



ISSN Print: 2664-844X
ISSN Online: 2664-8458
NAAS Rating (2025): 4.97
IJAFS 2025; 7(9): 89-106
www.agriculturaljournals.com
Received: 10-05-2025
Accepted: 15-06-2025

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Reimagining crop rotation for resilient and sustainable intensification in Sub-Saharan Africa: Innovations, gaps, and scalable pathways

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DOI: <https://www.doi.org/10.33545/2664844X.2025.v7.i9b.735>

Abstract

Compounding agricultural issues in Sub-Saharan Africa (SSA) include population pressure, land fragmentation, and climate variability, all of which endanger environmental sustainability and food security, reduce agricultural resilience, and exacerbate rural poverty. Over 90% of farming in SSA being rain-fed, the sector is vulnerable to climate variability. Despite these challenges, SSA holds potential for agricultural transformation through innovative, sustainable farming practices like agroecology, climate-smart agriculture, and organic techniques. One important but little-used tactic for boosting agroecosystem resilience and promoting sustainable intensification is crop rotation. Crop rotation has improved soil fertility, reduced pest pressures, increased yield stability, and promoted ecological balance in SSA. Crop rotation, particularly with legumes and cereals, offers benefits like improved soil health, yield stability, and dietary diversity. However, adoption is constrained by infrastructural deficiencies, policy gaps, and limited access to resources. This review summarizes the history, contemporary methods, and creative approaches to crop rotation in SSA. The integration of native crops, cover crops, crop-livestock synergies, maize-legume systems, and the use of digital and geospatial technologies to maximize rotation planning are all given particular attention. To identify adoption barriers and routes, socioeconomic enablers and institutional innovations such as farmer field schools, climate-smart villages, and public-private partnerships are analyzed. This review synthesizes crop rotation practices in SSA, highlighting innovations, challenges, and actionable frameworks for sustainably intensifying production while preserving ecological integrity. Ultimately, reimagining crop rotation in SSA is essential for achieving resilient and equitable food systems.

Keywords: Crop rotation; agroecosystem resilience; sustainable intensification; climate-smart agriculture; crop-livestock integration; GIS-based land suitability

Introduction

Agriculture in Sub-Saharan Africa (SSA) stands at a critical juncture, facing intensifying pressures from climate change, land fragmentation, and rapid population growth. Together, these stressors threaten food security, reduce agricultural resilience, and exacerbate rural poverty. Over 90% of farming in SSA is rain-fed, rendering the sector particularly vulnerable to shifts in climate variability and extreme weather events (Tesfay, 2024) ^[161]. Predicted increases in temperature and changes in rainfall patterns are expected to lower agricultural productivity and amplify food insecurity across the region (Calzadilla *et al.*, 2009; Tesfay ^[161], 2024).

Compounding the climate crisis is the issue of land fragmentation, largely driven by demographic expansion. Population growth, while offering a potential labor force, has resulted in diminishing landholdings and forced cultivation on marginal lands, leading to soil degradation and diminishing returns (Maja & Ayano, 2021) ^[86]. As farm sizes shrink, sustainable land management becomes increasingly complex, particularly for smallholders with limited resources. With the SSA population projected to double by 2050, the corresponding increase in food demand places additional stress on agricultural systems already nearing their ecological and productive limits (Tesfay, 2024) ^[161].

Despite these daunting challenges, SSA holds considerable potential for agricultural transformation. Innovative, sustainable farming practices rooted in agroecology, climate-

smart agriculture (CSA), and organic techniques have emerged as promising solutions. These systems, when contextually adapted, offer pathways to both mitigate environmental risks and enhance livelihoods (Schilling, 2023; Kleemann, 2013) ^[140, 73]. Yet, widespread adoption remains constrained by infrastructural deficiencies, policy inertia, and a lack of regionally adapted guidelines.

Among the array of sustainable strategies, crop rotation has long been recognized for its role in promoting agroecosystem resilience. In SSA, it offers notable benefits, such as improved soil health, increased yield stability, and greater dietary diversity through the integration of legumes and cereals (Thierfelder *et al.*, 2013; Selim, 2019; Acevedo-Siaca & Goldsmith, 2020) ^[163, 143, 2]. Rotations with legumes, for example, enhance nitrogen fixation, reduce the need for synthetic fertilizers, and suppress pests and weeds through the disruption of pest life cycles (Dakora & Keya, 1997; Zohry & Ouda, 2018) ^[33, 187].

However, the implementation of crop rotation is not without limitations. In many regions, high-input crops like soybeans remain inaccessible to resource-poor farmers due to their associated input requirements and underdeveloped markets (Acevedo-Siaca & Goldsmith, 2020; Thierfelder *et al.*, 2013) ^[163, 2]. Knowledge gaps also persist, particularly in terms of agroecological zoning and the lack of tailored technical support for diverse farming environments (Sithole & Olorunfemi, 2024) ^[148]. Consequently, many smallholders continue to favor monoculture systems, driven by market demand and cultural preferences, despite the known ecological disadvantages.

To address these bottlenecks, innovations in crop rotation systems have begun to emerge. Integrating climate-resilient crops, orphan legumes, and low-input strategies such as push-pull technology offers new opportunities to enhance sustainability and productivity (Khan *et al.*, 2014; Vidigal *et al.*, 2019) ^[70, 170]. For instance, soy-maize rotations not only improve soil fertility but also diversify diets and mitigate pest pressures (Acevedo-Siaca & Goldsmith, 2020) ^[2]. Similarly, promoting drought-tolerant crop varieties and legume seed systems can increase farmer resilience against climatic and economic shocks (Makarim *et al.*, 2017; Breen *et al.*, 2024) ^[87, 22].

In spite of the promise of these practices, several gaps remain. Limited access to resources, inadequate extension services, and weak policy support hinder the scaling of crop rotation innovations. Effective implementation requires context-specific frameworks that consider environmental variability, sociocultural preferences, and market dynamics. Research efforts must also prioritize participatory approaches to co-develop locally adapted rotation strategies, grounded in both scientific evidence and indigenous knowledge systems.

This review aims to provide a critical and future-focused synthesis of crop rotation practices in SSA, highlighting key innovations, unresolved challenges, and actionable frameworks. By systematically evaluating the agronomic, environmental, and socioeconomic dimensions of crop rotation, the article seeks to inform strategies that can sustainably intensify production while preserving the ecological integrity of agroecosystems. Ultimately, reimagining crop rotation in SSA is not merely an agronomic exercise; it is an essential step toward achieving resilient and equitable food systems.

2. The Evolving Role of Crop Rotation in Sub-Saharan Africa

2.1 Historical Roots and Traditional Systems

The foundations of crop rotation in Sub-Saharan Africa (SSA) are deeply rooted in the region's agrarian history, shaped by millennia of environmental adaptation and indigenous knowledge. Agricultural activity in SSA began more than 5,000 years ago, with early communities in the Sahara and Sahel regions gradually transitioning from pastoralism to cultivation. This evolution saw the domestication of native crops such as sorghum and millet, and the emergence of diverse farming systems, including rudimentary forms of crop rotation (Stalker, Warburton, & Harlan, 2021; Smith, 2019) ^[152, 149].

Traditional crop rotation was often integrated with mixed farming systems that included livestock, enabling nutrient recycling and improved soil health. Practices such as *décrue* agriculture in the Niger Delta reflect sophisticated uses of seasonal flooding and crop sequencing to manage soil fertility and pest cycles (Stalker *et al.*, 2021) ^[152]. These practices were not merely functional but culturally embedded, with farming communities adapting rotation strategies in response to climatic variability and resource availability (Lane & Shoemaker, 2017) ^[77].

However, the resilience of these traditional systems has been challenged in recent decades. The introduction of monocultures, expansion of cash cropping, and diminished reliance on indigenous crops have contributed to the erosion of rotation practices. Consequently, many smallholder systems now suffer from nutrient depletion and reduced biodiversity, underscoring the need to reintegrate adaptive and sustainable rotation strategies rooted in traditional knowledge (Smith, 2019; Lane & Shoemaker, 2017) ^[149, 77].

2.2 Dominance of Maize-Legume Systems: Achievements and Saturation

In contemporary SSA agriculture, maize-legume rotations have emerged as the dominant form of crop rotation. This system owes its popularity to the agronomic synergy between maize and legumes, particularly the nitrogen-fixing capabilities of legumes, which enhance soil fertility and support robust maize yields (Sahoo *et al.*, 2023) ^[135]. In addition to ecological benefits, these rotations improve dietary diversity, offering critical micronutrients to rural households (Acevedo-Siaca & Goldsmith, 2020) ^[2].

Maize-legume systems also contribute to economic stability for smallholders. Higher yields and diversified harvests translate into increased income and better risk management in the face of fluctuating weather and market conditions (Breen, Ndlovu, McKeown, & Spillane, 2024) ^[22]. Furthermore, legumes such as beans and groundnuts offer ground cover that reduces erosion and suppresses weeds, promoting long-term land sustainability (Sahoo *et al.*, 2023) ^[135].

Despite their widespread adoption, these systems face signs of saturation. Constraints such as limited access to high-yielding legume varieties, inadequate extension support, and underdeveloped markets restrict further productivity gains and broader dissemination (Breen *et al.*, 2024; Acevedo-Siaca & Goldsmith, 2020) ^[22, 2]. Regional studies also reveal that yield benefits from legume rotations are highly site-specific, suggesting the need for context-sensitive recommendations (Mwila *et al.*, 2024) ^[106]. These limitations highlight a critical gap in current agricultural support systems and point to the necessity for innovation beyond maize-legume models (Table 1).

Table 1: Major maize-legume rotation types across SSA regions

Region	Rotation type	Key benefits	Key challenges
Southern Africa	Maize-Groundnut	Enhances nitrogen fixation, improves soil texture	Limited groundnut seed availability
Eastern Africa	Maize-Beans	Improves household nutrition and income	Susceptible to pest and disease outbreaks
West Africa	Maize-Cowpea	Drought-tolerant legume; supports food security	Weak market linkages for cowpea
Central Africa	Maize-Soybean	High nitrogen contribution; good income potential	High input requirement; low soybean adoption
Sahelian zones	Millet-Legume (Cowpea)	Suitable for dryland; maintains soil fertility	Limited extension services and seed systems

2.3 New Drivers - Climate Volatility, Demographic Pressure, and Market Shifts

The evolving landscape of SSA agriculture is increasingly shaped by external pressures climate change, demographic shifts, and volatile markets that are redefining the role and design of crop rotation systems. Climate volatility has introduced erratic rainfall patterns, prolonged droughts, and more frequent extreme weather events, directly threatening yield stability. Projections estimate a 0.28 percentage point annual reduction in economic growth due to rising temperatures, emphasizing the urgency for adaptive, resilient cropping systems (Carleton & Hsiang, 2016; Mikayelyan & Vardanyan, 2023) ^[25, 97].

Simultaneously, rapid population growth and urbanization place immense strain on arable land, infrastructure, and food systems. Migration from climate-affected areas further alters labor dynamics and rural economies, demanding more intensive and sustainable land use practices (Breckenfelder *et al.*, 2023; Guillén & Ontiveros, 2014) ^[21, 50]. These demographic trends not only increase demand for food but also necessitate efficient use of increasingly fragmented landholdings.

Market dynamics, driven by technological advancements and shifting trade patterns, add another layer of complexity. The integration of green technologies and carbon pricing mechanisms creates new opportunities for environmentally aligned agriculture, while also posing challenges for resource-limited farmers to access inputs and benefit from emerging value chains (Mikayelyan & Vardanyan, 2023) ^[97]. These transitions highlight the need for crop rotation systems that are not only ecologically sound but also economically viable and socially inclusive.

Together, these drivers push the boundaries of conventional crop rotation, requiring innovative approaches that combine traditional wisdom with scientific advancements. The future of crop rotation in SSA will depend on how well these systems are adapted to withstand systemic shocks while fulfilling the region's growing demand for sustainable intensification.

3. Rethinking Rotation: Crop Rotation as a Resilience-Building Strategy

3.1 Conceptual Framework Linking Rotation to Ecological Resilience

Ecological resilience in agroecosystems is deeply influenced by land-use decisions, with crop rotation emerging as a central strategy for sustaining biodiversity and ecosystem function. Conceptual frameworks that link crop rotation to ecological resilience are increasingly used to understand and predict the impacts of agricultural practices on biodiversity, ecosystem services, and long-term sustainability (Prasad *et al.*, 2010) ^[124]. These models identify direct and indirect drivers of biodiversity change, such as climatic variability, socio-economic pressures, and land-use intensity, and evaluate their influence on functional diversity and species richness.

Empirical studies show that crop rotation contributes to ecological resilience by maintaining functional redundancy, a key factor in ecosystem stability. For instance, reductions in functional redundancy (having multiple species doing similar functions), often driven by simplified land-use systems (in the system influences and boosts soil health), make ecosystems more vulnerable to additional stressors (Weeks *et al.*, 2025) ^[173]. Scenario simulations further highlight how spatial patterns of land-use intensity correlate with ecological resilience, reinforcing the utility of predictive frameworks in agroecological planning (Huo *et al.*, 2025) ^[61]. While these models enhance our understanding, they are constrained by the inherent non-linearity and context-dependence of ecological responses (Kuang *et al.*, 2024) ^[74], underscoring the need for adaptive and site-specific rotation strategies. Notably, Crop rotation supports biodiversity in the agroecosystem which is vital for various ecological functions including soil health maintenance, pest and disease regulation, biodiversity enhancement, and nutrient cycling. Also, crop rotation in model indicates that, it disrupts pests and diseases, which in turn improves ecosystem services. Strengthening these ecological aspects leads to better crop productivity which in turn contributes to the stability of the agroecosystem and enhances its resilience against climate shocks (Figure 1).

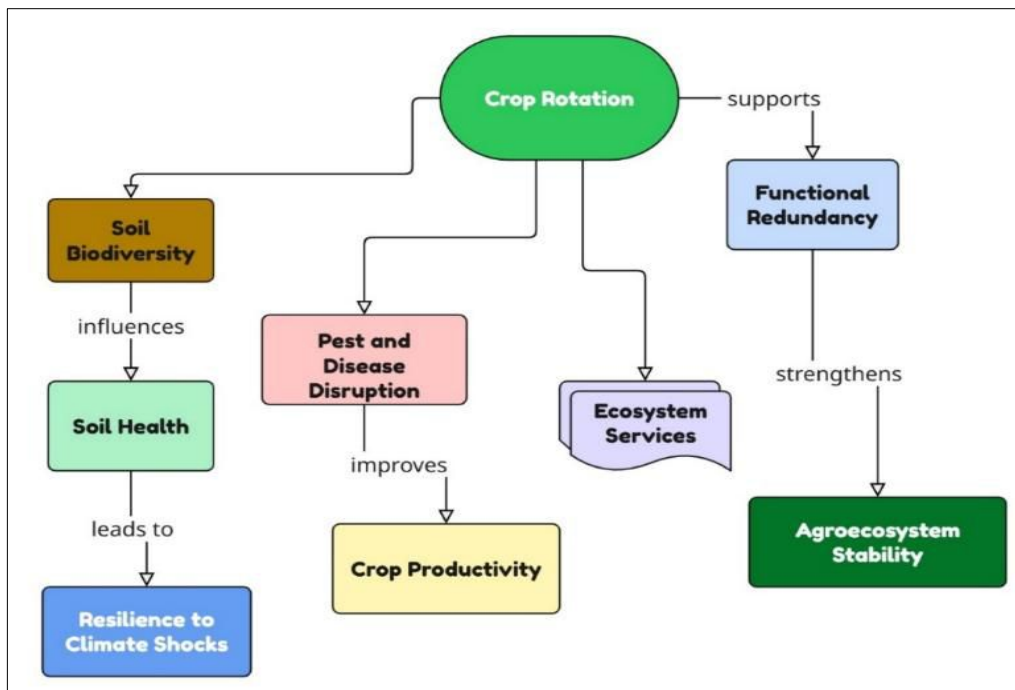


Fig 1: Conceptual model linking crop rotation to ecological resilience

3.2 Rotation's Role in Climate Adaptation and Risk Reduction

As climate variability intensifies, crop rotation has gained recognition as a key adaptation strategy in building agroecosystem resilience. Rotation-based diversification buffers agricultural systems against climatic shocks by improving yield stability, enhancing soil health, and optimizing resource use. Long-term evidence from North

America shows that diversified crop rotations can increase maize yields by up to 28.1% and significantly reduce yield losses during drought years by as much as 89.9% in extreme cases (Bowles *et al.*, 2020)^[19] (Figure 2). These findings are corroborated by similar results in Europe and Asia, where rotation complexity increased output even under poor growing conditions (Bybee-Finley *et al.*, 2024)^[23].

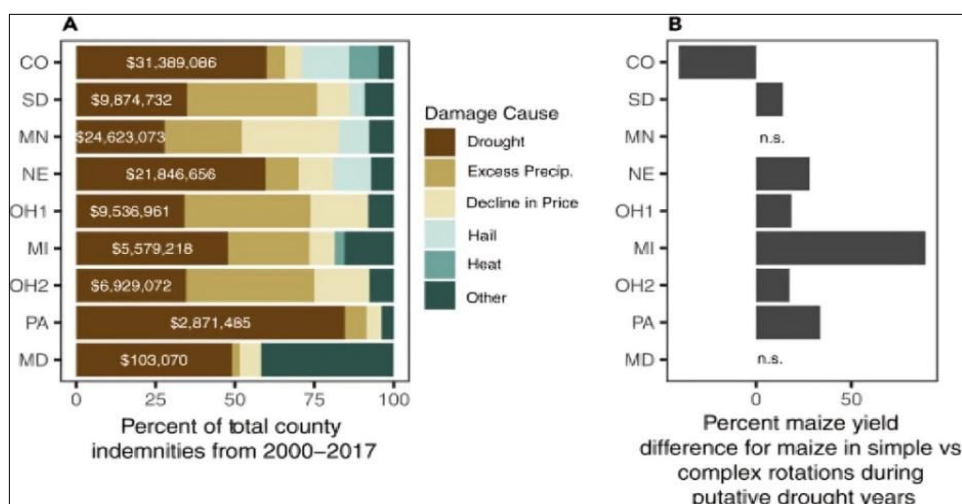


Fig 2: Yield performance under rotation vs. monoculture under climatic stress (Bowles *et al.*, 2020)^[19]

Rotating legumes with cereals enhance nitrogen fixation, boosts soil organic matter, and reduces dependence on synthetic inputs, which contributes to both climate change mitigation and adaptation (Zou *et al.*, 2024)^[189]. Additionally, these practices lower greenhouse gas emissions, improve water retention, and increase biodiversity, creating more robust production systems (Crop Rotation and Climate Change Adaptation in Argentina's Agriculture Sector, 2022; Yu *et al.*, 2022)^[181]. However, the transition toward rotational diversity may face economic barriers, particularly in low-productivity zones where

returns on diversification are marginal unless supported by incentives (Czettritz *et al.*, 2023)^[171].

Model-based assessments further reinforce these findings. Simulations of durum wheat-legume systems in Mediterranean environments show improved soil organic carbon sequestration and reduced emission intensities, validating crop rotation as a cost-effective climate adaptation mechanism (Farina *et al.*, 2018)^[39]. Together, these outcomes point to the urgent need for policy frameworks that promote rotation-based resilience, especially in vulnerable agricultural systems.

3.3 Diversity as a Buffer: Beyond Two-Crop Systems

Moving beyond conventional two-crop systems, diversified crop rotations involving oilseeds, vegetables, or drought-tolerant species offer enhanced ecological and economic resilience. Multi-species rotations create functional complementarity, where different crop traits contribute to yield stability and stress tolerance. In dry years, rotations that included small grains improved soybean yields by up to 22%, demonstrating the role of crop diversity in buffering climatic extremes (Gaudin *et al.*, 2015) ^[47]. Similarly, benefits of rotational diversity are maximized with the inclusion of two to four species, beyond which marginal returns tend to decline (Costa *et al.*, 2024) ^[29].

Environmental advantages are equally compelling. Long-term studies show that increasing crop rotation diversity reduces agrochemical use while maintaining or even enhancing productivity (Davis *et al.*, 2012) ^[34]. In the North China Plain, introducing legumes and cash crops into traditional monocultures resulted in a 39% reduction in nitrous oxide emissions and improved soil microbial activity, highlighting the environmental dividends of diversified systems (Yang *et al.*, 2024) ^[180]. Furthermore, crop diversification supports weed suppression, reduces herbicide resistance development, and strengthens pest control, contributing to broader system resilience (Weisberger *et al.*, 2019) ^[174].

Economic studies confirm that diversified rotations are not only sustainable but also profitable. Reduced input costs, improved yield stability, and enhanced ecosystem services position multi-crop systems as viable alternatives to input-intensive monocultures (Manski *et al.*, 2024) ^[190]. Despite these benefits, barriers such as limited farmer knowledge, risk aversion, and lack of market support persist. Overcoming these challenges will require targeted extension services, participatory experimentation, and supportive

policies that de-risk the transition toward rotation-based diversification.

4. Innovations in Crop Rotation Systems

4.1 Rotations with Indigenous Crops - Sorghum, Millet, Bambara Groundnut

The integration of indigenous crops such as sorghum, millet, and bambara groundnut into crop rotation systems presents a strategic opportunity to enhance agricultural sustainability, food security, and climate resilience in Sub-Saharan Africa (Table 2). These crops are highly adapted to semi-arid climates, require fewer external inputs, and contribute significantly to soil fertility and biodiversity. Millets and sorghum are nutritionally dense, containing high levels of iron, zinc, fiber, and protein, which are essential in addressing widespread micronutrient deficiencies in vulnerable populations (Evans Ongwae, n.d.). Their inclusion in cropping systems not only diversifies diets but also offers alternatives to heavily consumed staples like rice and wheat (Raj *et al.*, 2024) ^[128].

From an ecological perspective, millets and sorghum enhance soil structure and fertility, reduce erosion, and improve organic matter content (Raj *et al.*, 2024) ^[128]. Their drought tolerance and low water requirements make them ideal for areas prone to water scarcity (Kumar *et al.*, 2015) ^[76]. Intercropping systems such as sorghum-groundnut combinations optimize land use efficiency, nitrogen cycling, and reduce production risks in marginal lands (Maman *et al.*, 2017) ^[88].

Nonetheless, despite their potential, adoption remains limited due to market constraints and sociocultural perceptions of these crops as “poor man’s food” (Evans Ongwae, n.d.). Strengthening value chains, promoting awareness, and advancing breeding programs are crucial steps to mainstreaming these crops in rotation systems.

Table 2: Comparative attributes of indigenous crops in rotation systems

Crop	Nutritional value	Drought resistance	Input needs	Market access
Sorghum	High in protein and iron	High	Low	Moderate (varies regionally)
Millet	Rich in fiber, iron, and zinc	Very High	Very Low	Limited but improving
Bambara Groundnut	High in protein and amino acids	Moderate to High	Low	Poor (considered underutilized)

4.2 Use of Cover Crops and Green Manures

Cover crops and green manures play a pivotal role in regenerative agriculture by enhancing soil health, improving nutrient cycling, and offering natural pest and disease suppression. Their inclusion in rotation systems supports the ecological integrity of farming systems while improving crop performance.

Leguminous cover crops contribute to nitrogen fixation, improving soil fertility and reducing the need for synthetic fertilizers (Mackowiak, 2014) ^[85]. Brassicas and sudangrass are known for their biofumigation properties, suppressing soil-borne pathogens and enhancing microbial diversity (Larkin, 2021) ^[78]. These crops also reduce erosion, improve water infiltration, and strengthen soil structure (Blanco-Canqui & Lal, 2023) ^[17].

Beyond physical benefits, cover crops significantly boost ecosystem services. When integrated with composted manure, green manures increase biodiversity indicators and improve yields in organic systems (Talgre *et al.*, 2013) ^[158]. In Brazil, the adoption of cover crops in no-till systems has shown measurable improvements in soil aggregation and

biological activity, promoting long-term productivity (Souza *et al.*, 2024) ^[151].

While the benefits are substantial, challenges such as labor costs, management complexity, and region-specific performance remain. Nevertheless, when carefully selected and managed, cover crops and green manures form a critical component of resilient rotation systems.

4.3 Crop-Livestock Integrated Rotation Systems: Synergies and Trade-Offs

The integration of crop and livestock systems offers a synergistic approach to sustainable intensification. This model enables nutrient recycling, diversified income, and resilience to environmental and market fluctuations.

Manure from livestock provides a renewable source of nutrients, enhancing soil fertility and organic matter content, thereby reducing dependence on external inputs (Aslam *et al.*, 2024) ^[10]. Grazing animals on crop residues also supports weed suppression and reduces labor demands. Conversely, crops benefit from improved soil structure and water retention, leading to higher productivity (Figure 3).

However, trade-offs include potential competition for land, nutrient imbalances from over-application of manure, and disease transmission risks between livestock and crops.

Effective integration requires strategic spatial and temporal planning to harmonize productivity with ecological balance.

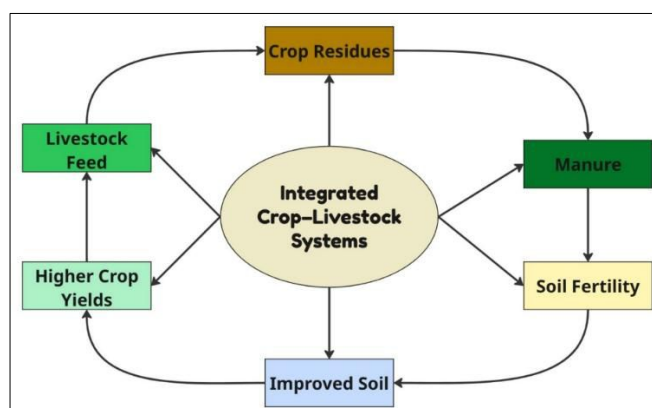


Fig 3: Crop-livestock integrated system dynamics

4.4 Decision Support Tools, Remote Sensing, and Mobile Apps for Rotation Planning

Digital technologies are revolutionizing crop rotation planning by offering data-driven decision-making tools that enhance precision and sustainability. Internet of Things (IoT) sensors and machine learning algorithms enable real-time monitoring of soil moisture, nutrients, and climatic conditions to optimize crop sequences (Sujata *et al.*, 2024) [153].

The AgroTutor mobile application exemplifies farmer-centric technology that delivers geo-localized advice on

crop choice, yield forecasts, and financial planning (Bayas *et al.*, 2020) [79]. These platforms encourage farmer participation and contribute real-time field data that inform adaptive rotation strategies.

Intelligent decision support systems like VELOS use remote sensing and GPS to monitor crop health and optimize pest management, thereby reducing chemical inputs and improving resource efficiency (Theodorou *et al.*, 2023) [162]. While technological barriers persist especially in rural, low-infrastructure areas the potential for scaling smart rotation planning tools remains high (Figure 4).

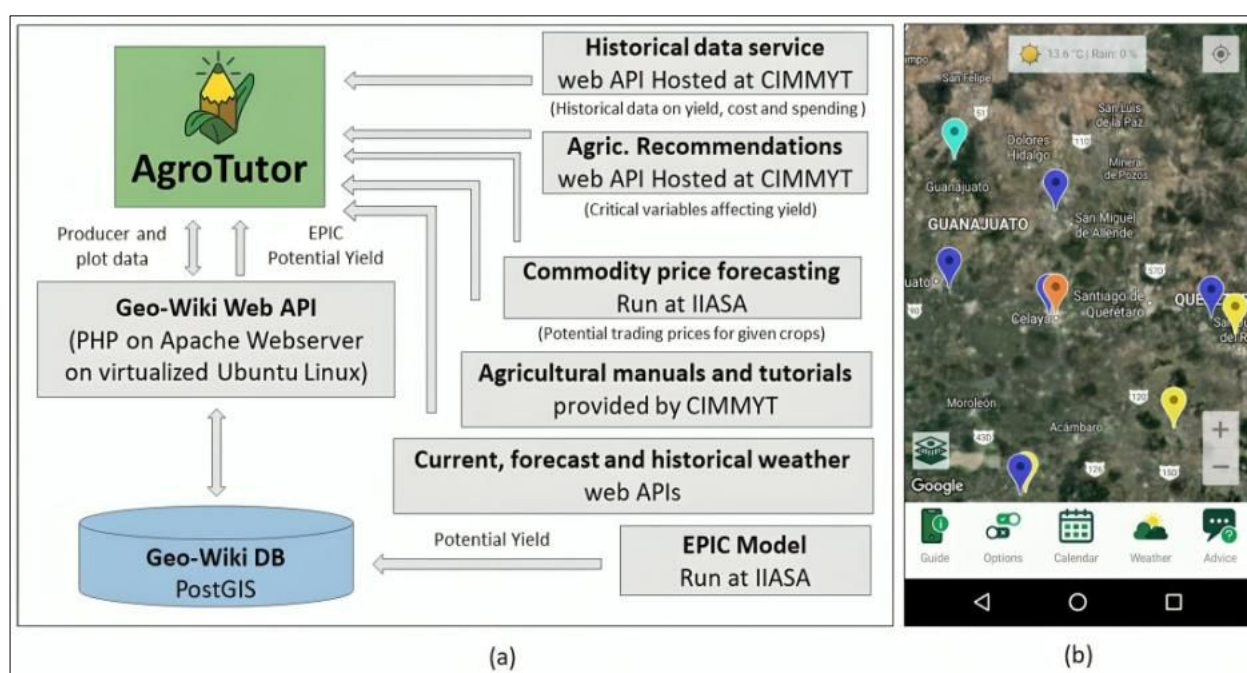


Fig 4: (a) AgroTutor data structure with its components and (b) a display of the main screen of the mobile application. Geo-Wiki is the current server at the International Institute for Applied Systems Analysis (IIASA) where data are stored and processed.

4.5 GIS-Based Land Suitability Mapping for Rotation Optimization

Geographic Information Systems (GIS) have become indispensable for optimizing crop rotation through land suitability analysis. By integrating data on soil characteristics, topography, and climate, GIS enables precise matching of crops to suitable land parcels, thus enhancing productivity and sustainability.

Analytical Hierarchy Process (AHP) techniques, used in conjunction with GIS, help evaluate multiple criteria to rank land suitability for various crops (Singha *et al.*, 2020) [146]. For instance, a GIS-AHP study in West Bengal revealed that 29.2% of land was highly suitable for rice, supporting evidence-based crop rotation planning (Singha *et al.*, 2020) [147].

GIS also facilitates the identification of appropriate crop sequences that maintain soil fertility and pest suppression. In Upper Egypt, GIS models guided the optimal allocation of land for sugar beet and other crops, leading to improved soil conservation and agricultural output (Zakarya *et al.*, 2021) ^[182].

Despite its promise, the application of GIS requires accurate and regularly updated data, as well as training for local stakeholders. Investing in these capacities is essential for leveraging GIS in rotation planning at scale.

Table 3: Case studies on GISs-based rotation optimization

Country/Region	Crops Involved	GIS Criteria Used	Key Outcomes
West Bengal, India	Rice, Pulses	Soil texture, slope, rainfall, land use	Identified 29.2% of land as highly suitable
Upper Egypt	Sugar beet, Wheat	Soil fertility, drainage, proximity to markets	Optimized land use; improved crop yields
Ethiopia (Tigray)	Teff, Lentils	Elevation, slope, erosion risk	Targeted zones for erosion-resistant crops
SSA (Pilot areas)	Maize, Soybean	Rainfall, soil organic matter, pH	Enabled precise site-specific rotation plans

5. Socio-Economic and Institutional Enablers

5.1 Farmer Knowledge Systems and Barriers to Adoption

Farmer knowledge systems in Sub-Saharan Africa (SSA) are foundational to the successful adoption of crop rotation practices. These systems are shaped by a complex interplay of socio-demographic, economic, and institutional factors. Age, gender, household size, and farming experience significantly influence farmers' understanding and willingness to adopt rotation techniques (Kinyua *et al.*, 2023) ^[172]. Experienced farmers, particularly older ones, are more likely to understand the agronomic benefits of crop rotation and integrate it into their practices (Table 4).

Access to agricultural extension services plays a critical role in facilitating knowledge transfer. However, spatial disparities in service availability limit many farmers' ability to acquire and implement crop rotation knowledge

(Gwandu, 2016) ^[151]. Moreover, indigenous knowledge systems though rich in contextual insights can sometimes conflict with formal recommendations, leading to resistance or selective adoption of innovations (Bagnall-Oakeley *et al.*, 2004) ^[14].

Economic constraints further impede adoption. Farmers with limited financial resources often lack the capacity to invest in inputs required for successful rotational systems, such as legume seeds or fertilizers, particularly in high-input systems like maize-soybean rotations (Acevedo-Siaca & Goldsmith, 2020) ^[2]. In contrast, those with market access are more inclined to adopt crop rotation due to its economic incentives (Bagnall-Oakeley *et al.*, 2004) ^[14]. Addressing these structural barriers requires participatory approaches that integrate formal extension with locally relevant knowledge frameworks and economic support.

Table 4: Socio-demographic factors influencing crop rotation adoption

Factor	Influence on adoption	Notes
Age	Older farmers more likely to adopt	Due to accumulated experience and land tenure security
Gender	Men dominate strategic decisions	Women's adoption increases where they manage own plots
Landholding Size	Larger plots support more diverse rotations	Smallholders often stick to monoculture for subsistence
Access to Extension	Strongly correlated with rotation adoption	Extension gaps common in remote or conflict-prone areas
Education Level	Higher education improves uptake	Linked to better understanding of long-term soil benefits

5.2 Gendered Dynamics and Household-Level Decision Making

Gender dynamics significantly shape household-level decision-making processes around agricultural innovation, including crop rotation. While women are increasingly involved in daily agricultural tasks, their influence on strategic decisions remains limited due to entrenched patriarchal norms and asset disparities (Shibata *et al.*, 2020) ^[145]. In many contexts, men control decisions related to income-generating crops, reinforcing gendered inequalities in resource access and innovation uptake.

Even when women assume more responsibilities as seen in cases of male migration their bargaining power remains nominal, and decisions are often made jointly but unequally (Mohan *et al.*, 2022) ^[101]. In other cases, decision-making authority may appear shared, but underlying power asymmetries persist, with women seeking approval for significant choices (Sun, 2010) ^[156].

These patterns are influenced by intersecting factors such as education, household composition, and socio-economic status. For instance, higher educational attainment correlates with more egalitarian decision-making structures (Nurseha, 2024) ^[113]. Despite growing recognition of these dynamics, institutional interventions often fail to account for the

nuanced ways gender affects adoption. Promoting gender-equitable extension strategies and strengthening women's agency in agricultural decision-making are essential for inclusive innovation.

5.3 Market Linkages and Value-Chain Alignment

Robust market linkages and value-chain integration are essential enablers of crop rotation adoption and sustainability. When farmers are connected to markets, they are more likely to diversify their production and invest in soil-enhancing practices like rotation, due to higher returns and reduced risks (Devaux *et al.*, 2016) ^[36]. For instance, contract farming and cooperative marketing have enabled farmers in Tanzania and Vietnam to secure higher producer prices and access better inputs (Herrmann *et al.*, 2018; Khong, 2022) ^[58, 71].

However, several structural barriers limit the reach and efficacy of these linkages. Geographic remoteness, weak infrastructure, and social disparities restrict access to commercial networks, especially for marginalized communities (Iw *et al.*, 2012) ^[65]. Furthermore, misalignments between public policy and market incentives hinder the development of inclusive value chains, impeding smallholder participation (Ahmed *et al.*, 2016) ^[5].

To enhance crop rotation adoption, market development strategies must focus on reducing transaction costs, improving aggregation, and supporting inclusive contract models (Pingali *et al.*, 2019)^[123]. Strengthening value chains not only enables rotation adoption but also stabilizes incomes and improves food security.

5.4 Case Studies of Community or Cooperative-Led Rotation Initiatives

Community-based and cooperative-led initiatives have demonstrated notable success in scaling sustainable agricultural practices, including crop rotation. Their strength lies in leveraging collective action, shared knowledge, and local governance structures. For example, the Bangkit Bersama Cooperative in Indonesia succeeded by emphasizing transparent communication, conflict resolution, and shared goals (Ivanka & Sembiring, 2017)^[64]. Similarly, community-led carbon credit projects in Timor-Leste revealed that strong local engagement and defined governance frameworks are key to project sustainability (Cruz, 2024)^[32].

These initiatives often rely on informal relationships, mutual trust, and shared leadership, fostering an adaptive environment that supports experimentation and learning. Such collaboration enhances resilience and innovation, enabling communities to address challenges such as resource scarcity and climate variability (Manju Prem S *et al.*, 2024)^[188].

Despite their potential, cooperative models face challenges such as unequal participation, fluctuating member commitment, and vulnerability to external economic pressures. Sustained success requires institutional support, capacity building, and mechanisms that align cooperative goals with broader policy and market frameworks (Scotts, 2011)^[142]. Investing in these grassroots models is critical to creating scalable, context-sensitive rotation systems across SSA.

6. Policy, Governance, and Scaling Pathways

6.1 Policy Blind Spots and Fragmentation Across Ministries

Policy fragmentation remains a critical barrier to the widespread adoption and scaling of sustainable crop rotation systems in Sub-Saharan Africa. Ministries of agriculture, environment, and rural development frequently operate in silos, leading to overlaps, inefficiencies, and policy contradictions. This sectoral orientation results in missed opportunities for integrated rural development and environmental conservation (Gawith & Hodge, 2019)^[48].

Agricultural policies often prioritize short-term productivity without considering long-term environmental sustainability, while rural development frameworks may neglect agricultural transformation in favor of infrastructure or health (Partridge, Olfert, & Ali, 2009)^[119]. Furthermore, traditional rural policies frequently ignore ecosystem services, despite their vital role in sustaining agricultural livelihoods (Gawith & Hodge, 2019)^[48]. This misalignment hampers the effective use of public resources and undermines the potential for climate-resilient agricultural innovation.

To correct these blind spots, institutional reform must focus on enhancing inter-ministerial coordination and mainstreaming ecosystem-based approaches across policy domains. Emphasizing place-based strategies that account

for the unique needs and capacities of rural communities rather than uniform, sector-driven agendas offers a more inclusive path toward agricultural sustainability (Forney, 2016)^[44].

6.2 Role of Extension Systems and Public-Private Partnerships

Extension systems and public-private partnerships (PPPs) are vital enablers of knowledge dissemination, technology adoption, and inclusive agricultural innovation. Contemporary extension systems now prioritize climate resilience and sustainability, offering training that integrates agroecological principles with digital tools (Allahyari, 2009; Raji, Ijomah, & Eyieyen, 2024)^[7, 128]. Farmer Field Schools and ICT-based platforms have been particularly effective in delivering context-relevant learning and enhancing adaptive capacity (Roy & Swargiary, 2025)^[131].

PPPs enhance these efforts by mobilizing resources, fostering innovation, and bridging institutional gaps. In South Africa, PPPs have demonstrated the ability to strengthen food security and improve extension service delivery by pooling private sector agility with public sector reach (Raidimi & Kabiti, 2017)^[127]. Notably, partnerships have facilitated the deployment of advanced technologies such as pest forecasting tools and precision farming contributing to productivity and environmental gains (Manohar *et al.*, 2024)^[89].

Nevertheless, the success of extension systems and PPPs is often constrained by the digital divide, limited funding, and weak regulatory frameworks (Ferroni & Castle, 2011; Sahoo *et al.*, 2024)^[42, 134]. Addressing these bottlenecks will require targeted investment in infrastructure, improved accountability mechanisms, and inclusive models that reflect local realities.

6.3 Institutional Innovations for Scaling: Farmer Field Schools, Innovation Platforms, and Climate-Smart Villages

Innovative institutional approaches offer promising pathways for scaling climate-resilient crop rotation systems across diverse agroecological zones. Farmer Field Schools (FFS) provide experiential learning environments where farmers co-develop context-specific solutions through participatory methods. This model has proven effective in integrating indigenous knowledge with scientific practices, fostering autonomy and informed decision-making (Osumba, Recha, & Oroma, 2021; Review of Farmers Field School, 2023)^[117, 130].

Innovation platforms extend this engagement by convening stakeholders farmers, researchers, policymakers, and private actors to collaboratively address agricultural challenges. These platforms facilitate co-creation of solutions and knowledge exchange, enabling systemic adaptation to climate and market shifts (Turyasingura & Chavula, 2022)^[167]. Their multi-actor design promotes synergy across sectors, making them particularly effective for overcoming institutional inertia and fragmented governance.

Climate-Smart Villages (CSVs) represent a holistic approach, integrating crop diversification, weather monitoring, resource conservation, and participatory governance to build local resilience (Karri & Nalluri, 2023)^[68]. These villages align local development priorities with climate-smart agriculture principles, embedding adaptive practices in community planning. The CSV model

emphasizes inclusivity, often targeting women and youth to promote equitable participation in resilience-building (Figure 5).

While these institutional innovations have demonstrated success, scaling them remains a challenge due to high

operational costs, need for skilled facilitators, and contextual variability. A strategic integration of FFS, innovation platforms, and CSVs tailored to regional needs could offer a scalable, cost-effective framework for promoting climate-smart crop rotation systems across SSA.

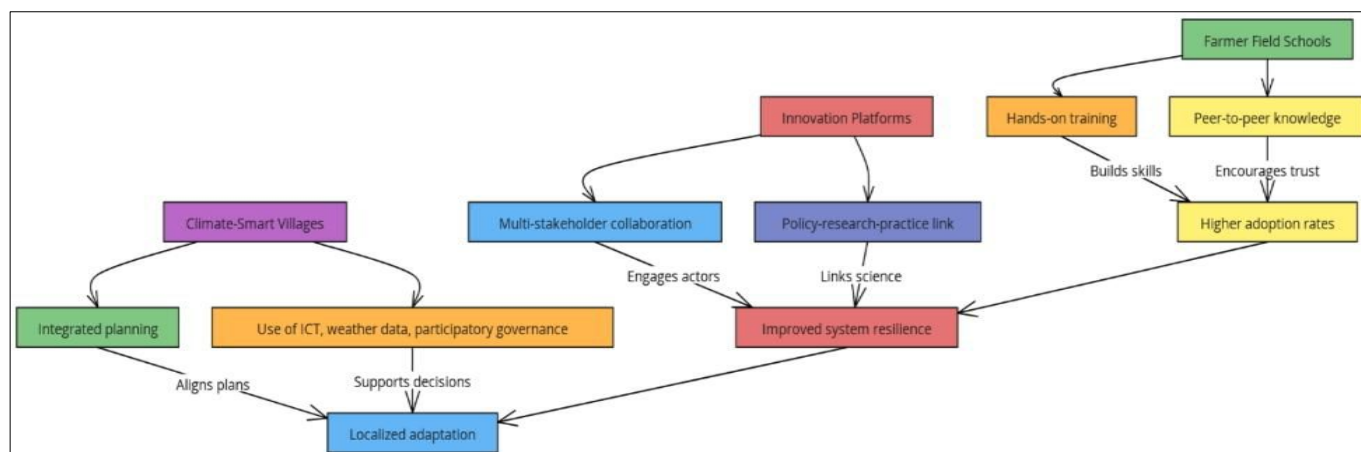


Fig 5: Institutional innovation pathways for scaling crop rotation

7. Synthesis: A New Framework for Mainstreaming Resilient Crop Rotation

7.1 Proposed Framework Integrating Agroecological, Socio-Economic, and Technological Dimensions

Mainstreaming resilient crop rotation in Sub-Saharan Africa demands an integrated framework that brings together agroecological, socio-economic, and technological dimensions. Such a holistic approach is essential for developing systems that are both productive and adaptive to climatic and market-related uncertainties.

Agroecologically, crop rotation enhances soil health by fostering microbial diversity and improving nutrient cycling, thereby reducing dependence on synthetic fertilizers (Zou *et al.*, 2024; Gan & Scherer, 2022) ^[189, 46]. It also promotes biodiversity and natural pest regulation, enhancing the resilience of farming systems to biotic and abiotic stressors (Yu *et al.*, 2022; Azeem *et al.*, 2023) ^[181, 12].

On the socio-economic front, low-input rotational systems have been linked to greater financial stability and higher farmer satisfaction, particularly in risk-prone environments (Cradock-Henry, 2021) ^[30]. Diverse cropping systems also improve market responsiveness and livelihood resilience, enabling producers to adapt to shifting economic conditions (Yu *et al.*, 2022) ^[181].

Technological innovations are critical in supporting this integrated framework (Figure 6). Tools such as precision agriculture platforms, remote sensing, and decision-support apps help optimize crop choices, monitor environmental variables, and guide real-time adjustments (Cradock-Henry, 2021) ^[30]. Continued research and breeding for climate-resilient varieties further reinforce system adaptability (Azeem *et al.*, 2023) ^[12]. However, widespread adoption is constrained by knowledge transfer limitations and market access barriers, necessitating institutional and policy support.

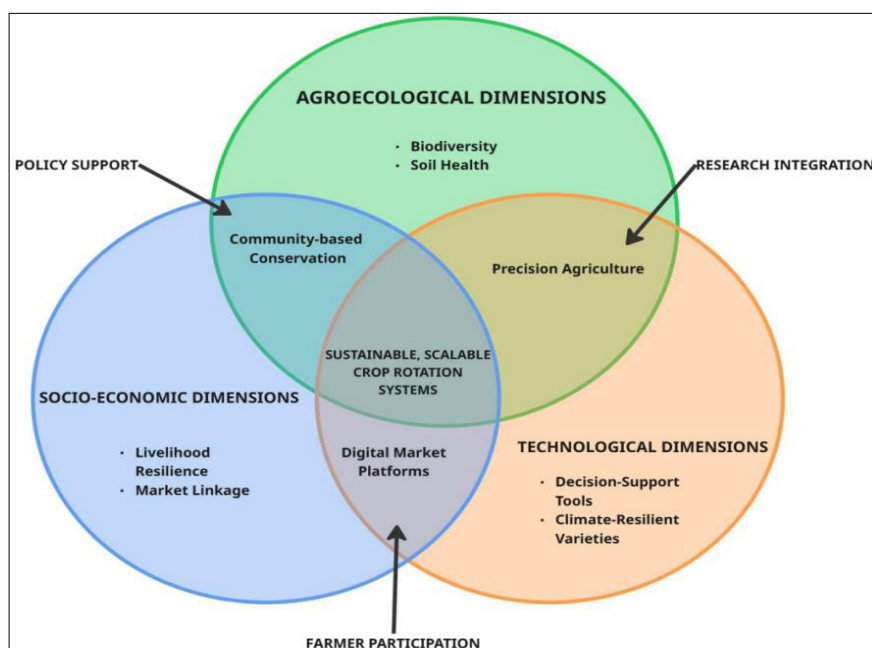


Fig 6: Integrated framework for mainstreaming crop rotation

7.2 Guiding Principles for Scaling: Flexibility, Contextualization, Inclusivity

A successful strategy for scaling crop rotation must be guided by the principles of flexibility, contextualization, and inclusivity. These principles ensure that rotation systems are relevant, adaptive, and equitable.

Flexibility in crop selection allows farmers to adapt rotational sequences to seasonal conditions, resource availability, and market demands (Chongtham *et al.*, 2017)^[28]. Crop diversity in rotations enhances pest suppression and climate resilience while reducing reliance on agrochemicals (Aslam *et al.*, 2024)^[10].

Contextualization ensures that practices are tailored to local agroecological conditions and socio-economic realities. For example, the use of drought-tolerant crops in arid zones optimizes productivity while conserving water (Makarim *et al.*, 2017)^[87]. Economic viability remains essential; rotation strategies must generate tangible returns to incentivize adoption, especially among smallholder farmers (Selim, 2019)^[143].

Inclusivity involves engaging farmers and communities in planning and implementation. Participatory models that incorporate traditional knowledge increase farmer ownership and adherence to sustainable practices (Farooq *et al.*, 2019)^[40]. Recognizing gender roles and socio-cultural dynamics further enhances the relevance and equity of rotation systems (Chongtham *et al.*, 2017)^[28].

Despite these strengths, the successful implementation of these principles requires ongoing support through capacity building, market development, and policy alignment.

7.3 Alignment with Regional and Global Goals - CAADP, SDGs, Climate Targets

Resilient crop rotation systems align closely with the goals of regional and international frameworks such as the Comprehensive Africa Agriculture Development Programme (CAADP), the Sustainable Development Goals (SDGs), and global climate commitments. These systems simultaneously advance ecological integrity, economic viability, and social well-being (Vaijnath Kantiram Chavan *et al.*, 2024)^[190].

Crop rotation contributes to SDG 2 (Zero Hunger) by improving soil fertility, enhancing yield stability, and enabling sustainable intensification (Selim, 2019; Aslam *et al.*, 2024)^[143, 10]. It also supports SDG 13 (Climate Action) by reducing greenhouse gas emissions and promoting carbon sequestration (Brankatschk & Finkbeiner, 2017)^[20]. By minimizing chemical inputs and increasing agroecosystem resilience, crop rotations advance SDG 15 (Life on Land) and foster biodiversity conservation.

At the regional level, CAADP's focus on boosting agricultural productivity and resilience is directly supported by crop rotation, particularly through National Agricultural Investment Plans that prioritize soil health and climate-smart practices (Diallo & Wouterse, 2022)^[37]. Implementing rotational strategies as part of CAADP's broader framework enhances resource efficiency and builds systemic resilience to climate shocks (Ouda & Zohry, 2018)^[187].

Nevertheless, to fully leverage these synergies, crop rotation must be embedded within interdisciplinary policy initiatives that bridge agricultural, environmental, and economic sectors. The development of adaptive management tools, such as crop rotation planning software and scenario-based

models, will be essential for aligning local practices with global sustainability targets (Schoening *et al.*, 2022)^[141].

8. Future Research and Implementation Gaps

8.1 Need for Interdisciplinary, Longitudinal, and Participatory Rotation Trials

Despite the well-documented benefits of crop rotation, significant knowledge gaps remain regarding its long-term impacts across diverse agroecological and socio-economic contexts in Sub-Saharan Africa. To address these gaps, future research must prioritize interdisciplinary, longitudinal, and participatory trials that integrate agronomy, ecology, socioeconomics, and farmer experiences.

Interdisciplinary approaches enhance understanding of crop rotation's multifaceted benefits. For example, incorporating plant protection, soil science, and environmental monitoring reveals how legume-based rotations improve soil nitrogen levels through biological fixation and reduce reliance on synthetic fertilizers (Zou *et al.*, 2024; Selim, 2019)^[189, 143]. Integrated pest management (IPM) strategies, derived from cross-disciplinary insights, show that diversified rotations disrupt pest life cycles and lower chemical dependency (Aslam *et al.*, 2024; Muniappan & Heinrichs, 2018)^[10, 104].

Longitudinal studies are crucial for capturing cumulative ecological benefits and socio-economic trade-offs over time. However, most existing trials are short-term and rarely participatory. Engaging farmers in trial design and implementation ensures that research reflects field realities and supports scalable, adaptive practices (Selim, 2019)^[143]. Barriers such as weak knowledge transfer mechanisms, limited market incentives, and resource constraints must be addressed through inclusive, stakeholder-driven frameworks.

8.2 Metrics and Monitoring Tools for Resilience and Sustainability

The mainstreaming of crop rotation in sustainable agriculture is hampered by a lack of standardized, practical metrics for measuring resilience and sustainability outcomes. Existing tools often prioritize economic performance over ecological or social dimensions, limiting their utility for holistic assessment (Schoening *et al.*, 2022)^[141].

Analytical Hierarchy Process (AHP) has been identified as a robust tool for evaluating sustainability based on multi-criteria decision-making and stakeholder preferences (Nisperos & McKenzie, 2018)^[108]. Life Cycle Assessment (LCA) provides an integrated framework for assessing environmental impacts, including carbon footprint, energy use, and soil health (Hassan *et al.*, 2025)^[55]. These tools, when complemented with farmer-friendly platforms, offer potential for participatory monitoring (Table 5).

However, most monitoring systems are not easily accessible to smallholder farmers due to technological and financial barriers (Getahun *et al.*, 2024)^[49]. The development of inclusive, scalable tools that combine traditional indicators (e.g., soil texture, crop vigor) with digital applications (e.g., remote sensing, mobile dashboards) is essential for tracking progress across diverse farming systems (Meul *et al.*, 2010)^[96]. Co-designing these tools with end-users will increase adoption and ensure that sustainability is measurable and actionable at the farm level.

Table 5: Comparison of metrics and monitoring tools for rotation systems

Tool/Framework	Primary use case	Accessibility to Smallholders	Strengths	Weaknesses
AHP (Analytic Hierarchy Process)	Sustainability evaluation, land suitability ranking	Moderate (needs facilitation)	Participatory, adaptable to local criteria	Requires technical support and training
LCA (Life Cycle Assessment)	Environmental impact assessment	Low	Comprehensive, aligns with SDGs	Complex; data-intensive and expensive
Remote Sensing and GIS	Rotation planning, soil monitoring	Moderate	Spatially extensive, scalable	Requires satellite data and interpretation
Mobile Dashboards (e.g., AgroTutor)	Decision support, crop guidance	High (with smartphone access)	Farmer-friendly, real-time data	Dependent on connectivity and app literacy

8.3 Cross-Scalar Analysis - From Plot to Policy

To ensure the transformative potential of crop rotation, future research must bridge the gap between field-level practices and macro-level policy decisions through cross-scalar analysis. Such integration allows insights from on-farm experimentation to inform national agricultural strategies and vice versa.

At the micro level, factors such as farmer cognition, landholding size, and household composition influence rotation decisions (Zhang *et al.*, 2025) ^[183]. Macro-level constraints, including land-use policies and subsidy frameworks, shape the enabling environment for these decisions. For instance, national policy incentives often favor simplified rotations, inadvertently degrading soil health in high-potential areas (Socular *et al.*, 2021) ^[150].

Cross-scale models, such as dynamic programming and Bayesian simulations, offer valuable tools for analyzing the long-term effects of crop rotation policies and identifying optimal intervention points (MacEwan & Howitt, 2019; Paton *et al.*, 2015) ^[83]. Moreover, integrating empirical plot data with geospatial analysis enhances predictive capacity for regionally appropriate crop rotation strategies (Upcott *et al.*, 2022) ^[169].

While cross-scalar methods are powerful, they face institutional and logistical challenges, including high transaction costs and limited data interoperability (Working Across Scales, 2023) ^[178]. Overcoming these barriers requires institutional investment in data infrastructure and policy processes that enable knowledge flows between farmers, researchers, and policymakers.

Conclusion

Crop rotation stands as a critical, yet underutilized, pathway toward building resilient agroecosystems and achieving sustainable intensification in Sub-Saharan Africa. In the face of mounting 21st-century challenges including climate volatility, land fragmentation, and rapid population growth reaffirming the role of crop rotation is essential. As demonstrated, diversified rotation systems not only enhance soil health and biodiversity but also buffer agroecosystems against climate risks, stabilize yields, and promote economic resilience (Zou *et al.*, 2024; Yu *et al.*, 2022) ^[189, 181].

Recent innovations in crop rotation strategies, such as the incorporation of indigenous crops, use of cover crops and green manures, integration with livestock systems, and adoption of digital decision-support tools, offer promising avenues for sustainable transformation (Raj *et al.*, 2024; Souza *et al.*, 2024; Sujata *et al.*, 2024) ^[128, 151, 153]. Institutional innovations, including Farmer Field Schools, innovation platforms, and Climate-Smart Villages, have demonstrated that participatory, community-driven models are vital for scaling rotational practices (Osumba, Recha, & Oroma, 2021; Karri & Nalluri, 2023) ^[117, 68].

Nevertheless, significant gaps remain. Limited interdisciplinary, longitudinal research constrains the understanding of rotation's long-term ecological and socio-economic impacts (Selim, 2019; Zou *et al.*, 2024) ^[143, 189]. Metrics for monitoring resilience and sustainability are still fragmented and often inaccessible to smallholders (Schoening *et al.*, 2022) ^[141]. Moreover, there is a critical need for cross-scalar analyses that bridge plot-level practices with broader policy frameworks to create an enabling environment for sustainable agricultural transformation (MacEwan & Howitt, 2019) ^[84].

In moving forward, a concerted call to action is necessary. Researchers must prioritize participatory, interdisciplinary trials that integrate biophysical, economic, and social dimensions, while developing accessible metrics for resilience and sustainability. Policymakers must address policy fragmentation and design cohesive strategies that incentivize and support rotation-based farming systems through targeted subsidies, extension services, and market development. Practitioners including extension agents, development organizations, and farmer cooperatives must champion adaptive, inclusive models that align technological innovations with indigenous knowledge systems.

Reimagining crop rotation for resilient agroecosystems is not merely a technical adjustment but a transformative agenda for sustainable development in Sub-Saharan Africa. Achieving this vision requires an integrated, multistakeholder approach that embeds ecological principles, economic viability, and social inclusivity at the core of agricultural systems. Only through such a comprehensive, context-sensitive strategy can crop rotation realize its full potential as a foundation for future food security, rural prosperity, and ecological resilience.

Acknowledgement

We thank the journal for considering this review article for publication

Declarations

Funding

The authors declare that this research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of Interest

There is no conflict of interest.

Availability of data and material

Data will be made available upon request.

Authors' contributions

Concepualization: J.A.K., F.P.M. Software: J.A.K. Validation: B.Y.K., F.P.M. Formal analysis: J.A.K., F.P.M., B.Y.K. Investigation: P.K.A., A.S.E.A. Writing-original draft: J.A.K., A.S.E.A., P.K.A., Writing-review & editing: B.Y.K., F.P.M. Visualization: J.A.K., F.P.M. Supervision: B.Y.K. All co-authors reviewed the final version and approved the manuscript before submission.fig

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