Operationalization of On-farm Experimentation in African Cereal Smallholder Farming Systems

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Abstract.

Past efforts have concentrated on linear or top-down approaches in delivering precision nutrient management (PNM) practices to smallholder farmers. These deliberate attempts at increasing the adoption of PNM practices have not yielded the expected outcomes, that is, increased productivity and nutrient use efficiency at scale. This is because technologies generated by scientists with minimal farmer involvement often are not well tailored to the agroecological, socio-economic, and cultural complexities of smallholder farming systems. Using a pilot case study, we show how a farmer-centric research process in which PNM innovations are co-designed and co-developed can be operationalized. An account is made of the approaches, methods, and tools applied to evaluate how on-farm experimentation (OFE) improves farmer learning and strengthens the capacity of current innovation systems to support innovation. We used a mixed methodology that combined agronomic, spectral, and socio-economic data to answer questions about farmer learning, decision-making, and management-change processes. A simple experimental design was employed, wherein smallholder farm-scale plots (2 ha or less) were divided into an optimized treatment (OT) and a farmer practice (FP). We collected maize yield measurements from 20 and 10 Cote d'Ivoire and Kenya trial sites. Spectral data from Sentinel-2 satellites assessed yield variability within and across farms and monitored crop performance within a season. These results were subsequently validated by farmers and other stakeholders at post-harvest dialogue (PHD) meetings using the focus group discussion approach. A competency assessment and a survey were carried out to augment the analysis. The results in Kenya show a trend in farmers' maize yield improvement over time as a result of their involvement in the OFE process and an increased propensity to experiment and improve management. Although the scientist-led optimized treatment (OT) generally outperforms the farmer practice (FP), farmers are improving season by season as they add to their learning. Digital tools used in the project, such as yield maps, could be pivotal in improving farmer decision-making and the overall management of their farms. The OFE process also provides a platform to link to wider innovation systems with ramifications for scaling of PNM.

Keywords.
on-farm experimentation, precision nutrient management, satellite imageries, yield variability, co-design, co-development, co-learning

Introduction

Historically, agricultural innovation has predominantly followed a top-down approach, where technologies developed by scientists are transferred to farmers with minimal input from the end users. This method has often failed to account for the diverse agro-ecological, socio-economic, and cultural traces that characterize smallholder farms, resulting in suboptimal adoption and application of these technologies (Adolwa et al., 2017; Lindblom et al., 2017).

The challenges facing agriculture today—spanning environmental, social, and economic domains—demand a paradigm shift towards more inclusive and collaborative forms of research. Agriculture faces global challenges that require innovation processes to be urgently developed to address social, ecological, and economic concerns. It has been a long-standing recommendation to place farmers at the center of innovation processes to ensure that solutions are aligned with their needs and aspirations (Lacoste et al., 2021). On-farm experimentation (OFE) is a recent form of collaborative experimental research that involves building productive relationships between farmers and scientists. OFE is an innovation process that engages agricultural stakeholders in mutually beneficial experimentation to support farmers' management decisions. OFE represents a growing global community recognizing that innovative pathways that address contemporary agricultural challenges can be created through farmer-scientist collaboration (Lacoste et al., 2021; Reckling & Grosse, 2022).

Sustainable intensification strategies that entail increased fertilizer access and use are crucial in improving sub-Saharan Africa's crop production and food security. However, the heterogeneous nature of smallholder farms necessitates the customization of fertilizer application to specific farming conditions to maximize yield, profitability, and nutrient use efficiency (Chivenge et al., 2022). Precision nutrient management (PNM) practices as undergirded by the 4R Nutrient Stewardship Framework of the right sources of nutrients, right rates, time, and place promotes context-specific solutions that are central to the Africa Fertilizer and Soil Health action plan.

Recent studies emphasize the importance of directly co-designing and co-developing agricultural innovations with farmers to ensure these technologies are appropriately adapted to local contexts (Roques et al. 2022). This fosters greater acceptance and practical applicability of agricultural technologies and enhances farmers' capacities to innovate and adaptively manage their farming practices. Participatory processes involving farmers, advisors, and scientists, and incorporating on-farm trials and quantitative approaches, can foster co-learning among participants, leading to a greater understanding of the potential for more sustainable cropping systems (Thorburn et al., 2011). Rather than promoting the large-scale implementation of prescribed management practices, facilitating farmers in identifying their solutions is more effective. As such, it is highly pertinent to amalgamate scientists' and practitioners' knowledge and learning methods. However, the factors that can enable on-farm experiments conducted collaboratively by farmers and researchers to become a powerful tool in implementing novel and/or more sustainable practices must first be determined. Efficient knowledge interfacing is often impeded by the inherent inclination for learning to occur within homogeneous groups. Learning is optimized when new information can be easily assimilated into existing knowledge structures, thus enhancing memory retention and recall. Consequently, individuals tend to adopt learning patterns that prioritize subject matter congruent with their existing knowledge base (Adolwa et al., 2017; Roux et al., 2006).

In this vein, a study conducted across Cote d'Ivoire and Kenya has demonstrated how OFE can be operationalized to enhance farmer involvement and learning. The study has provided insights into how farmers can actively participate in and benefit from scientific research by employing a mixed methodology that integrates agronomic data, spectral analyses from Sentinel-2 satellites, and socio-economic assessments. Using spectral data to monitor crop performance and yield variability within these smallholder farms validates the experimental results. It offers a scalable, cost-effective method for assessing and enhancing crop management practices. By focusing on co-learning and the active involvement of farmers in the innovation process, OFE has the potential to significantly transform smallholder farming systems in Africa, making them more productive and sustainable. The objectives of the study are:

- To assess how on-farm experimentation (OFE) improves farmer learning.
- Give an account of the approaches, methods, and tools used to operationalize OFE in African smallholder systems.
- Explore how OFE can strengthen the capacity of current innovation systems to support PNM innovation.

Methods

Study sites

The study was conducted in northern Côte d'Ivoire (Poro, Bagoué, and Tchologo regions) and Kenya (Machakos, Embu, Meru, Siaya, and Kakamega counties; Fig. 1). Northern Côte d'Ivoire falls within the cereal-root crop mixed farming system of West and Central Africa whereas the sites in Kenya are part of the maize mixed farming systems found in East, Central and Southern Africa (Garrity et al. 2012). This portends contrasting biophysical, cropping, and socio-cultural patterns. For instance, northern Cote d’Ivoire has a uni-modal rainfall pattern and one cropping season, whereas Kenya has a bimodal one with two cropping seasons per annum. However, for both regions maize is the main cereal crop, and it is grown in association with legumes, root crops, and cotton in intercrop, rotation, or relay sequences.

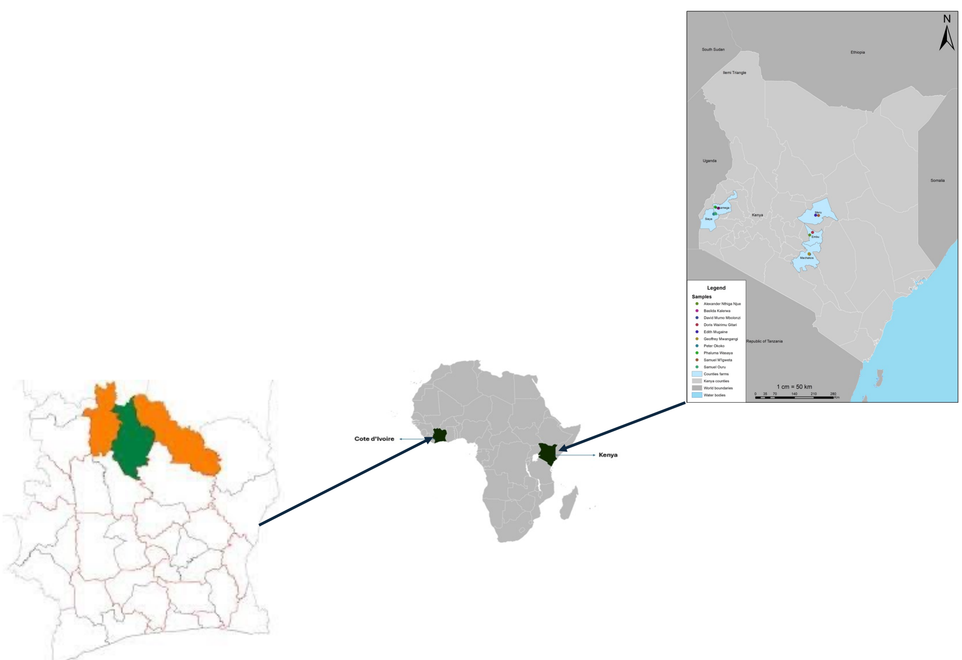

Fig 1. Map showing the study countries and regions

On-farm experimentation trials

On-farm experimentation trials (10 in Kenya and 20 in northern Côte d'Ivoire) were established under the auspices Nutrient-Catalyzed Agricultural Transformation (NUTCAT) project between June and September 2021 using tenets of OFE, which requires an interdisciplinary approach integrating key aspects of agronomic, social, and data sciences. The OFE process for the NUTCAT project follows six phases and several steps or activities (Fig. 2). It started with engagement, where the cooperating farmers and sites were identified. Subsequently followed by the acquisition of agronomic (yield, biomass), spectral (Sentinel 2 data for KML) and socio-economic data.

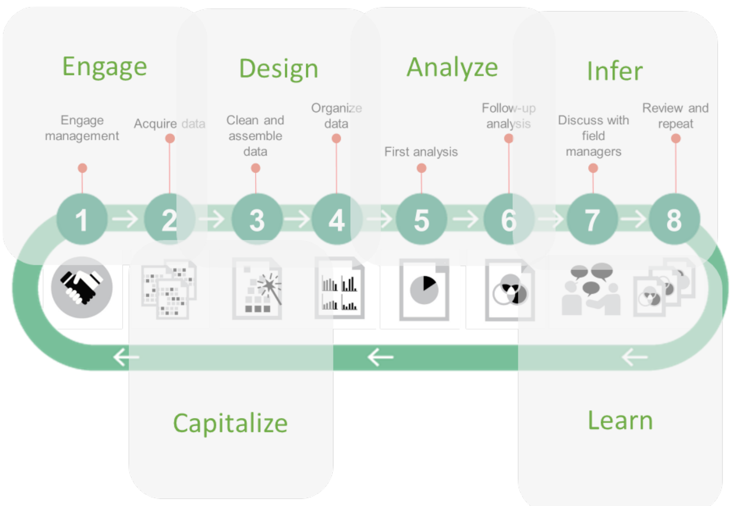

Fig 2. The OFE process for NUTCAT (adapted from Lacoste et al. 2021)

The trials use simple, easy-to-understand designs with two treatments, (1) Optimized treatment (OT) and (2) Farmer practice (FP), for clarity of effect and involve relatively large plot sizes (2 ha or less). The OT is researcher designed and managed and is defined by a team of local cropping system experts, i.e. the Cereal Improvement Team (CIT), as the combination of practices and inputs that is required to produce an attainable yield target specific to the agro-ecological zone (AEZ) within the country. The FP treatment is farmer-managed and mirrors exactly the practices and inputs the farmer was planning to apply in that season. In Kenya's OT, a balanced nutrient application rate of NPKSZn (150:50:60:15:0.5) was applied as fertilizer Di-ammonium Phosphate (DAP), Muriate of Potash (MOP) and UREA-S for a yield target of 6-7.5 t/ha. The standard good agricultural practices (GAP) were adopted. Manure (5 t/ha) was also applied from the third season onwards. As expected, farmers management practices were variable with the use DAP fertilizer as basal and CAN for top dressing representing a nutrient rate of NPK (78:24:0), manure (1 t/ha), hybrid seed and select GAP (e.g. recommended spacing). In Côte d'Ivoire, a nutrient application rate of NPK (120:60:70) was applied as NPK (14-18-18) and UREA (46%) fertilizer for a yield target of 4 t/ha. The standard good agricultural practices (GAP) for that agroecological zone were adopted. Farmers used a variety of management practices including the use NPK fertilizer as basal and Urea for top dressing but lower rates than OT with invariable application of GAP in terms of weed control, crop density, pesticide control etc.

Remote sensing data

Remote sensing techniques were used to describe the variation in crop performance within and between smallholder farmers' fields or treatments with a degree of reliability that enables sub-field specific agronomic management decisions. Such techniques are useful for the generation of credible but relevant insights using data from 'real system' experiments (Lacoste et al., 2021; Roques et al. 2022). Remote sensing technologies used in this study were the Sentinel 2 satellites, which have spectral bands at 10-m and 20-m resolution and cover the visible, red-edge, NIR and short-wave-infrared (SWIR) regions and the PlanetScope satellites, which have 8 spectral bands at 3 m resolution, and cover the visible, near red-edge and NIR regions. Spatial variation in crop reflectance was correlated with grain yield using a 3 x 3 grid harvesting pattern in each plot (Fig. 3). Drones were also used to generate very-high-resolution (2-5 cm) imageries of the large-size treatment plots. In Kenya's case, the images are based on the green, red, red-edge and NIR bands from a Mavic 3M drone.

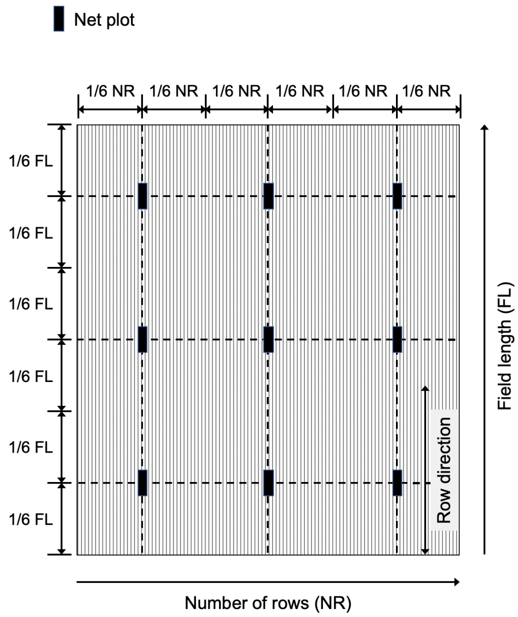

Fig 3. Georeferenced 3x3 harvest grid harvest pattern used for NUTCAT OFE trials (later expanded to 6x6)

Surveys and post-harvest dialogues

A detailed farmer survey was conducted in the two countries to understand the socio-economic context in which the farmers operate in and the drivers of their decision-making. The surveys were conducted between July and November 2023. In Ivory Coast, the respondents were majorly sampled from Sinematiali, Frekessedougou, Korogho and Boundiali districts with a total of 413 interviews being conducted. On the other hand, in Kenya, the farmers who participated in the survey came from Kakamega, Siaya, Embu and Machakos counties. A total of 524 farmers were interviewed in Kenya. The data collected was analyzed and inference made from the results in collaboration with farmers and other stakeholders at post-harvest dialogue (PHD) workshops.

A multi-stage sampling strategy was employed. At country, district and village levels, the selection was purposive, but at the household level selection was random. Our key respondents with regards to sampling were the NUTCAT farmers and therefore they served as our starting point for treatment villages. The skip-interval method (Dossa 2011) was used, whereby the NUTCAT farmer served as the central reference point from which enumerators could take different directions interviewing every fifth household. For control villages, the enumerators could start from the central part of the village skipping households and interviewing. All NUTCAT farmers that were available participated in the survey. The survey data was collected electronically using computer-assisted personal interviewing (CAPI) on the SurveyCTO platform. Well trained enumerators were issued with similar tablets of the same brand and model to ensure consistency and avoid potential difficulties with the platforms.

Post-harvest dialogue workshops

The PHD workshops facilitated discussions about what worked best in farmers' maize fields and brought in supporting technical and scientific advice from other project stakeholders including regional extension staff, agronomists, and APNI scientists. This open engagement with farmers is, by design, a core aspect of the OFE platform, which seeks a co-learning environment that encourages farmer participation in landscape-scale research while providing a means to better understand the learning, decision-making and management change processes of farmers themselves.

Participating farmers as well as neighboring farmers who had gained interest in the activities throughout the crop season gathered in these workshops held in June 2022 and May 2023 in Côte d'Ivoire and July 2022 and September 2023 in Kenya. During these engagements, focus group discussion (FGD) and in-depth interview approaches were supported by evidence drawn from agronomic and remote sensing data collected during the season (Fig. 4). Farmer engagement with extensionists, agronomists and other agricultural stakeholders provided an opportunity to share observations and lessons learned, initiate plans for subsequent season's plantings, and fine-tune the optimized treatment (OT) packages.

Data analysis

The analysis for the yield data was performed in R (*version of R-4.4.0*). For each treatment within each season, the mean grain yield was calculated. To assess the relative variability of grain yield within each treatment and season, the coefficient of variation (CV) was computed. CV is a normalized measure of dispersion and is particularly useful for comparing variability across different groups with different means. The trends in mean grain yield across the seasons for both treatments were visualized using line plots. Each treatment's mean grain yield was plotted against the respective seasons to illustrate temporal changes and facilitate comparison.

Qualitative data from the FGDs were transcribed and carefully analyzed to uncover key themes and patterns regarding innovation awareness and learning by farmers, management change and experimental processes of farmers based on their learning and co-learning between farmers and other actors. Following Mayanja et al. (2022), the data were analyzed using content analysis and grouped the data under several thematic issues related to experimentation and management change processes, farmer decision making and digital tool use. The first stage of the content analysis involved transcribing all audio transcripts. In the next analysis stage, the researcher got used to and analyzed the interview material well. This was done through in-depth reading and coding of all transcripts within the study objectives and research questions. After coding, the codes were grouped into sub-themes in the third step of an Excel spreadsheet. In the final step, the secondary themes were grouped into main themes to give an idea of the research question. To minimize subjectivity, the co-authors independently coded the transcripts. Findings were then compared, and consensus reached. Qualitative findings were1`d then presented using themes, codes, and quotes from participants' narratives.

Fig. 4 Focus group discussion with NUTCAT farmers.

Indepth interviews were also carried using competency-based tool (CRS 2021), to assess the skills competency levels of farmers who now had been through two or more iterations of the OFE process. The main competency being assessed here was on the capacity of these smallholder farmers to continuously learn and innovate on their farms.

Results and discussion

Socio-economic characterization and PNM adoption risk factors

Farming households in Kenya are smaller in size than those in northern Côte d'Ivoire but the heads of the former have more years of formal education (Table 1). Interestingly, Côte d'Ivoire farmers are of a higher economic status than their counterparts given their higher incomes and expenditure levels. The major source of income for both Kenyan and Côte d'Ivoire farming households is derived from crop farming and livestock husbandry.

Table 1. Socioeconomic characteristics of Kenyan and Cote d' Ivorian farmers

Characteristic	Kenya		Côte d'Ivoire	
	Mean	SD	Mean	SD
Household Size	5.3	2.3	10.7	4.9
Years of Education of Head	8.3	3.8	2.2	3.3
Years of Farming Experience	26.9	15.6	25.3	9.6
Monthly Net Income (USD)	130.1	146.9	215.6	253.5
Monthly Expenditure (USD)	90.2	87.7	113.6	119.2
Years living in the village	37.7	18.4	39.1	12.7

Maize-mixed cropping systems dominate the smallholder farming systems, with most farmers applying inorganic fertilizers on maize i.e. > 85% in Kenya and > 80% in Côte d'Ivoire. The mean revenues from maize sales were relatively modest, however, ranging from 120 – 1803 USD/ha. In Kenya, DAP was the most used fertilizer for basal application and CAN was used for top-dressing. In Côte d'Ivoire, NPK and Urea were most used for basal and top-dress applications, respectively. Mean application rates in Kenya were for DAP 121 kg/ha and CAN 93 kg/ha at a cost of 107 USD/ha and 73 USD/ha, respectively (Table 2). These rates are half of the agronomically optimal rates for these agro-ecological zones. Naturally, many farmers will not apply fertilizers optimally as they find them to be costly. Mean application rates in Cote d' Ivoire for NPK were 161 kg/ha and Urea 93 kg/ha at a cost of 115 USD/ha and 69 USD/ha, respectively. Slightly over half of the sample of farmers in our sample apply GAPs such as use of recommended practices and intercropping or rotation.

Most farmers did not have access to subsidized fertilizers; hence these inputs were beyond the reach of many due to high costs (Table 2). Similarly, many farmers did not obtain agricultural credit or adequate training in the use of fertilizers. Weather and climatic risk factors to input use affect the two countries variably. For Kenya, farmers reported erratic weather patterns whereas in Cote d'Ivoire drought events are more likely to occur. After fertilizer costs or credit crunches, the most urgent issues for farmers are field pests and/or diseases and low soil fertility. About a third of farmers in East Africa seek and test for relevant solutions, whereas only a very small share in Côte d'Ivoire experiment (Table 2). Most East African farmers prefer to experiment on entire fields.

Table 2. Characterization of farmer management practices in Kenya and Cote d'Ivoire

Characteristic	Kenya		Côte d'Ivoire	
	Mean	%	Mean	%
Maize yield (Kg/ha)	1001.3		3643.6	
Maize revenue (USD/ha)	119.6		738.5	3.3
Farmers applying DAP		65.8		-
DAP applied (kg/ha)	121.3		-	
Farmers applying NPK		19.8		87.7
NPK applied (kg/ha)	105.1		115.1	
Farmers applying CAN		50.6		-
CAN applied (kg/ha)	92.5		-	
Farmers applying Urea		3.6		85.5
Urea applied (kg/ha)	95.3		68.6	
Farmers applying animal manure		70.4		7.6
Animal manure applied (kg/ha)	4006.3		926.4	
Farmers using recommended spacing in maize		56.1		54.6
Farmers intercropping/rotation in maize		77.2		11.4
Farmers who find fertilizers costly		92		99.5
Farmers with access to subsidized fertilizers		19.5		29.8
Farmers who test potential solutions		28.1		1.0
Farmers who share results & learnings		55.1		0
Farmers who obtained credit		14.1		0.7
Farmers who received agricultural training		24.2		14.8
Likelihood of erratic weather patterns		61.8		1.0
Probability of drought		27%		60.0
Probability of pest & disease attack		75%		54.9

The influence of OFE on farmer learning and yield outcomes

Based on the socio-economic characterization, most farmers are applying inputs sub-optimally resulting in low maize productivity. Cereal productivity, more so maize productivity, is an important indicator of food security in Kenya and northern Côte d'Ivoire. Insights from the pilot study on on-farm experimentation point to a progressive increment in maize grain yield in farmers' fields based on continuous farmer learning that is supported by the OFE platform (Fig. 5). While OT consistently outperforms FP and is on a more stable upward trajectory, the yield in the latter is characterized by a steeper upward trajectory except for the second season (LR2022), which suggests a positive learning curve among farmers involved in the OFE process. The poor performance of the second season is a result of the low amount and poor distribution of rainfall in the eastern region of Kenya (Machakos, Embu and Meru) in that season (Adolwa et al., 2022). Therefore, there was widespread crop failure in that region. In the subsequent seasons, there was a considerably large increase in yield outcomes that corresponded with co-learning, engagements and support farmers were getting from their involvement in OFE. It is worth noting that farmers' productivity started to assume a positive trajectory after the first PHD in Kenya was held in July 2022. By actively involving farmers in the research and development process, and jointly assessing the outcomes of the experiments a deeper understanding was fostered. This assertion is in line with the other findings on OFE processes where farmers' involvement in agronomic experimentation led to increased learning and higher acceptance of technologies (Laurent et al., 2022; Roques et al., 2022). Hence, this resulted in a behavioral change in farmers, contributing to their increased competency to apply PNM practices.

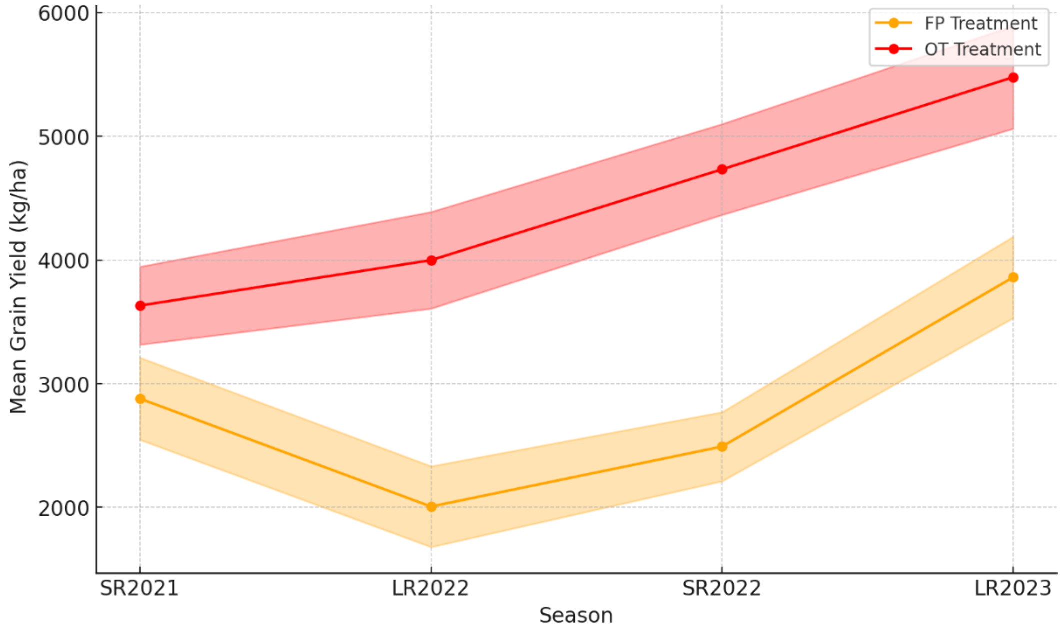

Fig. 5. Trend of yields across seasons by treatment and the differential effect of OT and FP on maize productivity in Kenya over time. Bands represent co-efficient of variation.

Using the competency-based tool described earlier, we assessed the skills competency levels of farmers who had been through two iterations of the OFE process. The main competency assessed was the capacity of these smallholder farmers to continuously learn and innovate on their farms using the available (often scarce) resources. Recommended spacing (75 by 25cm), compost or manure use, and the right fertilizer timing were the practices most tested across the five Kenyan counties (Fig. 6). As expected, farmers were more amenable to testing technologies not entailing additional costs or that could be implemented with locally available resources. Farmers, for instance, understood the importance of the right plant population in terms of both optimal access to nutrients and sunlight as well as maximal land utilization. Similar to Côte d'Ivoire, farmers here were keen to ensure they applied fertilizers at the right time to avoid wastage and optimize nutrient uptake for increased productivity. The smallholders also trialed improved maize seed varieties and applied pesticides to deal with recurring problem of pest infestation. Some solutions such as the use of herbicides for weed control were not tested as much as farmers found them costly. Their verdict was that these new practices were better in terms solving specific problems e.g. low productivity than what they were previously practicing. However, in terms of the affordability and social and cultural compatibility of the practices they may have been better or did not make a difference. These farmers indicated their intention to increase the scale of implementation of the practices they have tested and share their experiences with other farmers within and beyond their village. Indeed, the survey results showed that 55% of farmers who experiment shared the results and learning with other farmers within and beyond their communities (Table 2). Thus, this case study illustrates how OFE could effect a behavioral change process as a precursor to improved yield and possibly income outcomes.

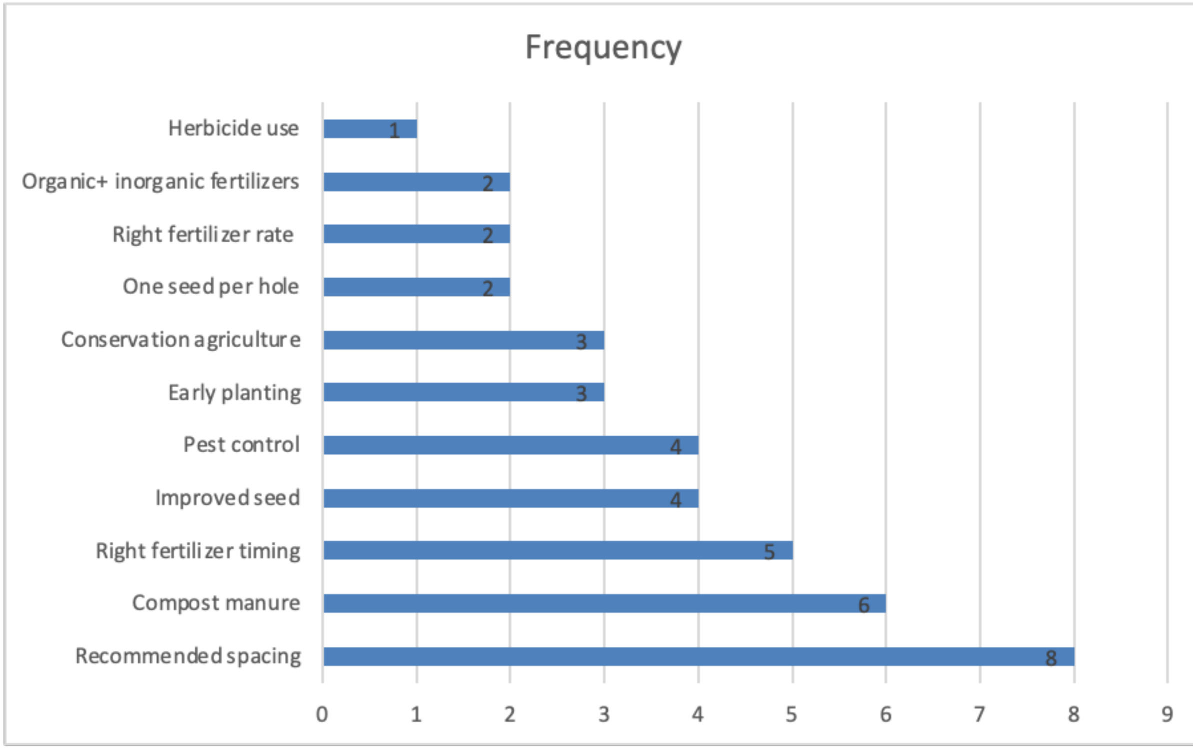

Fig. 6. Practices tested by Kenyan farmers in the previous season (Long-rain 2023)

Operationalization of OFE and its capacity to strengthen innovation systems

The NUTCAT pilot study operationalized OFE by applying its principles, which revolve around farmer-centric engagement, real systems (research at scales that are meaningful to the farmer), relevant design (site selection, experimental design, performance indicators), evidence-driven (standardized data protocols), specialist-enabled (adds value through proper scientist engagement), and scaling through co-learning and networks (Lacoste et al. 2021). Therefore, we used an interdisciplinary approach combining and integrating agronomic, social, and digital data to generate actionable and scalable insights. In addition, the steps outlined in Fig. 2 were necessary to properly and effectively orient OFE in the select farming systems.

The PHD workshops offered a viable platform on which to jump-start OFE operationalization as this was when proper engagements with farmers and other stakeholders commenced. The first PHD in Côte d'Ivoire was held in June 2022 and that of Kenya a month after. In this first set of PHD the discussions centered on innovation awareness and learning, and management change of farmers based on their learning and co-learning processes. The OFE experiments had been in operation for at least one year by the time the dialogues took place. Agronomic yield results from the experiments together with accompanying satellite imageries were shared with farmers to help review the results and inform decisions on how to improve management for the following season (see Adolwa et al. 2022b). The second set of PHDs were held the following year (in 2023) to build on these initial lessons by assessing how farmers implemented management changes on their fields in the second season, what they learned in the process and whether they shared these learnings with other farmers or stakeholders. Using the satellite imageries and yield maps, the scientific team and farmers were able to explore some of the underlying causes of variability within-field and between fields (Fig. 7). Causes of variability included neighboring shady trees (upper eastern Kenya), edaphic factors (lower eastern Kenya), management e.g., input use and rate, pesticide use, use of organics (all), pest and disease infestation e.g., Striga, *Spodoptera frugiperda or Armyworm* (western Kenya, Côte d'Ivoire), soil fertility gradients (western Kenya), topography (Côte d'Ivoire), and climatic factors (Côte d'Ivoire). The farmers were also aware of what this variability cost them in quantifiable terms. For example, farmers reported on losses of 4 to 10 bags (90 kg) in their FPs translating to as much as US $600. The yield maps enabled the farmers to have a clearer picture of where to make improvements in their fields, so they utilized them to plan better for the next season.

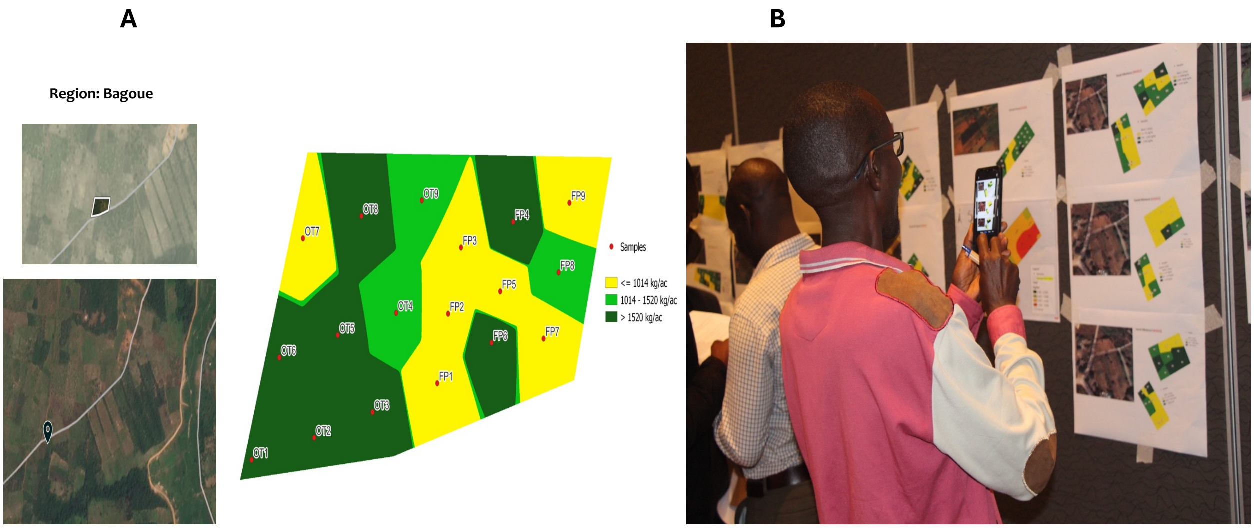

Fig 7. Natural color images captured with PlanetScope (late growth season October 2022) and yield maps of a farmer's field in Bagoue region, Côte d'Ivoire (A). Kenyan farmer using digital tools to help in farm management planning (B).

Another purpose of the PHDs was to link farmers with the wider agricultural knowledge innovation systems (AKIS), which in this project we refer to as CIT, and facilitate cross-learning. The AKIS typically consist of the national agricultural research systems, extension, academia, non-governmental organizations, and community-based organizations. The CIT experts got to learn about some of the emerging, contextual issues that were affecting maize production e.g. fall armyworm (*Spodoptera frugiperda)* infestation, inefficiencies in the fertilizer supply chain, soil fertility constraints, fluctuating weather patterns and others. Based on this knowledge, the optimal fertilizer rates, and sources, as well as yield targets for subsequent seasons were revised. For instance, the agronomic protocol was revised to include organic amendments while the yield targets for western Kenya were revised downwards to 6 t/ha and those for eastern Kenya to 4.5 t/ha. Therefore, NUTCAT OFE, with its potential for transformative agronomy in Africa, is linking with wider AKIS and value-chain actors to scale up not only PNM technology but also the process that empowers farmers to be agents for transformative change (Alexandre et al. 2023; Adolwa et al. 2022a).

Conclusion

This study underscores the importance of integrating smallholder farmers into the innovation process through OFE to enhance PNM practices in African cereal farming systems. Our findings reveal that a farmer-centric approach, characterized by co-designing and co-developing agricultural innovations, boosts farmer learning and management capabilities. The results from Kenya OFEs demonstrate that while OT still outperforms traditional FP, there is a discernible trend of improvement in FP yields over time, indicative of effective learning and adaptation. The use of mixed methodologies, including agronomic assessments, spectral data from Sentinel-2 satellites and PlaneScope, socio-economic surveys and FGDs, has proven effective in validating these innovations. Our study also shows that translational issues that revolve around fertilizer pricing and temporal issues pertaining to climate change, vagaries of weather and pest and disease pressure affects farmer decisions on the implementation of PNM.

The next steps entail fostering and growing OFE collaborative networks and further positioning them within existing AKIS. This study provides compelling evidence that OFE, supported by digital tools and wider innovation actors, can transform smallholder farming systems in Africa. By aligning scientific innovations with the practical realities of smallholder farmers, OFE not only improves productivity and nutrient use efficiency but also empowers farmers to become active participants in the agricultural innovation ecosystem.

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