UNIVERSITY OF COPENHAGEN

MSc in Global Forestry
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Integrating Genetic and Livelihood Analysis in Assessing the Success of Restoration Activities: Case of Two Vachellia Species and the COPERWI Seed Cooperative in Rwanda

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ABSTRACT

This thesis investigates how to evaluate the success of restoration using biophysical and socioeconomic variables. Two native species, *Vachellia sieberiana* and *Vachellia kirkii,* endemic to Rwanda, were used for genetic assessment, and the potential socioeconomic impact was assessed utilizing a case study of active members of a seed cooperative who are mainly local farmers. The two complementary components first examined the breeding seed orchards (BSOs) of this research area. Using principles of quantitative genetics, the study evaluated the height for genetic variation present within and among native family populations. Then the second component investigates the baseline income-generating activities of farmers in the seed cooperatives to assess the livelihood quality of seed collectors and their household income.

The total height of all families was measured six months after planting at the three trial sites, and Pearson correlation coefficients were used to evaluate family stability. *Vachellia sieberiana* correlations were moderate: Site 2 and Site 3 ($r = 0.69$), Site 1 and Site 3 ($r = 0.66$), and Site 1 and Site 2 ($r = 0.65$). They showed consistent performance across sites, although environmental variation likely influenced family performance rankings. For *Vachellia kirkii*, Site 2 and Site 3 showed a strong correlation ($r = 0.84$), indicating stable performance under similar site conditions. Weaker correlations for Site 1 and Site 2 ($r = 0.43$) and Site 1 and Site 3 ($r = 0.42$) reflected greater environmental differences and more variable genetic expression. The interviews also indicated that seed collection offered a small yet dependable addition to household income, and participation in these activities was influenced both by the division of labor between men and women and by the ease of accessing seed sources. These support the need for restoration programs to link genetic performance monitoring with measures that address the economic realities of collectors. Raising seed prices to better reflect the time and effort involved, along with expanding market opportunities, could improve earnings for participants while still supporting restoration targets.

Keywords: restoration, tree seed system, seed cooperative, quantitative genetics

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List of Abbreviations

AFR100 : African Forest Landscape Restoration Initiative

BSO: Breeding Seed Orchard

FLR: Forest and Landscape Restoration

G × E : Genotype-by-Environment

MAP: Mean Annual Precipitation

NTSC: National Tree Seed Centre

RFA: Rwanda Forestry Authority

RWF: Rwandan Franc

TREPA: Transforming Eastern Province through Adaptation project

CHAPTER ONE

1.0 Introduction

Across many regions globally, efforts to restore degraded ecosystems are increasing due to rising concerns over biodiversity loss, climate change, and rural vulnerabilities. Rwanda, which has committed to restoring 2 million hectares of deforested and degraded land by 2030 under the AFR100 and Bonn Challenge initiatives, is investing heavily in forest and landscape restoration (Lal et al., 2020, Gichuki et al., 2019). . Achieving successful long-term restoration requires benefits for both the environment and local communities.

An essential component of any effective restoration is the use of appropriate planting materials, primarily genetically. Native tree species that are well adapted to local conditions have greater chances of success and can help sustain ecosystem stability (Oliver et al., 2015). Nevertheless, within species, there can be significant differences in traits such as seedling height and growth rates, which are influenced by genetics and environmental factors. Recognizing this intraspecific variation is essential for restoration in different landscapes (Broadhurst, 2012). Trees like *Vachellia kirki*i and *Vachellia sieberiana*, occurring naturally in Eastern and Southern Africa, are gaining recognition for their ecological and socioeconomic importance. These trees are well known to improve soil fertility through nitrogen fixation and offer fodder, a good fuelwood source, and shade for animals (Sade, 2018). In Rwanda's Eastern Province, these species are used in reforestation projects due to their resilience in dry environments and are currently established in a restoration trial site to serve as a future seed source. However, their genetic performance within and among families at different sites is not yet known. As restoration scales up, understanding how these species perform under various conditions and whether they possess enough genetic variation to adapt and thrive becomes increasingly essential.

At the same time, restoration has the potential to improve rural livelihoods, but only if local people are meaningfully involved. Many different organizations support the national programme on Forest Landscape Restoration in Rwanda. More than 56 million seedlings are planted every year.

This is a very impressive investment in improving the livelihoods of the rural and urban populations in the country.

In Rwanda, tree seed is collected, in part, through cooperatives such as COPERWI, which supplies native seed to the national tree seed center (NTSC). These cooperatives give rural farmers a way to earn income outside the main farming or other activities seasons. However, the seed collection process in Rwanda remains underexplored in the literature. How profitable is it for those involved? How does it fit with other livelihood activities? And what challenges do seed collectors face seasonally or economically?. As global restoration efforts like the AFR100, Bonn Challenge, and UN Decade on Ecosystem Restoration grow, it's essential to have strong and clear tree seed systems to meet demand and ensure genetic quality. It is important to stress the need for strong tree seed systems to protect genetic diversity and make ecosystems more resilient. These will be significant for ensuring that native species are included in new or upcoming restoration projects.

This research, therefore, critically examined two key aspects of restoration success, focusing on the performance of the two native Vachellia species and the seed collection experiences of members of the COPERWI cooperative in Eastern Rwanda. By integrating genetic analysis and livelihood data, this study offers a more comprehensive understanding of what makes restoration effective, not just in theory but also in practice.

1.1 Importance of Genetic Diversity in Successful Restoration

Genetic diversity is an important foundation for any successful forest and landscape restoration program. It ensures that planted tree populations can survive, adapt, and remain productive when conditions change, whether due to climate variability, pests, or disease outbreaks (Jalonen et al., 2018; Hoban et al., 2018), For species like Vachellia, which contribute to improving soil fertility, providing fodder, and supporting broader ecosystem functions, preserving a wide genetic base is essential for conservation.

Despite the importance of genetic diversity, seeds commonly used in restoration in sub-Saharan Africa, including Rwanda, are usually from poorly documented sources. Global assessments highlight common challenges such as limited seed availability, absence of provenance records, and low genetic diversity, which can hinder restoration success (Jalonen et al., 2018). Seed systems are identified as informal, which results in limited quality control and reduced genetic diversity (Giacomini et al., 2023). Without comprehensive provenance data such as geographic origin, parent tree identity, and collection date, it's challenging to ensure that the seed is comes from both locally adapted and genetically diverse stands. This leads to the risk of maladaptation, inbreeding, and diminished long-term resilience (Oliver et al., 2015; Nevill et al., 2016).

Breeding seed orchards (BSOs) address many of these challenges. These are plantations of carefully selected parent trees designed to produce genetically improved and consistently high-quality seed for reforestation, agroforestry, and restoration programs. Parent trees, often referred to as plus trees, are chosen for traits such as growth, desirable stem form, and resistance to pests, diseases, and environmental stresses (Neale and Kremer, 2011; Kang et al., 2o24). BSOs may be established as clonal orchards, using vegetative propagation of selected genotypes, or as seedling orchards, using sexually reproduced seedlings from controlled or open-pollinated families.

For this study, the Vachellia BSO was established by the Transforming Eastern Province through Adaptation (TREPA) program under CIFOR–ICRAF through collaboration with RFA (Lillesø and Ngethe, 2023). The orchard contains multiple families planted in structured blocks, making it possible to track seed origins and evaluate performance for traits such as height growth and survival. This structure helps deliver genetic improvements and also safeguards diversity, ensuring that the seed source remains resilient to future environmental changes (Hoban et al., 2018; Jalonen et al., 2018).

It will take several years before the orchard produces seed at a large scale. Until then, restoration programs must rely on interim sources, such as managed seed production areas and carefully documented wild stands. Using only sources with reliable provenance information during this period is essential to avoid narrowing the genetic base and to ensure compatibility with the improved material that will come from the orchard (Nicodemus, 2025; Jalonen et al., 2018).

Once the Vachellia BSO reaches full maturity, it will offer a steady supply of high-quality, site-adapted seed. This will reduce dependence on opportunistic and poorly documented collection, improve the traceability of planting material, and help Rwanda meet both its ecological restoration targets and the livelihood needs of local communities.

The examined species for this study, *Vachellia kirkii* and *Vachellia sieberiana* BSOs, are found in the Nyagatare in the eastern province map in Figure 3. Both are known to be important tree species of the rural people in this district's environment, both economically and socially, as described by Sade. (2018). There isn't much research on their genetic diversity in Rwanda, especially within the same family. Therefore, this research evaluates genetic variation in families as seen in height, including the variation in trials during the early stages of orchard development.

1.2 Importance of Seed Collection and Its Livelihood Impact

This section describes how seed cooperatives function and their role within Rwanda's broader tree seed system. It explains their role in seed collection, handling, and supply, and how they are structured to support restoration and reforestation efforts.

1.2.1 Rwanda's Tree Seed Center (RTSC)

The National Tree Seed Centre (NTSC) was first established in 1993 as the national authority for forest reproductive material certification when Rwanda joined the OECD Forest Seed and Plant Scheme (Kuhlmann et al., 2025). Its operations were disrupted by the 1994 conflict but were restored in 1995 through the Seeds of Hope initiative led by CIAT with support from ICRAF, CSIRO, and other partners. Since then, it has been under Rwanda's forestry administration, now overseen by the Rwanda Forestry Authority (Kuhlmann et al., 2025)..

The tree seed center's core activities involved procuring, verifying viability, storing, and distributing seeds for reforestation, agroforestry, and ecological restoration. As a section under the Rwanda Forest Authority (RFA), it ensures that there is a constant supply of seed when necessary for successful projects on tree planting, ecosystem restoration, and reforestation. These structures hold much importance in the seed sector, where infrastructure for seed access, quality control, and record-keeping is inadequate or absent. Restoration practitioners may end up using planting material that is not well-adapted or lacks genetic diversity, which can reduce both the effectiveness and longevity of restoration efforts (Zinnen et al., 2021).

The RTSC establishment of this sector is essential to the success of restoration efforts. It has the purpose of quality control in practice, seed processing, and the coordination of tree seed distribution in Rwanda. The system is still evolving with challenges linked to document for tree seed systems in Africa, including the need to manage many species with different phenology (Lillesø et al., 2018). Compared to crop seed systems (CSS), tree species take several years to reach reproductive maturity, which delays seed availability. Managing numerous species, each with distinct flowering and fruiting cycles, adds to the complexity. Other literature identified variations in climate, soil, and other site conditions, making it challenging to maintain consistent seed quality and supply (Lillesø et al., 2011; Atkinson et al., 2021).

Recent Rwanda sector reviews under the TREPA programme report that informal and small-scale channels often run by cooperatives provide an important share of planting material but are weakly documented and only partially linked to national reporting; they also highlight capacity gaps in provenance choice and genetic quality assessment (Lillesø and Ngethe, 2023). At broader scales, studies show that restoration outcomes are frequently constrained by limited access to high-quality seed and by seed sourcing that does not match site conditions (Jalonen et al., 2018; Lillesø et al., 2018). These findings point to the need to strengthen both technical and institutional components of Rwanda's seed system to support restoration and rural livelihoods.

1.2.2 Why Seed Cooperative?

The Rwanda seed cooperatives serve as an important group supporting the operations of the national tree seed center. They collect, handle, and deliver tree seeds in an organized way for restoration and afforestation projects. Most cooperative members are local community residents (Nduwamungu et al.,2025; Mugabo, 2024). Cooperatives have been known to work with NTSC for many years. RFA records show that in 2007, after decentralization, seed collection duties were moved from government staff to farmer cooperatives, promoting training for these cooperatives and encouraging them to follow simple seed collection procedures such as straight boles, free from pests and diseases, among others (Lorenzo, 2017).

The TREPA project, funded by the Green Climate Fund and led by IUCN in collaboration RFA, has expanded on this system. One of TREPA's priorities is to improve the country's tree seed and seedling supply by building the skills and capacity of both the NTSC and the cooperatives that collect seed for it (Lillesø and Ngethe, 2023). According to the TREPA seed-sector review, RFA has formal agreements with ten cooperatives to collect seed for the NTSC. This arrangement was put in place in 2019 and is shown in a location map in Figure 1 (Lillesø and Ngethe, 2023).

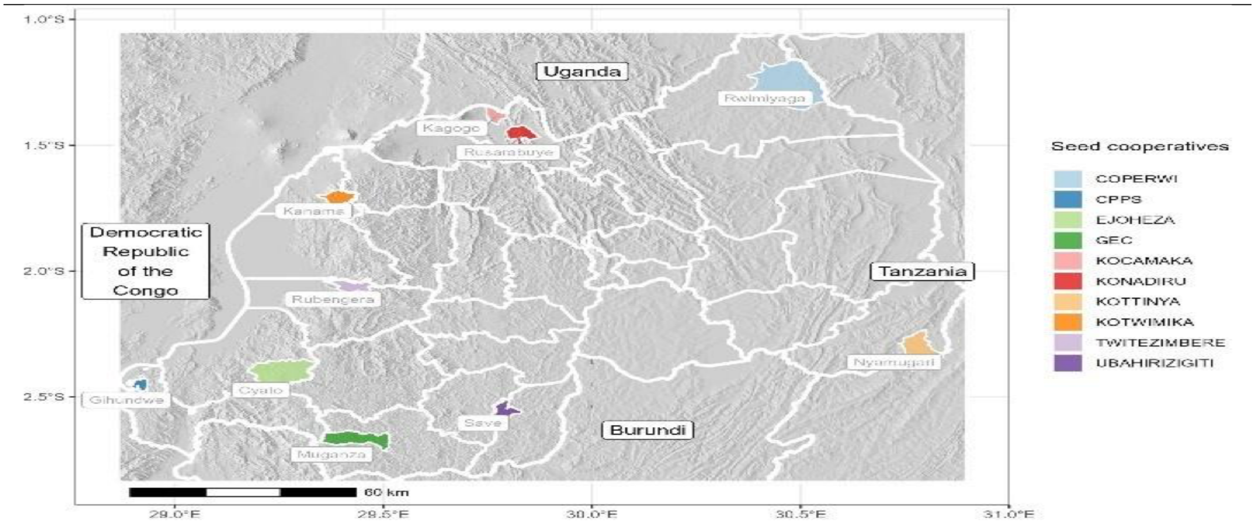

Figure 1. Map adapted from the TREPA Seed Cooperative Reviewin Rwanda (Lillesø and Ngethe, 2023)

In Rwanda, seed cooperatives play a central role in linking livelihoods with national restoration programmes. They coordinate the work of local collectors and supply seeds to the National Tree Seed Centre, while the RFA, with support from partners such as CIFOR–ICRAF, offers training, oversees quality, and provides overall guidance (Ouedraogo et al., 2024). The membership for seed cooperative is usually open to anyone within the community who is willing to join, which has encouraged participation from smallholder farmers.

During the discussion with the COPERWI members, the benefits were clearly stated, but so were its challenges. These collectors described the unavailability of proper harvesting tools and market demand for certain tree species. These issues affect both the quality of seeds delivered and how much members can rely on seed collection for income. Broader seed-sector assessments in Rwanda confirm that informal networks still dominate the market in terms of crop system which is the same for the seed system, with recent figures from the southern province showing that more than 60% of farmers get their seed through these informal channels (Muhizi et al., 2024; Ouedraogo et al., 2024). Strengthening cooperatives by improving skills, equipment, and market access would not only help secure better quality seed for cropping but also forest restoration that will enable seed collection a more dependable livelihood for rural households.

1.3 Objectives and Hypotheses

The biological and socioeconomic aspects of afforestation in Rwanda were examined by combining genetic analysis of two Vachellia species with an assessment of the livelihood, to understand how restoration efforts can be both ecologically sustainable and socially beneficial.

1.3.1 General and specific objectives

The general objective of this research is to evaluate factors affecting climate-smart afforestation in Rwanda. While the specific objectives are:

1. To evaluate the genetic variation in breeding seed orchards of *Vachellia kirkii* and *Vachellia sieberiana*
2. To assess how participation in the seed collection of tree species influences the livelihoods of local farmers, including income levels and socioeconomic stability.

1.3.2 Hypotheses and research questions

Building on the background and objectives of this research, the study is guided by two main hypotheses. That is,

1. H_1: There is considerable genetic variation within both Vachellia species in the Breeding Seed Orchard (BSO).
2. H_2: By collaborating in cooperatives to collect seed for restoration programs, rural people benefit by increasing their household income.

To guide the analysis and contribute practical insights to reforestation strategies in Rwanda, this study addresses the following research questions:

1. What are the heritability estimate variations observed in height?
2. What percentage increase is observed in the income? (per day or annum and compare with the minimum wage, due to seed collection activities)

CHAPTER TWO

2.0 Materials and Methods

This chapter outlines the methods used to investigate the objectives of this study. The first part detailed the procedures for evaluating the genetic variation in the BSOs of *Vachellia kirkii* and *Vachellia sieberiana* to assess their diversity and performance. The second part describes the approach used to assess how participation in the seed collection of tree species influences the livelihoods of local farmers, including income levels and socioeconomic stability.

2.1 BSOs Site Description and Environmental Variables for Genetics Analysis

The total of 56 half-sib families for *Vachellia kirkii* and 63 for *Vachellia sieberiana* were sampled. To capture environmental variability, field trials were established in November 2024 at three different locations per species. *Vachellia kirkii* trials were planted at Gatsibo (Gahoko), Gatsibo (Ntete), and Kirehe. While *Vachellia sieberiana* trials were established at Gatsibo (Gahoko), Gatsibo (Ntete), and Kayonza, resulting in six trials in total. Each trial followed a fully randomized block design with 10 blocks per site. Half-sib families were randomly assigned to plots within each block and replicated using multiple seedlings per family. Seedlings were spaced at 3 m × 3 m to minimize competition and allow for individual growth assessment. No fertilizer or irrigation was applied after the initial establishment phase. This design permitted seedling performance to reflect their natural genetic potential under conditions influenced by local soil and climate.

Environmental conditions varied across trial sites as seen in the provenance data, especially for *Vachellia kirkii*, seeds were from different locations with notable differences in soil texture (clay: 372–403 g/kg; sand: 350–408g/kg), soil pH (60–62), and mean annual precipitation (MAP: 825–877 mm). While *Vachellia sieberiana* families were collected from a single location in eastern Rwanda, (clay: 373–436 g/kg; sand: 383–435 g/kg), soil pH (59–61) and mean annual precipitation (MAP: 842–875mm). The trial sites were seen to cover a range of soil types from Umbric Leptosols to Dystric Regosols and drainage classes from poorly to moderately well-drained. These variations created an environmental gradient suitable for assessing the stability of genetic performance across sites.

2.1.1 Research species

The first species studied is *Vachellia kirkii*, which is known as umukinya in Rwanda and is commonly called the floodplain acacia. It grows naturally along seasonal rivers and floodplains. It has been shown to perform well on alluvial soils that occasionally become waterlogged. It is crucial for maintaining riverbank stability, enhancing soil fertility, and supporting healthy riparian ecosystems (Mugunga et al., 2021).

The second species is *Vachellia sieberiana*, a strong, fast-growing leguminous tree that thrives in many soil types, but it does best in well-drained loams in areas with moderate to low rainfall. It is also known as umunyinya and the paperbark acacia. Farmers and herders in Rwanda see the tree as highly valuable because it enhances soil fertility through nitrogen fixation, which benefits agroforestry, reduces erosion, provides fodder during dry seasons, and offers shade for livestock and crops (Githae et al., 2007). Both species are important to rural life in more ways than just their ecological roles. People use their bark for animal feed, traditional medicine, and various household uses. However, factors such as overgrazing, leaving fire patterns, and land conversion have altered their distribution and abundance in some areas.

2.1.2 Measured Trait

Plant height was the variable assessed and was used as an indicator of early growth performance. Measurements were conducted in May 2025, approximately six months after planting. Height was measured in centimeters from the base of the seedling at ground level to the tip of the terminal shoot using a standard measuring tape. This trait was selected due to its relevance in evaluating initial seedling vigor under natural growing conditions.

2.1.3 Quantitative Genetic Analysis and Cross-Site Correlation

Each of the six trials was analyzed independently to estimate variance components and narrow-sense heritability (h^2) for total tree height. All statistical analyses were performed using R (version 4.3.0).

Variation in height Model: $Y_{ijk} = \mu + B_i + F_j + \varepsilon_{ijk}$ (equation 1)

Where: Y_{ijk} is the height of the k^{th} Individual from the j^{th} Family in the i^{th} block

μ is the overall mean

B_i is the fixed effect of the i^{th}block

F_j is the random effect of thej^{th} Family and

ε_{ijk} Is the residual error term.

ANOVA was conducted using a linear model. Variance components were estimated using the expected mean squares method. Additive genetic variance (V_A) was derived from the family mean squares, and narrow-sense heritability (h^2) was calculated as shown below:

$$V_A = 4 \times \left[\frac{(MS_{family} - MS_{residual})}{n_{rep}}\right], \qquad V_P = V_A + MS_{residual} \quad \text{and} \quad h^2 = \frac{V_A}{V_P}$$

Where;

MS_{family} refers to the mean square attributed to family effects,

$MS_{residual}$ represents the residual mean square,

n_{rep} denotes the number of individuals assessed per family, and

V_P is the total phenotypic variance.

2.1.4 Correlation Analysis Across Sites

To assess the consistency of family performance across environments, Pearson correlation coefficients were calculated using R (version 4.3.0). For each species, mean seedling height per family was computed at each trial site. These values were used to generate a correlation matrix comparing family-level growth performance across sites. This analysis was conducted to evaluate the stability of early growth across different environments if families were consistently performing for height across sites. A strong positive correlation indicates that families performed consistently across sites, while weaker correlations would imply a greater influence of environmental variability on growth performance.

2.2 Case Study Description and Livelihood Variables for Socioeconomic Analysis

This section describes the selected seed cooperative, its operational context, and the livelihood variables assessed for socioeconomic analysis.

2.2.1 Case Study Description

COPERWI seed cooperative was established in 2020, comprising a total of 42 members, of whom 19 are female and 23 are male. It is located in Nyagatare, part of the eastern province. The eastern province has two zones, with the COPERWI cooperative in zone 1. Zone two mainly covers Kirehe, Ngoma, Rwamagana, and Bugesera, while zone one includes Gatsibo, Kayonza, and Nyagatare districts. The figure below shows the Iburasirazuba province and the subdivision (districts):

Map ID	Name
1	Nyagatare
2	Gatsibo
3	Kayonza
4	Rwamagana
5	Ngoma
6	Kirehe
7	Bugesera

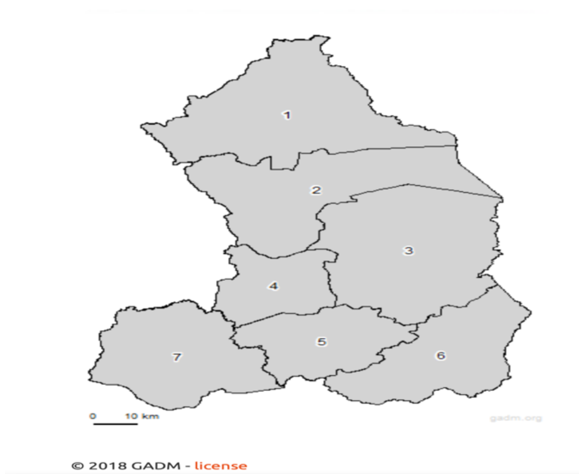

Figure 2. District division of the Eastern province of Rwanda. *source data from GADM*(GADM.ORG)

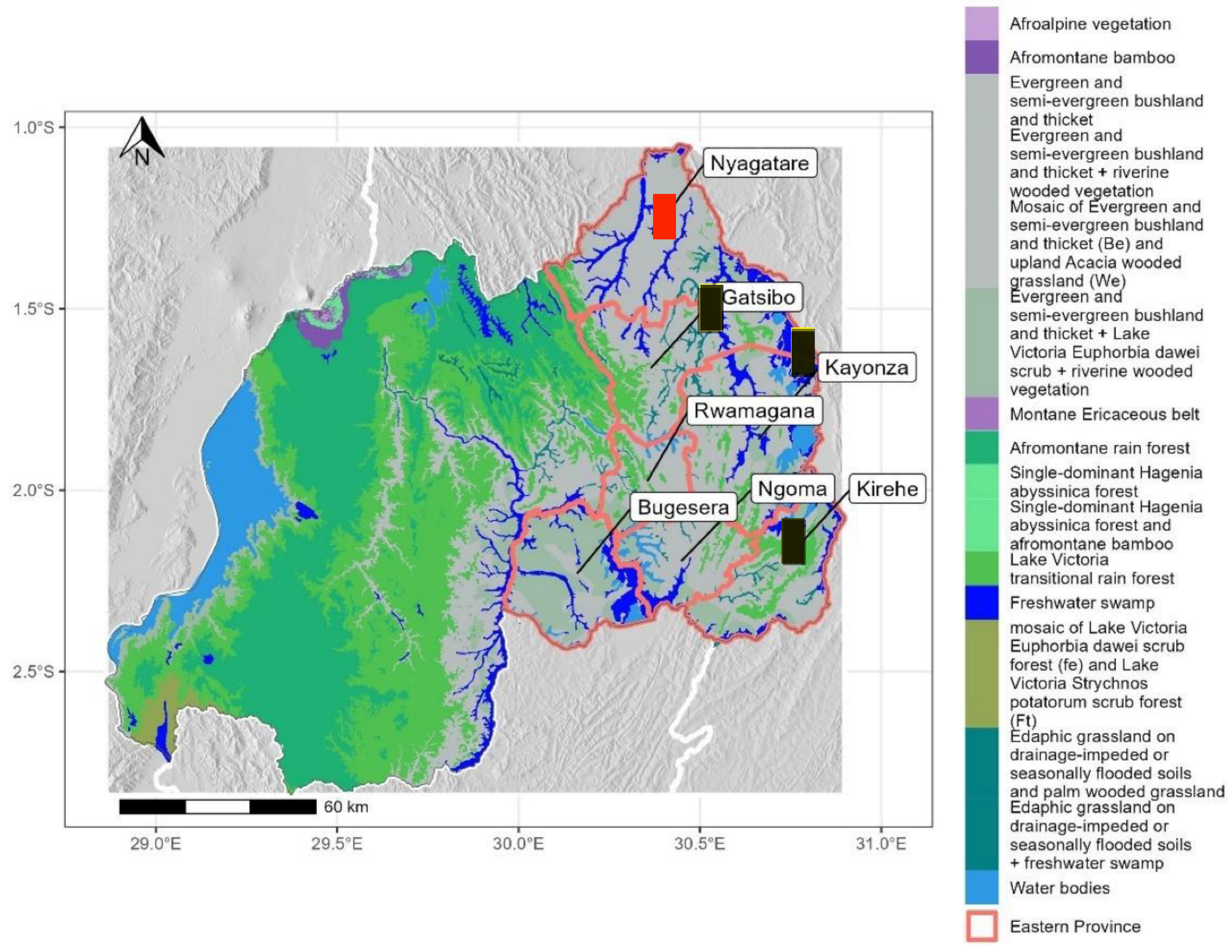

Figure 3. Map of Rwanda showing the eastern province. The BSOs are in black and the COPERWI cooperative is red. source map. Ouedraogo et al. (2024)

COPERWI is a community-based cooperative that brings together people with limited means to work collectively in activities that can improve income and create jobs. Interviews were held with 16 members who were available at the time of this fieldwork. Seven of the people interviewed were women, and nine were men, and most combined seed collection with other activities.

2.2.2 Livelihood Description and Case Study Members' Baseline Activities

Figure 4. shows the picture taken during this fieldwork visit. COPERWI Mushroom Bed. Local seed collectors are sorting out seeds and soap production as a group.

In the rural economy of Nyagatare District, most people make a living by farming small plots of land, often combining crop growing with raising animals. Interviews with cooperative members revealed that farm sizes vary from 0.5 to 5 hectares, either through leasing or inheritance. The main crops that are grown include maize, beans, and cassava, among others. For many farmers in Nyagatare District's rural economy, collecting seeds is a way to make extra money. Most people make a living by farming small plots of land, which generally means growing crops and raising animals. The activities differed by gender and age, with women predominantly engaged in subsistence production and men frequently active in labor markets or cooperative endeavors.

Seed collection is a seasonal but important source of supplementary income, undertaken mainly by members of cooperatives recognized by as shown in Figure 1. Collection is carried out from designated mother trees, following NTSC instructions such as straight stem form and fully mature fruit. While it forms part of the broader livelihood system as both an income-generating and community-based activity, several challenges were identified during this study.

2.2.3 Livelihood Analysis Variables

To achieve the second research objective, an interview survey was made using KoboToolbox, and data were also recorded to explore how participation in seed collection impacts household livelihoods in Nyagatare District. The interview questions in the appendix focused on participants' livelihood profiles, such as their farm size, types of species collected, and other income sources, and timing of other activities. These questions are aimed at understanding broader income-generating activities and to identify periods of overlap or conflict with different activities.

Part of the questions addressed seed value, proximity, and different species collected for market price comparisons, benefits received, as well as constraints. These questions were used to gather data for income estimation and to evaluate how access to and distance from seed sources influence participation in seed collection. All interviews were cleaned in Excel, transcribed, and examined using thematic analysis in NVivo. This was done by systematically reading through the transcript to identify recurring ideas or issues related to the research objectives. They were grouped into themes, such as constraints in seed collection, benefits of cooperative membership, and the timing of seed activities in relation to other activities. These themes provided a structured way to interpret participants' experiences and link them to the study's objectives, which was important to answer the research questions of this study.

2.2.4 Ethics and Practicality

The dataset for genetic analysis of the Vachellia BSOs was obtained from the TREPA team. Species family information in the orchards had been documented a week before the start of this research. All analyses were performed using the provided dataset with authorized permission.

This research also considered ethical standards for social science fieldwork, ensuring respect, voluntary participation, and confidentiality for all participants in the interview. Before each interview, participants were informed about the study's purpose, their right to withdraw at any time, and that their identities would be kept anonymous. The cooperative president arranged interviews with his members who are willing to participate at a convenient time to avoid disrupting income-generating schedules or household responsibilities. A trained local interpreter assisted in facilitating clear and culturally appropriate communication between the researcher and participants.

Considering TREPA's proactive involvement in delivering technical training to the cooperative and engaging its members in restoration activities, a succinct summary of the study's findings will be communicated to the coordinator after this project. This is to ensure that the results could contribute to ongoing capacity-building initiatives, the project coo, and reinforce the connection between research findings and practical applications

CHAPTER THREE

3.0 Results

This section presents findings from both the biological and social analysis of the study. The first part showed the result on the genetic diversity of *Vachellia kirkii* and *Vachellia sieberiana* in breeding seed orchards, focused on how well these species do and how diverse they are. The second part presented findings on how seed collection activities affected people's livelihood, including how rural populations profited from and got involved in restoration projects through seed collection.

3.1. Genetic Variability

This section presents the findings on the height variable for *Vachellia kirkii* and *Vachellia sieberiana* in the breeding seed orchards. Results on height performance variation among families and across the three trial sites were shown in this section . The subsections that follow provide a detailed breakdown for each species, highlighting patterns of genetic variability and site-related differences.

3.1.1. Genetic Variation in Seedling Height of *Vachellia kirkii*

Heritability estimates and associated variance components for total seedling height in *Vachellia kirkii* are presented in Table 1. In Gatsibo Gahoko and Gatsibo Ntete, narrow-sense heritability values of 0.32 were recorded. Family effects were statistically significant in both sites, with p-values of 2.28×10^{-6} and 9.59×10^{-6}, respectively. In Kirehe, the heritability estimate was 0.04, and the family effect was not statistically significant ($p = 0.113$). Additive variance was highest in Gatsibo Ntete (523.66) and lowest in Kirehe (90.16), indicating genetic expression inconsistency. Residual variance was highest in Kirehe (2137.34), compared to 1177.89 and 1113.02 in Gahoko and Ntete, respectively.

Table 1. Estimates of Narrow-Sense Heritability, Additive and Residual Variance for Seedling Height in Vachellia kirkii Across Three Trial Sites

Research Species	Trials	*n*	mean	*p value*	Additive variance	Residual Variance	Heritability (h2)
Vachellia kirkii	Gatsibo Gahoko	42.00	103.17	2.28352E-06	349.42	757.76	0.32
Vachellia kirkii	Gatsibo Ntete	55.00	113.46	9.5931E-06	523.66	1113.02	0.32
Vachellia kirkii	Kirehe	54.00	104.10	0.113	90.16	2137.34	0.04

3.1.2 Genetic Variation in Seedling Height of *Vachellia sieberiana*

Estimates of narrow-sense heritability (h^2), additive variance, and residual variance for total seedling height in *Vachellia sieberiana* across three trial sites are summarized in Table 2. Heritability values were consistently high across sites, ranging from 0.65 to 0.77. The highest estimate was recorded in Gatsibo Gahoko ($h^2 = 0.77$), followed by Gatsibo Ntete ($h^2 = 0.74$) and Kayonza ($h^2 = 0.65$). All three trials showed highly significant family effects, with p-values below 0.001. The highest additive variance was observed in Gatsibo Ntete (1783.72), while the lowest was in Gatsibo Gahoko (1024.85). Residual variance was lowest in Gahoko (315.30) and highest in Ntete (629.31).

Table 2. Estimates of Narrow-Sense Heritability, Additive and Residual Variance for Seedling Height in Vachellia sieberiana *Across Three Trial Sites*

Research Species	Trials	*n*	mean	*p value*	Additive variance	Residual Variance	Heritability (h2)
Vachellia sieberiana	Gatsibo Gahoko	60.00	66.10	2.28E-06	1024.85	315.30	0.77
Vachellia sieberiana	Gatsibo Ntete	59.00	75.23	5.31E40	1783.72	629.31	0.74
Vachellia sieberiana	Kayonza	59.00	58.33	1.40E-54	1037.15	556.68	0.65

3.1.3 Family Height Variability

This subsection gives a detailed result on the mean height observed for each research species, as shown below

3.1.3.1 *Vachellia kirkii* Family Response to Environment

Mean seedling height varied notably across the three trial sites, as represented in Figure 5. Mean site 2 generally recorded higher values, with several families, particularly Family 29, showing exceptional performance. Families 1, 2, and 21 also stood out for their consistent growth across all sites, indicating strong genetic potential and adaptability. In contrast, some families showed uneven performance. For example, Family 29 performed well at Site 2 but poorly at Sites 1 and 3, illustrating how environmental conditions influenced growth. These patterns observed suggest that both genetics and site-specific factors affected seedling height.

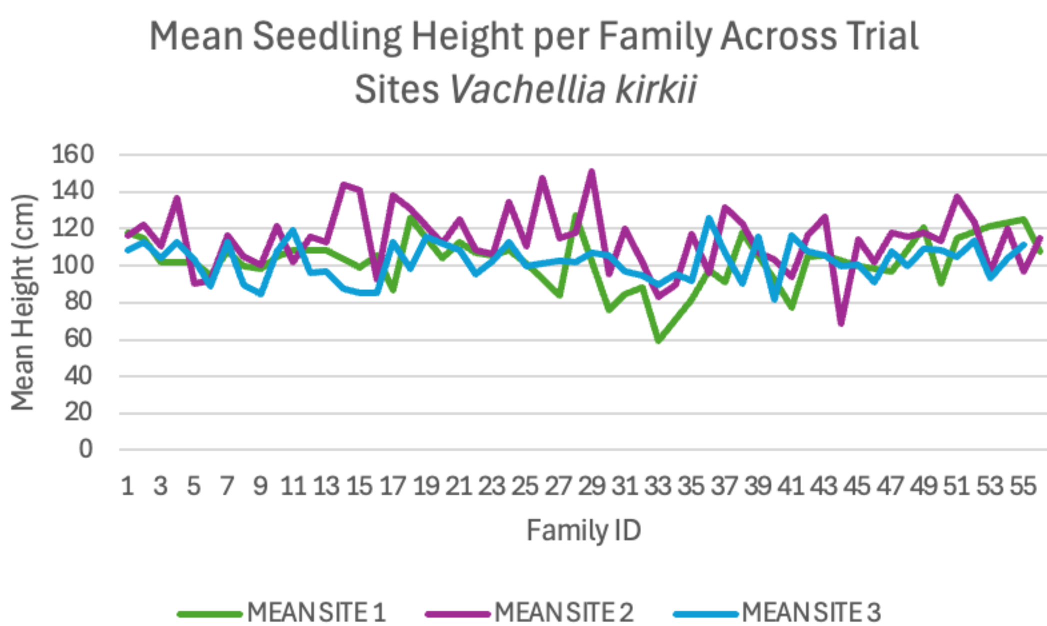

Figure 5 shows the mean height of each family of *Vachellia kirkii*

3.1.3.2 Phenotypic Correlation *Vachellia kirkii*

Pearson correlation analysis (Figure 6) showed a strong positive relationship between Site 2 and Site 3 (r = 0.84), indicating that families tended to perform similarly in these two environments. This suggests that conditions at Sites 2 and 3 may be more alike, allowing genetic potential to be expressed consistently. In contrast, Site 1 showed weaker correlations with both Site 2 (r = 0.43) and Site 3 (r = 0.42), pointing to more variable performance. This reflects environmental differences that make Site 1 more challenging or less predictable for seedling growth.

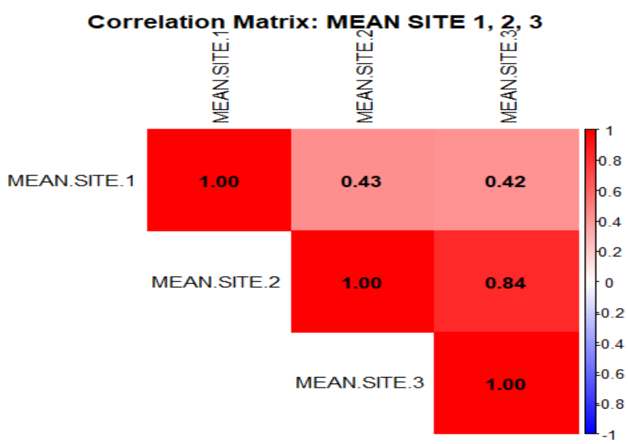

Figure 6 shows the correlation result for Vachellia kirkii

3.1.3.3 *Vachellia sieberiana* Family Response to Environment

The growth patterns of *Vachellia sieberiana* showed clear differences across sites and families in Figure 7. Site 2 supported the tallest seedlings, with some families like 11, 41, 58, and 62 reaching over 100 cm. This suggests that Site 2 provided better conditions for this species to thrive. However, performance across the sites was inconsistent. Many families showed significant height differences from one site to another. For example, Family 13 grew well in Site 2 but much less in Site 3, while Family 31 did the opposite. Some families, like 38, remained fairly average across all sites without major spikes or drops. This inconsistency points to a strong environmental influence. In other words, *Vachellia sieberiana* responds more dramatically to where it's planted. Only a few families managed to perform well across multiple sites, showing the kind of adaptability that could be useful for wider planting.

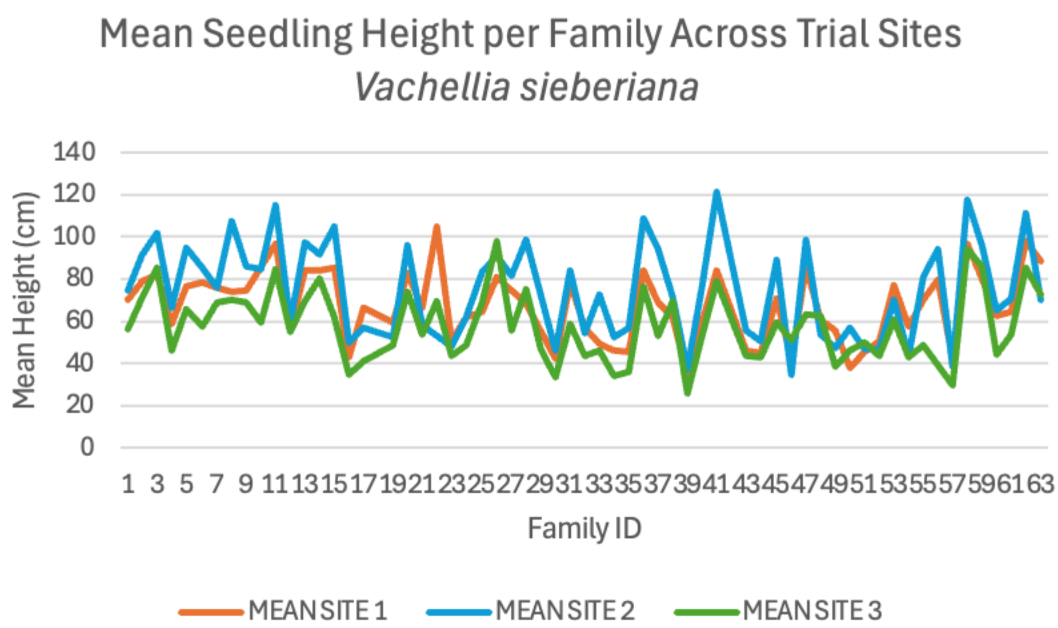

Figure 7 shows Mean height of the family of Vachellia sieberiana

3.1.3.4 *Vachellia sieberiana* Phenotypic Correlation

The results in Figure 8 showed moderate yet meaningful relationships among all site combinations. The strongest correlation was between Site 2 and Site 3 (r = 0.69), indicating that families performing well in one environment generally did similarly in the other. This suggests some environmental similarity or compatibility in how growth conditions affected height. The correlations between Site 1 and Site 2 (r = 0.65) and Site 1 and Site 3 (r = 0.66) were slightly lower, reflecting more variability in family performance at Site 1. This pattern supports earlier observations that Site 1 may have different growing conditions, possibly influencing the expression of genetic potential in some families. These results confirm that while some families maintained stable growth across all sites, others were more sensitive to specific environments. The correlation patterns highlight the importance of testing planting material across diverse locations to identify families with both strong and consistent performance.

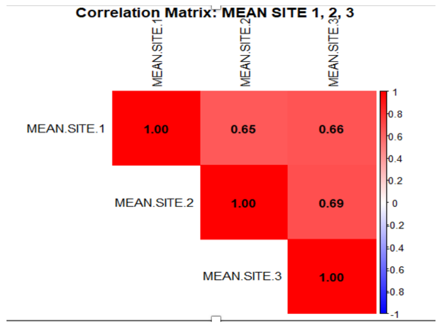

Figure 8 shows the Correlation matrix in Vachellia sieberiana

3.2. Impacts of Seed Collection on Rural Livelihoods

The economic contribution of seed collection was evaluated by comparing household income with other livelihood income sources. Baseline income identified was a reference to determine whether seed collection functioned as a primary or supplementary income. Quantifying both seed collection and baseline income enabled the assessment of its relative importance within household livelihoods and its potential role as a sustainable income-generating activity.

3.2.1 Estimating Seed Collection and Baseline Income

Figure 9 compares earnings from regular livelihood activities with income from seed collection, using data from the 11 respondents who had both sources of income. Participants who relied solely on seed collection were not included in this comparison because there was no secondary income to evaluate. But their earnings were considered later to reflect the full extent of livelihood reliance on seed collection. While baseline incomes varied significantly, with some respondents earning as much as RWF 1,000,000 (approximately USD 710) annually, the situation was different for seed collection. Only four respondents (3, 6, 8, and 10) earned more than RWF 150,000 (about USD 115) from seed, and only two (3 and 10) reached or exceeded the Anker Living Wage benchmark for rural Rwanda at RWF 197,848 (around USD 152) per month as of June 2024 (Anker Research Institute, 2024). For the majority, seed income was less than RWF 60,000, underlining how marginal this activity remains as a source of livelihood; it is far from enough to meet basic living needs or drive long-term economic improvement for most collectors.

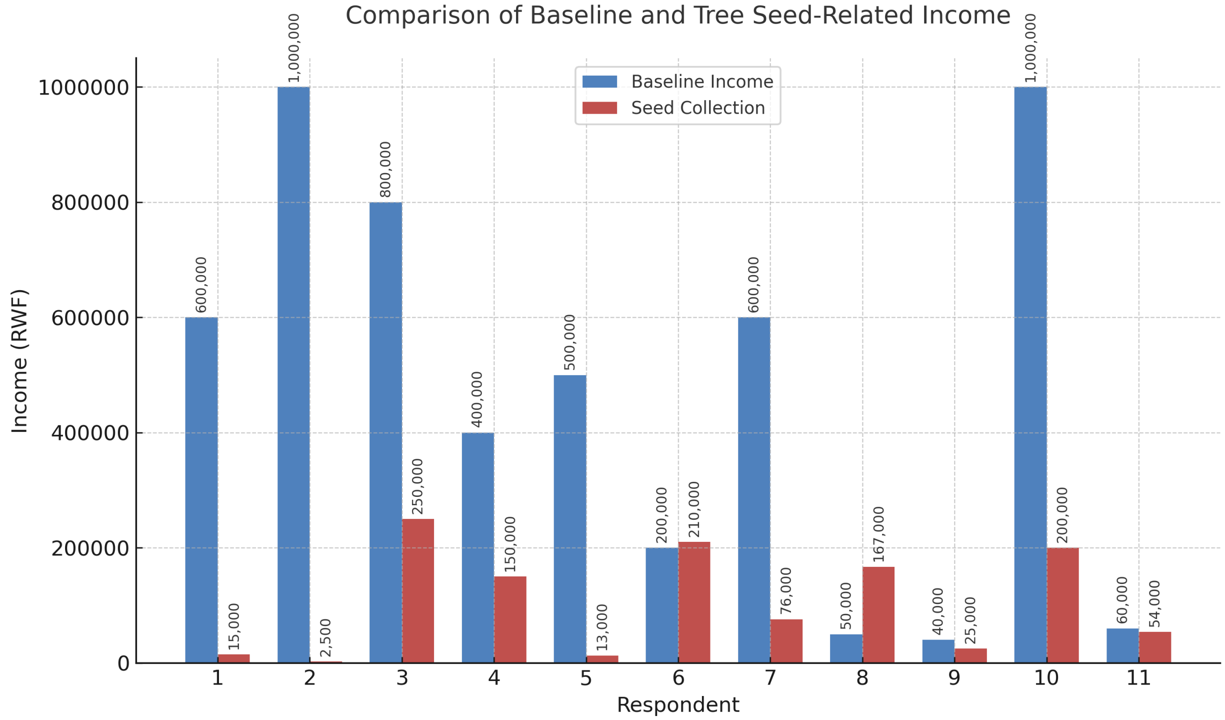

Figure 9 Comparison of Baseline and Tree Seed-Related Income Among Cooperative Members

3.2.2 Overlapping Income Generating Activities

Data on overlapping income-generating activities were collected to determine whether seed collection coincided with other livelihood sources and to assess its relative importance within the household, as shown below:

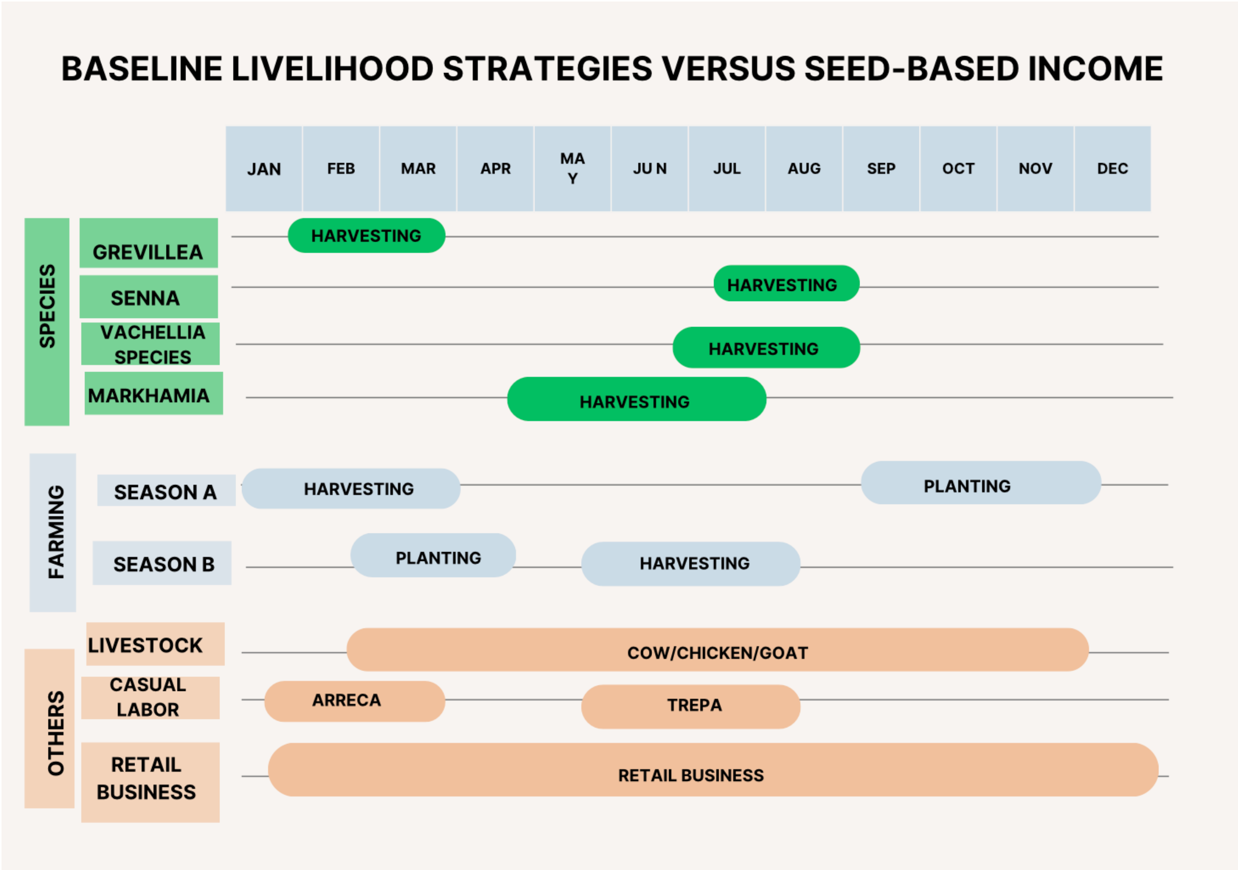

Figure 10. Seasonal calendar of seed harvesting, farming activities, and other income sources for 2024, as reported by participants during the 2025 field survey

The seasonal calendar above (Figure 10) illustrates various activities in a year. It shows that seed harvesting for this research species, *Markhamia lutea* and *Senna spectabilis,* mainly happens from February to September, covering the end of Season A and most of Season B. In Season B, seed collection usually coincides with labor-intensive agricultural activities such as planting, weeding, and crop harvesting, requiring households to divide their time between farming and seed collection. Beyond farming, respondents also engaged in small-scale trade, casual labor, and livestock rearing, which added further competition for labor. In August–September, when farming activities ease, Senna spectabilis and Vachellia species continue to be harvested. However, income records from this study show no marked increase in earnings from seed collection during this period. This indicates that although seasonal overlaps impact the duration of seed collection, they are not the only factor influencing participation, but also the order made by NTSC and access to seed sources play a crucial role in how households prioritize seed collection alongside other livelihood activities.

3.2.3 Species Collected and Market Value

Data on tree species collected and their corresponding purchase prices from structured interview responses with cooperative members are shown in Table 3. The market value is defined as the price per kilogram paid to collectors by TREPA or the NTSC with RFA signed approval at the time of the survey. Table 3 shows the list of species along with their respective prices. These data were used to estimate the potential income from each species, determine whether the returns were proportional to the effort required for collection, and compare seed collection income with other baseline livelihood activities. All seeds collected by the cooperative during this study period were in direct response to purchase orders from the NTSC. Harvesting decisions were mainly driven by the list of a species in the NTSC order, aided by practical factors like the proximity of seed sources, ease of handling, and the perceived trade-off between collection effort and potential earnings.

Table 3. Seed species collected by cooperative members during the last paid season, with TREPA and NTSC purchase prices, percentage of collectors involved, and main reported reasons for collection. Note: Official seed prices from RFA and TREPA purchase orders are provided in the appendix, alongside prices reported during interviews.

Scientific Name	Common Name	TREPA Price/kg(RWF)	RFA Price/kg (RWF)	Collectors (%)	Main Reported Reason
Calliandra calothyrsus	Calliandra	7000	1500	30	Ease/Proximity
Eucalyptus camaldulensis	Eucalyptus	800	N/A	25	Common in farms,
Gliricidia sepium	Gliricidia	9000	1300	25	Ease/Proximity
Grevillea robusta	Silky Oak	17000	1700	100	Ease/Proximity
Leucaena leucocephala	Lead tree	1000	N/A	25	Ease/Proximity
Maesopsis eminii	Maesopsis	400	N/A	25	Ease/Proximity
Markhamia lutea	Nile Tulip Tree	1500	1500	94	High seed abundance; cited for income potential
Persea americana	Avocado	1000	N/A	25	Ease/Proximity
Senna siamea	Siamese cassia	4500	500	25	Common in farms,
Senna spectabilis	Spectacle Pod	1700	2000	30	Ease/Proximity
Vachellia kirkii	Whistling Thorn	5000	N/A	30	High price but difficult to handle
Vachellia polyacantha	White thorns	4000	1500	30	High price but difficult to handle
Vachellia sieberiana	Paperbbark thorn	2000	N/A	25	High price but difficult to handle

Among the study's species, Vachellia kirkii had the highest TREPA purchase price (RWF 5,000/kg) but was collected by only 30% of cooperative members. *Vachellia sieberiana* buying cost from the cooperative in 2023 was RWF 2,000/kg and was collected by 25% of members. Vachellia polyacantha, although not part of the species in this study, had a high market value of RWF 4,000 per kilogram and was harvested by approximately 30% of surveyed members. Among the three Vachellia species recorded, the predominant barrier to participation is handling difficulties, primarily due to the thorny nature of the tree and the necessity for protective gear during harvesting. Female harvesters reported avoiding *Vachellia kirkii* and *Vachellia sieberiana* due to the physical risks involved.

Price comparisons with RFA data were only possible for *Vachellia polyacantha* (TREPA RWF 4,000/kg and RFA RWF 1,500/kg), as no RFA price records were available for Vachellia kirkii or *Vachellia sieberiana*. The relatively low collection rates (25–30%) for the research species, despite their higher market value, gave insights that accessibility and ease of handling have a stronger influence on collection involvement than price alone. This therefore impacts the contribution of seed collection to household income when comparing seed collection earnings to other livelihood activities, as shown in Figure 9.

Other species, including *Grevillea robusta,* were collected by all (100%). Participants frequently cited its accessibility, as trees are often located near homesteads, reducing travel time and the need for specialized equipment. This ease of access allowed collectors to integrate seed collection with other livelihood activities, particularly during peak agricultural labor periods. *Markhamia lutea* was the second most frequently collected species (93.8%). Despite a moderate market price of RWF 1,500/kg, it was valued for its high seed yield and low harvesting effort. *Gliricidia sepium* (25%) and *Calliandra calothyrsus* (30%) were harvested in smaller volumes and mainly to fulfill orders, as other species too are based on orders from NTSC, as reported in this survey. *Eucalyptus camaldulensis* (25%) and *Maesopsis eminii* (25%) were also collected infrequently; while both are commonly found, they have relatively low market prices S*enna spectabilis* (30%) and *Senna siamea* (25%) showed similar trends. Although the cooperative noted the absence of restrictions on delivery quantities for all seeds, making it appealing to harvest as much as possible, NTSC is still the demand determinant, which decides which species are collected. The extent of active collection for any seed species is shaped by physical accessibility, handling ease, and price considerations.

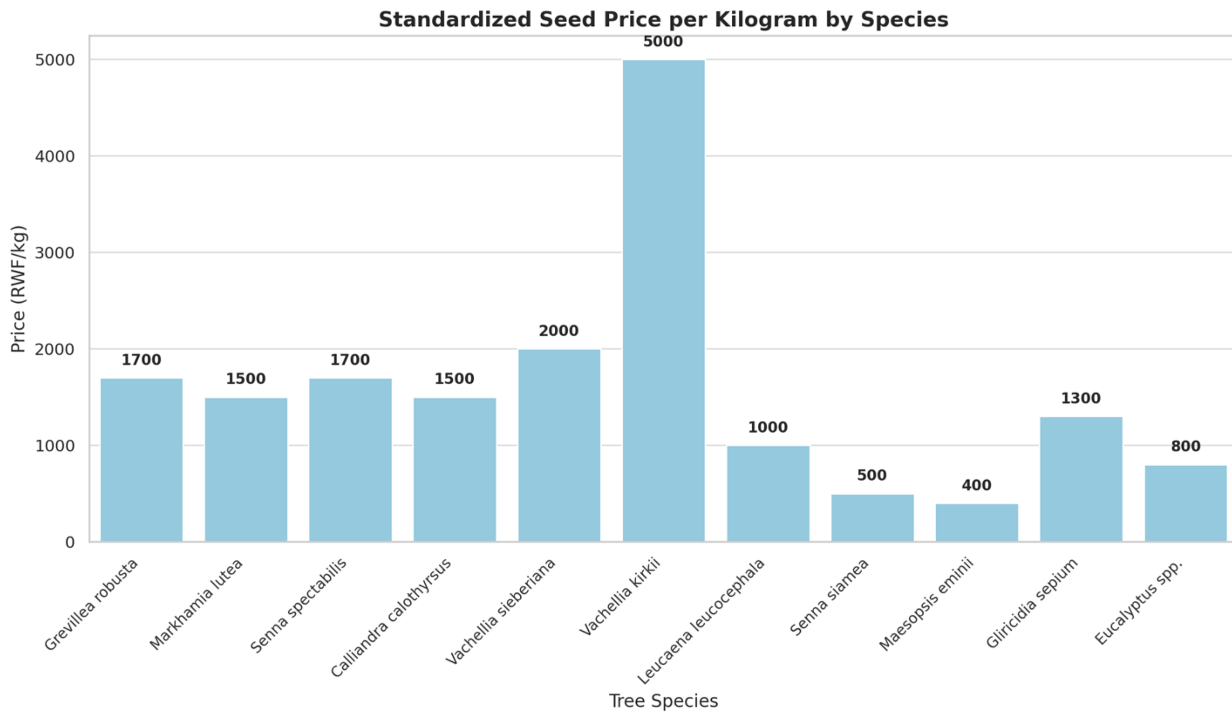

Figure 11: The Market Value of Seed/kg for the Last Collection Season reported by the cooperative

Prices reported by cooperative members, as shown in Figure 11 above, often differed from official TREPA and RFA rates. For example, *Vachellia sieberiana* was listed at 4,000 RWF/kg by TREPA, yet some members reported receiving 2,000 RWF/kg. This pattern was repeated for other species, with collectors' reported earnings often falling below official rates, suggesting tax or price adjustments as a bias during the interview.

Despite these, high prices recorded combined with easy access still made certain species attractive. Grevillea robusta (officially 1,700 RWF/kg) was collected by all members because trees were located near homes, making them quick to harvest alongside farming duties. Cooperative allocation of seed collection tasks, as seen from the interview shows that orders for thorny species, were often assigned to men. At the same time, women focused on species that could be harvested without long travel or additional tools.

3.2.4 Estimation of Proximity

Proximity to seed sources was repeatedly mentioned as the key factor shaping collection patterns. All species in this study were harvested because of NTSC and TREPA orders; collectors often expressed what they would have loved to be collecting if there was a choice, as those nearer to their homes. This choice was tied to ease of access and the time required for travel, rather than price or seed availability alone, or orders. To make the responses comparable, walking times were converted into estimated cycling distances using an average rural cycling speed of 10–12 km/h on mixed terrain, equivalent to about 5–6 km for every 30 minutes of walking, adopting Parkin et al.'s (2017) research method.

As shown in Table 4, *Grevillea robusta* was the most accessible species with 100% collectors, with average travel distances shown in Table 4 as between 5–8 km on average. *Markhamia lutea* followed closely at 6–10 km. *Gliricidia sepium* (15–20 km) and *Senna spectabilis* (16–30 km) were located further away, while all *Vachellia* species were the most distant, requiring travel of 30–40 km on average. Ranking the species from most to least accessible gives the following order, shown in Figure 7. Bicycles were the main mode of transport for distances above 5 km, while nearby sites were often reached on foot. Motorcycles were occasionally used for longer trips, but this option was limited by cost and availability.

Gender influenced how proximity affected species selection. Women (Interviews 11, 13, and 15) generally prioritized species that were accessible within shorter travel distances and time constraints. Men, although also collecting from short distances, were seen to undertake longer trips to gather species from farther distances. Species located within a 10 km radius of the collectors' residences were harvested by a greater proportion of respondents, whereas those located 20 km or more away were harvested less frequently unless explicitly mandated by NTSC orders.

Table 4. Distance Covered for the Most Collected Species by Bicycle

Species	Distance Range (km)	Accessibility Rank	TREPA Price/kg (RWF)	Collectors (%)
Grevillea robusta	5–8	1	1700	100
Markhamia lutea	6–10	2	1500	94
Gliricidia sepium	15–20	3	1300	25
Senna spectabilis	16–30	4	1700	30
Vachellia kirkii	30–40	5	5000	30
Vachellia sieberiana	30–40	5	2000	25

Rank 1 = most accessible; Rank 5 = least accessible, based on reported one way distances on average.

3.2.5 Challenges of Seed Collection

Seed collectors in the cooperative face a combination of physical, logistical, and financial constraints that determine not only how much they can collect, but also whether collection is worthwhile. Accessing seed trees is often the first challenge. Many are located on steep hillsides, rocky terrain, or other hard-to-reach areas. Respondents (Interviews 1, 7) described climbing slopes with ropes or hiring casual labour to access trees. Interviews 11 and 13 reported similar challenges, indicating the presence of difficult terrain.

There is a limited number of basic harvesting and transport tools, including long-handled pruners, sickles, protective gloves, and sacks for carrying seeds (Interviews 3, 4, 10, 11, 12, 14, 16). Without these, harvesting takes more time, requires greater physical effort, and can be risky, especially for thorn-bearing species such as Vachellia kirkii. Transport is another challenge. In the absence of bicycles, motorcycles, or vehicles arranged by the cooperative, members often have to hire transport during peak planting seasons when costs are high for instance,Some collectors reported travelling up to 30 km to reach seed collection sites (Interviews 3, 10, 14), which increased transport costs and reduced net earnings, especially during peak planting seasons. Paying for transport or for casual labourers to carry seeds reduces the income earned from collection.

Limited income were primarily linked to having one customer causing low fixed purchase prices, in which seeds are sold exclusively to the NTSC through the cooperative. This arrangement eliminates opportunities for price negotiation or alternative buyers. All participants agreed that

NTSC prices were low, particularly when compared to payments from NGOs such as CIFOR–ICRAF (TREPA) for similar work when hired as casual labors to source for specific kilogram of seed in case of excess they grow in the nursery. Several respondents noted that the time and effort required for seed collection did not correspond to the compensation received, with one member (Interview 9) remarking, "Even after all the work, the money doesn't really change anything at home.

Collection zones are also a challenge, and are defined by the access rights, which permit harvesting in farmlands, schools, and some areas within national parks. After collection, these areas are usually marked to indicate completed harvesting. In some cases, collectors reported being asked for permits before being allowed to harvest. According to Interview 13, overlapping collection zones, where multiple collectors target the same area, can reduce individual harvests. When orders are requested from the cooperative, the president instructs members to start collecting seeds in pairs (male and female). They typically search for unmarked trees, those without the paint used to indicate prior collection, before beginning harvest.

3.2.6 Cooperative and Household Benefit

This section assessed the benefits from two angles: the benefit as a member and the benefit to individual households. The dual perspective supports understanding seed collectors and the evaluation of their livelihoods.

At the cooperative level, Members consistently described the cooperative as more than a platform for seed sales. For some, it represented the most reliable cash income available, allowing them to cover essential expenses like school fees and other essential needs. Although collections were generally modest compared to other activities, the certainty of payment secured through guaranteed orders from the Rwanda Forestry Authority made it a valued part of their annual income (Interviews 2, 11, 14).

Beyond the small income, participants said they gained technical benefits through training, such as identifying healthy seed-bearing trees, evaluating seed maturity, and using proper harvesting techniques (Interviews 1, 6, 12). While the cooperative sells only to the Rwanda Forestry

Authority under the NTSC section, these skills provided are said to be essential for efficiently fulfilling orders. Respondents also noted that such skills could be applied in other situations, such as temporary nursery work or NGOs project. It would position them to take advantage of any future opportunities should market access expand. All women participants emphasized social and financial advantages, including access to small loans as a form of supportive peer relationships within the group (Interviews 5, 14).

Table 5 : Benefit Category of as reported from COPERWI group

Benefit Category	**Description**	**No. of Participants**	**Example Quotes**
Income and Financial Support	Regular income, ability to cover needs like school fees, and employment opportunities	9	"I use the money to pay my children's school fees." "The cooperative serves as a job opportunity."
Training and Knowledge	Skills in seed collection, restoration, and environmental awareness	7	"I received training”. They taught me how to care for trees and seeds."
Social Empowerment and Networks	Confidence, personal growth, savings groups, and social connections	4	"The cooperative opened her mind by giving her confidence. "She gets paid and gets to know other people."
Access to Markets and Resources	Buyers, storage, market coordination, legal access to collection areas	6	"He is assured there will be buyers." "They submit to the cooperative for storage."
Incentives and Institutional Support	Loans, pension, insurance, project access	3	"They pay insurance like a pension. "Opportunity to take a loan."
Shared Goals and Cooperation	Mutual support and shared vision among members	2	"They have a common goal of helping each other."

Table 6: Assets accumulated by interview group

Use of Income	*n*	%
Livestock purchase	7	44
Children's school fees	7	44
Personal needs	4	25
Asset purchase	3	19

At the household level, seed collection primarily functioned as an additional income source, alongside farming and small businesses. Although the earnings were limited, respondents reported deliberately using this income to strengthen household assets and improve security.

Buying livestock was a common investment (44%), with members purchasing goats, chickens, pigs, or cows to save money. For example, Interview 1 bought two goats and Interview 13 bought three chickens. Education expenses were cited by an equal proportion of respondents (44%), with seed income used to pay school fees at both primary and university levels (Interview 3, 10, 11, and 14). Other uses included immediate household and personal purchases (25%), such as food, clothing, and mobile phones, as well as larger asset acquisitions (19%), like motorbikes or mobile phones. Participants all said "the income of seed collection is not sufficient," aside from two, emphasizes that seed income alone was insufficient to sustain a household; instead, it provided flexibility in budgeting and met specific financial needs when combined with other livelihood sources, particularly farming. Despite its limitations, the stability of seed income through the RFA orders was valued as a predictable contribution to rural livelihoods. Members expressed that improving market access and increasing seed prices could substantially enhance its role, particularly if future opportunities allowed diversification beyond the current single-buyer system.

3.3 Genetics and Livelihood Considerations for a Successful Restoration

The two research questions: (1) whether *Vachellia kirkii* and *Vachellia sieberiana* breeding seed orchards harbor sufficient genetic variation for effective restoration (H_1), and (2) whether cooperative seed collection contributes meaningfully to rural livelihoods (H_2) were affirmed by the findings of this research, providing important insights for sustainable restoration practices in Rwanda

3.3.1 Genetic and Livelihood Influence on Restoration Performance

The average height assessed across families in the BSOs showed a lot of diversity among species, which shows that selective improvement is possible while still being adaptable making the BSOs to serve as a future seed source. As seen in chapter 3.1, environmental differences at specific sites affect how traits are expressed. However, genetic variation within species was observed, which makes restoration possible. This finding corresponds with the literature on restoration genetics. It is commonly agreed that keeping genetic diversity and choosing genotypes that are adapted to an area are important ways to make ecosystems more resilient and keep them working well throughout time (Bustos-Korts et al., 2019). Lobo et al. (2018) examined phenotypic plasticity and underscored the significance of genetic variation in facilitating plant adaptation to fluctuating environmental conditions (Lobo et al., 2018).
Chapter 3.2 showed seed collection as a good secondary source of income. However, it is still a solid way to diversify income, especially with COPERWI´s agreement with the NTSC. Participants used seed collection income to pay for children´s school fee, buy minor things, and meet their family necessities at some point, all of which in a way important to their livelihood. Research on non-timber forest products (NTFPs), state that NTFPs can add to rural incomes (10% to over 30% in different situations), backs up this role (Derebe et al., 2023). Likewise, research on agricultural cooperatives repeatedly underscores enhanced household wellbeing resulting from cooperative membership (Ahmed and Mesfin, 2017). However, the biological characteristics of Vachellia species studied and social limitations on labor and transportation influenced collecting patterns. For instance, Vachellia kirkii was harvested less often since it was harder to handle and farther away, even if it was priced more. Female members interacted with

species that were easier to find, which supports the idea that gender roles affect access to forest resources (Shackleton et al., 2011).

This trend has an obvious effect on restoration. Considering Lillesø's Ethiopia guide (2024), which highlighted that restoration success depends on sourcing genetically appropriate, well-documented seed matched to local site conditions and collected from sufficient, well-chosen parent trees, which together improve growth, survival, and resilience. So, if challenging but genetically viable seed sources are under-collected, the genetic aspect for restoration efforts will diminish. To avoid this, strategies should be provided to improve collections that are of good quality across species and sites.

Therefore, this study shows that restoration works best when planting material quality and the community's livelihood are ensured. BSOs give you genetically sound material that will be a future seed source, while cooperatives give you social institutions for getting seeds. To keep genetic diversity, though, cooperatives need improved support for species procurement that are hard to get to, such as transportation and harvesting tools. The rules in Rwanda should be made flexible in a way that seed cooperatives, not only this case study but also others, have more than one customer for better negotiation of prices, and prices paid for seed species be made fair enough to compensate for the efforts of collecting them. In restoration research nowadays, there is a push to include genetic protections in livelihood frameworks. This way, restoration projects will be strong both ecologically and socially.

3.3. 2 Outcome and Its Policy Relevance

This research sheds light on what makes restoration efforts truly effective, bringing together both the lived experiences of rural seed collectors and the biological performance of native tree species. By examining how *Vachellia sieberiana* and *Vachellia kirkii* grow in two BSOs, the study explores genetic variation within and between species and how that variation influences growth, resilience, and outcomes in field restoration. It also considers why collectors choose certain species over others, with decisions often shaped by perceived economic value and ease of procurement. These choices offer valuable insight into how livelihood impacts restoration success in rural landscapes.

3.3.3 Limitations and Appeal for Further Research

First, the biological assessment for genetics focused only on seedling height as a measure of early growth, which was useful as a quick indicator of performance; thus narrowed focus and excluded other traits such as diameter, pest and disease tolerance, and adaptability to environmental stress. The absence of genotype-by-environment analysis further limited the ability to evaluate how *Vachellia kirkii* and *Vachellia sieberiana*. Without testing performance across a range of environments, it was not possible to determine how each species' growth potential changes with differing site conditions.

The Socioeconomic, consisting the livelihood component, used only interviews with 16 cooperative members, although 18 were interviewed altogether, but 2 were discarded due to perceived bias conducted over three days. These provided valuable qualitative insights, but the short fieldwork and small sample size may not fully represent seasonal changes in income or the diversity of experiences within the cooperative as 11 were farmers.

Future studies should incorporate multiple growth traits, extend genetic trials across varied environments, and undertake longer-term, larger-scale livelihood surveys. Expanding both the biological and socioeconomic scope would create a stronger evidence base for aligning restoration strategies with both ecological suitability and community needs.

CHAPTER FOUR

4.0 Conclusion

This research demonstrates that tree seed cooperatives in Rwanda, as exemplified by COPERWI, are an important part of restoration, while also revealing operational and structural constraints that limit their potential. From a genetic perspective, provenance trials showed distinct differences in early growth performance between *Vachellia kirkii* and *Vachellia sieberiana*. Vachellia kirkii has seen, achieved greater mean heights under favorable site conditions, and *Vachellia sieberiana* exhibited higher and more consistent heritability estimates across sites, indicating stronger genetic control over growth traits and greater stability in varied environments. Showing that *Vachellia sieberiana* families are well-suited for breeding or improvement programs targeting restoration in heterogeneous landscapes, whereas *Vachellia kirkii* may require more site-specific conditions to reveal growth potential.

On the socioeconomic, species collection was primarily determined by NTSC purchase orders, yet factors such as proximity to seed sources, terrain difficulty, among other constraints strongly influenced participation, which reduced income as seen. Women were seen to prioritize seeds near their respective homes due to safety and time, while men traveled further and handled thorn-bearing species (*Vachellia kirkii* and *sieberiana*). The fixed-price, single-buyer mode seen for seed sales guaranteed market but restricted income potential and negotiation opportunities when compared to farming system generally in Rwanda. Income from seed collection was generally modest, with most participant relying on farming as their primary livelihood and using seed income to meet immediate needs such as school fees, food, or small livestock purchases at some point.

Training provided through CIFOR–ICRAF and other restoration partners strengthened participants' technical skills in species identification and seed handling, improving efficiency. However, persistent barriers, including long travel distances, a lack of protective and harvesting equipment limited the productivity and collectors safety.

The integration of genetic performance with livelihood when considering restoration would help in carrying out projects that meet objectives. Biologically, targeted species when genetically stable like *Vachellia sieberiana* can enhance planting success and resilience. Socially, addressing logistical constraints, implementing flexible pricing mechanisms, opening up the seed market would increase the impact on the livelihood of seed collectors in Nyagatare and Rwanda generally positively.

The approach of addressing the limited availability of high-quality seed sources through the establishment of BSOs, the underutilization of cooperative potential, and operational barriers to participation, this research provides a framework for aligning restoration objectives with rural development needs. Such an approach ensures that reforestation in Rwanda delivers ecologically resilient plantings while supporting the communities who sustain the process, thereby contributing to national forestry targets and AFR100 commitments.

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Appendices

Appendix 1. An interview survey guide designed for field data collection on seed value, proximity, constraints, benefit, and income is shown here.

Seed collection activity of Coperwi cooperative 14/08/2025, 21:06

Seed collection activity of Coperwi cooperative

Name of Participant

____

Are you a part of another seed collection group?.
YES or NO Name of Organization:

____

Do you collect seeds? Is seed collection your only source of income? If no, what other source of income do you have?
Income and Income range

____

How many hectares of land do you own? Do you get your seeds from your farmland?

____

What kinds of crops do you grow on your farm?
Aside from your main crops, do you grow anything else on your farmland, such as trees, vegetables, herbs, or other plants? why

____

Is seed collection an essential part of your subsistence? What species of seeds do you primarily collect, and how far do you travel from home to gather seeds for each species? (If the research species is not listed, inquire about it and the local name.)

____

Which seed cooperative have you been collecting seeds for? When did you join the COPERWI project? Do you collect seeds for only COPERWI now? Why?

____

Why did you join the seed cooperative group? What is the advantage of belonging to a seed cooperative group?

____

Do you have direct access to the market for selling your seeds, or do you only collaborate with non-governmental organizations (NGOs)? Which organization are you currently supplying your seeds to? Any private organization?
Name of Organization

____

How satisfied are you with the payment for seed compared to other project like casual labor (AREECA)?
Better, Worse or Same Payment

____

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Do you receive any special training for seed collection? When do you typically collect seeds, especially those of Vachellia species? (Month/Season) And how do you know seeds are ready for collection?

Can you describe how you choose which trees to collect seeds from, and what qualities you look for? Any special tool for seed collection?

Are these trees sometimes located in difficult areas like steep slopes or dense forests? If so, how do you manage to reach them, and do you usually mark or track the trees you collect from?

Do NGOs or RFA give you any instructions about which trees to collect seeds from? Do you have a preference for any specific tree species?

What do you do with the surplus during harvest?

What mode of storage do you adopt for preservation? Why did you choose that storage method? Have you found it effective?

Species

Method of Seed Storage

Row

Do you sell your seeds individually or in groups? Is there a minimum quantity required to sell your seeds individually or in groups?

How many kilograms of seed for each species did you or your group collect during the last seed collection season?

How much are you paid per seed kilogram?
Kg

Are you satisfied? What have you achieved from seed collection?

Can you estimate how much you earn from other activities and other project like arecca? Compare it with seed collection.

is there negotiation for the prices, how has it helped to be profitable?

Is your income from seed collection sufficient for your household needs?

Ranking Exercise of Common Income (baseline) Activities
1. very important income source 2. important income source 3. not so important income source

What are the most significant challenges you face in collecting seeds or while visiting seed sources?

What is your opinion about Vachellia species and their use for the restoration project?

Is there something you would like us to know about?

Appendix 2: Last official sale draft of species ordered by NTSC by the approval of RFA.

PURCHASE ORDER L2903000000/00161/24

Budget Agency: 2903-RWANDA FORESTRY AUTHORITY (RFA)
Department/Project: 2903000-RWANDA FORESTRY AUTHORITY
Cost Center: 2903000000-RWANDA FORESTRY AUTHORITY
Cost Center TIN: 111194286
Creation Date: 05-Oct-2023

COMMITMENT TYPE	CURRENCY CODE	RATE TYPE	EXCHANGE RATE
Goods	FRW	SELLING	1.000000

SUPPLIER DETAILS	CONTRACT DETAILS
TIN: 118831088	**Number:**
Name: COPERWI LTD	**Name:**
Address: RWANDA	

BUDGET INFORMATION

Budget Line: 2903000000-1032903-A8018401-334701-XXXXX - Agriculture grains
Program: A8-Terrestrial Ecosystems And Forest Resource Management
Output: A80184 - Quality forest seeds and seedlings is ensured
Activity: A8018401 - Forestry seeds are collected and distributed to different customers
Input (Economic): 334701 - Agriculture grains
Funding: 03-Own Revenues

COMMITMENT DESCRIPTION

PAYMENT FOR SEEDS PURCHASE FROM COOPERWI

S/N	DESCRIPTION	QUANTITY	UNITY COST	TOTAL VAT	TOTAL TAXES Incl.	TOTAL FRW
1	Acacia polyacantha	30.00	1,500	0	45,000	45,000
2	Croton macrostachyus	30.00	3,000	0	90,000	90,000
3	Markhamia lutea	100.00	1,500	0	150,000	150,000
4	Senna spectabilis	20.00	2,000	0	40,000	40,000
					Total Amount:	**325,000**

Amount in words: Three Hundred Twenty Five Thousand Rwandan Franc

SMART IFMIS DIGITAL SIGNATURES

Created By:	Verified By:	Approved By:
Digitally signed by RFA(ACCOUNTANT) Date: 2023.10.05 08:30:28 CAT	Digitally signed by RFA(DIRECTOR OF FINACE) Date: 2023.10.05 13:19:50 CAT	Digitally signed by RFA(DIRECTOR GENERAL) Date: 2023.10.06 14:52:40 CAT

Appendix 3: TREPÅ purchase order for specific species approved by RFA

PURCHASE ORDER L2903000000/00492/23

Budget Agency: 2903-RWANDA FORESTRY AUTHORITY (RFA)
Department/Project: 2903000-RWANDA FORESTRY AUTHORITY
Cost center: 2903000000-RWANDA FORESTRY AUTHORITY
Cost Center TIN: 111194286

Commitment type: **Goods** Creation date: **22-Feb-2023** Fiscal Year: **2022/2023**

Budget information

Budget Line: 2903000000-1032903-A8014901-334701-XXXXX - Agriculture grains
Program: A8-Terrestrial Ecosystems And Forest Resource Management
Ouput: A80149 - Quality forest seeds and seedlings is ensured
Activity: A8014901 - Forestry seeds are collected and distributed to different customers
Input (Economic): 334701 - Agriculture grains
Funding: 03-Own Revenues

Supplier Details

TIN Number	Supplier Name	Address
118831088	COPERWI LTD	RWANDA

Contract Number: PAYMENT FOR PURCHASING OF SEEDS FROM COPERWI BATCH 2 2 023
Currency rate: **1.000000**

S/N	Description	Quantity	Unit Cost (FRW)	Total VAT (FRW)	Total (FRW) Taxes Incl.	Total Local Currency
1	Acacia kirkii	20.00	5,000	0	100,000	100,000
2	Acacia sieberana	30.00	2,000	0	60,000	60,000
3	Caesalpinia decapitala	20.00	1,000	0	20,000	20,000
4	Caliandra calothyrsus	20.00	7,000	0	140,000	140,000
5	Callitris robusta	25.00	3,000	0	75,000	75,000
6	Cedrella serrata	25.00	4,000	0	100,000	100,000
7	Croton megalocarpus	20.00	3,000	0	60,000	60,000
8	Cupressus lusitanica	10.00	2,000	0	20,000	20,000
9	Eucalyptus terticornis	20.00	3,400	0	68,000	68,000
10	Gliricidia sepium	10.00	9,000	0	90,000	90,000
11	Grevilea robusta	400.00	17,000	0	6,800,000	6,800,000
12	Leucaena diversifolia	20.00	2,000	0	40,000	40,000
13	Markhamia lutea	20.00	1,500	0	30,000	30,000
14	Sena siamea	20.00	4,500	0	90,000	90,000
15	Sena spectabilis	50.00	2,000	0	100,000	100,000

Amount in words: Seven Million Seven Hundred Ninety Three Thousand Rwandan Franc **TOTAL AMOUNT : 7,793,000**

1. Prepared by:	2. Verified by:	3. Approved by:	4. Received by:
Title: ACC	Title: DOF	Title: AG	Title:
Name: Faustat	Name: S. Claudine	Name:	Name:

RWANDA FORESTRY AUTHORITY