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A Comprehensive Policy, Scientific, and Practical Analysis of Forest Seedling Production, Planting, and Maintenance for Environmental Protection in Rwanda: A Case Study of Kageyo-Kahi Site, Kayonza District

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Abstract

Forest landscape restoration has emerged as a central pillar of Rwanda's environmental governance and climate resilience strategy, reflecting a deliberate shift toward integrated and sustainable natural resource management. This paper offers a comprehensive analysis of forest seedling production, planting, and maintenance, highlighting the intersection of scientific innovation, institutional coordination, and environmental security. Drawing on Rwanda's experience at the Kageyo-Kahi site in Kayonza District, where 611,112 seedlings were planted at a total investment of RWF 156,669,118, the study examines how the Rwanda Agriculture and Animal Resources Development Board (RAB), the Ministry of Agriculture and Animal Resources (MINAGRI), and the Rwanda Reserve Force (RRF) collectively advance reforestation objectives. It further evaluates international collaboration with the Chinese Academy of Tropical Agricultural Sciences (CATAS) in strengthening nursery management and propagation capacity. Employing a qualitative, policy-analytical methodology, the paper demonstrates that Rwanda's forestry progress is attributable to an integrated governance model that aligns science, policy, and operational support. Persistent challenges including seedling quality inconsistencies, monitoring gaps, and climate variability continue to affect long-term sustainability. The paper argues that effective forest landscape restoration requires a holistic, adaptive approach combining scientific rigour, institutional synergy, active community participation, and robust environmental security mechanisms to ensure resilient ecological outcomes.

Keywords

Afforestation, Seedlings, Climate Resilience, Biodiversity, Policy, Community Engagement, Rwanda Reserve Force, Sustainability

1. Introduction

1.1. Global and National Context

Forests perform critical ecological functions carbon sequestration, biodiversity conservation, watershed regulation, and livelihood support that underpin human well-being and ecosystem stability at both local and global scales [1]. Globally, deforestation and land degradation constitute some of the most urgent environmental challenges of the twenty-first century, threatening climate stability and the livelihoods of hundreds of millions of people who depend on forest resources for food, fuel, and income [1].

In Rwanda, these global pressures intersect with unique national circumstances: high population density and a predominantly mountainous landscape have historically intensified soil erosion, deforestation, and unsustainable land-use practices [2]. Such degradation has jeopardized ecological resilience and constrained sustainable economic development, creating a pressing need for strategic state intervention.

In response, Rwanda has embedded forest landscape restoration (FLR) within its broader national development planning. The programme integrates scientific research, policy coordination, and community engagement to restore degraded landscapes, enhance ecosystem services, and strengthen adaptive capacity to climate change, thereby aligning ecological sustainability with socio-economic advancement [3].

1.2. Institutional Landscape

The success of Rwanda's forestry initiatives is largely attributable to deliberate coordination among multiple institutional actors, each contributing complementary expertise. RAB provides the scientific foundation for managing national seed systems, conducting forestry research, and ensuring technically sound implementation of reforestation programmes [2]. MINAGRI functions as the principal policy authority, developing legal frameworks, setting national standards, and overseeing programme execution across districts [3].

The Rwanda Reserve Force (RRF), operating under the Ministry of Defense, contributes enforcement capacity, logistical coordination, and community mobilization, bridging the gap between policy intent and field-level implementation [4]. Collaboration with the Chinese Academy of Tropical Agricultural Sciences (CATAS) facilitates technology transfer and the adoption of advanced nursery management practices [5]. The synergy among these institutions underpins a holistic governance model that integrates scientific rigour, policy oversight, security

mechanisms, and global technical expertise.

1.3. Environmental Protection as a Security Issue

A defining dimension of Rwanda's environmental strategy is the explicit recognition that environmental degradation constitutes a national security concern. Illegal logging, land encroachment, and resource conflicts not only threaten ecological integrity but also exacerbate social tensions and undermine sustainable development [6]. These challenges necessitate the active involvement of security institutions.

By integrating the RRF into environmental governance, Rwanda operationalizes a hybrid model in which civilian, scientific, and security functions are coordinated. This approach reflects the principle that long-term forest landscape restoration depends on both environmental stewardship and the maintenance of social and institutional security [7].

1.4. Research Problem

Despite large-scale tree-planting initiatives, several persistent challenges continue to undermine the effectiveness of Rwanda's forestry programmes. Tree survival rates remain inconsistent, partly due to variations in seedling quality, inadequate post-planting care, and site-specific ecological constraints [2]. Illegal logging, land encroachment, and livestock grazing within restored areas pose further structural threats [2]. Existing monitoring and evaluation systems are frequently insufficient to track growth, health, and protection of planted trees at scale, limiting evidence-based management [8]. These factors raise critical questions about the overall effectiveness and resilience of Rwanda's integrated forestry governance model.

1.5. Research Objectives

This paper pursues four interrelated objectives. First, it provides an in-depth analysis of seedling production systems, examining the scientific principles, nursery management practices, and quality-control measures underpinning forest restoration. Second, it evaluates tree-planting and maintenance practices including site selection, species adaptation, post-planting care, and long-term management to assess their contribution to survival rates and ecosystem resilience. Third, it examines the role of the RRF in environmental governance, exploring how enforcement, protection, and community mobilization enhance compliance and safeguard forest resources. Fourth, it assesses environmental outcomes carbon sequestration, biodiversity conservation, soil and water regulation alongside the socio-economic impacts of forestry programmes on local communities.

2. Literature Review

2.1. Ecological Restoration Theory

Ecological restoration is a scientific and strategic approach aimed at recovering degraded ecosystems to a state of functional integrity. It emphasizes conservation

and enhancement of species diversity, reestablishment of ecological processes such as nutrient cycling and soil formation, and the pursuit of long-term sustainability so that restored systems can withstand environmental stressors over time [9]. In the Rwandan context, restoration initiatives prioritize the reforestation of degraded hillsides, the integration of agroforestry systems, and landscape-level interventions that address watershed management, habitat connectivity, and soil stabilization [3]. These approaches simultaneously enhance ecosystem services and contribute to national climate resilience and an understanding reinforced by recent nationwide, tree-level carbon assessments in Rwanda that support restoration planning by linking ecological outcomes to socio-economic and land-use context [10].

2.2. Silvicultural Theory and Seedling Quality

Silviculture, as a scientific discipline within forestry, emphasizes the controlled establishment and management of forest stands to optimize ecological function, productivity, and sustainability [11]. Central to successful silvicultural practice is seedling quality, encompassing genetic attributes, morphological traits such as stem height and root development, and physiological resilience including tolerance to drought, pests, and soil variability [12]. Empirical evidence consistently demonstrates that poor-quality seedlings characterized by weak root systems, low vigor, or limited genetic adaptability directly contribute to low post-transplantation survival rates, undermining reforestation efforts [2]. Effective silvicultural programmes therefore prioritize rigorous seed selection, propagation under controlled nursery conditions, and ongoing morphological monitoring [1].

2.3. Agroforestry and Sustainable Land Use

Agroforestry integrates tree cultivation within agricultural systems to optimize ecological and socio-economic outcomes [13]. By incorporating trees into croplands, agroforestry enhances soil fertility through organic-matter addition, nitrogen fixation by leguminous species, and reduced nutrient leaching [14]. These improvements in soil health contribute to higher crop productivity, microclimatic moderation, and reduced erosion [2]. Agroforestry also strengthens climate resilience by providing shade, reducing wind erosion, conserving water, and diversifying landscapes [15]. In the Rwandan context, adoption of agroforestry aligns with national strategies for sustainable land use and forest landscape restoration, simultaneously supporting rural livelihoods and ecological sustainability [3].

2.4. Environmental Governance and Multi-Actor Systems

Modern environmental governance is increasingly recognized as a multidimensional and adaptive process requiring the coordinated engagement of multiple institutional and community actors [16]. Institutional coordination is essential to align policies, research, and operational resources across ministries, specialized agencies, and local authorities, ensuring that forest restoration interventions are

implemented coherently and efficiently [2]. Such coordination enables the integration of RAB's scientific findings with MINAGRI's national policy directives, translating technical knowledge into actionable programmes [3].

Community participation is equally critical, as sustainable environmental outcomes depend on local knowledge, ownership, and stewardship [17]. Engagement of communities in tree-planting, maintenance, and monitoring not only strengthens social buy-in but also creates feedback mechanisms for adaptive management [14]. Enforcement mechanisms constitute another vital component. The inclusion of the RRF within environmental management reflects a hybrid governance model in which civilian expertise is complemented by security and operational capacity, allowing for protection of vulnerable ecosystems from illegal logging and encroachment while supporting community mobilization [4].

2.5. Security and Environmental Protection

Environmental degradation carries profound socio-economic and security implications. Loss of forest cover, soil fertility, and water resources can exacerbate competition over scarce natural resources, potentially triggering local and regional conflicts [6]. Such competition undermines agricultural productivity, food security, and rural incomes, intensifying social tensions in communities dependent on natural resources [18]. Security institutions can address these multidimensional threats by monitoring sensitive areas, deterring illegal logging, preventing poaching, enforcing environmental law, and supporting disaster response and resilience-building initiatives [19]. Rwanda's integration of the RRF into environmental management exemplifies a proactive approach linking ecological stewardship with national security, demonstrating that sustainable environmental governance requires a coordinated, multi-sectoral strategy addressing both ecological and human dimensions [7].

3. Methodology

3.1. Research Design

This study adopts a qualitative, descriptive, and analytical research design structured to provide an in-depth understanding of Rwanda's forest landscape restoration strategies and their multifaceted impacts [20]. The research integrates three complementary approaches: policy analysis, a comprehensive literature review, and a case study evaluation of the Kageyo-Kahi site.

The case study evaluation is informed by the author's primary field observations and operational data capture while serving directly as site manager and coordinator. The study also integrates quantitative operational metrics extracted from administrative and budget reports compiled by the implementing agencies including seedling volumes, project investments, and nursery and field survival percentages evaluated descriptively to contextualize field outcomes.

For the literature review component, sources were selected according to three criteria: 1) relevance to forest seedling production, plantation maintenance, envi-

ronmental governance, or Rwanda's specific agro-ecological context; 2) publication or issuance between 1989 and 2023; and 3) availability in English or French. Peer-reviewed journal articles, books, and grey literature (government reports, institutional publications, and international organization documents) were all eligible. Sources were identified through database searches (Google Scholar, FAO publications portal) and direct review of RAB, MINAGRI, and RRF institutional repositories.

Numerical figures seedling counts, investment costs, and survival rates are treated as documentary evidence drawn from institutional reports and are subjected to critical interpretive analysis rather than statistical testing. Where a single institutional source is the sole basis for a figure, as is the case for most Kageyo-Kahi-specific values, this is noted explicitly and the figure is treated as a reported estimate rather than an independently verified measurement, consistent with methodological conventions for qualitative policy research incorporating administrative data [21].

3.2. Data Sources

The study draws on three principal categories of evidence: government reports, providing authoritative insight into national forestry policy and institutional performance; academic literature, offering rigorous analyses of silvicultural practices, agroforestry, and socio-economic forestry impacts; and institutional publications from RAB, MINAGRI, the RRF, and CATAS, providing technical guidance and operational data [20].

3.3. Analytical Framework

The analytical framework is structured around five interrelated dimensions: seedling production (nursery management, genetic and morphological quality, propagation, institutional oversight); tree-planting practices (site selection, species adaptation, planting density, ecological-socio-economic integration); maintenance activities (post-planting care, soil and water management, pest control, monitoring); environmental outcomes (carbon sequestration, biodiversity conservation, soil stabilization, water regulation, livelihood contributions); and the integration of security mechanisms into environmental governance, highlighting the RRF's roles in enforcement, protection, community mobilization, and disaster response [21].

4. Policy Context

4.1. National Environmental Policy Framework

Rwanda's environmental and forestry initiatives rest on a robust legal and policy architecture. The Rwanda National Forest Policy (2010) establishes the strategic target of raising national forest cover to 30% of total land area by 2025, through afforestation, reforestation, and sustainable forest management [22]. The Green Growth and Climate Resilience Strategy (2011) integrates climate-smart forestry,

ecosystem restoration, carbon sequestration, and community-based forest management into national climate adaptation strategy [23]. Environmental Organic Law No. 04/2005 provides the foundational regulatory framework for environmental protection, including responsibilities for afforestation and sustainable land management [24].

The Forest Policy of 2018 and the accompanying Law N˚ 72/2018 relating to forestry strengthen this architecture considerably, introducing specific provisions on afforestation and reforestation, delineating responsibilities between public institutions and private actors, enforcing regulations against deforestation and illegal resource exploitation, promoting climate-resilient tree species, and providing incentives for private-sector investment through tenure security [25]. These instruments align with Rwanda's National Strategy for Transformation (NST1) and Vision 2050.

Implementation is coordinated by MINAGRI, with RAB providing technical research, seedling production, and extension services, and the Rwanda Environment Management Authority (REMA) ensuring regulatory compliance [26]. Implementation is decentralized to district level; districts such as Kayonza play a pivotal role in local forest management, with technical guidance from RAB and operational support from local authorities and community organizations [27].

4.2. Policy Implications for the Kageyo-Kahi Site

The Kageyo-Kahi afforestation initiative in Kayonza District exemplifies the practical translation of national environmental policy into localized action. By planting 611,112 seedlings across the site, the project directly advances the strategic objective of increasing forest cover to 30% by 2025 [22]. Technical supervision is provided by RAB [28]; local authorities facilitate community mobilization; and environmental agencies monitor regulatory compliance [26].

Financially, the project is supported through a combination of government budget allocations, community contributions, and development-partner support [23]. This integrated governance and funding model ensures alignment between national policy objectives and localized ecological and socio-economic outcomes, making Kageyo-Kahi a replicable model for climate-smart afforestation across Rwanda.

5. Forest Seedling Production

5.1. Technical Processes

Seedling production constitutes the foundational step in Rwanda's forest landscape restoration effort, because the quality and vigour of seedlings directly determine the success of planting and maintenance activities that follow [2]. The process begins with careful seed selection prioritizing genetically superior, disease-free, and ecologically adaptable seeds, with provenance and species suitability evaluated to match seedlings with specific planting sites [12].

Nursery establishment involves the construction of controlled environments

that optimize light, temperature, moisture, and soil conditions. RAB has established both centralized and decentralized nurseries incorporating raised beds, shade management, and sterilized growth media to minimize seedling mortality [2]. Growth management encompasses calibrated watering regimes, fertilization schedules, pest and disease controls, and regular monitoring of morphological traits. Training of nursery staff, supported by technical collaboration with CATAS, has supported the adoption of advanced propagation techniques including clonal propagation and grafting [5].

5.2. Genetic Quality

Genetic quality is a critical determinant of seedling performance and long-term forest resilience. Selecting seeds with superior genetic attributes ensures that seedlings are well adapted to local environmental conditions including variations in altitude, rainfall, soil fertility, and temperature [11]. High-quality genetic stock enhances growth rates, improves tolerance to pests, diseases, and abiotic stresses, and contributes to the ecological stability of restored forests.

Given Rwanda's diverse topography and microclimates, seedlings derived from locally adapted genetic material generally exhibit higher survival rates than non-local or hybridized stock [2]. By prioritizing genetic quality, Rwanda improves immediate reforestation success while enhancing the capacity of restored ecosystems to provide long-term services including carbon sequestration, biodiversity conservation, and watershed protection [5].

5.3. Nursery Management

Effective nursery management encompasses irrigation, shading, soil management, and integrated pest and disease control [1]. Calibrated irrigation promotes root development and nutrient uptake, particularly important where rainfall distribution is highly variable [12]. Shading protects seedlings from excessive solar radiation and moderates temperature fluctuations. Integrated pest management, biological controls, soil sterilization, and careful monitoring maintains healthy seedlings while minimizing environmental impact [14].

RAB's nursery system combines traditional silvicultural knowledge with modern techniques and technical guidance from CATAS [5]. Meticulous nursery management supports strong root systems, robust stems, and adaptive physiological traits, increasing post-transplantation survival and contributing to long-term forest productivity [3].

5.4. Role of the Rwanda Reserve Force in Seedling Production

The RRF plays a role in safeguarding the operational and ecological integrity of seedling production programmes [4]. By patrolling nurseries and implementing perimeter controls, RRF personnel help prevent unauthorized access and protect seedlings from theft, vandalism, and destruction. The RRF also provides logistical support for seedling distribution, assisting in the safe transport of seedlings from cen-

tralized and decentralized nurseries to planting sites across Rwanda's varied terrain [4], which supports the effectiveness of large-scale reforestation campaigns.

5.5. Case Study: Kageyo-Kahi Seedling Production

At the Kageyo-Kahi site in Kayonza District, seedling production is guided by species-specific ecological requirements and national forestry policy. Priority species include Eucalyptus spp. for rapid biomass accumulation and soil stabilization; Callitus robusta for agroforestry integration and support of understory crops on erosion-prone slopes; and native species such as Markhamia lutea and Albizia spp. for biodiversity restoration and nitrogen fixation [27].

Through these practices, the site is reported to achieve nursery survival rates exceeding 85%, consistent with RAB's national benchmark of a ≥85% 30-day post-transplantation survival rate for certified nurseries [2]. This figure is drawn from institutional monitoring records and should be understood as reported rather than independently audited. It is also worth noting, for context, that independently published Rwandan studies of comparable agroforestry and public plantings have found considerably lower average survival on the order of 30% to 65%, depending on land tenure and the intensity of post-planting care [29]. This gap does not necessarily indicate a problem with the Kageyo-Kahi figure, but it does underline that a rate this high depends on the sustained, RAB-supervised conditions described in this section rather than reflecting typical unsupported plantings nationally.

6. Tree Planting

6.1. Ecological and Technical Factors

Successful tree planting in Rwanda depends on careful assessment of soil conditions, rainfall patterns, and species suitability. Soil texture, fertility, pH, and drainage capacity are primary considerations, as well-prepared soils support robust root establishment, enhance water retention, and reduce erosion susceptibility particularly important in Rwanda's hilly landscapes [2]. Planting is typically timed to coincide with the onset of the rainy season, ensuring sufficient moisture for initial root establishment [3]. Microclimatic variations are mapped to optimize species placement and reduce drought-induced mortality risk [14].

Species selection is equally vital: matching tree species to site conditions and ecological objectives maximizes survival rates and ecosystem benefits. In Rwanda, indigenous and fast-growing species are prioritized for reforestation and agroforestry programmes, balancing biodiversity conservation, timber production, soil stabilization, and climate resilience [5]. Evidence from national programmes indicates that seedlings matched to local soil and climatic conditions tend to outperform non-adapted species [2].

6.2. Institutional Collaboration

Rwanda's large-scale tree-planting campaigns are characterized by a highly coordinated, multi-institutional approach. RAB provides technical guidance on site

selection, species suitability, planting density, and post-planting care [2]. MINAGRI mobilizes policy frameworks, coordinates implementation across administrative units, and ensures national campaigns align with climate resilience planning, watershed management, and socio-economic development goals [3].

The RRF contributes operational and logistical support, securing planting sites, preventing unauthorized access, and assisting in seedling distribution to remote or difficult-to-access areas [4]. Case evidence from campaigns in Rwanda's Eastern and Southern Provinces indicates that this coordination is associated with improvements in reported seedling survival and operational efficiency, as documented in RAB programme evaluations [2].

6.3. Role of the Rwanda Reserve Force in Planting Campaigns

RAB's 2022 annual tree-planting report documents a comparison of 12 planting sites in the Eastern and Southern Provinces, finding that sites at which RRF personnel provided logistical coordination and security reported seedling survival rates averaging approximately 75% - 82% at 90 days post-planting, compared with approximately 60% - 70% at equivalent sites without RRF support [2]. The report attributes the difference to faster seedling distribution, reduced vandalism, and higher community attendance during planting events, rather than to agronomic factors. This comparison is drawn from an institutional report produced by one of the agencies whose performance is being assessed; the figures have not been independently verified, sites were not randomly assigned to treatment conditions, and observed differences may partly reflect pre-existing variation in site accessibility or community organization. The association between RRF involvement and improved outcomes should therefore be treated as indicative rather than causal.

At its heart, the role of the RRF in agriculture and environmental conservation can be understood as a simple but powerful idea: national security is not only about protection, but also about building and sustaining life [30], as reinforced by the human development literature [31]. In Rwanda, the RRF is increasingly framed as a partner in everyday development, supporting agriculture and environmental protection initiatives across the country [32].

When farmers need support during planting seasons, the RRF steps in to provide labor, coordination, and community mobilization [33]. When communities require seedlings, the RRF contributes by establishing nurseries, raising planting materials, and facilitating distribution in collaboration with institutions such as RAB and MINAGRI [34]. When the environment faces challenges such as soil erosion, deforestation, or climate change, the RRF participates in tree planting, land restoration, and conservation of wetlands and watersheds [35]. This approach reflects a national philosophy that development and security are interconnected, and that sustainable progress requires integrating environmental protection, food security, and institutional support systems [36] [37].

What makes this model notable is the combination of strengths: the technical

expertise provided by RAB and MINAGRI, and the discipline, organization, and rapid mobilization capacity of the RRF [38]. Together, these institutions create a system in which policies designed at the national level are also implemented within local communities [39]. In this sense, the RRF acts as a bridge linking policy to practice, and security to development [40].

6.4. Case Study: Kageyo-Kahi Planting Operations

At the Kageyo-Kahi site, a total of 611,112 seedlings were planted at a total project investment of RWF 156,669,118, as documented in the Kayonza District budget report and RAB's 2022 annual forestry programme report [41]. Planting was timed to coincide with the rainy season, while site preparation including ridge construction, planting-hole preparation, and soil enrichment with organic matter supported seedling establishment [42].

RRF involvement supported operational efficiency, discipline, and community participation throughout the campaign. Personnel enforced adherence to technical planting protocols correct spacing, planting depth, and post-planting care and monitored seedling handling by both community volunteers and paid workers [7]. Their logistical coordination reduced delays, minimized seedling wastage, and helped maintain planting schedules despite challenging terrain [3].

7. Maintenance Practices

7.1. Importance of Post-Planting Maintenance

Maintenance is a critical determinant of both the success and environmental impact of afforestation projects. Proper maintenance directly influences seedling survival rates, ensuring that investments in nursery production, planting, and community labor translate into established forests capable of delivering long-term ecological benefits [43]. High survival rates enhance cost-effectiveness and maximize functional outcomes including soil stabilization, erosion control, water regulation, and carbon sequestration [3]. In Rwanda's hilly landscapes and variable rainfall conditions, rigorous maintenance is essential for ensuring that reforested areas contribute meaningfully to biodiversity restoration and sustainable land management.

7.2. Core Maintenance Practices

Weeding is conducted manually during the first 12 - 18 months after planting to remove competitive vegetation that may inhibit seedling growth, particularly in Rwanda's upland landscapes where aggressive grasses and shrubs compete with young trees for water, light, and nutrients [44]. Mulching using organic material such as crop residues or compost applied around seedling bases conserves soil moisture, reduces evaporation, prevents surface erosion on slopes, and contributes to nutrient cycling over time.

Pruning is performed selectively to encourage vertical, straight growth, reducing disease incidence and structural deformity while enhancing timber quality in

species such as Eucalyptus spp. and Callitus robusta [28]. Adequate and timely watering, particularly during the dry season, prevents moisture stress, with irrigation schedules aligned to local evapotranspiration rates and rainfall patterns [28]. Integrated pest management combining biological controls and environmentally safe treatments protects seedlings from mortality and growth retardation while preserving ecosystem health.

Continuous monitoring forms an integral part of maintenance, with regular surveys assessing seedling mortality, growth performance, and the presence of pests or diseases. Data collected informs adaptive management, allowing for timely interventions including replacement planting, pest control, or soil amendments [45].

7.3. Role of the Rwanda Reserve Force in Forest Protection

The RRF's maintenance-phase contribution extends beyond organized labor. RRF personnel monitor forested areas to help ensure seedlings are properly maintained and early-stage threats are identified promptly [4]. The RRF's Dedicated Site Security Unit (DSSU) contributes to preventing illegal tree cutting, poaching, and encroachment. Through collaboration with local authorities and community groups, the RRF supports enforcement of forest protection regulations under Rwanda's National Forest Policy [25].

7.4. Case Study: Forest Protection at Kageyo-Kahi

At the Kageyo-Kahi site, coordinated forest protection measures are reported to have supported the long-term success of the reforestation investment. RRF presence is associated with reduced illegal logging, safeguarding the investment in 611,112 seedlings [4]. Monitoring and mitigation of livestock encroachment has been particularly important given Kayonza District's proximity to agricultural lands, where grazing and land-use pressures pose a persistent threat to young plantations.

By combining these maintenance practices weeding, mulching, pruning, monitoring, and security enforcement, the Kageyo-Kahi project reports field survival rates of 70% - 90% [4]. These figures are site-reported estimates derived from nursery monitoring records and field surveys conducted by RAB extension staff; they have not been subjected to independent third-party verification. As in Section 5.5, it is worth noting that this range sits above the 30% - 65% average survival reported in independently published studies of comparable Rwandan plantings [29], which is consistent with the more intensive, RRF-supported maintenance regime described at this site, but also means the figure should not be read as broadly representative of unsupported community plantings nationally.

8. Environmental Outcomes

8.1. Soil Conservation

Afforestation at Kageyo-Kahi plays a role in addressing Rwanda's most pressing environmental challenge: land degradation and erosion on hilly terrain. Tree roots

anchor the soil, reducing surface runoff and helping prevent landslides, while leaf litter and organic matter improve soil structure and fertility. Eucalyptus spp. and Callitus robusta establish dense root networks that stabilize slopes, while Markhamia lutea and Albizia spp. enhance soil biodiversity, fostering microbial communities that contribute to nutrient cycling [28]. By reducing soil erosion, reforestation helps protect adjacent agricultural fields and reduce sedimentation in watercourses particularly relevant in Kayonza District given its rainfall variability [46].

8.2. Water Regulation

Tree canopies intercept rainfall, reducing the kinetic energy of raindrops that dislodge soil particles, while root systems enhance soil infiltration and facilitate groundwater recharge. The presence of diverse tree species improves soil porosity and water-holding capacity, helping stabilize stream flows and reduce flood intensity during heavy rains. Forested catchments can also help maintain dry-season water availability, benefiting agricultural activities and communities that rely on rivers and springs.

8.3. Carbon Sequestration and Climate Mitigation

The carbon sequestration potential reported here is a projection, not a measured outcome. No biomass inventory or flux measurements have been conducted at Kageyo-Kahi at the time of writing. The projection is derived from species-specific mean annual increment (MAI) figures and carbon-fraction coefficients drawn from Rwanda's national forest carbon monitoring framework and climate-change mitigation guidelines [47] [48], within the framework of Rwanda's nationally determined contributions to the Paris Agreement. Applying those coefficients to the 611,112 seedlings and the species mix described in Section 5.5, and assuming an average 20-year rotation, the project is estimated to sequester in the range of 4.6 million tonnes of CO_2-equivalent a figure highly sensitive to actual survival rates, species growth performance under local conditions, and future management practices. This estimate should be understood as indicative and subject to revision once field measurements are available; readers should treat it as a planning projection rather than a verified quantity.

Rwanda's Nationally Determined Contributions have been submitted to the United Nations Framework Convention on Climate Change and form part of the country's obligations under the Paris Agreement. All countries are required to submit an updated plan every five years, each with a greater level of ambition. Beyond the site-level projection above, national tree-level carbon assessments indicate that trees outside forests including farmland and plantation trees of the kind planted at Kageyo-Kahi already account for a substantial share of Rwanda's aboveground carbon stock, underscoring the national relevance of site-level restoration investments of this kind [10]. Reforestation initiatives such as Kageyo-Kahi may also contribute to localized climate regulation, including temperature moderation and improved microclimatic conditions; this effect is plausible based

on the broader forestry literature, but unlike the national carbon-stock evidence just cited it has not yet been directly measured at this specific site and should be treated as a hypothesis for future monitoring rather than an established finding.

8.4. Biodiversity

The introduction of native species particularly Markhamia lutea and Albizia spp. fosters habitat complexity supporting pollinators, birds, and small mammals [28]. Restored forest cover enhances ecological connectivity in fragmented landscapes, enabling species movement and genetic exchange [49]. Native trees also promote soil microbial diversity and contribute to natural pest regulation. Recent field research on native Rwandan tree species more broadly confirms their agroforestry and restoration potential, with several native species showing competitive growth performance alongside exotic species under Rwandan conditions. Beyond ecology, increased biodiversity provides socio-economic advantages including pollination of nearby crops, potential ecotourism opportunities, and non-timber forest products. Integrating biodiversity considerations into afforestation aligns with Rwanda's National Biodiversity Strategy and Action Plan [50].

The biodiversity benefits described in this section are inferred from the ecological literature on native species and from comparable Rwandan sites rather than from systematic biodiversity monitoring (species inventories, pollinator counts, or soil microbial assays) conducted at Kageyo-Kahi itself; site-specific ecological monitoring remains a priority for future work.

8.5. Environmental Security

The RRF plays a role in reinforcing environmental protection at Kageyo-Kahi. Structured oversight supports protection of seedlings, established forests, and watershed areas from illegal logging, encroachment, and other activities that could compromise the ecological integrity of restored landscapes [4]. Beyond forest protection, the RRF contributes to disaster preparedness and response including early warning, rapid mobilization during floods or landslides, and coordination with local authorities [51].

9. Discussion

9.1. Rwanda's Integrated Governance Model

Rwanda's forestry initiatives exemplify a highly integrated governance model in which RAB, MINAGRI, and the RRF are coordinated toward common environmental objectives [3]. This multi-layered approach helps ensure that forest landscape restoration is scientifically sound, administratively coherent, and socially inclusive [9]. Multi-actor collaboration extends to international partners: CATAS provides training, technology transfer, and research collaboration [5]. The model's hybrid character, combining civilian expertise and security-sector capacity, supports compliance with environmental regulations, safeguards nursery sites, and mobilizes communities [7].

9.2. Strengths of the Current Approach

Three interconnected strengths underpin Rwanda's progress. Institutional synergy among RAB, MINAGRI, and the RRF supports harmonized seedling production, planting campaigns, and maintenance activities [9]. Strong political commitment evidenced by the Forest Policy of 2018, Law N˚ 72/2018, and the allocation of public resources for large-scale reforestation has fostered institutional accountability and programme continuity [52]. Active community engagement, mobilized through the RRF and awareness campaigns by RAB and MINAGRI, provides both labor and knowledge for operational efficiency while strengthening social ownership of restored landscapes [17]. Sites with high community involvement tend to report higher seedling survival, lower incidences of vandalism, and stronger adherence to maintenance protocols [2].

9.3. Persistent Challenges

Despite significant progress, several challenges limit the full realization of Rwanda's forestry objectives. Monitoring gaps remain a pressing concern: coverage and frequency of seedling-survival tracking and forest-health assessment are uneven, particularly in remote or rugged terrain [9]. Climate variability fluctuations in rainfall, drought events, and rising temperatures affects soil moisture, seedling establishment, and species survival, requiring flexible management strategies and climate-resilient species selection [2]. Rwanda's mountainous topography amplifies these risks, as microclimatic differences between valleys and hilltops produce uneven growth performance across planting sites.

Resource constraints also affect programme quality: financial limitations can restrict procurement of high-quality seedlings, irrigation equipment, and technical personnel, while logistical challenges affect seedling distribution and site accessibility [7]. Additionally, the current approach risks prioritizing numerical planting targets in ways that may inadvertently undermine ecological quality, as a focus on meeting quantitative goals can overshadow the need for biodiversity, appropriate species selection, and long-term sustainability [4]. Reporting often emphasizes the number of trees planted rather than ecosystem outcomes such as carbon sequestration, biodiversity restoration, or soil recovery.

At the community level, incentive structures for farmers remain insufficiently aligned with long-term forest management objectives. As a result, tree planting may be perceived as a short-term obligation rather than a sustained livelihood strategy, leading to inadequate post-planting care and low survival rates in some areas [38].

9.4. Critical Assessment and Strategic Directions

Rwanda's reforestation framework demonstrates ambition and institutional coherence, yet critical analysis reveals structural tensions requiring attention. Independent scholarship on Rwanda's broader development model has characterized it as a form of "developmental patrimonialism" highly centralized, top-down, and

target-driven, which is effective at mobilizing institutions and resources but can, in the same way, marginalize local voice and overlook ecological heterogeneity across districts [37]. Overlapping mandates among MINAGRI, RAB, and REMA, combined with limited data-sharing mechanisms, can constrain efficiency and adaptive management.

Strengthening monitoring systems through investment in remote sensing, geographic information systems (GIS), and community-based reporting mechanisms would enhance surveillance and enable adaptive management [3]. Prioritizing ecological quality over quantity in seedling production and species selection, with emphasis on locally adapted, drought-tolerant species, would help ensure that restored forests are resilient under climate variability [2]. Expanding community-centred incentive programmes aligned with long-term stewardship would help transition tree planting from short-term obligation to sustainable livelihood strategy [17]. Sustained collaboration with CATAS and other international partners provides continued access to advanced research, training, and technology [5].

10. Lessons Learned

The Kageyo-Kahi experience offers several practical lessons for the design and implementation of future reforestation initiatives in Rwanda and comparable contexts. Integrated planning aligning nursery production, species selection, and planting schedules with site-specific soil, topographic, and climatic conditions supports higher survival rates, faster growth, and stronger ecosystem service delivery [27]. Community engagement that offers training, capacity-building, and meaningful incentives to local farmers and cooperative groups fosters ownership and encourages proper maintenance. Systematic monitoring that collects data on seedling survival, growth performance, and ecological impacts enables adaptive management [45].

Independently published, site-level research on Rwandan plantings including in eastern Rwanda provides a useful benchmark for what unsupported community and public plantings typically achieve (in the range of 30% - 65% survival), against which more intensively supported sites such as Kageyo-Kahi can be compared and their added value assessed [29]. Ground-level assessments of soil and land health in Kayonza and neighboring Nyagatare districts further show that erosion risk and soil organic carbon vary substantially by land cover type, reinforcing the case for prioritizing tree cover on the most degraded plots within any given restoration site [45].

Strategic cost optimization including bulk seedling procurement and leveraging community labour can help reduce project expenditure without compromising quality, supporting scalability and replicability of afforestation programmes across diverse districts [8]. Strengthening enforcement of forest protection regulations at district and community levels, through collaboration between the RRF, local authorities, and community policing initiatives, is important for preventing illegal harvesting, overgrazing, and encroachment [22]. Finally, building long-term eco-

logical studies, evidence-based technical guidelines, and knowledge-dissemination mechanisms including demonstration plots, participatory learning, and extension services is essential to bridge the gap between research and practice [5] [28].

11. Conclusion and Recommendations

11.1. Conclusions

Rwanda's approach to forest seedling production, planting, and maintenance at the Kageyo-Kahi site in Kayonza District embodies an integrated model of environmental governance in which scientific expertise, policy frameworks, and security mechanisms converge toward sustainable forest landscape restoration. RAB provides technical rigour in nursery management, seedling quality, and species selection. MINAGRI supplies strategic policy guidance, programme coordination, and climate-resilience alignment. The RRF strengthens operational efficiency, secures planting sites, and facilitates community mobilization, illustrating that the integration of security actors into environmental governance can support compliance, reduce resource losses, and foster stewardship without undermining participatory principles.

The Kageyo-Kahi case, 611,112 seedlings planted at an investment of RWF 156,669,118, with projected contributions to soil stabilization, water regulation, carbon sequestration, and biodiversity restoration, illustrates both the achievements and the ongoing challenges of Rwanda's model. Long-term success will depend on a strategic shift from quantitative planting targets to qualitative forest landscape restoration: improving monitoring systems, strengthening community-centered incentives, prioritizing ecological species adaptation, and sustaining international technical partnerships.

11.2. Recommendations

First, strengthen inter-institutional coordination. Formal coordination mechanisms among RAB, MINAGRI, and the RRF including regular joint planning, data sharing, and operational oversight should be institutionalized to ensure alignment across seedling production, planting campaigns, and maintenance activities [3].

Second, invest in monitoring and evaluation systems. Remote sensing, GIS-based surveillance, and community-based reporting should be systematically deployed to track seedling survival, forest health, and ecological outcomes, enabling evidence-based adaptive management [8].

Third, promote climate-resilient species selection. RAB should continue developing context-specific protocols for selecting drought-tolerant and ecologically adaptable species based on local environmental conditions and projected climate trajectories [1].

Fourth, establish clear legal mandates for the RRF's environmental role, with explicit responsibilities and accountability mechanisms that maintain a balanced approach between enforcement and participatory governance [19].

Fifth, expand community participation and incentive frameworks, positioning reforestation as a sustained livelihood strategy rather than a policy obligation [17].

Sixth, support research, innovation, and knowledge dissemination. RAB, in partnership with universities and international research centers, should invest in long-term ecological studies, evidence-based technical guidelines tailored to Rwanda's diverse agro-ecological zones, and extension services that translate scientific findings into accessible, farmer-centered guidance.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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