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UNLOCKING INTENSIFICATION IN LEGUME-DRIVEN SYSTEMS

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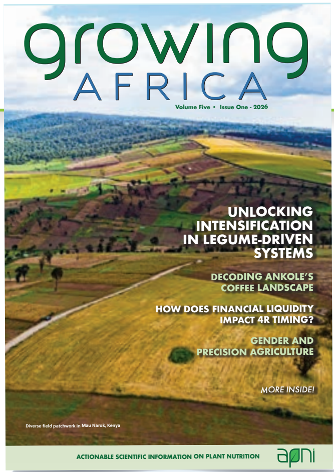

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Inside this Issue

Welcome to our first issue of *Growing Africa* for 2026. It is a pleasure to bring you another collection of practical, science-based articles designed to support the advancement of sustainable and productive agriculture across the continent.

Across Africa, farmers face an increasingly complex production environment. Soil degradation, climate variability, market uncertainties, and changing input costs continue to place pressure on agricultural systems. Our feature article examines the links between nutrient management, market access, and sustainable intensification in legume-based systems across Africa. What might be holding back legume-drive intensification in our smallholder cropping systems?

We are also pleased to present a two-part feature on Gender and Precision Agriculture in Africa, examining both the barriers and opportunities facing women and youth in accessing precision agriculture technologies. As 2026 marks the International Year of the Woman Farmer, this discussion is especially timely and important.

Additionally, we highlight recent work in Kenya exploring the often-overlooked role of financial liquidity in determining whether farmers can apply nutrients at the right time. Additional articles examine nutrient management in Morocco's olive systems, the socio-economic factors shaping soil fertility decisions in Ghana, and the diverse realities of coffee-banana farming systems in Uganda.

Beyond agronomic practices, this issue encourages us to think more broadly about the connections between soil health, crop nutrition, livelihoods, and even human health outcomes. The evidence continues to show that investments in better crop nutrition can deliver benefits far beyond the farm gate.

Thank you for your continued interest in *Growing Africa*. We hope the knowledge and experiences shared in these pages inspire new ideas, productive discussions, and practical action. Questions about article submissions can be answered by our guide for authors (https://growingafrica.pub/about).

More information about the publication process can be obtained by contacting our staff directly. Together, we can continue advancing science-based solutions that strengthen African agriculture and improve livelihoods across the continent.

Sincerely yours,

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Unlocking Intensification in Legume-Driven Systems: The Role of Markets and Input Access

By Esther Mugi-Ngenga, William Adzawla, Pamela Pali, Brayan Valencia, Shamie Zingore, and Thomas Oberthür

Legume-based systems can drive sustainable intensification in sub-Saharan Africa (SSA), but their success, especially with legume–cereal integration and phosphorus (P) fertilization, is constrained by market access *Using baseline data from 1,064 households in Ghana, Tanzania, and Malawi, this study assesses readiness to achieve productivity, nutrient-use, and economic targets under Legume-Driven Intensification (LDI). Results show strong spatial variation: Tanzania relies more on intercropping but has very low fertilizer adoption (6%), while Malawi shows higher readiness (46%). Increasing distance from markets reduces commercialization and economic viability. Overall, market access critically shapes outcomes, highlighting the need for localized input delivery and spatially targeted strategies to enable effective scaling of LDI interventions.*

Legume-based production systems provide multiple benefits, including improved soil fertility, higher yields, enhanced food and nutritional security, increased incomes, and greater resilience among farming households in Africa. They also deliver a range of ecosystem services, such as diversified nutrition for humans and livestock, conservation of agrobiodiversity, and enhanced climate resilience (Tesfai et al., 2019). As such, they are essential for sustainable intensification and food system transformation (Phiri et al., 2024). Specifically, crop yields can increase by 30-35%, nutrient-use efficiency by 25-30%, and the impacts of pests and diseases on yields can be reduced by 20-25% under legume intercropping systems (Akchaya et al., 2025). In addition, legume-based cropping systems enhance soil carbon (C) and nitrogen (N) stocks, reduce bulk density, and improve soil cation exchange capacity (Ananda et al., 2022). Consequently, these production systems offer a promising approach to addressing substantial yield gaps and accelerating sustainable agricultural production.

To move beyond subsistence agriculture and address severe soil nutrient deficiencies, modern legume-driven intensification requires a transition to an optimized genotype × environment × management (G×E×M) framework. Central to this transition is the strategic implementation of 4R Nutrient Stewardship (Right Source, Right Rate, Right Time, and Right Placement) (APNI, 2021; Johnston and Bruulsema, 2014), particularly with targeted P fertilizers. Such an approach can maximize biological N fixation, reduce use of C-intensive nitrogen (N) fertilizers, and improve economic returns. However, the successful adoption and scaling of this strategy depends heavily on the socioeconomic environment, particularly the transaction costs associated with a farmer's physical distance from agricultural input and output markets.

The availability of and access to efficient output markets are critical catalysts and moderating factors in legume-based production systems. The von Thünen location theory (von Thünen, 1826) posits that agricultural land use is distributed according to distance from a central market and the associated transportation costs. These factors determine land rents, influence crop allocation decisions, and create concentric production zones (Park, 1996; Kellerman, 1989; von Thünen, 1826). The adoption and intensity of legume production are strongly influenced by market access (Barnes et al., 2026). Output markets shape food systems by serving as hubs for agricultural information, facilitating access to improved inputs, incentivizing the cultivation of high-value crops and market-oriented production, enhancing productivity, and reducing post-harvest losses. Collectively, these factors contribute to improved livelihood outcomes, including higher incomes, enhanced food security, and reduced poverty. Conversely, limited market access increases input costs through higher transaction costs and reduces the effective prices farmers receive for their produce. Connecting farmers to markets is widely recognized as a key pathway for agricultural development and for achieving the Sustainable Development Goals (SDGs), particularly SDG 1 (No Poverty) and SDG 2 (Zero Hunger) (Villar et al., 2023), while also supporting broader rural economic development. Improving access to both markets and productivity-enhancing inputs, such as P fertilizers, is among the most promising strategies for enhancing household dietary diversity (Koppmair et al., 2017).

Despite these opportunities, access to output markets remains limited across SSA due to resource constraints, high transaction costs, remoteness, information asymmetries, and limited business skills among farmers (Ma et al., 2024; Otekunrin et al., 2019; Jebesa, 2019; Stifel and Minten, 2017). In Ghana, for example, weak market integration and limited market linkages continue to constrain smallholder farmers, including women and youth (Annaful and Annan, 2025). Similarly, in Malawi, market opportunities for legumes have declined due to unfavorable and inefficient trade policies (Kakwera et al., 2025). Beyond the limited policy support for legume-based intercropping, markets for legumes remain underdeveloped (Tesfai et al., 2019). These challenges can trap smallholder farmers in cycles of low productivity, low income, and persistent poverty. Although agricultural markets in SSA are undergoing rapid transformation, the physical distance between production sites and market hubs remains a critical determinant of economic development and food security at both regional and national levels.

To establish a contextual baseline, this study hypothesizes that proximity to output markets positively influences baseline commercialization and initial fertilizer adoption. Consequently, a farm's distance from markets is expected to act as a primary moderator of the likelihood of achieving targeted improvements in Total System Productivity (measured by the Land Equivalent Ratio, LER), P-fertilizer adoption, and economic viability (defined as a benefit-cost ratio [BCR] > 2). Accordingly, the specific objectives of this study are to:

(1) assess the initial readiness for targeted LER improvements by mapping baseline cropping systems along market-distance gradients;

(2) evaluate spatial constraints on existing fertilizer use as an indicator of the likelihood of achieving the target of 15% P-fertilizer adoption; and

(3) analyze commercial production orientations to assess the geographic risks associated with achieving the economic viability targets of legume intensification.

Study area

Research study was conducted across three country corridors representing distinct agroecological and market contexts in SSA (**Table 1**). In Ghana, the study corridor included the Central Gonja District in the Savannah Region and the Kintampo North

Table 1. Characteristics of the study districts.

Country	Ghana		Malawi		Tanzania	
Region	**Savannah**	**Bono East**	**Central Region**	**Central Region**	**Dodoma**	**Dodoma**
District	Central Gonja	Kintampo North	Mchinji	Salima	Kongwa	Mpwapwa
Rainfall (mm)	1,100	1,100-1,500	900-1,267	900-1,267	500-800	500-800
Urban population (%)	70.5	58.6	4.6	9.0	26.8	11.6
Population density (persons/km²)	17	27	214.8	256.2	110	54
Major crops	Groundnut, soybean, maize, rice	Groundnut, maize, yam	Soybean, groundnut, maize	Groundnut, soybean, maize	Groundnut, pigeon pea, maize, sunflower	Groundnut, common beans, maize, sunflower

District in the Bono East Region. These adjacent districts are located within the Guinea Savannah and Transitional agroecological zones. Average annual rainfall ranges from approximately 1,100 mm in Central Gonja to between 1,100 and 1,500 mm in Kintampo North, with most rainfall occurring between May and October. While both districts are predominantly agrarian, Kintampo North is less urbanized than Central Gonja, with urbanization rates of 58.6% and 70.5%, respectively. Population densities are approximately 27 and 17 persons/km², respectively (City Population, 2021). The two districts are well connected by a motorable road network, which facilitates market access and commercialization. Crop production is the primary livelihood activity, with groundnut, cowpea, and soybean being the principal legume crops.

In Tanzania, the study was conducted in the Kongwa and Mpwapwa districts of the Dodoma Region. The area has a semi-arid climate, receiving between 500 and 800 mm of rainfall annually, and is characterized by bushland and thicket vegetation, with a substantial proportion of land under cultivation. The population is predominantly rural. Kongwa is considerably more densely populated than Mpwapwa (110 vs. 54 persons/km²) and has a higher urbanization rate (26.8% compared with 11.6%) (City Population, 2022a, 2022b). Most households engage in the cultivation of crops such as groundnut, millet, and maize, alongside livestock production. The legume subsector is constrained by the limited availability of input suppliers in many villages, making it difficult for farmers to access improved seed, fertilizers, and crop protection products. In addition, road infrastructure is often poor, particularly during the rainy season, limiting farmers' ability to transport legumes to collection points and markets. These constraints reduce both the quantity and quality of legume production, making it difficult for traders and processors to secure reliable supplies for competitive markets.

In Malawi, households were surveyed in the Mchinji and Salima districts of the Central Region. The districts receive approximately 900 mm and 1,267 mm of annual rainfall, respectively. Population density is relatively high, with Salima being more densely populated than Mchinji (256.2 vs. 214.8 persons/km²). Salima also has a higher urbanization rate (9.0%) than Mchinji (4.6%) (City Population, 2023). Compared with the study areas in Ghana and Tanzania, these districts have shorter road networks. The Central Region is one of Malawi's major agricultural zones and has strong potential for both cash crops, such as tobacco, and food crops, including maize and legumes. Cowpea, groundnut, and soybean are the principal legume crops grown for both household consumption and income generation. Legume products are marketed through both formal and informal channels, with informal markets being particularly widespread across districts and rural trading centers. However, the sector faces several production and marketing challenges, including inadequate extension services and inefficiencies in market systems, such as farmers' inability to consistently meet consumer quality and specification requirements.

Household survey data and analysis

Primary data was collected through structured household surveys administered to 352 farm households in Ghana, 351 in Tanzania, and 361 in Malawi (N = 1,064). The surveys captured plot-level characteristics, including farm size (ha), crop type, yield (t/ha), fertilizer application status, farming orientation (subsistence versus commercial), food security status, and self-reported travel time from the homestead to the nearest market. In this analysis, physical distance to the nearest output market was used as a measurable proxy for assessing baseline constraints on input adoption and production orientation. However, we acknowledge that market access is inherently multidimensional, and that physical distance often interacts with other critical factors, including transportation costs, infrastructure quality, and institutional conditions, to determine the degree of market integration. These primary data provide a spatially explicit analytical framework to assess the likelihood of achieving targeted agronomic and economic key performance indicators (KPIs). The data were analyzed descriptively and are presented using summary statistics and graphical visualizations.

Implications of market distance on production orientation

Farmers' production orientation is shaped by the availability of and access to output markets (**Figs. 1** and **2**). Decisions regarding input use, crop selection, production systems, scale of operation, enterprise specialization, and level of intensification are associated with the availability of reliable, accessible, and efficient output markets. For example, access to profitable markets can determine whether farmers produce primarily for subsistence or commercial purposes. Similarly, the presence of accessible markets can encourage the adoption of inputs (e.g., improved seeds and fertilizers) and modern technologies, promote the cultivation of high-value and market-preferred crops, and stimulate production expansion to meet market demand. The data show that, during the five years preceding data collection, most farmers had access to a ready market for their grain legumes. Specifically, 92.0%, 66.8%, and 54.7% of farmers in Ghana, Malawi, and Tanzania, respectively, reported having access to a ready market. Despite this, market distance is associated with the extent to which market access translates into changes in production orientation and outcomes. On average, the nearest output market was located 12.3 km, 5.7 km, and 22.6 km from farmers' homes in Ghana, Malawi, and Tanzania, respectively. The relatively long average market distance in Tanzania may partly explain the lower level of market access reported by farmers over the preceding five years. In contrast, the relatively short market distance in Malawi is likely associated with the country's smaller land area, which may place markets and other social infrastructure closer to farming communities. Below, we map baseline cropping systems, fertilizer use, and commercial production orientations along market-distance gradients to evaluate initial readiness for legume-driven intensification and to assess the geographic risks associated with achieving the LDI's KPIs.

Market distance is generally negatively associated with production intensity, although the nature and strength of this relationship vary across local contexts, including transportation systems, market structures, and production objectives. A clearer picture of this association emerges when examining the median distribution of production scale across the three countries (**Fig. 1A**). In Ghana, most farmers cultivating less than 2 ha and between 2 and 5 ha are located beyond their respective group median distances, whereas those cultivating more than 5 ha are more evenly distributed around the median. Despite these differences, monocropping remains the dominant production system, while crop rotation is concentrated among farmers located 2-10 km from markets (**Fig. 1B**). In Malawi, farms are generally smaller and exhibit an uneven distribution across production scales. Most farmers cultivating between 0 and 5 ha are located below the median market distance, whereas those cultivating more than 5 ha tend to be located farther from the median distance (**Fig. 1A**). Monocropping is also widespread in Malawi; however, farmers located farther from markets tend to shift from crop rotation toward intercropping systems (**Fig. 1B**). In Tanzania, where many farmers are located relatively far from markets, intercropping is widely practiced regardless of market distance (**Fig. 1B**). This predominance of intercropping suggests a higher baseline readiness to achieve targeted improvements in Total System Productivity (LER). The relatively few farmers practicing crop rotation tend to be located closer to markets.

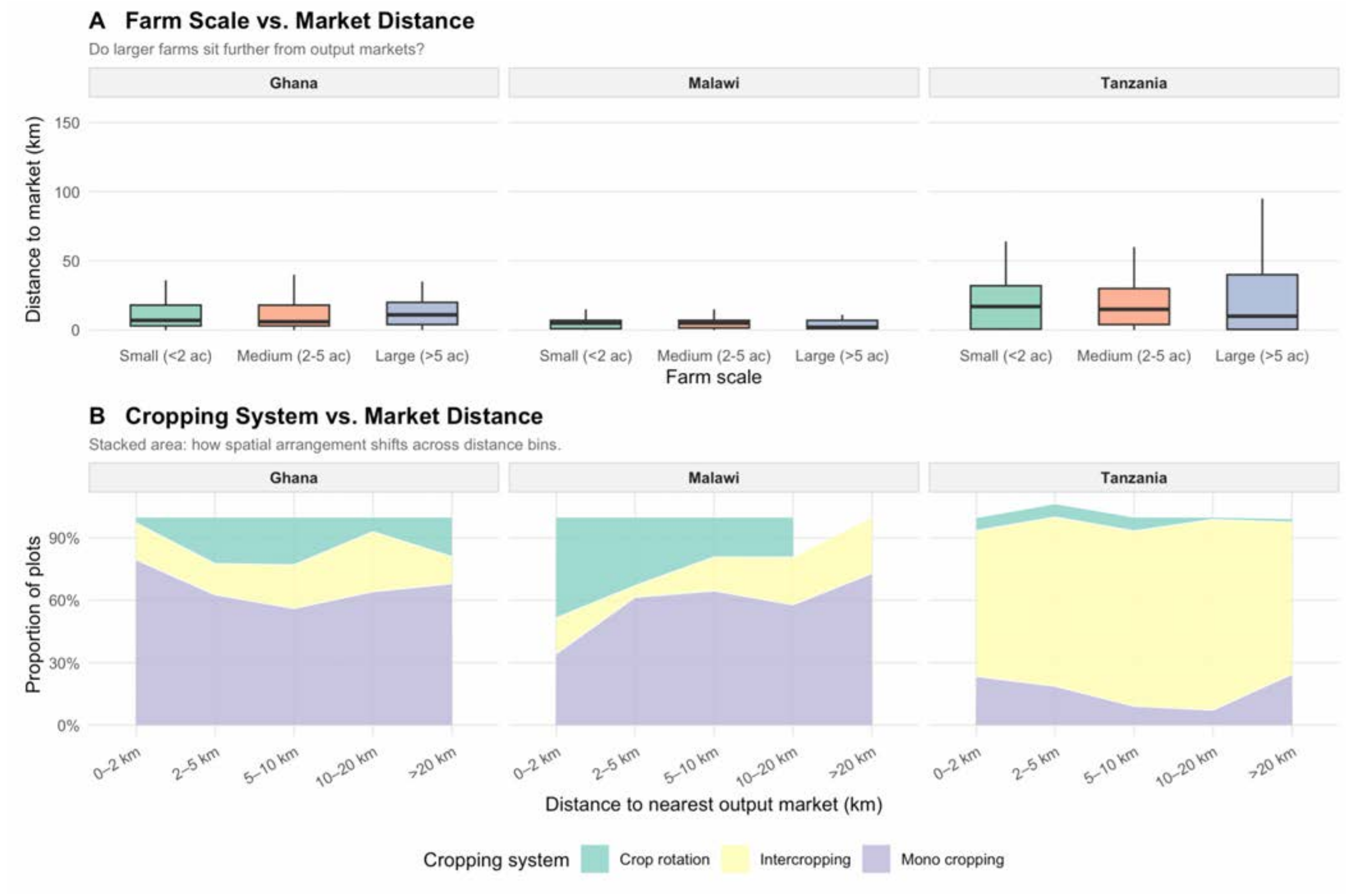

Figure 1. Effect of market distance on production scale and cropping systems in Ghana, Malawi and Tanzania.

Overall, the relationships among market distance, production scale, and cropping systems are highly context-specific. This suggests that local factors—including agroecological conditions, transportation infrastructure, market development, and institutional arrangements—play important roles in moderating the influence of market distance on production decisions and intensification pathways.

Because the adoption of fertilizers depends on both the availability of functioning input supply chains and farmers' willingness to invest in soil fertility management, the existing spatial patterns of inorganic fertilizer use (**Fig. 2A**) provide a useful baseline proxy for assessing a community's readiness to adopt targeted P-fertilizers under the 4R Nutrient Stewardship framework. The primary nutrients supplied by fertilizers were N and P, although a small number of farmers, particularly in Ghana, applied fertilizers containing additional nutrients such as sulfur (S) and zinc (Zn). In Ghana, most farmers using inorganic fertilizers were located relatively close to markets (**Fig. 2A**). In Malawi, the median market distance was similar for both fertilizer users and non-users. However, most farmers applying fertilizer were located within 10 km of a market. This suggests that while market access may not strongly influence the decision to use fertilizer, it is associated with application intensity, likely because transportation costs affect the affordability and accessibility of inputs. The results for Tanzania differ markedly from those of Ghana and Malawi. Despite the relatively low prevalence of fertilizer use, fertilizer users were generally located closer to markets, at an average distance of approximately 2 km. Overall, these findings indicate that the relationship between market access and fertilizer use is context-specific. Market-related constraints appear to limit fertilizer adoption readiness more severely in Tanzania than in Malawi and Ghana.

Farmers engaged in legume production primarily for commercial purposes generally exhibited median market distances like those producing for subsistence or other purposes, with the notable exception of Tanzania (**Fig. 2B**). In Ghana, farmers with a predominantly commercial orientation were distributed relatively evenly around the median market distance, whereas those producing mainly for subsistence or other purposes were concentrated

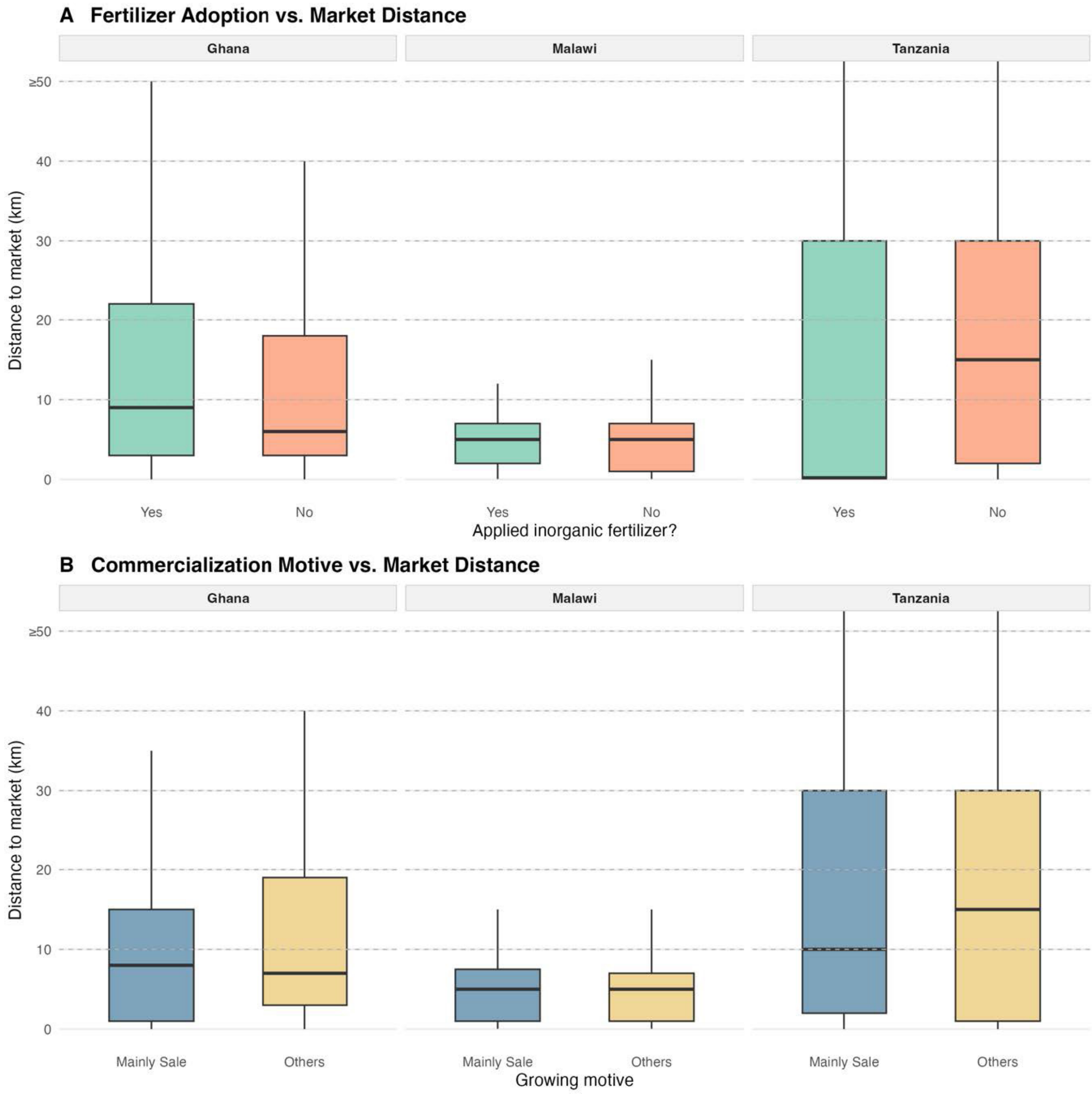

Figure 2. Effect of market distance on farmers' decision making (fertilizer use and commercialization motives) in Ghana, Malawi and Tanzania.

beyond the median distance. In Malawi, the distribution of both groups was generally skewed toward locations below the median market distance. In Tanzania, commercially oriented farmers were located at shorter median distances from markets, although some were situated considerably farther away. Importantly, the clustering of farmers with a predominantly commercial production orientation near markets suggests lower transaction costs and stronger market integration. These conditions provide a favorable baseline for achieving higher levels of economic viability and commercialization under legume-driven intensification. Conversely, farmers located farther from markets may face greater barriers to realizing the economic benefits associated with intensified legume production, owing to higher transportation costs, reduced market participation, and weaker access to market information and services.

Implications for LDI on productivity, nutrient use, and economic viability

The spatial baseline mapped in this study reveals that physical distance to markets acts as a critical boundary condition influencing the likelihood of achieving the core KPIs of LDI. With respect to Total System Productivity, LDI aims to increase the LER by leveraging cereal-legume synergies. The findings demonstrate substantial differences in baseline readiness for achieving this KPI across the target countries. In Tanzania, where intercropping predominates regardless of market distance, the structural foundation for improving LER is already in place. Consequently, LDI interventions can focus primarily on optimizing planting arrangements and integrating P fertilizers to enhance system productivity. In contrast, the widespread dominance of monocropping across all market-distance categories in Ghana, while presenting significant opportunities for LDI interventions, suggests that achieving LER targets will require overcoming entrenched agronomic practices through intensive farmer capacity-building and extension efforts. Favorable biophysical conditions in more remote areas may currently compensate for suboptimal agronomic management and low input use. Therefore, introducing improved management practices, including P-fertilizer application and cereal-legume intercropping, into these fertile but underserved areas represents a potentially high-impact pathway for accelerating productivity gains.

Regarding nutrient use and efficiency, the LDI target of increasing P-fertilizer adoption faces substantial, spatially defined challenges. If baseline fertilizer use is treated as a proxy for readiness to adopt P fertilizers, the 6% adoption rate observed in Tanzania indicates a severe input-supply constraint. Because the relatively few fertilizer users are concentrated near markets, achieving LDI's P-fertilizer adoption targets across broader geographic areas is unlikely without complementary supply-chain interventions, such as the establishment of last-mile agro-dealer networks. In contrast, Malawi's baseline fertilizer adoption rate of 46% suggests a relatively high level of readiness for P-fertilizer adoption. In such contexts, LDI efforts can shift from basic input awareness and access toward improving P-use efficiency through the implementation of 4R Nutrient Stewardship principles.

The achievement of economic viability targets, particularly increased net income and system-level BCRs, is also strongly influenced by market distance. The findings indicate that commercial production (i.e., primarily for sale) generally declines as market distance increases, particularly in Tanzania and Malawi. In more remote locations, the transaction costs associated with acquiring inputs and transporting harvested legume products to markets reduce profitability and often encourage subsistence-oriented production. Consequently, achieving a system BCR greater than 2 may be considerably more challenging in areas located beyond the median market-distance threshold unless LDI scaling strategies explicitly incorporate interventions that reduce transaction costs, such as digital market platforms (Kudama et al., 2021) and collective marketing arrangements (Magakwe and Olorunfemi, 2024).

While physical market distance serves as an important spatial indicator of the likelihood of achieving LDI KPIs, empirical evidence suggests that distance alone is an insufficient proxy for overall market access (Otekunrin et al., 2019). Market participation, commercialization, and input adoption are shaped not only by geographic proximity but also by a range of interacting constraints, including transportation costs, road quality, access to market information, and credit availability (Haile et al., 2022; Mdoda et al., 2024; Ingabire et al., 2017). Therefore, although the spatial baseline presented here effectively identifies geographic risks associated with P-fertilizer adoption and economic viability, successful LDI adoption and scaling strategies will require a combination of geographic targeting and institutional interventions. Such interventions may include strengthening producer organizations (Bizikova et al., 2020; Hill et al., 2021), enhancing extension and advisory services, and improving market linkages to unlock the full potential of LDI across diverse market-distance gradients.

Conclusion

To achieve the core KPIs of LDI, On-Farm Experimentation (OFE) and scaling efforts should be stratified according to market-distance gradients. Achieving the target of 15% P-fertilizer adoption in regions such as Tanzania will require the integration of agronomic interventions with supply-side market innovations, including digital input platforms and localized agro-dealer networks, to overcome the physical barriers associated with limited market access. While market distance has important implications for the achievement of LDI KPIs, these relationships are moderated by a range of country-specific factors beyond physical access to markets. These include market conditions, transportation and rural infrastructure, institutional support, and the effectiveness of agricultural service delivery systems. Consequently, country-specific strategies are needed to improve market accessibility and strengthen incentives for fertilizer adoption, productivity enhancement, and commercialization. The findings also reveal important differences in baseline cropping systems across countries.

The predominance of monocropping in Ghana and Malawi, contrasted with the widespread practice of intercropping in Tanzania, suggests differing levels of readiness for achieving productivity gains through legume-driven intensification. These contrasting production patterns warrant further investigation to better understand their underlying drivers and their implications for crop productivity, profitability, nutrient-use efficiency, and the long-term sustainability of legume-based production systems.

Overall, the study demonstrates that market access is a critical moderator of productivity, input adoption, and economic viability in legume-based farming systems. Integrating spatially targeted interventions with institutional and market-development strategies will be essential for reducing geographic disparities and maximizing the effectiveness and scalability of LDI interventions across diverse smallholder farming contexts in SSA. ■

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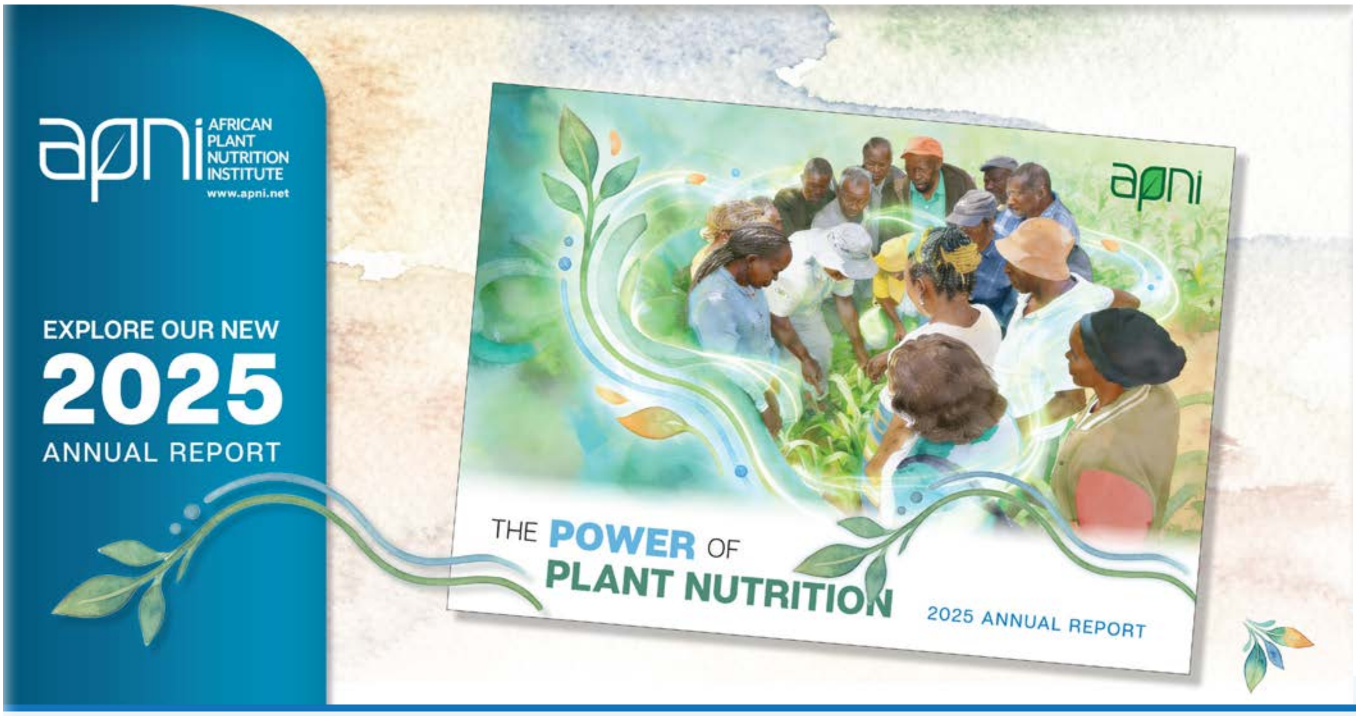

Our 2025 Annual Report highlights APNI's efforts to address **critical challenges in crop productivity, nutrition, farming system resilience,** and **institutional capacity through science-based innovation and practical solutions.** We demonstrate how advances in plant nutrition can contribute to more productive, sustainable, and inclusive food systems.

The realities of African agriculture continue to evolve. Climate variability, supply chain disruptions, and changing economic conditions create new challenges for farmers and agricultural systems. APNI is committed to agility, innovation, and evidence-based decision-making. Together with our partners, we work to generate credible scientific evidence, support technology adaptation and adoption, strengthen capacity, and inform policies and investments that can drive meaningful change.

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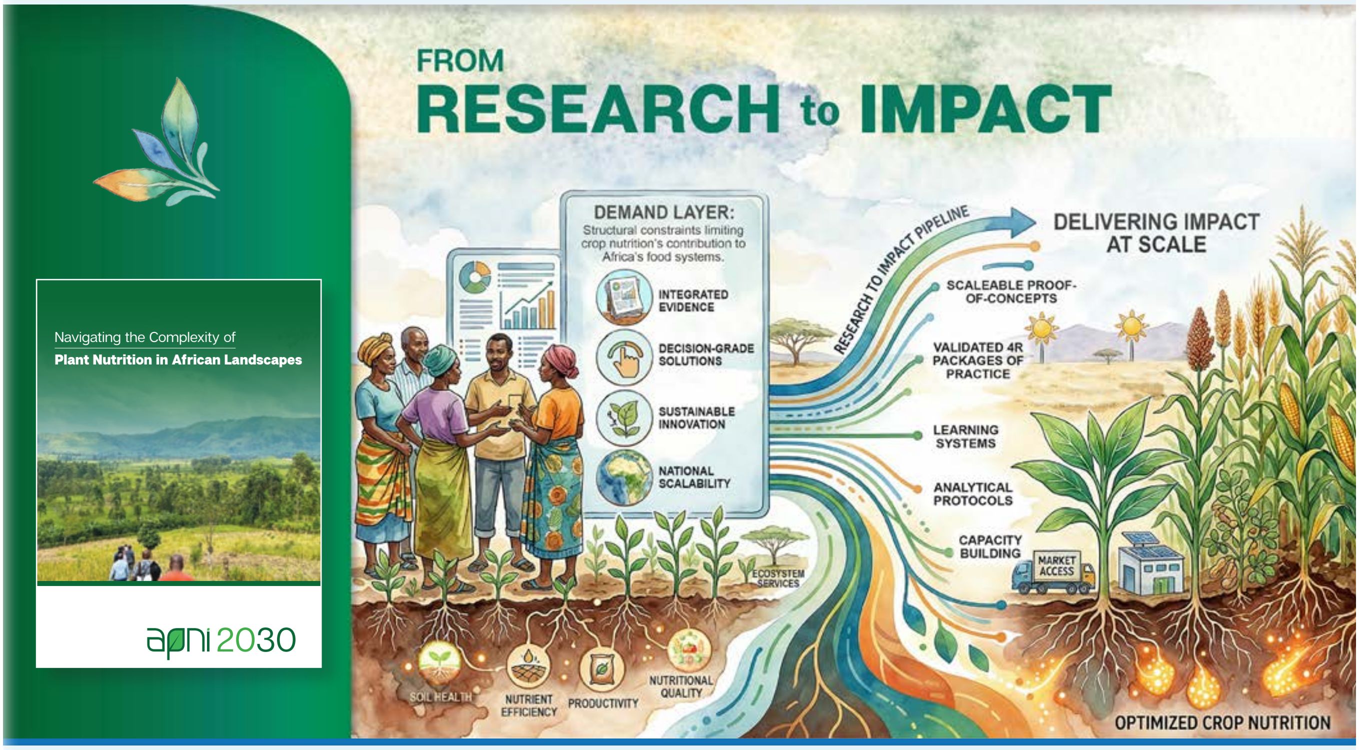

Our 2026–2030 strategy responds to a rapidly shifting African and global landscape marked by intensifying climate risks, worsening soil degradation, and rising demand for data driven and context specific agronomic solutions.

APNI2030 is structured around a clear progression from why research is needed to how it delivers impact at scale. The logic begins with a defined demand layer describing the structural constraints limiting the contribution of crop nutrition to Africa's food systems. Our solution pathways provide the strategic structure within which research is generated, synthesized, and applied.

Download APNI Strategy2030 here: **apni.net/strategy**

GENDER AND PRECISION AGRICULTURE IN AFRICA: PART 1

Lifting Gender-Based Barriers to Access and Adoption of Precision Agriculture Technologies

By Pamela Pali, Shamie Zingore, Thomas Oberthür, and Amy Sullivan

Precision Agriculture (PA) in sub-Saharan Africa (SSA) presents significant opportunities to enhance resource-use efficiency and sustainability. *However, its successful adoption remains constrained by persistent gender and youth disparities in access to resources, digital technologies, finance, training, and decision-making. These challenges are particularly salient in the context of the United Nations declaration of 2026 as the International Year of the Woman Farmer, which underscores the critical role of women farmers in global food systems and the urgency of addressing structural inequities that limit their full participation. Gender-sensitive approaches are critical for enabling more inclusive and sustainable agricultural development.*

Jane Njeri planting potatoes on her farm in Nyandarua County, Kenya. APNI/M.Waweru

Sub-Sahara Africa is characterized by high incidence of hunger and malnutrition due to low agricultural productivity. Low soil fertility, declining nutrient stocks, erratic rainfall, limited use of improved inputs, and inadequate access to knowledge and advisory services continue to constrain crop production.

Women are central to African agriculture. They account for approximately 70% of the agricultural workforce and contribute most of the labour required for planting, weeding, harvesting, and post-harvest handling (USAID, 2024). They also provide much of the family care-related work, including cooking, cleaning, water carrying, and elderly care (Chivenge and Connor, 2026). Women also have inequitable access to agricultural inputs and services and fewer land rights; 15% of land is controlled by women (USAID, 2024). Socio-economic, productivity, and time burden challenges result in a large gender productivity gap that can be greater than 30%.

Africa also has the world's youngest population (Oluwatayo and Ojo, 2024). Despite agriculture offering significant opportunities for employment, innovation, agribusiness development, and climate resilience, many young people face high levels of unemployment and underemployment, limited access to land and finance, inadequate technical skills, weak market linkages, and negative perceptions of agriculture as a low-return sector (Mac Té and Sy, 2025). Young women are particularly disadvantaged because of intersecting gender and age-related constraints.

Reducing these inequalities is not only a social objective but is also essential for improving agricultural productivity. PA provides an opportunity to address some of these challenges, but only if technologies are designed and delivered in ways that respond to the different realities faced by women and youth.

Precision agriculture beyond technology

PA is a data-driven approach that reduces temporal, metrical, structural, and translational uncertainties in smallholder farming systems, enabling more informed and site-specific management decisions. Time-, location-, and individual-level data can be used, combined with other information, to guide variable-aware management decisions that boost efficiency, yields, quality, profits, and sustainability (Andujar, 2023). PA decision support tools, such as mobile phones, satellites, drones, sensors, the Internet of Things, robotics, and farm automation, help monitor weather, soil, yield, diseases, and pests (UNDP, 2021). Across Africa, digital advisory platforms, mobile applications, remote sensing, geographic information systems, and soil diagnostic tools are becoming increasingly available to smallholder farmers. These technologies can support better decisions on planting dates, fertilizer management, irrigation scheduling, pest control, and harvesting (Njoroge et al., 2026).

Women and youth in Africa commonly use digital decision support tools (e.g., smartphone applications, SMS advisory systems, and AI-enabled extension tools), soil and crop sensing tools (e.g., portable nutrient meters), and drone services for field scouting, often provided as bundled services. For women, PA can reduce labor demands, improve access to information, increase productivity, and strengthen household food security. For youth, it creates new opportunities for employment and entrepreneurship through digital advisory services, data collection, equipment hires, and technology support businesses. However, access to technology alone is not enough. Farmers must also have the skills, resources, confidence, and enabling environment needed to use these tools effectively. Without deliberate efforts to address existing inequalities, PA risks widening rather than narrowing the gap between those who benefit from innovation and those who do not.

Overcoming the barriers

Long-standing challenges faced by female and youth farmers in traditional agricultural settings also apply to PA. These challenges are grouped into broad categories including infrastructure, information, skill, participation and inclusion, technology-based, financial, policy, etc. Some of these barriers are common to all forms of digital agriculture. Others are unique to PA because they relate directly to the affordability, accessibility, and usability of advanced technologies such as sensors, drones, digital platforms, and data-driven decision-support systems. Distinguishing between these different types of constraints is important because it helps identify where targeted interventions are needed to ensure that PA is both productive and inclusive. **Table 1** summarizes the major barriers affecting women and youth and assesses their implications for the successful implementation of PA.

What is the role of precision agriculture in addressing gender inequalities?

PA is designed to reduce decision uncertainty across the production cycle; however, men and women experience fundamentally different types of uncertainty due to divergent access to devices, skills, decision-making power, finance, and policy support. Women face uncertainty rooted in socio-cultural exclusion from technology use and credit discrimination, while youth face uncertainty due to inadequate financial products and mentorship gaps.

Based on Rowe (1994) and Marra et al. (2003), several types of uncertainty are associated with each challenge. These include technical uncertainty (yield and production variability), price uncertainty (market fluctuations), tenurial uncertainty (land ownership), political uncertainty (government policy), personal uncertainty (family welfare), and people's uncertainty (relationships with others).

Table 1. Precision agriculture-related challenges faced by women and youth.

Category		Gender and youth related challenges	Effectiveness in delivering PA strategies
Information	Generic	Device/internet access barriers for women and infrastructure and costs that affect the youth Many women lack access to devices (mobile phones), computers, and reliable internet, which hinders their ability to use digital tools and receive timely information on weather, markets, and best practices (FAO, 2023) Only 27% of women in Africa have internet access, and only 15% can afford to use it (FAO, 2023).	**Moderate:** PA can work with low-tech (SMS for timing), but full PA requires devices/internet; partial PA strategies still possible
Skills	Bidirectional	Non-tailored training for women and skill deficits for youth. Digital literacy gaps are common, with training programmes and extension services often not tailored to women's specific learning needs (Bisma et al., 2024, Mittal, 2025, Saha et al., 2024) Rural women face low digital literacy and social norms that hinder their participation in extension services (FAO, 2024), and digital illiteracy is a major constraint for women farmers to be technically empowered (Saha et al., 2024)	**Moderate-High:** PA requires higher technical skills than SMS advisories; literacy gaps prevent PA data interpretation and correct use
Participation & inclusion	PA-amplified Generic	Socio-cultural norms and structural constraints may restrict women's participation in decision-making and their ability to attend training or access resources (Guo and Akudungu, 2023) Negative cultural perceptions linked to women using agricultural machines inhibit technology adoption by women (Guo and Akudungu, 2023). Household power dynamics faced by youth.	**High:** PA requires complex decisions; excluding women from decision-making means PA data not being used for their fields, no precision benefits
Financial	PA-amplified Generic	Women face discrimination when applying for credit or participating in programmes, further limiting their adoption of new technologies (KIPPR, 2020, World Bank, 2021) Gaps exist in youth-specific programs, such as inadequate accessible financial products for agricultural technology ideation and uptake, which hinder young people's development and opportunities (FAO, 2023).	**High:** PA requires significant capital; credit discrimination blocks PA adoption while may not block cheaper conventional technology
Policy	PA-amplified Generic	Subsidies and support mechanisms tend to favor larger, male-dominated farms, which reinforce existing inequalities (Chivenge and Conner 2026)	**High:** PA tools can be expensive; if subsidies exclude smallholder women/youth, PA becomes exclusive to large commercial farms
Technology	Highly PA-specific	Very little attention has been paid to gender issues in technology development, especially the socio-cultural circumstances of women farmers (Abujala et al., 2022). PA technologies are frequently designed without considering women's physical needs or cultural context, making them less accessible or practical for female farmers (Abujala et al., 2022)	**High:** PA tools unusable for women = no data collection, no precision application, PA strategies fail for female farmers
Infrastructure Gaps	Most PA-specific	Women and youth face PA-specific barriers rooted in infrastructure gaps, such as poor infrastructure, affordability, and skill deficits. They have limited access to finance and inputs, and higher costs of PA tools such as sensors, drones, and data platforms, which are often out of reach for women and youth due to limited access to credit and financial services (FAO, 2023, UNDP, 2021)	**Critical:** Without affordable access/solutions, PA strategies cannot be implemented for smallholders

Marra et al. (2003) further categorized uncertainty in the context of technology adoption, including subjective (perceptions of risk and outcomes), epistemic (lack of knowledge or experience), random (inherent variability), and learning uncertainty (uncertainty reduced through experience).

Women and youth face fundamentally different uncertainty profiles than men in PA. Men primarily face technical and price uncertainty (inherent to farming: will crops yield? what will prices be?) Women face additional uncertainty due to information access gaps (epistemic), social exclusion from decision-making (people's), and institutional discrimination in credit/subsidies (political). This means PA's promise to reduce decision uncertainty is unequally distributed: men benefit from data-driven precision decisions, while women face compound uncertainty from both production risks and structural barriers.

A theoretical risk management framework can be created by merging Rowe's classification of decision-making uncertainty (temporal, metrical, structural, and translational) with the statistical concepts of Type I and Type II (**Table 2**). Type I and II errors are framed as a concrete checklist that redirects advice toward the prevention of Type I errors (harm/unintended consequences) and Type II errors (missed opportunities for women's agricultural domains). This classification demonstrates that a woman managing a secondary plot does not just need "more information"; she needs a targeted reduction in specific uncertainties. For instance, a raw weather forecast (e.g., "20 mm of rain expected") reduces metrical uncertainty for a meteorologist, but it creates translational uncertainty for a smallholder farmer who must calculate what that means for her freshly planted seeds.

Similarly, if PA designers deploy satellite imagery to optimize nitrogen on the husband's cash crop, they have successfully reduced his uncertainty. If they claim that this helps the entire household, but the woman's weeding burden increases due to the larger, fertilized canopy, the project has committed a Type I error (false positive impact on women). Conversely, if developers assume that IoT sensors are too advanced for post-harvest storage (a female-dominated domain) and only deploy them for commercial irrigation, they commit a Type II error (missed opportunity), leaving women entirely unserved by the PA revolution.

How does gender influence access to, and adoption of, precision agriculture technologies?

The framework outlined in **Table 2** demonstrates that successful PA depends not only on technological innovation but also on understanding how different groups make decisions and manage risk.

First, this framework distinguishes PA-specific barriers from generic digital agriculture barriers, which is important for design. This helps PA projects avoid over-investing in low-level digital fixes when the real constraints are hardware access, usability, and affordability.

Second, the framework improves the targeting of interventions by uncertainty type and decision area, so PA can be tailored to specific decisions rather than offered as a one-size-fits-all package. This makes PA more effective because advisory tools, training, and financing can be matched to the actual production decisions being made.

Lastly, the framework strengthens the case for gender-responsive and youth-inclusive PA as a productivity strategy and equity strategy. The framework goes beyond diagnosing exclusion by providing a practical approach for designing PA interventions that reduce decision uncertainty for different farmer groups.

PA strategies must address gendered uncertainty types (epistemic through training, people through participatory decision support, and political through inclusive policies) to achieve equitable uncertainty reduction across the production cycle. Therefore, effective PA strategies must be gender-transformative, addressing not only device access but also participatory decision support, tailored skills development, inclusive credit systems, and youth-specific innovation grants to ensure PA sustainability. ■

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Table 2. Examples of gendered decisions in the agricultural production cycle and uncertainty reduction.

Decision Area	Typical Gender Pattern in SSA	Primary Uncertainty (Rowe's)	Targeted PA Intervention	Error Avoidance (Type I / Type II)
Tactical Weather-Based Planning	Women often access weather data second-hand or through radio broadcasts aired during caregiving hours. They require localized forecasts that are directly linked to their specific crop duties.	**Temporal and Translational:** Uncertainty about *when* weather events will occur and *how* to convert probabilistic meteorological data into actionable farm steps.	Interactive Voice Response (IVR) platforms deliver hyper-local, task-specific advice (for example, "Heavy rain tomorrow; delay fertilizer") that is broadcast at times when women dictate	**Type I:** Sending a technical SMS ("70% chance of 15mm precipitation") that causes confusion and leads to inputs washing away. **Type II:** Providing forecasts only for the primary cash crop regions, ignoring the microclimates of women's plots.
Timing and Execution of Weeding	Women provide most of the labor for weeding, creating severe time poverty and labor shortages.	**Temporal and Structural:** Uncertainty about *when* weeds will peak and *how* local topography, moisture, and crop rotations interact to dictate distinct weed pressures.	Predictive models combine weather data with Topographic Wetness Indices and rotation history to deliver localized, plot-specific weed management advisories.	**Type I:** Sending a generic "time to weed" alert that misfires because her plot is in a flood-prone area with different weed dynamics. She wastes limited amounts of labor. **Type II:** Ignoring weed management in PA systems because modeling smallholder multi-cropping is deemed "too difficult."
Integrated Pest and Disease Management (IPM)	Women routinely scout for pests during weeding and harvesting and manage manual control. Men typically purchase and apply chemical pesticides to crops.	**Structural and Translational:** Uncertainty regarding pest life cycles on food crops and a lack of translation of safe chemical/biopesticide protocols to female farmers.	Mobile image-recognition apps are optimized to identify pests at the stages women encounter them (e.g. adult weevils in storage) and link them to non-chemical or safe-handling advisories.	**Type I:** Sending an automated PA alert to "spray fungicide immediately," which leads to community fines for the woman because she lacks the financial agency to buy the chemical. **Type II:** Designing pest-prediction algorithms solely for the cash crops managed by men, ignoring the invasive pests decimating household food crops.
Input Use on Women's Plots	Women manage secondary "food" plots on marginalized, highly variable soil, whereas men manage cash crops on better land.	**Metrical:** Uncertainty regarding the specific spatial variability of soil nutrients on localized, smaller plots.	Handheld, low-cost spectral soil sensors were used by women's cooperatives (VSLAs) to generate site-specific 4R nutrient recommendations.	**Type I:** Recommending a 4R fertilizer blend that is accurate but too expensive or unavailable locally, leading to debt accumulation. **Type II:** Failing to map women's plots because they are deemed "too small" or economically insignificant for soil sensing purposes.
Post-Harvest Handling and Storage	Women manage crop drying, processing, and storage, which are critical for value retention and food security.	**Structural and Temporal:** Uncertainty about the relationship between ambient humidity/temperature and aflatoxin/mold development over time.	Low-cost IoT moisture and temperature sensors in storage silos are linked to simple visual/audio alarms when thresholds are breached.	**Type I:** Designing sensors that require English literacy or complex digital dashboards for interpretation. **Type II:** Viewing PA as solely a "pre-harvest" discipline, missing massive post-harvest value.
Access to Advisories and Extension	Extension agents are often male, target male household heads, and deliver advice in technical formats that bypass female farmers.	**Translational:** Uncertainty in interpreting, communicating, and acting upon agronomic information due to literacy or cultural barriers.	Voice-based AI advisories in local dialects, delivered through community listening groups or interactive radio, are supported by female extension workers.	**Type I:** Translating raw agronomic data into local languages without adapting it to the crops that women grow. **Type II:** Assuming women cannot utilize digital advisories due to lower literacy, thereby excluding them from digital rollout.

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Top: Dr. Esther Mugi, APNI Associate Scientist, demonstrates how to use digital technology to producers. **Bottom:** Gender differences in the use of harvesting methods and technologies. APNI/M.Waweru

INTERNATIONAL YEAR OF THE
WOMAN FARMER
2026

Empowered women, transforming agrifood systems

GENDER AND PRECISION AGRICULTURE IN AFRICA: PART 2

Integrating Gender Sensitive Approaches into Precision Agriculture Programming

By Pamela Pali, Shamie Zingore, Thomas Oberthür, and Amy Sullivan

By advancing from gender-responsive to gender-transformative strategies, programs can address structural inequalities, enhance women's decision-making power, and improve adoption of innovations. The role of partnerships and evidence-based monitoring in achieving inclusive, productive, and sustainable agricultural systems in Africa are critical.

Importance of gender in precision agriculture

Integrating gender into Precision Agriculture (PA) is crucial for maximizing its effectiveness, inclusiveness, and sustainability. Ignoring gender risks developing technologies that primarily benefit a subset of farmers, limiting adoption, reducing productivity gains, reinforcing inequalities, and undermining the scalability and impact of PA interventions. Gender integration is both an equity imperative and a strategic investment that enhances the economic returns of PA. Evidence suggests that if women farmers had equal access to productive resources, technologies, finance, extension services, and training as men, their yields could increase by 20–30%, raising agricultural production in developing countries by 2.5–4% and reducing global hunger by an estimated 100–150 million (M) people (FAO, 2011). Beyond productivity, women's economic empowerment generates wider development benefits, as they are more likely than men to invest additional income in household nutrition, healthcare, and children's education, strengthening human capital and long-term growth.

Yet women remain underrepresented across agricultural value chains, comprising only 5–10% of agribusiness owners, with participation often confined to farm production rather than higher-value activities such as marketing, processing, and enterprise development. Expanding women's and youth's participation in agribusiness, digital agriculture, and other high-value segments of PA offers a practical pathway to reduce structural constraints, improve access to markets and finance, strengthen decision-making, and promote entrepreneurship. Embedding gender-responsive approaches throughout the PA project cycle thus enhances technology adoption, productivity, household welfare, resilience, and inclusive economic growth, while ensuring that precision agriculture contributes to equitable, sustainable, and transformative agricultural development.

According to UNIDO (2021), gender mainstreaming into the research project cycle requires adequate design, implementation, monitoring and evaluation, and scaled interventions that recognize the different roles, constraints, and opportunities of women, men, and youth throughout the agricultural production cycle. **Fig. 1** illustrates how gender considerations can be integrated across the PA project cycle.

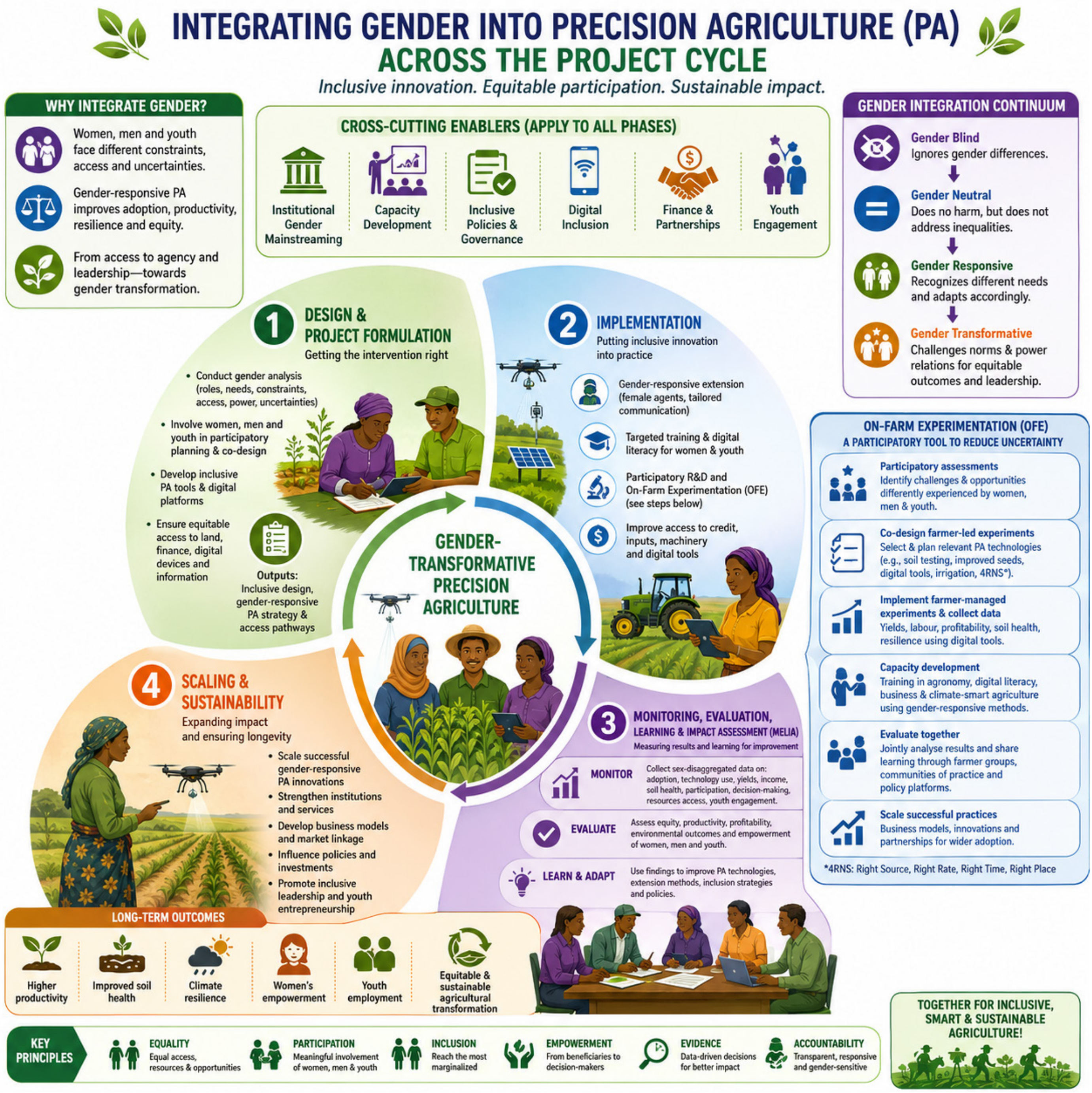

Figure 1. Gender integration into precision agriculture using the project cycle.

A. Project design

Gender integration begins during project formulation. A gender analysis should identify the roles and needs of women, men, and youth and addresses any gender inequalities so that women, men, and youth can equally access, participate in, and benefit from the resources, services, capacity development, and other activities offered by the project. Examples include:

(i) **Inclusive technology design:** Developing PA tools and platforms that address the specific needs and constraints of women and youth farmers, ensuring usability regardless of literacy or digital skills and physical limitations, thereby removing barriers that might otherwise limit women's and youth's effective use of PA innovations.

(ii) **Participatory approaches:** Gender analysis is used to involve both women and men in the identification, design, implementation, and evaluation of PA projects. Gender analysis will determine the key issues in the PA project and how the project or program affects women, men, and youth differently.

(iii) **Improved access to resources:** Promoting gender-equitable access to land, credit, digital devices and information. This can be achieved through policy reforms, targeted subsidies and partnerships with financial institutions.

Institutional gender mainstreaming within organizational processes (i.e., leadership roles, policy development, and accountability mechanisms) are important. Stakeholder capacity development (i.e. training policymakers, researchers, and extension agents) is also critical to applying a gender lens to their work, ensuring that gender-responsive PA becomes standard practice.

To ensure this during the design phase, a gender analysis can be conducted to understand how the PA intervention will affect gender at the community or household level. This will support the understanding of how the PA intervention will integrate gender into the project with consideration of understanding the uncertainties faced by women, men, and youth as posed by the intervention (**Table 1**).

Table 1. Differing strategies for integrating gender perspectives in precision agriculture projects..

Strategy (and what it means)	Example	Comment
Gender Blind: Assumes men and women benefit similarly; does not account for different constraints, power relations, or access gaps.	A generic sensor or drone advisory package was delivered to all farmers in the same way, without adapting for women's access to phones, literacy, or time constraints.	**Assumption**: All farmers are the same, which could overlook the fact that women may struggle to use the platform if they lack devices, Internet access, or decision-making power.
Gender Neutral: Does not intentionally disadvantage anyone but also does not actively address gender barriers.	Standard PA training on soil sensors, weather apps, or variable-rate fertilizer recommendations was offered to all farmers, with no deliberate exclusion but also no gender targeting.	It does not correct unequal access to digital tools, credit, or extension support.
Gender Responsive: Recognizes different needs of women, men, and youth and adapts design and delivery accordingly.	Bundled PA services that combine advisory messages, digital finance, and marketplace information delivered through channels women can access (for example, SMS, voice) Tailored extension on 4R Nutrient Stewardship using simplified visuals, local language, and demonstration plots managed by female farmers.	Women's and youth's different constraints are responded to by adjusting the delivery model, training format, and access pathway. Supports women to interpret PA recommendations regarding the right source, rate, time, and place of fertilizer application.
Gender Transformative: Goes beyond access to challenge unequal norms, power relations, and decision-making structures.	Women-led VSLAs are used as entry points for PA financing, technology uptake, and collective decision-making. Coaching women to participate in policy dialogue, advocacy, and evidence-based lobbying for PA and agricultural support programs. Multi-stakeholder efforts that challenge norms limiting women's use of agricultural machinery and digital tools.	It goes beyond access and strengthens women's economic power, confidence, and influence in farm decisions. Shifts women from being passive beneficiaries to active decision-makers in PA policy and governance. It addresses the social beliefs and power relations that prevent women from adopting PA technologies.

B. Project implementation

Successful implementation depends on ensuring that women, men, and youth can equally access project resources and services, participate in project activities and decision-making processes, and benefit equally from capacity development activities offered by the project, including the following:

(i) **Targeted training and extension services** to increase women's access to extension services and training using gender-responsive methods,

Female and male participants engaged in the 4R training session organized by the African Plant Nutrition Institute in Mwea, Kenya. APNI/M.Waweru

such as female trainers and tailored communication channels. This helps overcome barriers related to social norms and to limited mobility.

(ii) Participatory R&D programs and methods that ensure that women's preferences and challenges are considered, leading to higher adoption and impact. This includes integrating **on-farm experimentation (OFE) or farmer-led experimentation** that empowers farmers—particularly women and youth—to test and adapt technologies in their own contexts, fostering practical learning and enhancing technology relevance and adoption. OFE is a participatory, multi-actor, real-world experimentation approach which supports inclusive PA that is farmer-driven and participatory, conducted through co-learning between farmers and experts, and designed to generate locally relevant and scalable knowledge. OFE can be explicitly positioned as a participatory tool to reduce uncertainty (how variables interact locally) in a way that inherently avoids *Translational Uncertainty* (because the woman tests it herself, in her own context). It comprises distinct steps which provide opportunities for gender integration. **Participatory assessments** should be conducted to identify farming challenges and opportunities. Women, youth, and men often experience different constraints related to land access, labor, finance, technology, and decision-making. Understanding these differences helps tailor PA solutions to local conditions.

(iii) Co-designed farmer-led experiments to involve women and youth in planning farmer-led experimentation ensures that technologies are relevant, accessible, and acceptable to all users. Technologies such as soil testing, improved seeds, digital advisory tools, irrigation technologies, and climate-smart practices can be evaluated. Site-specific fertilizer recommendations can be developed using the 4R Nutrient Stewardship (4RNS) framework, which showcases the levels of change in gender-transformational approaches implemented in the program.

(iv) Implement farmer-managed experiments and collect data on yields, labor use, profitability, soil health, resilience, etc. Digital tools, mobile applications, and sensors can support monitoring and decision-making. Youth can contribute as technology service providers, data collectors and digital extension agents.

(v) Conduct capacity development providing farmers with required training in agronomy, digital literacy, business skills, climate-smart agriculture, etc. Gender-responsive training methods help overcome barriers limiting women and youth participation.

(vi) Joint evaluation of results shared through farmer groups, extension systems, and policy platforms using forums such as post-harvest dialogues, communities of practice, and policy dialogues.

(vii) Scaling successful practices through business case development models can improve productivity, reduce labor burdens, create youth employment opportunities, and strengthen the equitable participation of women, youth, and men in sustainable agricultural transformation.

C. Monitoring and evaluation

Gender integration ensures that women and men equally participate in monitoring and evaluation activities and decision-making processes. Data can be collected on women and men so that gender impacts are tracked to assess whether the PA project equally benefits women and men. Collecting sex-disaggregated data and regularly assessing the gender impacts of PA interventions will guide how starting strategies can be adapted to close gaps in project design and implementation.

The importance of multi-stakeholder collaboration and support

Multi-stakeholder partnerships between government agencies, NGOs, and private sector organizations enable the pooling of financial, technical, and human resources to develop and deliver solutions tailored to female, male, and youth farmers' needs. For example, bundled digital solutions, such as advisory services, digital finance, and online marketplaces can address the multiple barriers women face, but these require collaboration across sectors for effective implementation. Thus, joint initiatives can ensure that agricultural technologies and programs are designed with a gender lens that addresses the social and structural barriers unique to women. This includes developing gender strategies, setting targets for women's participation, and designing interventions that consider local norms and realities.

Partnerships with financial institutions and agribusinesses encourage innovative financing models, such as collateral-free loans based on production history, and facilitate digital payment systems, making it easier for women and youth to access and repay these loans. For example, collaborative support to community Village Savings Loan Associations (VSLA's) can provide a starting point for credit support to female farmers, as they comprise the largest membership in these organizations (IERC, 2021). Women-led VSLAs have been shown to improve women's economic status, social empowerment, and decision-making power in households and communities.

NGOs and government agencies working together can strengthen extension services and training programs, ensuring that women receive relevant information and support and building their skills to adopt new technologies. Multi-stakeholder efforts help to address deep-rooted gender norms by promoting women's leadership, participation in decision-making, and visibility in agricultural value chains.

Policy development processes also need to play a role. Coaching is required to enable women to better participate in policy dialogue alongside their male counterparts, who currently dominate the discussion, to teach women how to advocate, how to use evidence-based lobbying, how to be persuasive, and to have the confidence to conduct policy dialogue. ■

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Decoding Ankole's Coffee Landscape: Farmer Typologies and Livelihood Strategies from Uganda Coffee–Banana Systems

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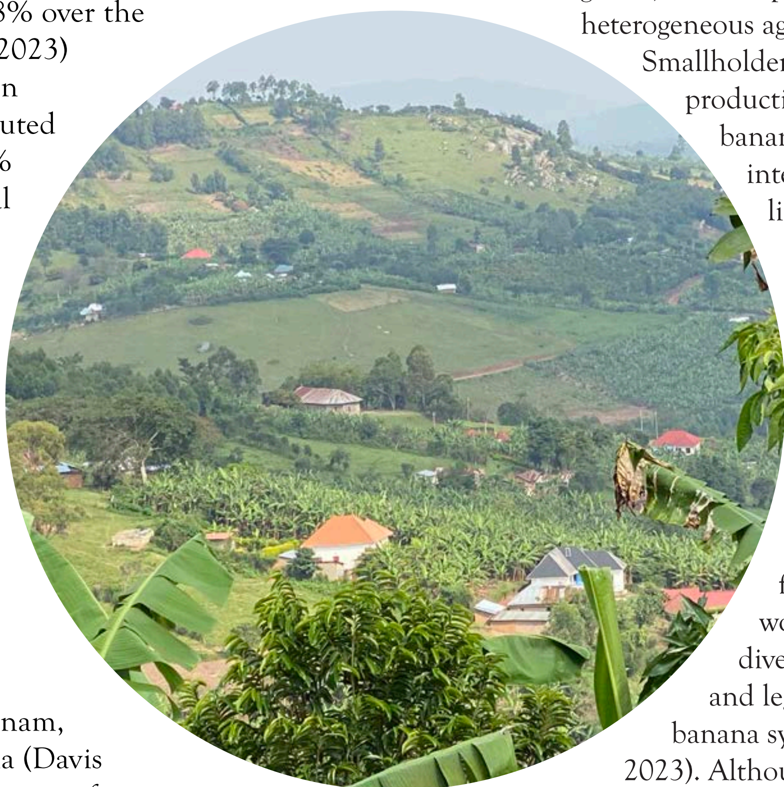
Coffee–banana systems are central to rural livelihoods in southwestern Uganda but vary widely in resource endowment and livelihood strategies. *Using baseline data from 470 households in Mitooma and Ntungamo districts, farm typologies were developed based on household assets and income sources. Two farm types emerged: coffee-dependent smallholders, and entrepreneurial, livestock-oriented asset-rich farmers. Coffee remained the dominant income source, while diversification through banana, livestock, and other enterprises contributed to household resilience. The findings highlight the need for typology-specific extension, nutrient management, and development interventions to improve productivity, resilience, and sustainability in coffee-based farming systems.*

Coffee is one of Uganda's most important traditional cash crops. Currently, an estimated 1.7 million (M) farmers cultivate coffee in the country. Coffee production has increased by 308% over the last 62 years (1961–2023) (FAOSTAT, 2026). In 2017, coffee contributed approximately 19.1% to the country's total exports, dominated by Robusta and Arabica, which are grown at an approximate ratio of 4:1 (ICO and UCDA, 2022). Notably, Uganda accounts for most of Africa's robusta output and is the fourth largest producer in the world, after Vietnam, Brazil, and Indonesia (Davis et al., 2023), and accounts for 7% of global Robusta exports (Kiwuka et al., 2021). Despite its extensive cultivation and export significance, average yields remain low, at approximately 500 kg/ha (ICO and UCDA, 2022), against a yield potential of >1.5t/ha. This yield gap contributes to the current annual production of 8 M 60-kg bags, falling 60% short of the 20 M bag export target set in Uganda's Coffee 2030 roadmap.



In Uganda, coffee is produced within heterogeneous agroecosystems. Smallholders dominate the production of coffee and bananas, which are often intercropped because of limited land resources (Jassogne et al., 2013). In central Uganda, the socioeconomic benefits of farm diversification strategies and intensified diversification in coffee-banana systems include income and food security, and women are more likely to diversify by including goats and legumes in their coffee-banana systems (Mpiira et al., 2023). Although half of south-western Uganda's coffee farmers still practice monocropping, the mutual benefits of coffee–banana intercropping systems have been reported. The Marginal Rate of Return (MRR) of adding banana to mono-cropped coffee was 911% and 200% in Arabica and Robusta systems, respectively. Coffee-

Ugandan coffee-banana system landscape. APNI/K.Majumdar banana intercropping showed banana yields of 20.19 t/ha/yr in intercrops vs. 14.82 t/ha/yr in monocrops (Arabica region) in the southwestern Ugandan districts of Masaka, Bushenyi, and Rakai (Van Asten et al., 2011).

However, soils are being depleted based on the current crop management practices within coffee-banana systems. For example, according to De Bauw et al. (2016), soil depletion on the slopes of Mount Elgon in eastern Uganda was caused by a lack of adequate nutrient replenishment as coffee has a high nutrient extraction rate under subsistence agricultural systems due to limited fertilizer application. Poor soil fertility is widely reported as a key limitation to the sustainability of coffee–banana cropping systems, where declining nutrient status, competition for resources, and inadequate management practices interact to reduce productivity and long-term system performance (Jassogne et al. 2013). Mukasa et al. (2025) recently characterized the adoption of recommended agronomic practices as low in coffee–banana systems. This impairs the sustainability of coffee cropping systems owing to the low productivity of coffee.

Diversifying coffee cropping systems can enhance the sustainability and resilience of smallholder farmers (Poncet et al., 2024). The "Uganda Carbon Coffee Project (UCCP)" funded by the African Plant Nutrition Institute (APNI) and OCP Foundation, aims to improve the livelihoods and climate resilience of smallholder producers in the coffee-producing landscapes of south-western Uganda. In this project, stakeholders use incentive-based approaches to address productivity and land degradation and improve livelihoods by rewarding sustainable land management and coffee-system diversification. Therefore, diversification is a key aspect of UCCP. Target stakeholders in the project are the Ankole Coffee Producers Cooperative Union (ACPCU), whose membership of 20,000 farmers produce coffee as a cash crop in the region; the Environmental Conservation Trust of Uganda (ECOTRUST), Producers Direct, Makerere University, and Université Mohammed VI Polytechnique (UM6P).

Linking farm types to sustainable livelihoods

The complexity of farming systems is simplified by categorizing farms into homogeneous groups or farm types (Alvarez et al., 2018). They identify patterns in heterogeneous structures and processes that determine the impact of agricultural policy incentives (Huber et al., 2024). The study uses the Sustainable Livelihood Framework and farm typology analysis to understand heterogeneity in asset endowments and livelihood strategies, and diversification theory to explain risk management choices, resilience, and farmer performance outcomes (**Fig. 1**). Under the farm typology setting, farmers with stronger household assets tend to adopt diversified livelihood portfolios

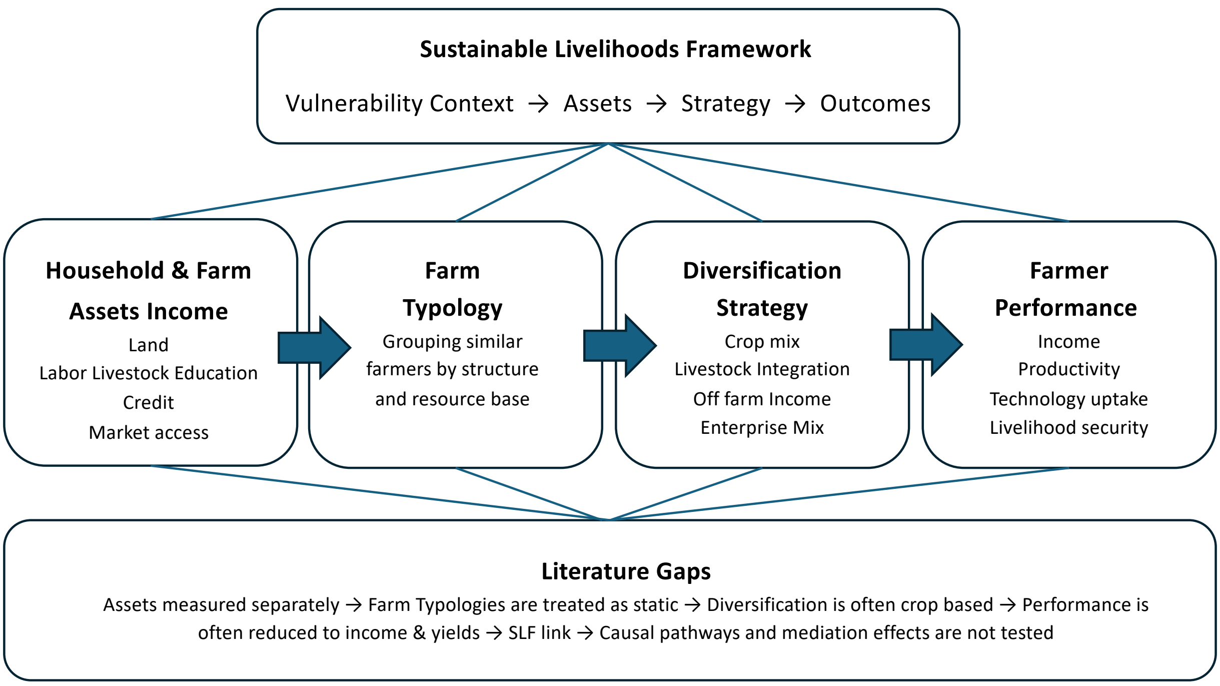


Figure 1. Conceptual framework linking household and farm assets, farm typology, diversification strategies, and farmer performance within the Sustainable Livelihoods Framework.

and achieve better performance outcomes, including higher income, greater resilience, and higher farmer adoption rates.

The literature gaps in the endowment-farmer typology-diversification-farmer performance nexus include causality, dynamics, and measurement gaps (**Fig. 1**). The associated literature primarily classifies farm typologies and lists diversification activities (Apanovich and Nyairo, 2025), while others outline the methodological framework for typology construction, that is, 'hypothesis-based typology construction' (Alvarez et al., 2018). However, fewer typologies are connected to a clear causal pathway from assets to strategy to performance over time. Farm typology literature is often described based on one-time surveys (Landais, 1998), hence presenting a cross-sectional bias in the results. Typologies are usually reported in a static manner, by classifying them as fixed categories which do not consider the dynamic nature of households that can evolve through specialization, diversification, or even through the de-accumulation of assets. This study addresses the literature gap by providing an understanding of "how farm typologies differ in livelihood strategies within coffee banana production systems and which variables explain the greatest heterogeneity across typologies" as a prerequisite to providing insights on diversification strategies and ultimately farmer performance.

Methodology

A household baseline survey was conducted between September and November 2023 in the coffee–banana production systems of the Mitooma and Ntungamo districts. Both districts are located in the Ankole region of Uganda and practice integrated crop livestock systems. Almost triple (40,000) the households in Ntungamo grew coffee compared to the approximately 14,000 households in Mitooma. In Mitooma, approximately 20,808 (52.3%) and 25,791 (64.8%) households grow bananas and keep livestock, respectively (UBOS, 2017). Ntungamo is a drier, semi-arid corridor with two pronounced dry seasons. It comprises the coffee–staple–livestock system under strong climate stress and moving toward irrigated intensification, whereas Mitooma has a higher altitude, with cooler and wetter highlands, characterized by a banana–coffee–dairy system with more stable perennials and slightly more diversified cash crops. Mitooma also faces challenges such as drought, hailstones, pests & diseases. The tree systems in Ntungamo are characterized by a drying savannah landscape with limited, fragmented tree cover and strong climate-driven stress, whereas those in Mitooma reflect a highland, more humid environment with structurally richer vegetation (grasslands–woodlands–forests–wetlands).

From a sampling frame of 500 identified households, 470 farmers were randomly selected and interviewed for this study. All respondents were members of societies affiliated with the Ankole Coffee Producers Cooperative Union (ACPCU). The survey was designed to characterize the agro-ecosystem as an entry point for the Uganda Coffee Carbon Project (UCCP), focusing on household assets, income sources, and prevailing agronomic practices. Informed consent was obtained from each participant prior to the interview, and data were collected using the KoBo Toolbox.

The collected data were analyzed to characterize the farming system and derive farm types. To classify the farm households across Ntungamo and Mitooma districts into distinct farm types, a Factor Analysis of Mixed Data (FAMD) combined with Hierarchical Clustering on Principal Components (HCPC) was executed in R based on a total of 22 categorical variables that assessed household income sources (six variables), expenditure (four variables), household assets (five variables), nature of the family house (four variables), energy source for lighting, energy source for cooking, and source of drinking water (**Table 1**.) Bootstrapping (i.e., repeated drawing of 100 random samples) was used to generate a mean cluster stability index.

RESULTS

Clustering of households into farm types

Up to 10 dimensions accounted for 57% of the variance in the sampled population (**Table 1**). Dimension 1 centered on quality of life and well-being, while the second dimension was related to investments in agricultural productivity. Together, these two dimensions accounted for 17.5% of the variance in the surveyed communities. Dimension 3 dealt with short-term income security, while 4, 5, and 6 covered long-term food and income security and well-being. These four accounted for 22.3% the variance in the surveyed population. Dimensions 7 to 10, describing the material well being and infrastructure access of farm households beyond farm income and production, amounted to 17.2% of the variance.

Table 1. Principal dimension loadings for farm households in Mitooma and Ntungamo Districts.

Variable	Dim. 1	Dim. 2	Dim. 3	Dim. 4	Dim. 5	Dim. 6	Dim. 7	Dim. 8	Dim. 9	Dim. 10
Income from trees	0.3	4.6	1.7	0.1	0.4	20.6	11.8	5.2	1.7	1.4
Income from non-farm business	0.1	0.3	30.3	0.7	6.5	3.7	0.8	0.2	0.4	0.9
Income from produce	4.3	3.4	23.7	8.5	0.3	0.0	0.2	0.4	1.3	0.0
Income from banana	2.6	2.7	0.6	10.9	22.3	0.6	1.4	0.0	0.8	0.5
Income from coffee	3.9	3.3	0.9	11.7	16.1	3.8	0.1	1.7	0.0	0.6
Income from Livestock	0.3	2.0	4.2	0.1	0.4	0.1	4.6	2.2	2.0	1.0
Expenditure on school fees	0.0	1.5	0.1	2.2	0.0	27.1	0.0	0.5	0.6	20.3
Expenditure on medication	1.6	0.5	5.5	25.3	14.7	2.8	0.8	1.9	0.8	0.1
Expenditure on food	0.1	9.4	3.3	10.4	3.2	3.6	13.6	3.0	0.2	0.4
Expenditure on agro-inputs	1.0	13.8	5.7	2.0	4.4	0.1	8.9	0.2	0.8	5.8
Assets: motorcycle	2.3	1.7	3.7	4.8	2.8	0.1	0.1	4.8	0.2	3.4
Assets: wheelbarrows	6.5	7.0	0.1	0.6	1.1	0.0	1.6	3.3	3.1	0.1
Assets: knapsack sprayer	0.6	14.5	0.6	1.8	0.1	1.0	3.0	3.9	0.1	11.0
Assets: solar panels	0.1	6.7	5.0	1.1	1.3	7.6	5.9	0.6	0.0	1.9
Assets: bicycle	0.5	3.0	0.8	0.2	0.2	2.0	9.0	13.5	4.8	6.8
House with electricity	17.6	2.3	0.8	0.0	4.7	0.0	0.5	1.0	1.1	0.7
House with glazed window	9.1	9.0	0.2	0.1	0.5	4.0	0.1	1.2	0.1	4.5
House wall material	8.6	3.5	1.3	0.7	2.4	7.1	4.6	9.3	1.0	15.4
House roof material	0.4	0.8	0.1	0.9	5.4	1.1	5.5	0.5	49.3	8.0
Water source for drinking	15.1	2.2	4.5	2.4	5.7	5.2	15.9	24.5	27.2	5.8
Energy source for cooking	6.1	3.1	5.7	12.7	1.2	1.4	3.8	12.0	0.0	10.7
Energy source for Lighting	18.8	4.8	1.1	2.6	6.2	8.2	7.8	10.0	4.4	0.9
[1]Eigen value	2.8	2.1	1.8	1.6	1.5	1.3	1.3	1.3	1.1	1.1
Variance percent	9.9	7.6	6.3	5.7	5.5	4.8	4.6	4.5	4.1	4.0
Cumulative variance (%)	9.9	17.5	23.8	29.6	35.1	39.8	44.4	48.9	53.0	57.0

[1]Eigen values measure the total amount of variation in the dataset that is captured by each specific dimension.

Two clusters were generated (**Fig. 2**), with very high stability indices of 0.994 and 0.944 for cluster 1 (hereafter referred to as farm type 1) and cluster 2 (hereafter referred to as farm type 2), respectively.

Farm and farmers socio-economic characteristics

Overall, the farm types exhibited significant differences in several key household attributes (**Table 2**). The findings suggest that the identified farm types are primarily differentiated by education, livelihood

Table 2. Household and farm characteristics.

Characteristic	Category	Farmer type 1 N=337		Farmer type 2 N=133		Chi-sq.	P-Value
		Freq.	%	Freq.	%		
Gender	Female	145	43.0	45	33.8	3.35	0.067
	Male	192	57.0	88	66.2		
Age	Youth (<34 years)	24	7.1	5	3.8	1.86	0.172
	Adult (>35 years)	313	92.9	128	96.2		
Occupation	Farming	321	95.3	120	90.2	4.16	0.041
	Non-farm	16	4.7	13	9.8		
Livestock	Yes	116	34.4	70	52.6	13.22	0.000
	No	221	65.6	63	47.4		
District	Mitooma	154	45.7	46	34.6	4.82	0.028
	Ntungamo	183	54.4	87	65.4		
Improved coffee variety	Users	34	10.1	12	9.0	0.12	0.726
	Non-users	303	89.9	121	91.0		
Plantation age	10+ years	273	81.0	97	72.9	3.71	0.054
	1-10 years	64	19.0	36	27.1		
Continuous variables		**Mean**	**SD**	**Mean**	**SD**	**T-Value**	**P-Value**
Experience		25.5	13.3	26.0	11.6	-0.34	0.736
Education		6.9	3.9	8.7	3.7	-4.57	0.000
Household size		6.7	2.8	7.0	3.4	-0.88	0.3811

Figure 2. Multidimensional scaling diagram (A) and dendrogram showing relationship between farm type 1 (Green) and farm type 2 (Red) across Mitooma and Ntungamo Districts, Southwestern Uganda.

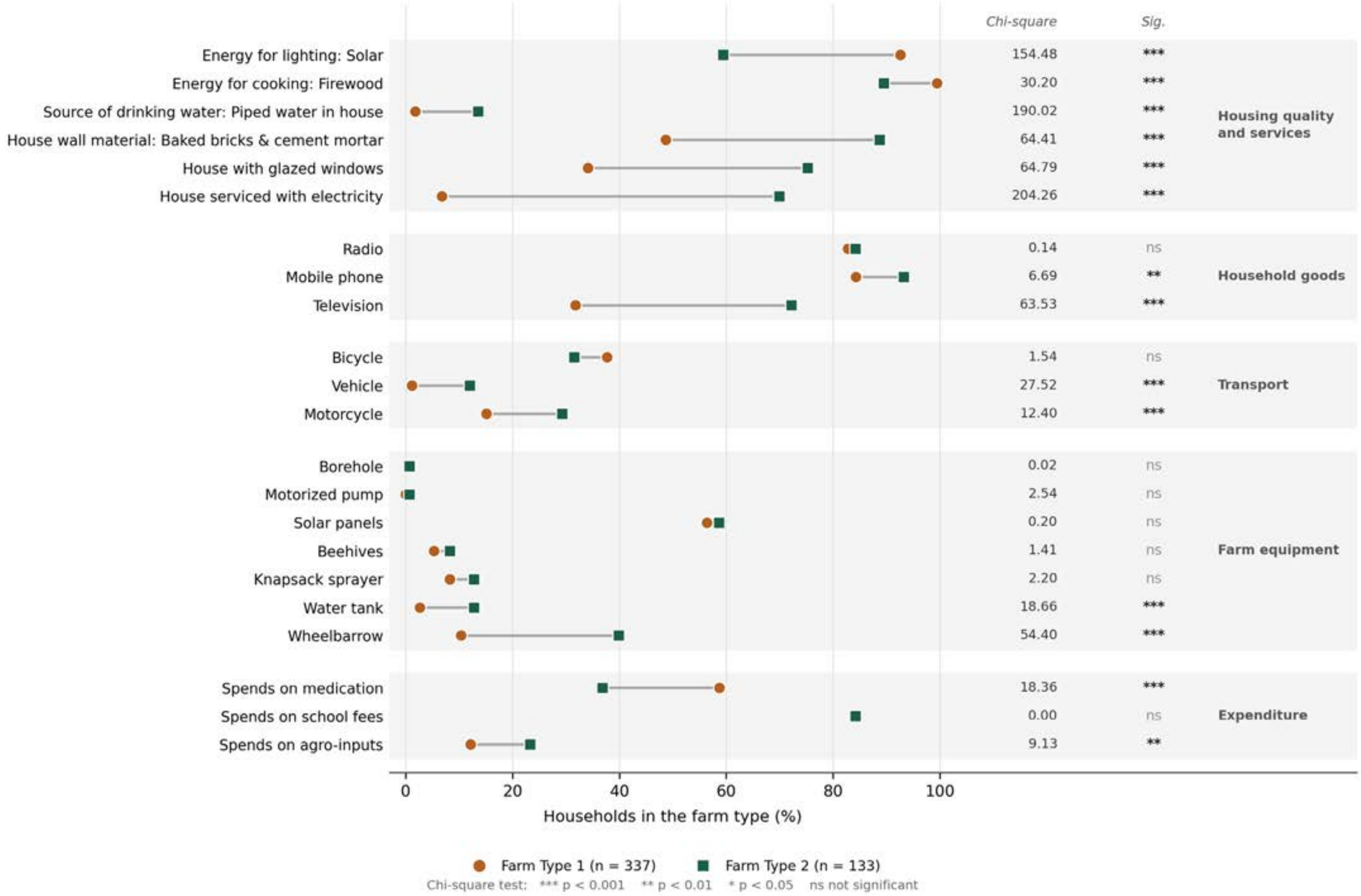


Figure 3. Asset ownership, housing quality and expenditure by farm type.

The markers show the percentage of households in each farm type owning the asset or reporting the condition, joined by a line whose length is the difference between farm types. The chi-square statistic and significance levels are presented in the right-hand columns. The variables are grouped by asset function and ordered by the difference within each group. For the multilevel variables, the marker shows the leading category, and the chi-square covers the full variable. Significance is from the chi-square test: *** p<0.001, ** p<0.01, * p<0.05, ns not significant.

diversification, livestock ownership, agricultural investment behavior, healthcare expenditure, and geographical location, while demographic characteristics and coffee farming experience remain broadly similar.

Farm type 2 households were more associated with the Ntungamo District (Chi-sq. = 4.82, $p = 0.028$), had more years of formal education (8.7 ± 3.7 vs. 6.9 ± 3.9; $t = -4.57$, $p < 0.001$), and were more likely to keep livestock than farm type 1 households. Type 1 households were more associated with Mitooma District, and more often cited the association with farming as their primary occupation (95.3% vs. 90.2%; Chi-sq. = 4.16, $p = 0.041$) and tended to have older coffee plantations (>10 years: 81.0% vs. 72.9%; $p = 0.054$).

Asset and Resource Endowment

The descriptive analysis reveals pronounced heterogeneity in household welfare and physical asset endowments between the two farm types (see **Fig. 3**).

Across all indicators examined, farm type 2 consistently demonstrated higher access to infrastructure and improved housing conditions, indicating a relatively stronger socioeconomic position than farm type 1.

Access to electricity showed the starkest contrast between typologies, with 69.9% of farm type 2 households connected, compared with 6.8% of farm type 1. Housing quality followed a similar pattern: farm type 2 households more often had glazed windows (75% vs. 34%) and permanent construction of baked brick and cement mortar (88.7% vs. 49%), whereas farm type 1 households more commonly occupied timber (38.9% vs. 6.8%) or unbaked-brick, mud-mortar dwellings (12.5% vs. 4.5%). Water infrastructure diverged similarly: farm type 2 households relied mainly on piped water, either outside the dwelling (59.4%) or within the compound (13.5%), whereas farm type 1 households depended primarily on wells (78.6%) and boreholes (11.6%), with only a small minority accessing piped water. Expenditure patterns also diverged, with type 2 households often associated with investing more in agricultural inputs (23.3% vs. 12.2%; Chi-sq. = 9.13, $p = 0.003$), while type 1 households associated with healthcare expenditure (58.8% vs. 36.8%; Chi-sq. = 18.36, $p < 0.001$).

Diversification strategies

The Cluster/Modality frequency evaluates the percentage of all farmers with a specific characteristic that is assigned to each cluster or farm type; this is

Table 3. Profiling metrics for farm types across Mitooma and Ntungamo Districts.

Dominant characteristic	Global (%)	Cluster/Modality (%)	Modality/Cluster (%)	p-value	c
		Type 1			
No connection to electricity	75.3	88.7	93.2	<0.0001	13.9
Dependency on well water	63.0	89.5	78.6	<0.0001	11.1
Solar for lighting	82.1	80.6	92.3	<0.0001	08.7
No glazed windows	54.3	87.1	65.9	<0.0001	08.1
House with timber walls	29.8	93.6	38.9	<0.0001	07.4
No wheelbarrow	81.3	79.1	89.6	<0.0001	07.0
No income from produce	57.0	82.8	65.9	<0.0001	06.1
Firewood for cooking	96.6	73.8	99.4	<0.0001	04.9
Expenditure on medication	52.6	80.2	58.8	<0.0001	04.3
Income from coffee	10.2	93.8	13.4	<0.0001	03.9
Assets: wheelbarrows	6.5	7.0	0.1	0.6	1.1
Dominant characteristic	**Global (%)**	**Cluster/Modality (%)**	**Modality/Cluster (%)**	**p-value**	**v-test**
		Type 2			
Connection to electricity	75.3	24.7	80.2	<0.0001	13.9
Lighting from electricity	63.0	12.6	98.3	<0.0001	12.5
Piped water outside of house	82.1	22.6	74.5	<0.0001	11.5
Baked bricks wall	54.3	60.0	41.8	<0.0001	08.4
Glazed windows	29.8	45.7	46.5	<0.0001	08.1
Possess wheelbarrows	81.3	18.7	60.2	<0.0001	07.0
Income from produce	57.0	43.0	43.1	<0.0001	06.1
Piped water inside the house	96.6	05.1	75.0	<0.0001	04.8
Charcoal for cooking	52.6	01.9	100.0	<0.0001	04.4
No expenditure on medication	10.2	47.4	37.7	<0.0001	04.3

compared against the global frequency which represents the percentage of farmers in the entire dataset that had this characteristic before clustering. The Modality/Cluster frequency evaluates the percentage of farmers in each cluster with a given characteristic (**Table 3**).

A chi-square test was used to evaluate the association between the resulting clusters and districts. Profiling metrics were generated using the FactoMineR package in R to characterize the clusters and farm types. These included the frequency indices Global, Cluster/Modality, and Modality/Cluster, as well as the formal v-test, where any value greater than 2 was considered statistically significant, and the higher it was, the more unique or defining that variable was for that cluster. The strongest distinguishing characteristics for farm type 1 (Cluster/Modality Frequency > 80%; v-test value > 7 and p-value < 0.0001) were no electricity connection to their houses, dependency on communal well water for drinking, using solar-powered lamps for lighting, no glazed windows in their houses, and timber walls. Farm type 1 households typically use firewood for cooking, have no wheelbarrows, and no income from produce (cereals) but mostly depend on income from coffee. Of the 10% global frequency of reporting income from coffee in the communities surveyed, 94% were farm type 1 households, indicating a strong tendency to depend on coffee rather than annual crops. Approximately 10% of farm type 1 households reported income from trees compared to only 4% for farm type 2 (**Table 3**). Farm type 1 households are also more likely to have income from banana (9.2%) than their farm type 2 counterparts (1.5%).

Overall, farm type 1 households are resource-poor and thus tend to stick to low-cost livelihood options and production strategies. However, they exhibit a strong trend toward diversifying their revenue streams beyond coffee to include trees, bananas, and non-farm businesses, unlike their counterparts in farm type 2. Farm type 1 households seem to prefer low-risk investments, mostly long-season crops, as income sources, unlike farm type 2 households, which seem to prefer quick turnover. The low-cost lifestyle chosen by farm type 1 households seems to expose them to affliction by disease, necessitating expenditure on medical treatment at a higher frequency than farm type 2 households (**Table 3, Fig. 3**).

Income, productivity and technology use

Soil and nutrient management practices

The technology-use characteristics showed a distinction in the soil and nutrient management characteristics. In terms of nutrient management characteristics, farm type 1 were primarily associated with the use of soil organic amendments (78% vs. 64%, Chi-sq. = 8.47, p<0.01) and animal manure (42% vs. 31%, Chi-sq. = 4.30, p<0.05), and although not significant, farm type 2 used more mineral fertilizer than farm type 1. The two farm types were associated with the use of distinctly different erosion and water-control structures. Farm type 1 was associated with more terracing structures (46% vs 28%), whereas farm type 2 with trenches (20% vs. 37%). More respondents from farm type 2 were associated with the use of more minimum tillage practices (4% vs. 11%).

Income and productivity

The household incomes reported across the two districts were farm enterprise sales and off-farm income (**Fig. 4**). Under farm enterprises, the sale of livestock and livestock products was significantly different (19% vs. 27%), where more farmers from farm type 2 were associated with the sale of livestock and livestock products than farm type 1 households (p<0.05). Under non-farm income sources, only farm type 2 households received pensions (0% vs. 5.3%). The ownership of non-farm businesses was highly associated with farm type 1 than farm type 2.

The total monthly household income was higher for farm type 2 households than for farm type 1 households (Uganda shillings (UGX) 373,925 (USD 100.2) vs. 256,667 (USD 68.9) (p<0.001) (**Fig. 5**). However, the seasonal revenue from banana was also higher for type 1 households (UGX 616, 659 (USD 165.6) vs. UGX 327,851 (USD 88)). Coffee-banana productivity was not significantly different across farm types.

Discussion

This study partially characterized the baseline situation of the coffee-banana systems in southwestern Uganda. It elaborates on a causal pathway from the farmer endowment status, mapping this to the farm type to indicate diversification patterns and measurement of coffee producers' performance. This analytical pathway provides a more holistic understanding of the farmer baseline context. It establishes the pre-project intervention conditions of the coffee-banana production systems and offers critical guidance for the effective design and implementation of the Uganda Coffee Carbon Project.

The study sample consisted of older coffee–banana producers with extensive farming experience,

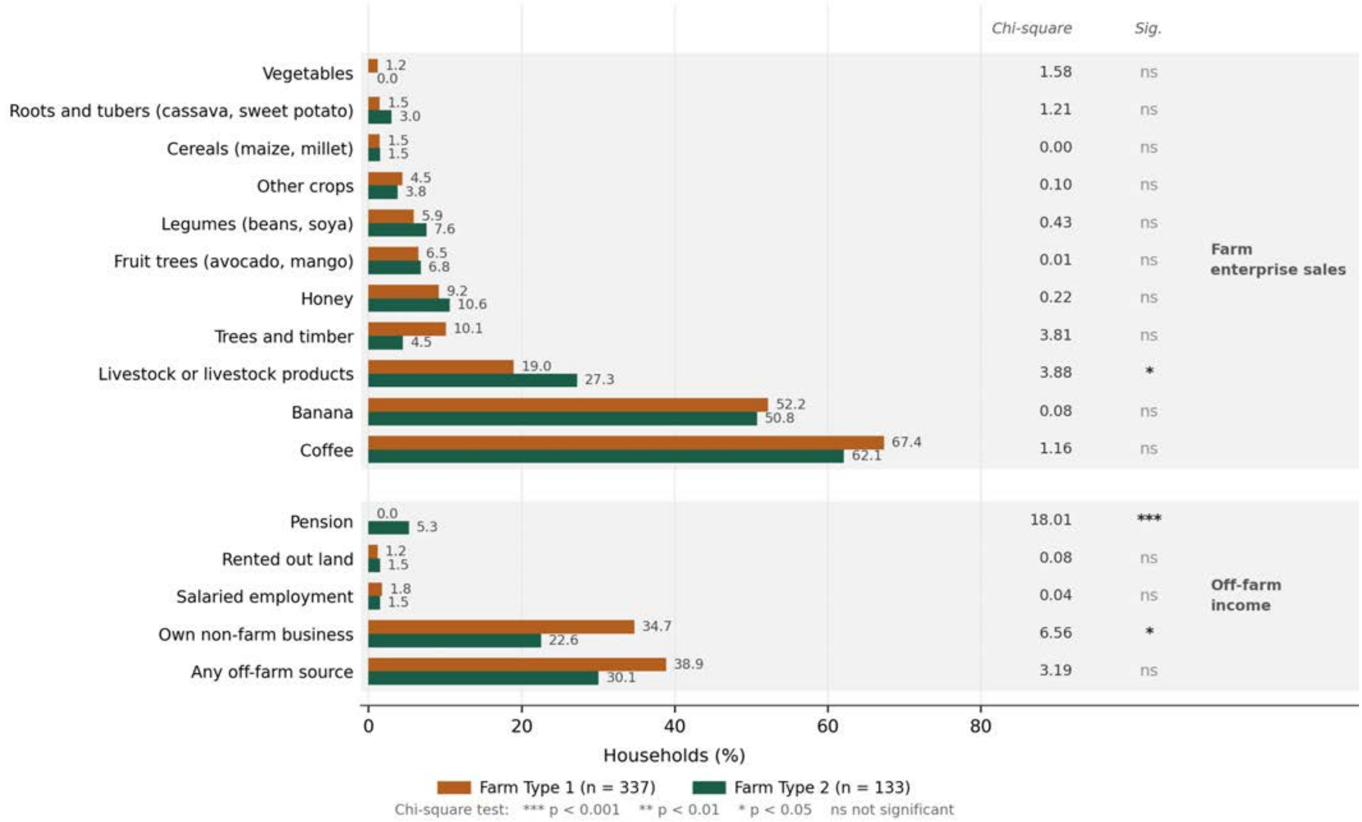


Figure 4. Diversification strategies and household income sources by farm type.

Bars show the percentage of households naming each income source, with values labelled and the chi-square statistic and significance level in the right-hand columns. The denominators were 337 and 133 households. The income-source question records supplementary sources and understates crop selling because many respondents recorded crop sales under a general produce category. Significance is from the chi-square test: *** p<0.001, ** p<0.01, * p<0.05, ns not significant.

managing coffee plantations that were over 25 and 10 years old, respectively. These plantations typically do not employ improved coffee varieties and inorganic inputs.

The cluster analysis identified two distinct categories of farmers based on geographical location, landscape characteristics, and resource endowment. Both categories engage in diversification; however, their risk management strategies differ. The diversification strategies among the clusters vary in terms of crop mix, livestock integration, off-farm income, and enterprise composition. The first category comprises farming-dependent coffee producers from Mitooma, while the second includes resource-endowed, non-coffee-dependent farmers from Ntungamo. The latter group exhibits higher and more diversified incomes and income sources, including livestock, livestock products, and pensions. They possess higher levels of education, greater asset endowment, superior housing, and better access to infrastructure. These farmers demonstrate greater risk tolerance, choosing to cultivate annual crops such as legumes (beans and soybeans) and are more inclined to use agro inputs. In contrast, the coffee-dependent farmers from Ntungamo exhibit more risk-averse production systems, cultivating perennial crops within coffee-banana systems, including trees, and owning non-farm businesses. Notably, coffee-dependent farmers achieve significantly higher seasonal income from banana sales compared to resource-endowed farmers. The distinction in the farmer outcomes and performance (i.e. productivity, income, income sources and technology use) is not as prevalent as the farm type and diversification distinction possibly due to drought, poor agronomic practices, etc. The association of farm type 2 with trenches (Ntungamo) and the association of farm type 1 with terracing (Mitooma) could be landscape-based soil and water conservation practices that are influenced by terrain. Nevertheless, the distinction in the use of organic materials by farm type provides an indication of the potential for the nutrient management approaches.

Implications for coffee system development and UCCP implementation

Targeted strategies for coffee farmers can facilitate income diversification and mitigate financial risk. This study provides several insights:

1. Developing strategies to enhance yield stability and resilience under variable weather conditions is essential. We provide evidence

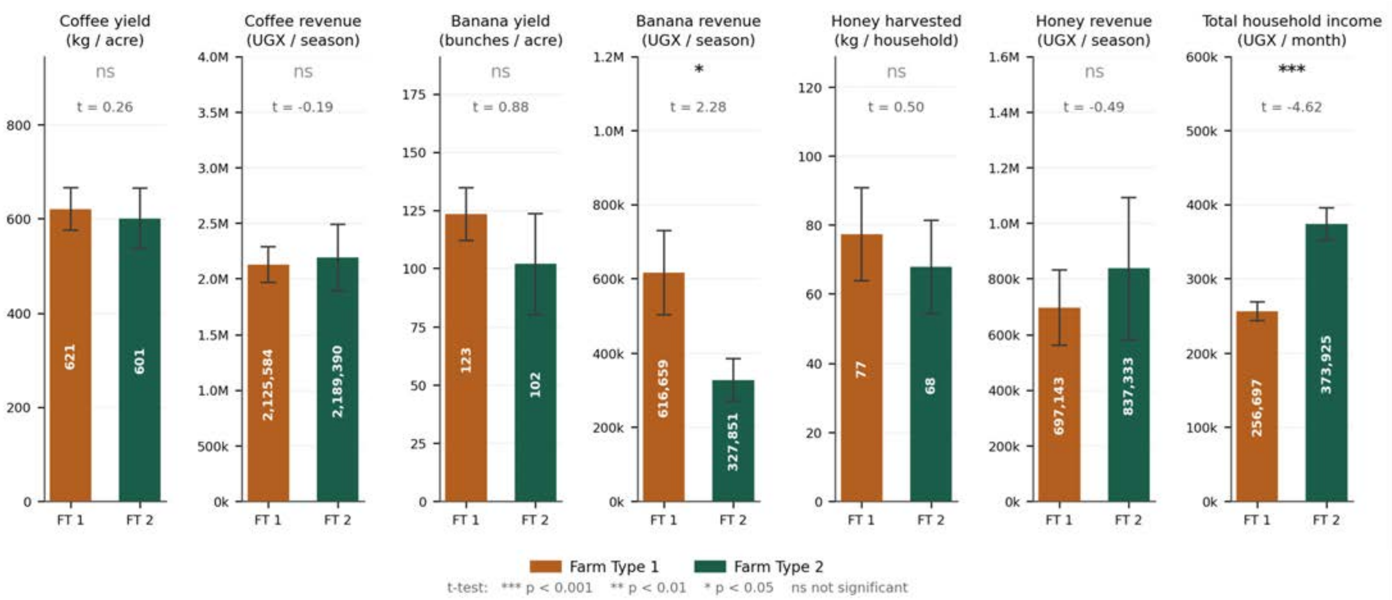


Figure 5. Crop and enterprise productivity and revenue by farm type.

for customizing 4R/nutrient recommendations to accommodate real farm heterogeneities. Applying a "one-size-fits-all" 4R approach to diverse farm types overlooks critical differences in resource endowment, livelihood orientation, and investment capacity, thereby supporting the development of site-specific precision agricultural decision-support systems. On-farm experimentation (OFE) could facilitate the evaluation of 4R nutrient solutions necessary for the two farm types to achieve improved productivity, income growth, and sustainability through the adoption of multiple benefit plant nutrition strategies. For instance, coffee-dependent households could benefit from focusing on 4R nutrient solutions tailored to coffee–banana systems. Enhancing the nutrition of coffee plants contributes to income diversification and resilience, underscoring the significance of coffee nutrition and the susceptibility of coffee-dependent households to price fluctuations and climate risks. These households cultivate indigenous trees within agroforestry systems, offering an additional safety net and the potential to benefit from carbon markets. For the resource endowed risk tolerant farm types, 4R nutrient solutions could be designed for cereal-legume systems to better serve resource-endowed farmers cultivating annual crops, including pulses to support legume driven intensification.

2. The analysis offers a practical segmentation tool for extension services, enabling the development of distinct messages, input bundles, and financing options for each farm type. For example, low-cost plant nutrition upgrades for coffee-dependent smallholders, more market-oriented packages, and integrated crop–livestock nutrient cycling for asset-rich households.
3. The empirical foundation of this study supports business development models (e.g., credit/insurance for asset-poor, coffee-dependent households; market linkage support infrastructure for livestock-oriented farms) to scale plant nutrition strategies and provides evidence to advocate for differential policies.

Conclusion

The endowment-farmer type-diversification-farmer performance aspects of a novel conceptual framework are examined to provide comparative details across typologies. Although the sample revealed distinct farm types and diversification strategies, these differences did not translate into a distinct causal pathway on farmer performance. Farm types were mostly not significantly distinct in their variations in productivity, income, or technology use. An in-depth (econometric) analysis is required to refine the understanding of farm types and enhance endline analysis to provide insights into household evolution, validation, and technology adoption specific to each type. ■

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Written informed consent was obtained from all participants before data collection. Participants were informed of the purpose of the study, the voluntary nature of participation, their right to withdraw at any time without penalty, and the measures taken to ensure confidentiality of their responses.

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How Socio-Economic Factors Shape Soil Fertility Management in Ghana's Smallholder Farms

By Kwame Agyei Frimpong, Ransford Opoku Darko, Selorm Akaba, Isaac Boateng, and Agnes Naa Abeley Abbey

Soil underpins Africa's food security, yet declining fertility continues to limit smallholder productivity and livelihoods. *In Ghana, this challenge is closely tied to socio-economic factors that influence farmers' ability to adopt improved practices. This study shows the need for a dual approach: locally tailored promotion to suit situations where district-level differences are impacting relative adoption rates for ISFM, and unified, broad-based support programs for 4R Nutrient Stewardship which shows evidence of more consistent uptake by farmers. Together, these strategies can improve yields, strengthen soil health, and build climate resilience.*

An extension officer (left) and Professor Frimpong (second to left) explain 4R and ISFM concepts while scouting field with farmers.

This research focused on two contrasting districts in Ghana: Sekyere South, located in the semi-deciduous forest zone, and Komenda-Edina-Eguafo-Abirem (KEEA), located in the coastal savannah. These regions differ not only in climate and crops but also in the socio-economic profiles of their farmers. Sekyere South is home to older, more experienced farmers who often practice mixed cropping, while KEEA's farmers are younger, more open to innovation, and more likely to specialize in monocropping.

The study engaged 100 smallholder farmers (50 from each district) in a series of workshops, surveys, and focus group discussions. The aim was to assess their awareness of two key soil fertility strategies: Integrated Soil Fertility Management (ISFM) and 4R Nutrient Stewardship (4RNS), and to explore how factors like education, land tenure, and access to resources influence their adoption of these practices.

Table 1. Demographic data describing farmers from the two districts involved in the study.

	Sekyere South	KEEA
Age*	49.6	38.4
Number of spouses	0.88	0.75
Household size*	9.2	5.6
Years of education	10.1	10.8
Income level, GHS	19,604	20,885
Years of farming*	20.7	12.3
Acres of land	9.0	7.7

The knowledge gap

One of the most striking findings was the information deficit. While 57.9% of farmers had heard of ISFM, only 43.2% were familiar with 4RNS (**Table 2**). This gap matters: without knowledge of best practices, farmers are less likely to adopt them, regardless of their potential benefits.

Despite this, over three-quarters of the farmers expressed willingness to implement both ISFM and 4RNS, provided they receive adequate training and financial support. A female farmer from KEEA summed up the sentiment: *"I regret that we have not had this kind of information in the past. I think that if we had known about proper soil fertility management, our livelihoods would have improved greatly by now."*

Socio-economic barriers

Education

Education emerged as a powerful enabler. Farmers with higher levels of education were more likely to adopt recommended practices, use agricultural information, and participate in capacity-building programs. In KEEA, a higher percentage of farmers had completed senior high school or university compared to Sekyere South, where more farmers had only primary or junior high education. This difference translated into greater openness to innovation and new technologies.

Land Tenure

Land security is another critical factor. Farmers who own their land or use family land are more motivated to invest in long-term soil fertility improvements. In contrast, those who rent or sharecrop are less likely to adopt practices that require upfront investment, fearing they may not reap the long-term benefits. In Sekyere South, 39.3% of farmers used family land and 33.9% owned their land, while in KEEA, cash rental was more common (35.3%).

Financial Resources

Unsurprisingly, money matters. Nearly half of KEEA farmers and over a third in Sekyere South cited inadequate finance as a major constraint. Access to credit, subsidies, and affordable inputs is essential, especially for young and female farmers who often face additional barriers. Most farmers rely on personal savings to finance their operations, with only a minority accessing loans.

Technical Support

Extension services are the lifeline for many smallholders. While 94% of farmers received some support from government extension agents, only a third accessed private sector advice. Notably, 5% of Sekyere South farmers reported receiving no technical assistance at all, highlighting gaps that need to be filled.

Demographics and Diversity

The study revealed significant demographic differences between the two districts. Sekyere South's farmers are older (average age 49.6 years) and have more years of farming experience (20.7 years) compared to KEEA (average age 38.4 years, 12.3 years of experience). Larger household sizes in Sekyere South suggest more available labor but also greater financial demands.

Table 2. Relative awareness amongst district farmers for ISFM and 4RNS practices.

	Awareness of practices		Willingness to adopt		Capacity building access	
	Sekyere South	KEEA	Sekyere South	KEEA	Sekyere South	KEEA
	(%)		(%)		(%)	
ISFM	57.1	58.8	78.6	76.5	92.9	100
4R	39.3	47.1	78.6	76.5	62.5	55.9

Gender dynamics are also shifting. While men still make up a slight majority, female land ownership is notable—18% in Sekyere South compared to 11% for men—challenging traditional norms and highlighting the importance of supporting women farmers.

Farming Systems

Farming practices reflect both tradition and adaptation. In Sekyere South, mixed cropping dominates (69.1%), providing resilience against pests, diseases, and market shocks. KEEA, by contrast, leans toward monocropping (47.1%), often driven by market demand and resource specialization. Organic amendments are more common in Sekyere South, where 61.5% of farmers use them, compared to 46.7% in KEEA. Animal manure is the most popular organic input, followed by compost. These practices are linked to improved soil fertility and long-term sustainability.

Adoption in Practice

Despite the challenges, 77.6% of farmers expressed willingness to adopt ISFM and 4RNS if given the right support. Willingness to adopt both practices was similar across districts—Sekyere South (78.6%) and KEEA (76.5%), which suggests that when barriers are addressed farmers are eager to innovate. However, the study found that adoption is not just about willingness; it's about capacity. Farmers need relevant training, financial support, and secure land tenure to make lasting changes.

The Role of Extension and Capacity Building

Training and extension services are vital. In both districts, most farmers rely on extension agents for advice, with radio as a secondary source (**Table 3**). Capacity-building programs are more widespread in KEEA, where 100% of farmers participated in at least one training, compared to 92.9% in Sekyere South (data not shown). Sekyere South farmers are more likely to be motivated by training alone, while KEEA farmers are more in need of a combination of training and financial support. One-size-fits-all approaches should be avoided, and interventions must be tailored to local realities.

Both ISFM and 4RNS aim to enhance soil health, increase crop productivity, and promote environmental sustainability. When implemented together, these approaches can generate synergistic benefits, such as improved soil structure, greater nutrient availability, and reduced environmental degradation.

Table 3. Insights into soil management practices and common agricultural extension advice channels within the two districts involved in the study.

	Sekyere South	KEEA
	(%)	
	Main soil management	
None	42.9	41.2
Mulching	17.9	23.5
Zero tillage	28.6	14.7
Cover cropping	10.7	20.6
	Motivation*	
Training	64.3	50.0
Financial support	35.7	26.5
Both	0.0	23.5
	Agriculture Advice	
Extension agents	80.4	82.4
Radio	19.6	17.6

*Significant difference between districts at $p < 0.05$.

However, the two approaches differ in how they are most effectively promoted and adopted. ISFM extension tends to require district-specific strategies that account for local agroecological conditions and socio-economic factors influencing the effectiveness of integrated soil, nutrient, and water management practices. In contrast, the study indicates that 4RNS has achieved steady acceptance, suggesting that a more standardized, broad-based extension approach can successfully promote its adoption without extensive localization.

To effectively support sustainable agricultural development, it is essential for extension services, public–private partnerships, and local government initiatives to work collaboratively in encouraging the adoption of both ISFM and 4R practices. Providing targeted subsidies or incentives for relevant inputs could further accelerate adoption, particularly among resource-constrained farmers.

This integrated approach has the potential to serve as a model for other regions in Ghana and similar agroecological zones. By addressing the need for localized ISFM strategies while maintaining consistent support for 4R practices, agricultural programs can improve sustainability, enhance resilience to climate change, and strengthen food security. Ultimately, this combined strategy is critical for advancing sustainable agricultural systems, especially in regions that are highly vulnerable to climate risks.

Policy implications and recommendations

The findings point to several actionable recommendations:

- **Tailored Interventions:** Support programs should be customized to farmers' socio-economic profiles, addressing specific needs related to age, education, income, and land tenure.
- **Land Tenure Reforms:** Secure land rights encourage long-term investment in soil fertility.
- **Strengthen Extension Services:** Expand both public and private advisory services, with a focus on reaching women and youth.
- **Financial Innovations:** Improve access to credit, microfinance, and input subsidies, especially for at-risk groups.
- **Capacity Building:** Scale up training programs, using both traditional and digital platforms to reach diverse audiences.

Towards sustainable soil and livelihoods

The future of African agriculture is highly linked to the success of smallholder farm householders. By understanding and addressing the socio-economic realities of farmers at the farm level, we can unlock the potential for sustainable soil management, higher yields, and improved livelihoods. Lessons from Ghana's Sekyere South and KEEA districts indicate that Africa's farmers, given the right considerations, are ready to grow, innovate, and feed the continent. ■

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Beyond the Rains: Financial Liquidity as a Determinant of 4R Nutrient Timing in Kenya

By Brayan Valencia, Ivan Adolwa, Martha Okumu, Joses Muthamia, Simon Cook, and Thomas Oberthür

The 4R Nutrient Stewardship framework can collide with the operational realities of African smallholders. *A diagnostic survey of 50 maize farmers across four Kenyan counties reveals a significant planting lag, reaching 10 days in Siaya, driven primarily by a critical liquidity window. While 91% of farmers cite a lack of immediate cash as the primary barrier to timely fertilization, topographical variability is also overlooked, with uniform application rates persisting despite recognized nutrient loss on slopes. To bridge this implementation gap, 4R recommendations must transition from static dates to adaptive "moving windows" that synchronize nutrient application with both environmental signals and the financial mobilization cycles of the household.*

Mr. Valencia (center) in survey discussions with Kenyan farmers.

Moving beyond top-down agronomy

Recent research emphasizes that top-down approaches to delivering precision nutrient management have historically generated limited economic impact for smallholders (Adolwa et al., 2026). The 4R Nutrient Stewardship framework is recognized for its ability to identify optimized packages of practice for fertilizer use—ensuring the Right Source is applied at the Right Rate, Right Time, and in the Right Place—through balanced considerations of economic, social, and environmental goals. However, it can be further adapted, and reimagined, as an entry point for precision agriculture that respects the complexity of the smallholder landscape (Njoroge, 2022).

This preliminary study establishes a baseline diagnostic for reimagining 4R delivery. Optimizing nutrient timing requires aligning field-level practices with the macro-climatic drivers that dictate African seasonal patterns. Central to this is the role of teleconnections, such as the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), which drive significant inter-annual variability in local climate events across Kenya.

The short rains are considerably less predictable than the long rains, largely because they are more strongly modulated by remote ocean conditions (Palmer et al., 2023). The Indian Ocean Dipole (IOD) is the main driver: when waters near the African coast run warmer than usual (positive phase), rainfall can triple; when they run cooler (negative phase), the rains can almost disappear. These extremes intensify during El Niño years, and the resulting "super-seasons" flood farmlands and wash away soils, crops, roads, and bridges.

The challenge: the friction of financial liquidity and topography

The implementation of 4R principles is frequently hindered by a "knowledge-action gap." Preliminary data suggests that "right time" is not merely a seasonal or meteorological target but also a socio-economic one. Financial liquidity can create a timing bottleneck. For example, if a farmer cannot access funds within the precise window of the first rains, the agronomic benefit of the fertilizer is diminished.

Furthermore, field-level spatial variability, specifically topography is rarely managed. Uniform nutrient application across varying slopes leads to systemic inefficiency (Vanlauwe et al., 2010; Zingore et al., 2007). The motivation behind this uniform application is rooted in long-standing cultural trends; with an average farmer age of 51 years, these traditional practices have been passed down for decades. Farmers often accept the trade-off of simplified labor over the complexities of variable-rate application. This leads to scenarios where nutrients are lost to runoff on upper slopes while being over-concentrated in deposition zones (Njoroge, 2022). In these zones, poor crop response is exacerbated by low soil fertility. Consequently, farmers apply high, equal rates of fertilizer across the entire farm to compensate for this inherent infertility, even though the local weather patterns make these slopes highly prone to both erosion and severe drought.

Methodology: a diagnostic baseline in four counties

An interview-based diagnostic assessment was conducted from January 27 to February 11, 2026, involving 50 maize farmers in Siaya, Kakamega, Embu, and Machakos. To ensure high-quality data and farmer trust, this assessment leveraged existing APNI-supported on-farm experimentation (OFE) networks. While OFE initiatives focus on actively engaging farmers to co-develop site-specific technologies (Adolwa et al., 2026), this specific study functioned as a diagnostic survey of those already-engaged farmers to evaluate spatial and temporal gaps in their current management. Data collection focused on quantifying the "liquidity buffer", the time required to secure funds for inputs, and evaluating behavioral responses to topographical heterogeneity and climate threats. To provide geographical context, the four sites represent a diverse cross-section of Kenya:

Siaya and Kakamega (Western Kenya): These sites are characterized by sub-humid climates with bimodal rainfall. Maize-based systems dominate, but they face high population pressure and declining soil fertility.

Embu (Central Highlands): Located on the moist windward slopes of Mt. Kenya, this site features high topographical relief and a humid climate, where intensive maize and coffee systems are common.

Machakos (Eastern Kenya): This is a semi-arid region with higher climate volatility and erratic rainfall. While cropping systems here are highly vulnerable to early-season dry spells and chronic drought, the area uses irrigation systems including small-scale wells and community dams to supplement water requirements and stabilize yields during periods of water stress.

The interaction of environment and solvency

The planting lag and the 3-day liquidity window

Results revealed that financial mobilization is the primary determinant of "right time" failure (**Fig. 1**). Across the cohort, 75.8% of farmers require more than three days to secure the necessary cash or credit for fertilizer. This financial constraint results in a significant planting lag, particularly in Siaya, where the delay between the ideal onset of rains and actual planting reached an average of 10 days.

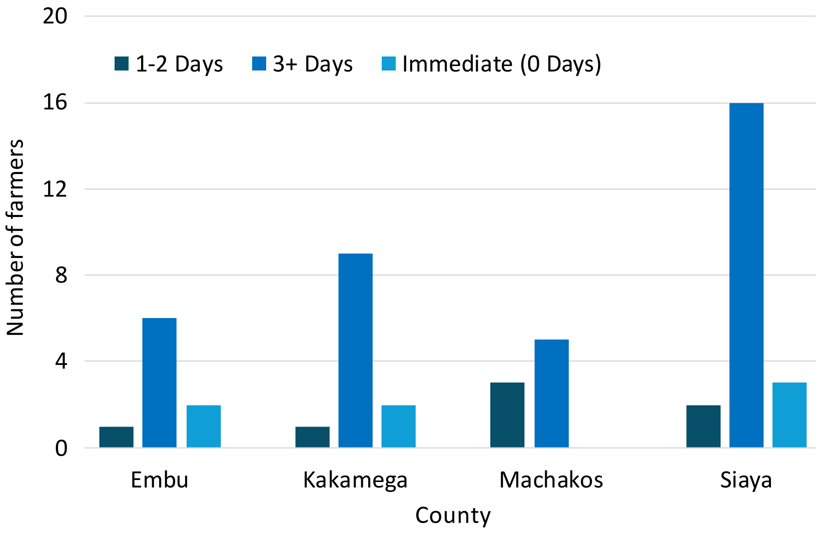

Figure 1. Fund access speed reported by surveyed farmers, by county, Kenya.

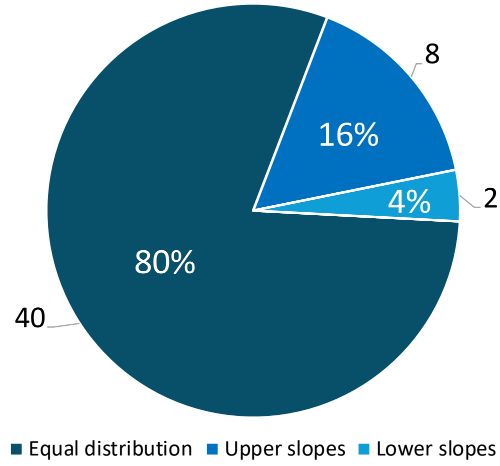

Figure 2. Preferred fertilizer management by Kenyan maize farmers according to slope position in the landscape.

Topographical uniformity despite recognized risk

While 4R principles advocate for the "right place," spatial implementation remains stagnant. Although farmers acknowledged higher nutrient wash-off on upper slopes, application rates remained uniform across 100% of the surveyed fields (**Fig. 2**). This common finding of avoiding any practice adjustment for topography indicates that current extension advice does not provide the technical confidence or tools necessary for site-specific placement (Njoroge et al., 2022).

Fig. 2 reveals that the vast majority (80%) of the 50 maize farmers surveyed in Kenya rely on equal distribution, applying fertilizer uniformly regardless of field topography. This "blanket" approach suggests that site-specific nutrient management is not yet a common practice, likely due to labor constraints or a lack of soil-testing resources. Indeed, prior engagements with farmers highlighted soil testing as a key requirement especially in Siaya (Unpublished report). Among the minority who do differentiate, 16% (8 farmers) prioritize upper slopes, most likely to mitigate soil erosion and nutrient loss. Only 4% (2 farmers) expressed a focus on lower slopes, which typically benefit from natural nutrient accumulation via soil and water redeposition and runoff.

Visible growth variability in a maize plots where fertilization was delayed (middle and right) due to a lack of immediate liquidity. Such delays often lead to stunted growth and increased vulnerability to early-season dry spells.

Behavioral response to climate volatility

Drought and stunted growth remain the dominant concerns for 85% of farmers. However, the reliance on traditional weather indicators over digital SMS alerts (used by only 3% of the cohort) suggests that farmers lack "confidence insurance." In other words, without a mechanism to mitigate the risk of applying expensive nutrients before a potential dry spell, farmers naturally default to conservative, delayed strategies.

Conclusion and call to action

This study's early findings establish that smallholder nutrient management is trapped between agronomic desire and financial inability. To enhance nutrient use efficiency, 4R recommendations must be transformed into adaptive "moving windows" that incorporate a financial lead time alongside environmental signals and topographical risk factors. By translating climate and landscape risks into clear, actionable agronomic insights, we can significantly de-risk timely fertilizer financing. When financial institutions and input suppliers are guided by these moving windows, they face vastly lower engagement hurdles, making conditional micro-loans or bundled finance-advisory products highly viable. Ultimately, this diagnostic serves as a foundational framework for developing climate-smart decision support tools that synchronize soil needs with farmer financial solvency, turning the liquidity bottleneck into an opportunity for innovative public-private partnerships. ■

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Effect of Soil pH on Nitrogen Response of Olive Orchards in Northern Morocco

By Intissare Mouamine, Ngonidzashe Chirinda, Amine El Khouni, Mahdi Dahane, Aziz Soulaimani, Hakim Boulal

Olive tree nitrogen (N) response in northern Morocco varied strongly with soil pH. *In alkaline soils, moderate N fertilization improved leaf N status, while higher rates showed no added benefit, whereas acidic soils showed little response due to sufficient baseline N availability. Results underscore the importance of tailoring N management to soil chemistry to improve nutrient efficiency and climate resilience in Mediterranean olive systems.*

Ms. Intissare Mouamine collecting olive leaf chlorophyll (SPAD) measurements at experimental site A (middle photo) and site B (right photo) in Ouezzzane, Morocco.

Olive trees (Olea europaea L.) are widely cultivated under Mediterranean climates and are valued not only for their fruit but also for high-quality olive oil production. As a perennial evergreen species, olive trees require balanced nutrition to sustain growth, fruit development, and resistance to environmental stresses.

Nitrogen (N) is one of the most critical macronutrients for olive trees. It plays a pivotal role in the synthesis of amino acids, proteins, nucleic acids, and chlorophyll, all of which are essential for photosynthesis and various metabolic activities (Erel et al., 2023). Unlike other nutrients, N has a strong influence on the vegetative vigor of olive trees and the timing and quality of fruit production. However, N deficiency is a common problem in olive orchards, especially under dryland farming systems or in soils with unfavorable properties such as low organic matter and poor moisture retention (Fernández-Escobar et al., 2009). N deficiency symptoms manifest primarily as chlorosis of leaves, reduced leaf size, delayed flowering, and diminished fruit yield (Roca et al., 2018). The uptake and assimilation of N in olive trees are highly influenced by water availability. Water scarcity or drought conditions can impair N uptake by reducing root growth, limiting nutrient diffusion in the soil, and decreasing nitrate reductase activity in leaves (Naija et al., 2014). As a result, N use efficiency declines under water stress conditions (Baccari et al., 2020).

Soil properties, including pH and texture, directly affect N availability and its form (nitrate or ammonium). These factors influence N mineralization and immobilization processes conducted by soil microorganisms (Zhou et al, 2019). In olive trees, low pH improved leaf macronutrient content and, thus, vegetative growth parameters, through the direct effect of pH on nutrient solubility (Beheiry et al., 2023).

Given the importance of N for olive production and the difficulty of its direct assessment, non-destructive methods based on chlorophyll quantification have gained prominence. Since chlorophyll molecules contain N, chlorophyll content in leaves is a reliable proxy for N status. Portable chlorophyll meters provide quick, real-time estimates of leaf N concentrations, enabling precision nutrient management without harming the plant (Boussadia et al., 2011).

Study details

The study was conducted in the Ouezzane region of northern Morocco, which is characterized by a sub-humid Mediterranean climate. The area receives an average annual precipitation of 650 mm and has a mean temperature ranging from 11°C to 26°C. Two independent experiments were conducted during the 2024/2025 olive growing season at two sites within the same rural community, located 4.5 km apart. The first site A (34.819192, –5.463778) had a clay soil texture with 2.45% organic matter (OM), 0.16 mg/kg total nitrogen (TN), 15 mg/kg available P_2O_5, 443 mg/kg exchangeable K_2O, and a soil pH of 8.5. The second site B (34.831284, –5.633601) was classified as clay loam, with 1.17% OM, 0.08% kg TN, 35.1 mg/kg P_2O_5, 133.7 mg/kg K_2O, and a soil pH of 6.2 (**Table 1**). The experiments were conducted on irrigated plots with surface water from a dam with a pH above 8 and a nitrate content <0.9 mg/l on 13-year-old 'Moroccan Picual' olive trees with a planting density of 100 trees per hectare. A randomized complete block design (RCBD) with three blocks was implemented.

Nitrogen (N) application was the main treatment factor, with rates based on a potential yield of 60 kg fruit per tree: 0% (control 0, T0), +50% (0.125 kg N/tree, T1), +100% (0.250 kg N/tree, T2), and +150% (0.375 kg N/tree, T3). The percentages of N input are expressed relative to the recommended N requirement (e.g., 50% corresponds to half of the recommended N requirement). Each experimental plot consisted of four central trees, surrounded by guard rows of six trees on either side and one tree at both the northern and southern borders. Ammonium nitrate (33.5%) was used as the N source, applied in two equal splits in April and June. Soil samples were collected in January (dormancy stage) from 14 trees per site, targeting the active root zone under the canopy. Samples were taken at two depths (0-20 cm and 20-40 cm), with four replicates per depth. Leaf samples were collected during dormancy in January before fertilization. From 24 trees per site, 100 leaves per tree were randomly collected to establish a baseline nutrient status. During the pit-hardening stage, chlorophyll content was measured non-destructively using a portable SPAD-502Plus chlorophyll meter on 20 young leaves per tree per treatment per block. Leaf N content was further estimated from SPAD values using the regression model developed by Boussadia et al. (2011), under the assumption that N represents approximately 3% of total chlorophyll content.

Results

In the alkaline soil (Site A), SPAD chlorophyll index values (Chl) differed significantly among N treatments ($p < 0.001$). T2 (+100% N) produced the highest Chl values, significantly exceeding T0 (control) and T3 (+150% N), while T1 (+50% N) was statistically similar to T2 but higher than T3. In contrast, no significant treatment effects were detected in the acidic soil (Site B), where all treatments exhibited statistically equivalent Chl values (**Fig. 1**).

Estimated leaf N derived from Chl measurements followed the same pattern. In the alkaline soil, T2 showed the highest N content, with T1 intermediate and T0 and T3 presenting lower values. However, in the acidic soil, estimated leaf N varied only slightly among treatments, and the mean comparison test detected no significant differences (**Fig. 2**).

Implications

The study provides valuable insights into the interactions between soil characteristics, N

Table 1. Soil chemical properties in site A (first site) and site B (second site).

	Site A 0–20 cm	Site A 20–40 cm	Site A 40–60 cm	Site B 0–20 cm	Site B 20–40 cm	Site B 40–60 cm
Clay, %	48.5 ±2.7	48.5 ±3.0	49.5 ±3.78	17.87 ±2.30	20.75 ±2.60	29.5 ±6.65
Silt, %	23.25 ±1.96	22.0 ±1.63	20.5 ±1.0	41.5 ±4.04	37.0 ±1.85	32.0 ±5.27
Sand, %	28.25 ±1.08	29.5 ±1.91	30.0 ±4.0	40.62 ±3.21	42.25 ±3.28	38.5 ±6.02
OM, %	2.45 ±0.11	2.16 ±0.06	2.15 ±0.12	1.17 ±0.18	0.85 ±0.12	0.85 ±0.22
TN, %	0.16 ±0.01	0.14 ±0.01	0.15 ±0.04	0.08 ±0.01	0.06 ±0.01	0.06 ±0.01
P_2O_5, mg/kg	15 ±3	8 ±2	9 ±1	35.10 ±11.25	26.39 ±12.26	8.51 ±5.81
K_2O, mg/kg	429 ±20.11	410.25 ±37.83	335.75±30.28	133.69 ±88.1	101.25 ±44.21	167.87 ±75.19
pH	8.58 ±0.01	8.58 ±0.02	8.61 ±0.01	6.20 ±0.31	6.12 ±0.12	6.51 ±0.13
$CaCO_3$, %	1.9 ±0.67	2.06 ±0.81	2.57 ±0.44	Very low	Very low	Very low

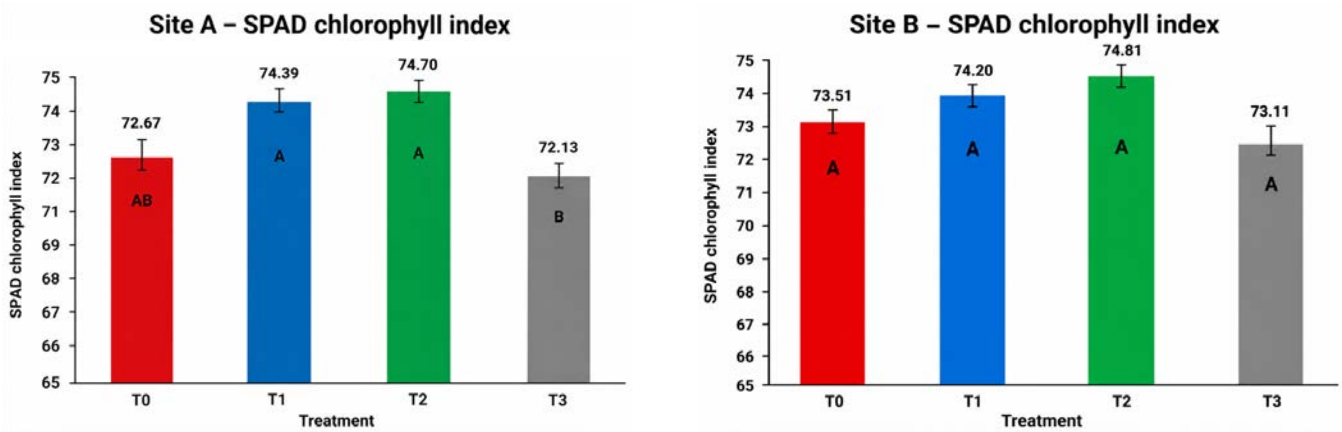

Figure 1. SPAD chlorophyll index values of olive leaves measured at the pit hardening stage under four N treatments (T0 = control 0, T1 = +50% N, T2 = +100% N, T3 = +150% N) in **alkaline (Site A)** and **acidic (Site B)** soils. Bars represent treatment means ± SEM. Different letters indicate significant differences among treatments within each soil type according to Tukey's HSD test at $p < 0.05$.

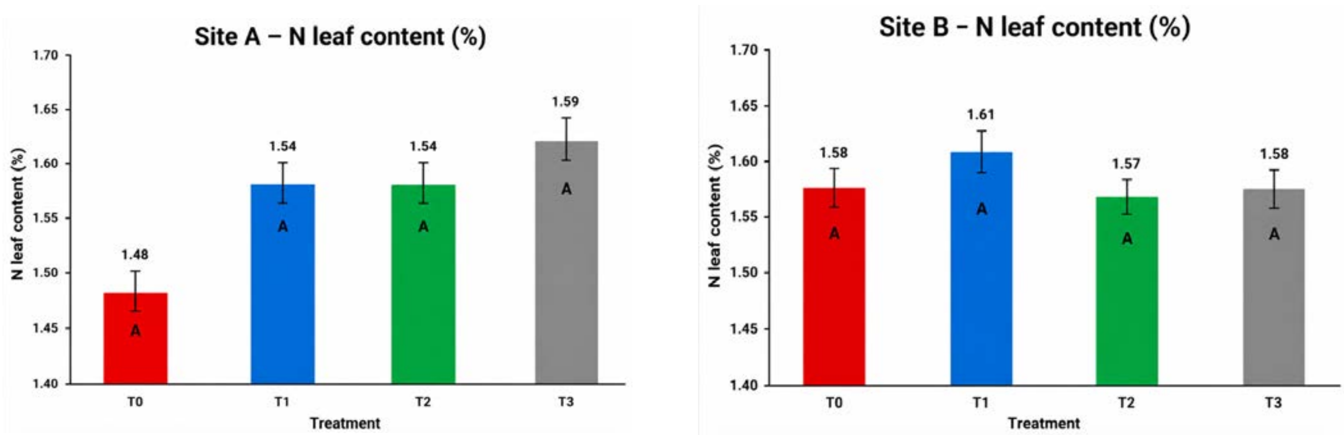

Figure 2. Estimated leaf N content (%) of olive leaves measured at the pit hardening stage under four N treatments (T0 = control 0, T1 = +50% N, T2 = +100% N, T3 = +150% N) in **alkaline (Site A)** and **acidic (Site B)** soils. Bars represent means ± SEM. Different letters indicate significant differences among treatments within each soil type according to Tukey's HSD test ($p < 0.05$).

fertilization, and nutrient uptake dynamics in olive trees. The contrasting soil properties at the two sites—alkaline clay soil (pH 8.53) and acidic clay loam (pH 6.29)—highlight the significant influence of soil chemistry on nutrient availability and plant response to fertilization. Soil pH is one of the primary factors regulating nutrient transformations, retention, and availability by influencing microbial activity, mineral solubility, and cation exchange processes. Previous studies have shown that changes in soil pH substantially modify the balance between inorganic N forms. As soil pH declines, nitrate concentrations decrease while ammonium accumulates, reflecting shifts in nitrification dynamics (Kuśmierz et al., 2023). Moreover, soil reaction has been positively associated with clay, exchangeable Ca, and $CaCO_3$ contents, and negatively correlated with sand content and the availability of micronutrients such as Fe, Mn, and Zn (Doğan and Gülser, 2020).

Alkaline soil exhibited a higher TN content in the soil but lower leaf N concentration (1.35%) below the adequate range (1.5–2.0%) defined by Fernández-Escobar (2019). This result suggests that despite the soil N reserves, the bioavailability of N to the olive trees was constrained by high pH conditions, likely due to reduced N mineralization and increased ammonia volatilization under alkaline circumstances (Fernández-Escobar et al., 2019). Conversely, the acidic clay loam soil, with lower TN but more favorable pH, facilitated adequate N uptake, evident in leaf N concentrations within the sufficiency range (1.64%). The beneficial effect of the moderately acidic soil observed in our study is consistent with previous reports showing that strongly acidic, Ca-deficient soils can impair olive growth, resulting in shorter trees with narrower trunks (Dent, 2020). However, the pH of the acidic clay loam site (6.29) remained within a range that appears favorable for N uptake without reaching the levels of severe acidity associated with growth limitations.

The Chl measurements using a portable SPAD meter, calibrated by the regression model from Boussadia et al. (2011), offered a non-destructive proxy for assessing leaf N status and physiological condition. The SPAD-derived leaf N estimates aligned with direct foliar analysis, displaying significant treatment effects only in the alkaline soil. In this soil, the highest N application rate (+150% N) led to a slight decline in leaf N content and chlorophyll accumulation compared to the +100% N treatment, implying a threshold beyond which N addition no longer benefits, or may even inhibit, nutrient assimilation and photosynthetic pigment synthesis (Ferreira et al., 2020). Such saturation could be attributed to imbalances in nutrient uptake or physiological stress caused by over-fertilization, consistent with findings from studies in Mediterranean cropping systems (Boussadia et al., 2011; Dag et al., 2016). These variations further illustrate the complexity of soil-plant nutrient interactions governed by soil physicochemical properties.

Conclusion

This work shows that what truly matters for olive tree nutrition is not only how much N is present in the soil, but whether the soil environment allows trees to use it. The contrast between the alkaline and acidic sites highlights this clearly: the same nutrient behaves very differently depending on soil pH. By using SPAD-derived estimates, this variability was captured at low cost and in real time, but the method still needs to be checked against the ongoing chemical analysis of leaf samples. This verification step is crucial to understanding how far the chlorophyll indices can be used as a proxy for N status. Beyond this, a bigger knowledge gap emerges as current regression models that link SPAD chlorophyll index values and leaf N are not adapted to the diversity of olive cultivars and growing conditions across the Mediterranean.

If the objective is that farmers make fertilizer decisions based on quick, affordable tools, calibrated models are needed for their varieties and soils. Future work should therefore aim at building such cultivar-specific relationships. Doing so would bring truly accessible precision fertilization, helping farmers reduce costs and environmental impacts while maintaining productivity in a climate where every unit of water and N matters. ■

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Does Improved Agronomy and Plant Nutrition Enhance Human Health Outcomes?

By Sara Lamsili and Kaushik Majumdar

Improved agronomy and plant nutrition are critical, yet often overlooked determinants of human health in Africa, influencing not only food security but also disease burden, income stability, and environmental resilience. *In Ghana, this challenge is closely tied to socio-economic factors that influence farmers' ability to adopt improved practices. This study shows the need for a dual approach: locally tailored promotion to suit situations where district-level differences are impacting relative adoption rates for ISFM, and unified, broad-based support programs for 4R Nutrient Stewardship which shows evidence of more consistent uptake by farmers. Together, these strategies can improve yields, strengthen soil health, and build climate resilience.*

What come to mind when thinking about primary factors influencing good human health outcomes? Hospitals, vaccines, and access to care are essential. However, an important and possibly overlooked determinant of mortality, disease burden, and quality of health—our soils—figures much earlier in the chain.

Improved agronomy and plant nutrition are not typically framed as public health interventions. Yet in most of Africa, where local agriculture underpins both diets and livelihoods, soil management decisions can influence anemia rates, child growth, infectious disease vulnerability, environmental exposure, and long-term economic stability (Pinstrup-Andersen, 2013; Webb and Kennedy, 2014).

Malnutrition and disease burden: The agricultural root

Across sub-Saharan Africa (SSA), malnutrition remains one of the leading contributors to Disability-Adjusted Life Years (DALYs) (GBD 2019 Risk Factors Collaborators, 2020). Iron (Fe) deficiency drives anemia, particularly among women and children. Zinc (Zn) deficiency weakens immune systems and increases susceptibility to diarrhea and respiratory infections. Protein deficiencies impair child development and cognitive performance.

In many rural regions, staple crops such as maize, sorghum and rice dominate diets. When these crops are grown in nutrient-depleted soils, their micronutrient content declines. The soil becomes a hidden determinant of dietary quality (Jones et al., 2013).

Improved plant nutrition including balanced nitrogen (N), phosphorus (P), potassium (K), and other secondary and micronutrient management can increase grain nutrient density. Agronomic biofortification, such as Zn or Fe application to soils or foliage, has shown measurable increases in grain nutrient concentrations (Cakmak, 2008; Joy et al., 2015; Hotegni et al., 2024). In populations heavily dependent on these staples, improved nutrient density can contribute to better micronutrient intake. While food production alone does not eliminate malnutrition, it strengthens one of the most foundational links in the nutrition chain.

Yield stability, poverty, and life expectancy

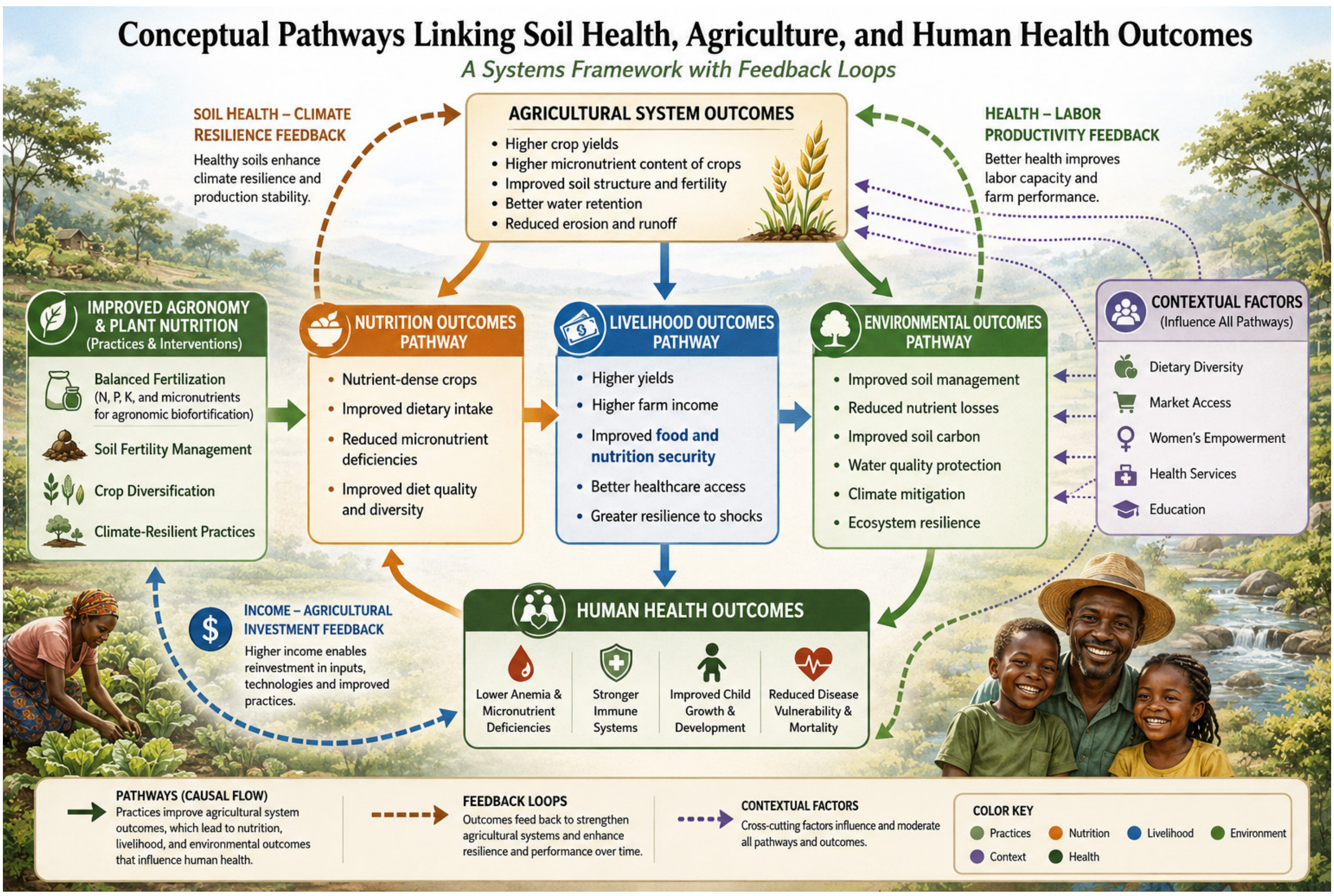
Agriculture is not only about food; it is also about income. In many African countries, farming remains the primary livelihood for rural households (World Bank, 2023). Crop failure due to degraded soils, erratic rainfall, or poor nutrient management does not just reduce food availability; it reduces resilience to shocks, income, access to nutritious diets, and healthcare access and outcomes.

Furthermore, improved agronomy increases yield reliability, soil water retention, climate resilience, and farm income stability (FAO, 2017). Income stability is one of the strongest predictors of health outcomes. Poverty is consistently associated with higher mortality rates, lower life expectancy, and greater disease burden (WHO, 2023). When farmers earn more and experience fewer production shocks, households are better positioned to afford healthcare, education, and diversified diets. In this way, soil fertility influences not just crop yields, but social determinants of health.

Environmental health and exposure risks

Environmental exposures significantly shape health outcomes across the continent. Poor nutrient management can contribute to water contamination, land degradation, and increased vulnerability to floods and droughts (WHO, 2023).

Sustainable agronomic practices including 4R-based fertilization (i.e., right source, rate, time and



place), integrated soil fertility management (ISFM), crop diversity, and agroforestry help reduce nutrient losses and improve ecosystem stability (FAO and ITPS, 2015).

Environmental conditions strongly influence public health outcomes, particularly in rural agricultural regions. Soil management plays a direct role in shaping the environment. Healthy soils with higher organic matter and better structure retain water and nutrient more effectively, reduce runoff, and limit soil erosion. This helps, for example, prevent the transport of sediments, nutrients, and contaminants into rivers and groundwater sources that communities rely on for drinking and household use. When soils are degraded, nutrient losses and sediment runoff increase, contributing to water contamination and raising the risk of diarrheal disease and other waterborne illnesses (WHO, 2023).

Improved crop management using 4R, ISFM, agroforestry, and crop diversification help stabilize landscapes and improve soil structure. These practices reduce land degradation, improve water infiltration and storage, and increase resilience to droughts and floods (FAO and ITPS, 2015). Land degradation and climate stress can intensify food insecurity, while extreme heat and shifting ecological conditions contribute to the spread of vector-borne diseases and heat-related illnesses (IPCC, 2022). By strengthening soil health, improved agronomic practices help reduce these environmental exposure risks and support healthier living conditions for rural communities.

Where the impact isstrongest

The link between agronomy and human health outcomes is strongest where:

- Diets depend heavily on locally produced staples
- Soil micronutrient deficiencies are widespread
- Food insecurity is prevalent
- Healthcare services are limited
- Agriculture drives household income

In these contexts, which describe many rural African regions, improved agriculture practice is critical to human health. It is a structural determinant of it. However, better agronomy alone does not automatically translate into better health outcomes. Movements towards dietary diversity, women's empowerment, access to markets, healthcare systems, and education all mediate the final impact (Ruel et al, 2013).

A shift in perspective

Human health outcomes including mortality rates, disease prevalence, DALYs, quality of life, and functional status are shaped by the interconnected One Health systems. Agriculture and soil health sit at the base of them. Improved agronomy and plant nutrition enhance human health outcomes not by acting as medicine, but by strengthening the environmental, nutritional, and economic foundations upon which health depends. In Africa, where most of the rural population depends on agriculture for both sustenance and income, investing in improved soil fertility and plant nutrition is more than an agricultural priority. It is a long-term public health strategy. Soil health is not just about productivity. It is about resilience and about equity and ultimately, it is about human and planetary well-being. ■

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Contributed by Michael Waweru, APNI Nairobi Office

Midseason spot application (side-dressing) of urea fertilizer in maize growing in Ol Kalou Sub-County, Nyandarua County, Kenya. This practice provides a critical nitrogen boost right before the nutrient demanding tasseling phase.

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