surveyed nurseries. A) Whether nurseries conduct their own seed collection or outsource their seed supply; B) Methods used by nurseries for outsourcing seed procurement.

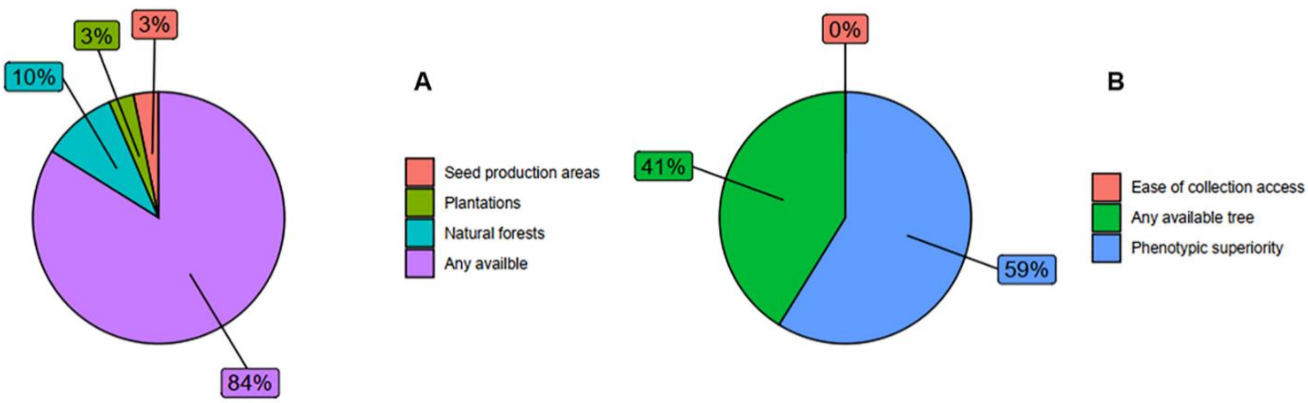

Figure 6. Survey responses on seed source population and mother tree selection. A) Types of populations from which seeds are collected; B) Criteria used for selecting specific mother trees

The majority of tree seed vendors (96%) reported having the required license to operate in this business (Table 2). However, when examining the authorities responsible for issuing these licenses (Figure 7A), the forestry sector is notably absent from the process. Instead, licenses are granted by the Cooperative Commission (65%), the Bureau of Agriculture (26%), and the Trade and Industry Commission (9%), primarily as a legal formality to run the business like any other commodity, without accounting for the peculiarities of the tree seed system.

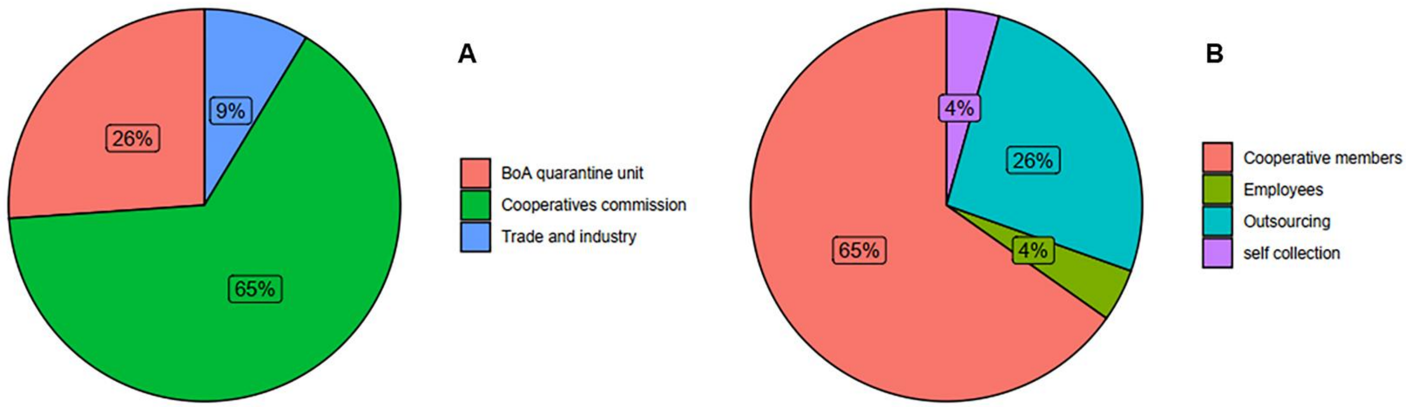

Figure 7. Licensing authorities and seed procurement methods of seed vendors. A) Authorities responsible for issuing licenses to seed vendors; B) Methods used by seed vendors to procure seeds

Table 2. Survey responses on giving genetic consideration during seed sourcing

No.	Questions	Responses		Proportion		Total responses
		Yes	No	Yes (%)	No (%)	
1	Do nurseries receive pertinent information (passport data) on the seed they outsource (e.g., location, climate, altitude, test results)?	3	20	13	87	23
2	Do nurseries face germination issues with outsourced seeds?	20	3	87	13	23
3	Do seed collectors consider the minimum number of mother trees when collecting seeds?	1	33	3	97	34
4	Do seed collectors account for minimum distances between mother trees during collection?	4	30	12	88	34
5	Do seed collectors follow established guidelines for seed collection?	19	10	66	34	29
6	Have seed collectors received training in seed handling?	24	10	71	29	34
7	Do seed vendors have the required license to operate?	22	1	96	4	23

Genetic Considerations in Seed Sourcing

Table 2 summarizes the responses regarding factors affecting the genetic quality of procured tree seeds. A significant proportion of nurseries (87%) reported that the seeds they purchase do not come with labels (or passport data) providing critical information such as the location, seed source population, collection date, or seed test results. The same percentage also noted experiencing germination issues with their outsourced seeds. Furthermore, 97% of seed collectors do not consider a minimum number of mother trees when collecting seeds, and 88% do not consider minimum distances between mother trees, which increases the risk of collecting genetically-related seeds, leading to inbreeding. While 66% of seed collectors claimed to follow established guidelines for tree seed collection, none of the surveyed vendors actually possessed written guidelines. Instead, they relied on training they had received, using their 'knowledge' from these trainings as a substitute for formal guidelines. About 70% of seed collectors indicated they had received some level of training in tree seed handling.

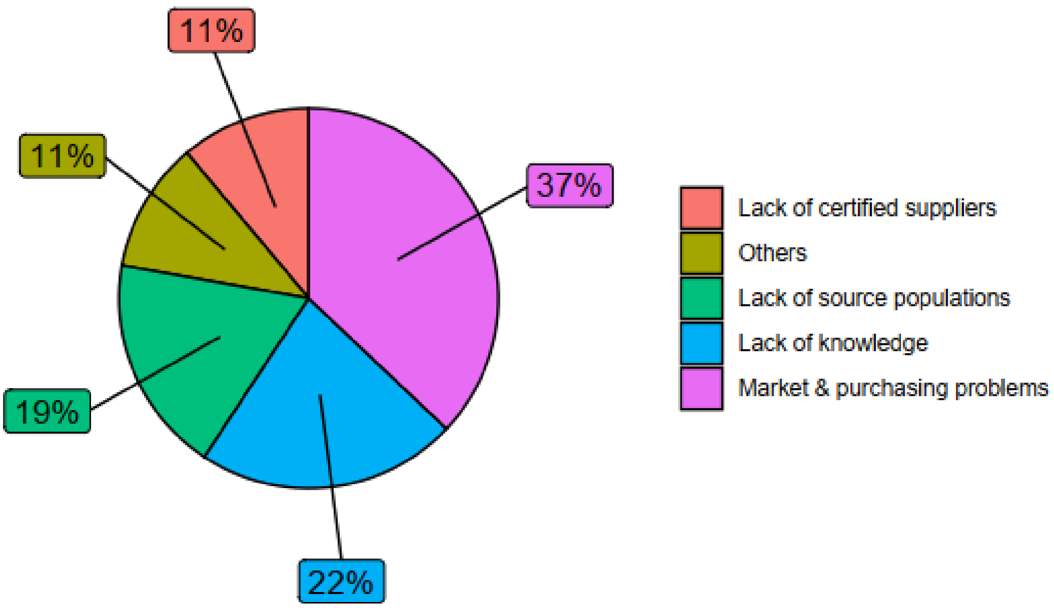

Figure 8. Major seed procurement challenges identified by tree nurseries and seed vendors

Figure 8 highlights the major challenges perceived by survey participants in procuring high-quality tree seeds. The most frequently cited challenge (37%) was the lack of market access, primarily related to the government's bidding-based purchasing system. This was followed by a lack of knowledge and awareness in tree seed collection and handling (22%), and a shortage of good source populations for seed collection (19%). Regarding market issues, respondents expressed concerns that the bidding system allows a few private dealers to dominate the market. These dealers, despite not collecting their own seeds, win bids and then procure any available seed afterward. Respondents attributed this to the government's open bidding system, which doesn't prioritize vendors offering higher-quality seeds but who cannot compete with private dealers on price. They also voiced concerns about corruption, noting that a few regular dealers, leveraging their financial influence, repeatedly manipulate the system to secure winning bids.

DISCUSSION

Native versus Exotic Tree Species

The predominance of exotic species in germplasm distribution for tree planting (Figures 1 – 4) reflects a longstanding preference for fast-growing non-native species over native trees—a trend persisting in current large-scale forest restoration initiatives as well. This preference is largely due to the rapid growth rates typical of exotic species, contrasting with the slower growth and limited silvicultural knowledge available for many native species (Lemenih & Kassa, 2014; Zeleke & Vidal, 2020; Negash, 2021). Although substantial knowledge gaps existed in the domestication, propagation, and management of native trees when exotic species were historically introduced, recent advances in native tree species propagation techniques now offer alternatives (Negash, 2010; 2021). Yet, nurseries and restoration practitioners still primarily rely only on a limited range of exotic species, hindering the practical application of native species. There is no clear direction or legislative support in the country's 10-year national forest development program (MEFCC, 2018) or the Green Legacy Initiative (Fikreyesus et al., 2022; Beyene & Shumetie, 2023) regarding the extent or specific locations for native tree planting. From a restoration perspective, however, native species should be prioritized for their adaptability to local environmental conditions, support for biodiversity, and enhancing essential ecosystem functions (Thomas et al., 2014; Negash, 2021).

The present study also revealed regional and seed center differences in species preferences and germplasm distributions (Figures 2 and 4). For instance, the Bahir Dar seed center's large distribution of *Acacia decurrens* corresponds to its increasing expansion in northwestern Ethiopia, where it is widely used for charcoal making to meet urban energy needs (Nigussie et al., 2020; Chanie et al., 2021). Similarly, larger distributions of *Sesbania* (at Dimma) and *Leucaena* (at EEFRI) seeds likely result from their roles in agroforestry, particularly as fodder and green manure (Lupwayi et al., 1999; Mengistu et al., 2002; Oosting et al., 2011; Lebrazi & Fikri-Benbrahim, 2021).

In southern Ethiopia, *Grevillea robusta* stands out as the most widely preferred species, both in seed distribution and nursery cultivation (Figure 4). Its popularity arises from its versatile applications as an ornamental and commercial tree, used along roadsides, in parks, homesteads, farm boundaries, and woodlots in restoration efforts. Unlike eucalyptus (described below), *G. robusta* has not been linked to severe ecological impacts, making it a favored agroforestry species despite being a nonlegume. It is commonly intercropped with maize and beans on smallholder farms and serves as a shade tree for coffee and tea in East Africa and Asia (Lott et al., 2009; Kehlenbeck et al., 2011; Nesper et al., 2017). However, assessments results on its performance in intercropping are inconsistent; while some report minimal competition with crops (e.g., Bucagu et al., 2013), others describe significant below-ground competition with herbaceous crops (Smith et al., 1999; Lott et al., 2009). Nevertheless, *G. robusta* remains highly valued for its fast growth and commercial appeal—its wood is prized for fuelwood, construction, and timber (Niyomfura et al., 2022; Bhandari et al., 2023), while its contribution to carbon sequestration makes it attractive for environmental service payment schemes like REDD+ (Kiyingi et al., 2016; Owate et al., 2017). Given its widespread planting in Ethiopia, further research into its agroforestry interactions, ecosystem restoration potential, and timber quality could maximize its economic and ecological benefits.

Another notable finding in this study is the distribution of Eucalyptus germplasm (*E. camaldulensis*, *E. globulus*, *E. saligna*, and *E. grandis*), which was minimal across seed centers except at Bahir Dar (Figure 2). Eucalyptus species were neither highly ranked in species preferences by surveyed nurseries and seed vendors in southern Ethiopia (Figure 4) nor commonly found in public nurseries. The cultivation and distribution of eucalyptus seedlings appear to be discouraged in public nurseries, apparently due to ecological concerns surrounding the species. Nonetheless, farmers' preference for eucalyptus plantations remains strong, especially in northern Ethiopia (Jenbere et al., 2012; Molla et al., 2022; Yimam et al., 2024). Most seedlings for these plantations are either produced by the farmers themselves or supplied by private nurseries (MEFCC, 2018; Tesfaw et al., 2022). Eucalyptus's seeds, which lack hard coats and germinate readily without pretreatment or special nursery facilities, enable easy seedling growth and contribute to the widespread plantings. Additionally, the seeds are very small, allowing large numbers of seedlings to be produced from a small quantity of seed (Figure 2B).

Since its introduction to Ethiopian forestry over a century ago, eucalyptus has been both celebrated and criticized (Jagger & Pender, 2002; Abebe & Tadesse, 2014; Jaleta et al., 2016; Negash, 2021). Critics emphasize ecological concerns, including aggressive water and nutrient consumption that outcompetes other vegetation and allelopathic chemicals that suppress plant growth beneath its canopy, often leaving the ground barren, described as "green on top, but Sahara beneath" (Negash, 2021). Advocates, however, highlight its economic importance in meeting Ethiopia's growing wood demand, alleviating poverty, and protecting remnant natural forests. Its rapid growth, resilience, and capacity to provide consistent cash flow make it a favorite among farmers, with some calling it a "living bank account" (Zerga et al., 2021). Consequently, eucalyptus plantations are expanding rapidly, particularly in the Amhara region, where districts like Mecha and Sinan have experienced substantial increases (Tesfaw et al., 2022; Molla et al., 2022; Yimam et al., 2024). Despite its benefits, this unregulated expansion poses risks to farmland productivity, food security, and ecological balance, underscoring the need for policies to balance economic gains with environmental sustainability (Bazzana et al., 2021; Alemayehu & Melka, 2022).

Seed Procurement Practices and Genetic Considerations

The survey results revealed that the tree seed procurement system is plagued by noncompliance with quality standards, with most nurseries relying on outsourced seeds with little passport data. Open bidding prioritizes low cost over quality, allowing private dealers to outcompete cooperatives whose members are trained in seed collection. Additionally, licenses issued by non-forestry authorities fail to address the unique needs of tree seed supply, resulting in unregulated participation by uncertified suppliers. This lack of regulation undermines the delivery of high-quality, certified tree seeds essential for successful restoration initiatives.

The results of this survey also indicated that seed dealers frequently overlook essential guidelines for genetic diversity in seed collection, such as those from ICRAF (Kindt et al., 2006) and the Royal Botanical Gardens, Kew (2003). These standards recommend collecting seeds from a minimum of 30 mother trees spaced 50–100 meters apart to reduce inbreeding and ensure genetic diversity. Although it is generally advised to collect small amounts of seeds from many trees rather than large quantities from a few (Rogers and Montalvo, 2004; Bozzano et al., 2014), this practice was not observed among the surveyed vendors. The neglect of these principles may stem from inadequate training or intentional oversight, as regulatory or incentive mechanisms for promoting high-quality seed collection are absent.

Germplasm collected through such practices is often inbred or lacks genetic diversity, which is essential for successful restoration. Seeds of low genetic diversity tend to produce seedlings with limited adaptation, potentially leading to higher mortality, slower growth, and reduced reproductive success over time (Rogers & Montalvo, 2004; Broadhurst et al., 2008; Broadhurst & Boshier, 2014; Thomas et al., 2014). Restoration projects that rely on germplasm from a few parent- trees risk establishing founder populations prone to inbreeding, ultimately reducing fitness in subsequent generations (Broadhurst & Boshier, 2014). Maintaining higher genetic diversity is especially important for restoration sites, which often face challenges like poor soil or low moisture, where inbreeding depression may intensify under such stressful conditions (Fox & Reed, 2010; Thomas et al., 2014; Sandner et al., 2021).

Current large-scale forest landscape restoration initiatives in Ethiopia (Kassa et al., 2022) are likely to face these challenges due to germplasm sourcing practices that capture potentially inbred and low-quality seed. This should be critically evaluated as the use of low genetic quality germplasm affects the success of both current and future restoration attempts. Forests established today are likely to become seed sources for future restoration activities. The Ethiopian Forestry Development (EFD) and other authorities leading restoration initiatives should devise policies, action plans, and regulatory frameworks to ensure the use of high-quality germplasm in restoration projects.

Some efforts are indeed underway to address these challenges, such as those by the EFD and the Provision of Adequate Tree Seed Portfolios (PATSPO) project, which is funded by the Norwegian government and implemented by ICRAF in Ethiopia (https://worldagroforestry.org/project/PATSPO-II). In partnership, the EFD and PATSPO have established a national Tree Seed Network (TSN) to create an effective tree seed system supporting the supply of quality tree seed for restoration efforts in Ethiopia (https://tss.epa.gov.et/ts-devt). However, the implementation of standards promoted by the TSN has largely failed to reach the grassroots level among seed vendors, nurseries, and other participants in the tree seed system. For example, the TSN has developed seed standards for about 30 tree species, specifying requirements for inspecting source populations, seed collection, physical characteristics, seed test results, and labeling. Unfortunately, stakeholders surveyed in this study were often unaware of these standards. Additionally, although TSN intends for seed provision to be done by network members, these practices were not widely followed in seed procurement processes surveyed. For instance, seed cooperatives included in this survey, which were organized by the southern Ethiopia tree seed center (a TSN member), were largely outcompeted by private seed dealers in the market despite providing better quality seed.

To ensure that high-quality germplasm reaches nurseries and that robust seedlings capable of adapting and sustaining on restoration sites are planted, the EFD and PATSPO should work to implement these standards at the grassroots level. Seeds should be collected and procured following these standards, and provided to the market only by certified seed suppliers who are TSN members. Additionally, introducing niche or specialty markets exclusively for certified suppliers could incentivize quality, offering a better alternative to the current open bidding system.

CONCLUSIONS

This study revealed that genetic principles in species selection and germplasm procurement are largely overlooked in current large-scale forest landscape restoration initiatives in Ethiopia. Survey results showed that few exotic species, such as *Grevillea robusta*, *Acacia decurrens*, *Eucalyptus spp*., and *Cupressus lusitanica* dominate seed distributions and nursery preferences, with native species notably underrepresented. Seed procurement practices also fall short of adhering to standards and guidelines that ensure the capture of intraspecific genetic diversity available in seed source populations. Tree seeds are often collected randomly from any available tree, disregarding standard requirements such as the minimum number of mother trees needed for a single seed collection and the minimum isolation distance between two adjacent mother trees to avoid inbred seed collection. The seeds also lack proper labels (passport data), making it impossible to trace them back to the source populations and match the afforestation sites with seed provenances. These practices risk the loss of evolutionary adaptive potential associated with genetically diverse seeds, which is crucial for survival and long-term sustainability of restoration projects.

These suboptimal practices in sourcing genetic material for forest restoration initiatives call for the EFD and other relevant authorities leading the restoration initiatives to devise policies and regulatory instruments that increase the share of native species in restoration projects and ensure the procurement of high-quality tree seeds. For seed sourcing, this includes strict inspection to ensure seeds are collected and distributed following set standards, and making sure only certified seed dealers participate in the seed market. To facilitate this, the EFD should seek authorization to license and regulate seed dealers, enabling stricter enforcement of compliance and greater control over seed quality. Additionally, the EFD needs to undertake assessments on the performance of restoration projects, including survival, growth, and genetic diversity studies comparing natural forest populations with those in restoration plantations.

CONFLICTS OF INTEREST

Authors declare that they have no conflicts of interest regarding the publication of this paper in the Journal of Science and Development.

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