growing AFRICA

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POST-HARVEST ASSESSMENTS OF ON-FARM MAIZE EXPERIMENTATION

EXPLORING CLIMATE SMART CROPPING SYSTEM SOLUTIONS

BUILDING A MAP OF BIOAVAILABLE PHOSPHORUS FOR AFRICAN SOILS

MORE INSIDE!

ACTIONABLE SCIENTIFIC INFORMATION ON PLANT NUTRITION

apni

growing AFRICA

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Inside this Issue

Welcome to our second issue of *Growing Africa*! We start with a feature introducing all the recipients of our 2022 Award and Grant programs. APNI is proud to support this innovative group of 17 scholars, researchers and educators that represent 9 countries across Africa. Note that we have provided our 2023 schedule of application deadlines inside as we look to continue these initiatives next year.

Since forum building is an important part of this publication's mission, this issue introduces two new opportunities to take advantage of. Our inaugural "*Ask an APNI Expert*" column covers the basics of what to consider while developing precision agriculture models. More plant nutrition-related questions are encouraged! Secondly, our brand-new photo contest is now accepting entries. The goals of the contest are to encourage the art of field scouting and crop diagnostics through the sharing of *crop nutrient deficiency imagery* (Category 1), and to promote illustrative examples of *plant nutrition research in action* (Category 2).

On the research side, we begin with a story providing early insights from a pan-African on-farm experimentation project on maize cropping systems. You'll learn how this farmer-led research model is establishing a co-learning environment that shows promise for scalability due to its ability to engage with participating farmers and others nearby. The common thread for the next two research articles is the challenge of managing for variability. First, Kenyan research on maize cropping systems clearly describes the degree to which nutrient responses vary across time and space. The study also provides short-term nutrient management options in this era of especially low access to affordable fertilizer inputs. Next, we learn about the major drivers and impact of a variable climate on Malawian farmers, and local research working to popularize a more sustainable and diversified cropping system. Crop diversification is the subject of the next article from Tanzania. Legume intercropping with maize shows both short and long-term residual nutrient benefits, as well as improved nutrient recycling and input savings on-farm. Lastly, we share a newly produced map of soil phosphorus (P) bioavailability for Africa. This map confirms that the continent's highly weathered soils combined with chronically low P input has generated widespread limitations compared to other regions of the world.

Finally, a reminder that *Growing Africa* strives to provide an outlet for your applied African-centric research on plant nutrition. If you are considering a submission, contact us or review *our guide for authors* available from our website: https://growingafrica.pub

Kind regards,

Gavin Sulewski

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Award and Grant Recipients for 2022

African Plant Nutrition Scholarships

Recipients of the 2022 African Plant Nutrition Scholar Award included ten students selected from advanced science programs focused on plant nutrition and the management of nutrients applied to crops in Africa. Each student received $2,000 (U.S. Dollars).

This initiative strives to encourage the brightest minds to focus on the critical target of continued advancement of the science of crop nutrition in Africa.

CAMEROON

Ms. Kah Kyria Ngiah-Sah, Doctorate Program, University for Development Studies, Tamale, Ghana

Area of Study: Effect of different levels of fertigation on yield and quality of vegetables in protected copping in the drylands of Cameroon.

Ms. Ngiah-Sah's work is focused on developing strategies to better manage the production of high yield and superior quality vegetable crops with improved water and nutrient use efficiency through micro and macronutrient application regimes. She is studying irrigation and drainage engineering at one of the African Centers for Excellence, the West African Center for Water, Irrigation and Sustainable Agriculture (WACWISA), established by the University for Development Studies. Her research will be conducted in gutter-connected greenhouses located in three different agro-ecological zones of Cameroon.

Ms. Chantal Atut TIKU, Doctorate Program, School of Engineering and Department of Agricultural Engineering, University for Development Studies, Tamale, Ghana

Area of Study: Effect of soil moisture and potassium inputs on yam planting material for seed yam production in Tolon district of Ghana.

Ms. Tiku's study seeks to address the nutrition-related problems in high quality seed yam production by assessing the efficiency of nutrient acquisition from organic and inorganic nutrient sources at different levels of potassium (K) content, and the effect on seed yam tuber yield, seed quality, and soil. Results will identify the yam variety most suitable for the uptake and efficient usage of K and the fertilizer recommendation that both maximizes yields and restores soil nutrients. The findings of this research will enhance the production of quality seed yam in their required quantities throughout the yam belt of west Africa and beyond.

ETHIOPIA

Mr. Bira Cheneke FEYISSA, M.Sc. Program, College of Agriculture and Environmental Sciences, Haramaya University, Dire Dawa, Ethiopia

Area of Study: Effect of Parkland Ziziphus spina-christi L. and Mangifera indica L. on selected physicochemical properties of soil and sorghum yield in Sofi District, Harari Region, Ethiopia.

Mr. Feyissa's research is intended to investigate the effects of parkland M. *indica* and Z. *spina-christi* trees on the selected physicochemical properties of soil and yield of sorghum within and outside the canopy of the tree and at varying soil depths in the region. The results will be useful to farmers and other stakeholders to give insight into the effects of parkland trees on soil fertility and sorghum yield in their farmlands. The information can also help in designing sustainable land use that could enhance the productivity of crops while maintaining and improving the resource base.

GHANA

Mr. Emmanuel HANYABUI, Doctorate Program, Department of Soil Science, University of Cape Coast, Cape Coast, Ghana

Area of Study: Yield, nutritional quality of pineapple and soil ecosystems delivery in low nutrient soil amended with inorganic and organic fertilizers.

The objective of Emmanuel's research is to use innovative precision agriculture tools to determine the effect of tailored or site-specific fertilizer applications, especially phosphorus (P), to improve pineapple yield and nutritional quality. This project will help predict variable inorganic NPK fertilizer application rates for profitable and ecologically sensible pineapple production. It is expected that the implementation of site-specific fertilizer application will increase pineapple yield, nutritional quality, and farmers' incomes.

KENYA

Ms. Sylvia Imbuhila BULETI, Doctorate Program, Jomo Kenyatta University of Agriculture and Technology, Juja, Kenya

Area of Study: Sustainable intensification of smallholder farming systems using push-pull as a template.

Ms. Buleti's study aims to identify opportunities for further intensification of push-pull technology in western Kenya, and to determine the effectiveness of select sustainable intensification practice on soil fertility, pest and weed management and crop productivity. Further intensification targets to diversify income and diets to enhance food security and improve farmers' livelihoods. Additionally, it will contribute to smallholder policy development for the achievement of sustainable development goals such as zero hunger.

MOROCCO

Ms. Mbarka OUTBAKAT, Doctorate Program, Agricultural Innovation and Technology Transfer Center (AITTC), Mohammed VI Polytechnic University (UM6P), Benguérir, Morocco

Area of Study: Valorization of phosphogypsum in agriculture as an amendment and a fertilizer.

Ms. Outbakat's research has installed pot trials at the UM6P experimental farm in Benguérir to evaluate the effect of Phosphogypsum (PG) on crops and soils affected by salinity and to investigate the safety of its application based on heavy metals and radioactive elements contents in the water-soil-plant system.

A field trial has also been installed at the UM6P experimental farm to evaluate the effect of PG as a low-cost fertilizer source.

NIGERIA

Mr. Yahaya Mohammad YUSUF, M.Sc. Program, Mohammed VI Polytechnic University (UM6P), Benguérir, Morocco

Area of Study: A comparison of soil phosphorus extraction methods for soil test-based P fertilizer recommendation for tomato production in Kano State, Nigeria.

Yahaya's objective is to evaluate different phosphorus (P) extraction methods for sustainable and economic use of P fertilizers and to develop a critical P concentration for fertilizer recommendation models for tomato production. His study will present the most effective method of estimating soil available P from which a mathematical model for integrating soil test P, P critical level, and P requirement factor for P fertilizer recommendation will be developed for increasing tomato production in Nigeria.

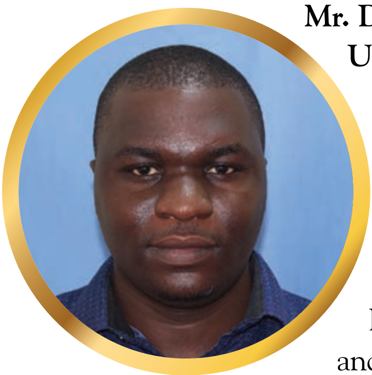
TANZANIA

Mr. Damiano Raphael KWASLEMA, M.Sc. Program, Sokoine University of Agriculture, Morogoro, Tanzania

Area of Study: Influence of organic carbon and nitrogen sources on bacterial ability to solubilize rock phosphate and enhance plant growth in acidic and calcareous soils.

Damiano is working to isolate and characterize phosphorus (P)-solubilizing microorganisms (PSMs) from acidic and calcareous soils of Tanzania, examine the influence of the local organic carbon sources and fertilizer-grade nitrogen sources for enhancing Minjingu Rock Phosphate solubilization by PSMs, and evaluate the ability of PSM-Rock phosphate formulation to enhance P availability and maize yields on these acidic and calcareous soils. This study addresses the current knowledge gap for the potential of PSMs and phosphatic biofertilizers sourced from local P reserves and organic wastes.

TANZANIA



Mr. Daniel Anyigulile MWAIKAMBO, M.Sc. Program, Applied Botany, University of Dar es Salam, Tanzania.

Area of Study: Assessment of the effects of soil physicochemical characteristics on fruit nutritional quality of local avocado germplasm grown in the Mbozi district.

Mr. Mwaikambo's study covers two objectives. First, to profile the nutritional quality of the local avocado fruits grown in the Mbozi district; the second is to assess the influence of soil physicochemical properties [soil texture, pH, CEC, EC, organic carbon, total nitrogen, available phosphorus, calcium, magnesium, and potassium] on the nutritional quality of local avocado fruits.

ZIMBABWE

Ms. Rumbidzai W. NYAWASHA, Doctorate Program, Department of Plant Production Sciences and Technologies, University of Zimbabwe, Mt Pleasant, Harare, Zimbabwe

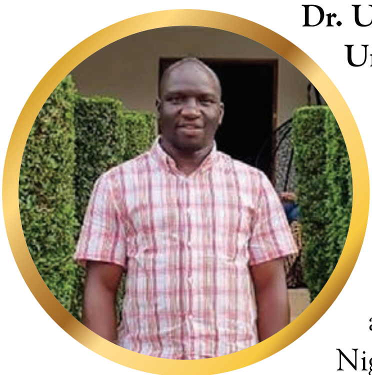
Area of Study: Soil organic carbon sequestration across scales in a subhumid region of Zimbabwe.

Ms. Nyawasha's main objective is to understand the biophysical and socio-economic drivers of soil organic carbon (SOC) sequestration at three smallholder farming scales (plot, farm, and village) in Murewa district, Zimbabwe. Building on previous research that has shown the important role resource endowment plays in influencing decision making on resource use and nutrient dynamics at plot and farm level; this study will use land use and land management information from local farmers to understand how long-term changes in land use patterns and management affect SOC content in the area.

Young African Phosphorus Fellowships

The Young African Phosphorus Fellowship supports early career researchers working within scientific programs contributing to our understanding and improved phosphorus management in African agro ecosystems. Each recipient receives $5,000 (U.S. dollars).

NIGERIA



Dr. Uchechukwu Paschal Chukwudi, Lecturer, Department of Crop Science, University of Nigeria

Area of Study: Judicious Phosphorus Management: Assessment of rice farmers' knowledge and best practices

Closing the P and other nutrient cycles is a critical issue that must be addressed both locally and worldwide in order to improve P usage efficiency, fulfill stricter water quality and nutrient criteria, and produce affordable food in sustainable agricultural systems. As studies point to the need for increased fertilizer use in Nigeria for bumper yield, there is a need to raise awareness among Nigeria's smallholder rice farmers, who account for 80% of the country's rice production, about the benefits of using P fertilizer judiciously to produce a high yield without endangering the environment. The broad objective of this study is to assess rice farmers' knowledge, perception, and use of phosphorus (P) fertilization in the derived Guinea Savannah agro-ecological zone of Nigeria.

ZIMBABWE

Mr. Tonny Phirilani Tauro, Lecturer (Soil Microbiology), Marondera University of Agricultural Sciences and Technology, Marondera, Zimbabwe

Area of Study: Rethinking P fertilizer recommendations for crop intensification in Zimbabwe: Mechanisms of unlocking microbial P immobilization

The study will focus on ways to unlock immobilized P in microbial biomass which is competing with crop. Increasing the application of inorganic P fertilizer is likely to offset microbial immobilization when other nutrients, particularly nitrogen (N), are adequately supplied. The synergic relationship between P and N indicates that an offsetting response is likely when N, potassium, sulphur, and carbon are non-limiting. Microbial immobilization and release will proceed while the highly reactive phosphate anions react with aluminum, iron, and clay materials. As such there is need to understand the actual pathway ultimately making P more available. The main objective of the study is to assess the impact of increasing P rates on soil available P, soil microbial dynamics, cereal yields and use efficiencies.

African Plant Nutrition Outreach Fellowships

The Outreach Fellowship support education, training, and communication programs relevant to improving the use and efficiency of plant nutrients in African agro ecosystems. Each year, awards of USD $5,000 each are available to innovative scientists, extension specialists, or educators working in Africa.

TANZANIA

Mr. George Mbyazita Karwani, Agricultural Research Officer, Tanzania Agricultural Research Institute (TARI), Selian, Arusha Tanzania

Area of Study: Establishing and Scaling-Up Site-Specific Nutrient Management Recommendations Using the *Nutrient Expert* Tool on Maize Smallholder Farming Systems in the Northern Zone of Tanzania

This study plans to establish and upscale site-specific nutrient management (SSNM) recommendations for maize smallholder farming systems as a suitable technological package for the Northern Zone of Tanzania. Demonstration trials will be established to verify the performance of SSNM recommendations derived from the *Nutrient Expert* (NE) tool. Further outreach will familiarize NE recommendations amongst smallholder maize farmers and extension officers as an alternative to blanket fertilizer recommendations. The study's participatory approach for the farmer managed trials, will involve farmers throughout the planning and implementation process, which will help to ensure high adoption of the technology within the targeted districts.

KENYA

Dr. Ruth Njoroge, Lecturer, Department of Soil Science, School of Agriculture and Biotechnology, University of Eldoret, Eldoret, Kenya

Area of Study: Experiential Learning on Climate Smart Nutrient Management (ECLINUM) in Uasin Gishu County, Kenya

This participatory project will implement on-farm trainings via a "Living Labs" approach involving farmer managed field plots demonstrating crop responses to appropriate fertilizer application and other integrated agronomic practices geared towards nutrient use efficiency. A qualitative soil fertility testing tool (QSFTT) is envisioned through transdisciplinary integration of science and indigenous knowledge. The simple decision support tool would provide farmers with a stepwise system of guidance to increase awareness on on-farm soil fertility status, provoke him/her to make the right decision regarding soil fertility maintenance, and increase motivation to seek expert guidance when needed.

African Plant Nutrition Research Fund

The aim of the African Plant Nutrition Research Fund (APNRF) is to enable scaling of improved nutrient and soil fertility management by synergistically extending research conducted in strategic priority areas of the African Plant Nutrition Institute. Each recipient has been granted up to US$20,000 per year for up to two years for relevant plant nutrition research work performed in Africa for the benefit of Africans.

Dr. Sibaway Mwango, National Coordinator Agricultural Natural Resources Management, TARI Mlingano, Tanga, Tanzania

Project: Guiding soil organic carbon sequestration potential under selected crop production systems in Tanzania

Organic carbon improves soil fertility, soil structure, soil moisture retention, soil pH, reduces soil acidity and soil health in general. Healthy soils are fundamental for sustainable and improved crop production and livelihood of farming communities. This project will study the contribution of various crop production systems to sequestered soil organic carbon for appropriate land resources management and minimized emission of greenhouse gases.

Dr. Nyambilila Amuri, Soil Scientist and Senior Lecturer, Sokoine University of Agriculture, Morogoro, Tanzania

Project: Fighting hidden hunger through micronutrient fertilization in maize and rice in Tanzania.

Previous research showed the potential of supplementation of zinc and iron in increasing rice yields and quality. This project seeks to streamline micronutrient fertilization to guide micronutrient fertilizer formulations, increase agricultural productivity, and alleviate hidden hunger in line with APNRF theme of enhancing soil health for improved livelihoods.

Dr. Mouna Mechri, Chief Engineer, National Institute of Field Crops (INGC), Bousalem, Tunisia

Project: In-season nitrogen management for wheat in Tunisia using proximal and remote sensing.

The project's goal is to develop satellite image-based models for nitrogen (N) uptake in wheat in Tunisia, which shall be used as the basis for a decision support system for optimizing N recommendations to wheat farmers. This development will be possible through upscaling of calibration models developed from data collected by proximal sensing of wheat field trial plots. The project will encompass both relatively low-cost proximal sensing as well as satellite remote sensing, and development of a workflow of model transfer from field measurements to satellite data. It is envisioned that the working model will be useful also for future projects and other crops.

Our Scholarships and Fellowships are made possible through APNI's partnership with Mohammed VI Polytechnic University (UM6P) and OCP Group (OCP S.A.). Funding for the African Plant Nutrition Research Fund is also made possible through APNI's partnership with the Mohammed VI Polytechnic University (UM6P).

Learn more about our Award and Fellowship programs at https://apni.net/awards. More information about the African Plant Nutrition Research Fund is available at https://apni.net/research-fund

Award and Grant Deadlines – 2023

AFRICAN PLANT NUTRITION SCHOLAR AWARD

The **African Plant Nutrition Scholar Award** was established to encourage development and success within graduate student programs specializing in the sciences of plant nutrition and management of crop nutrients in Africa. Students in the disciplines of soil science, agronomy, and horticultural science or tree crop science with a focus on plant nutrition are encouraged to apply.

Funding: Awards of USD $2,000 are available to ten graduate students.

Eligibility: Candidates must be currently enrolled in a M.Sc., M.Phil., or Ph.D. program as of the application deadline.

- **Call for Applications:** March 2023 • **Application deadline:** April 30, 2023
- Learn more at: www.apni.net/scholar-apply

AFRICAN PLANT NUTRITION RESEARCH FUND

Created through partnership between APNI and Mohammed VI Polytechnic University (UM6P), the **African Plant Nutrition Research Fund** is aimed at enabling the scaling of improved nutrient and soil fertility management in Africa. The fund also seeks to extend research initiatives that have synergy with the priority research areas of APNI.

Funding: Grant funding of no more than $20,000 USD per year, for up to two years, is available.

Eligibility: The lead applicant (Principal Investigator) must be from an African National Agricultural Research and Extension System (NARES) institution or African university. Students are not eligible for this award.

- **Call for Applications:** March 2023 • **Application deadline:** April 30, 2023
- Learn more at: www.apni.net/research-fund

YOUNG AFRICAN PHOSPHORUS AWARD

The **Young African Phosphorus Fellowship Award** was implemented to encourage the development of scientific programs relevant to understanding and improving phosphorus management in African agro-ecosystems.

Funding: Awards of USD $5,000 are available for up to five early-career scientists.

Eligibility: Full time scientists working at an African NARES institution or university, who are 45 years-old or younger at the closing date for applications, and who have completed their Ph.D. programs.

- **Call for Applications:** May 2023 • **Application deadline:** June 30, 2023
- Learn more at: www.apni.net/p-fellowship-apply

AFRICAN PLANT NUTRITION OUTREACH FELLOWSHIP

The **African Plant Nutrition Outreach Fellowship Award** was established to support researchers exploring innovative ideas for education, training and communication programs relevant to improving the use and efficiency of plant nutrients in African agro-ecosystems.

Funding: Awards of USD $5,000 are available to two recipients.

Eligibility: Scientists, extension specialists or educators working at an African NARES institution, African university, nonprofit organization, or in the private sector. Students are not eligible for this award.

- **Call for Applications:** July 2023 • **Application deadline:** August 31, 2023
- Learn more at: www.apni.net/outreach-fellowship-apply

Ask An APNI Expert

Question: How can I develop a model for precision agriculture?

Submitted by Tolera Goshu, Addis Ababa, Ethiopia

To answer this question, we need to first define "precision agriculture". Precision agriculture (PA) according to the International Society of Precision Agriculture is ***"A management strategy that takes account of temporal and spatial variability to improve sustainability of agricultural production."*** Notice that the word "technology" does not appear in the definition. Many people assume that PA is going to involve technology – sensors, satellites, computers, etc., but according to the definition, PA is about variability – how to measure it and how to manage it. Technology gives us tools to do this but developing a model for PA doesn't depend on it.

Crop performance can vary greatly across a landscape due to natural changes in soil properties plus the influence of field management history.

Now, let's talk about variability. Temporal variability refers to weather driven variation in crop performance. We all agree that production, particularly in rain-fed agriculture, can vary considerably from one year to the next. So, a PA approach would never assume that yield potential and the inputs required to achieve that potential are the same each year. Spatial variability refers to changes in the field that affect crop performance. These can be naturally occurring changes such as soil type, texture, or slope, or they can be due to management such as lack of uniformity in input applications.

So, where do we start to develop a model for PA? Yield history is information that every farmer regardless of size will know. Yield monitors are used for this in mechanized agriculture, but a smallholder farming 1-ha knows which part of the field consistently yields better than others and which part always seems to have problems. A simple sketch of the field is a great place to start. The farmer outlines "zones" of the field where consistent yield differences are observed. The next step is to determine the factors causing these differences. Some factors can be observed by the farmer. Are there differences in soil texture that affect nutrient and water availability? Are there physical soil differences (rocky, hardpan, lack of topsoil) that affect crop growth? These areas can be managed for lower yield potential compared with other parts of the field. A common source of variability is heterogeneity in soil fertility, which cannot be seen and need to be assessed using soil sampling. The PA approach can begin by collecting separate samples from within the farmer-defined zones from the yield map. This will allow the farmer to have variable fertilizer recommendations to optimize yield within each of the zones – leading to more efficient production overall.

Dr Steve Phillips, Principal Scientist, APNI, Benguérir, Morocco

Submit your plant nutrition related questions via our website https://growingafrica.pub/ask-an-APNI-expert
Selected questions, along with answers from our Institute's experts, will be published in future issues.

Post-Harvest Assessments of On-Farm Maize Experimentation Provide Key Checkpoints for Farmers and Stakeholders

By Ivan S. Adolwa, Simon Cook, Thomas Oberthür, Steve Phillips, Thérèse Agneroh, and Kokou A. Amouzou

The completion of the most recent maize-growing seasons in northern Côte d'Ivoire and Kenya (western and eastern regions) provided a first opportunity for farmers to share assessments from participating within a new on-farm research initiative for sub-Saharan Africa called NUTCAT - meaning Nutrient-Catalyzed Agricultural Transformation.

The NUTCAT project

The NUTCAT project was initiated in 2021 as APNI's flagship project for co-design, co-development and delivery of relevant precision nutrient management (PNM) innovations for cereal-based cropping systems in Africa. The project's objectives include: 1) improvement of cereal system production using precision nutrient management (PNM), 2) evaluation of grain yield potential and spatial variation in smallholder agriculture using remote sensing, and 3) promotion of farmer-centric innovation and co-learning through **On-Farm Experimentation (OFE)**. Therefore, NUTCAT is uniquely poised to implement a change process anchored on scalable behavioral change that is supported by agronomic insights and validated by data.

The On-Farm Experimentation Process

The OFE process for the NUTCAT project follows several steps or activities (**Fig. 1**). It starts with engagement, whereby cooperating farmers and experimental sites are identified. Acquisition of agronomic (yield, biomass), spectral (Sentinel 2 data) and socio-economic data are all important parts of this step.

To acquire agronomic data the project uses a simple experimental design wherein smallholder farm-scale plots (2 ha or less) are divided into an Optimized treatment (OT) and a Farmer practice (FP) treatment. The OT is defined by a team of local cropping system experts [i.e., the Cereal Improvement Team (CIT)], as the combination of practices and inputs required to produce an attainable yield target specific to the agro-ecological zone (AEZ) within the country. The FP treatment mirrors the practices and inputs the farmer was planning to apply that season. To date, about 268 trial sites have been established in seven countries across Africa (**Fig. 2**).

Co-learning via post-harvest dialogue

Open engagement with farmers is, by design, a key plank of the OFE platform. It seeks a co-learning environment that encourages farmer participation in landscape-scale research

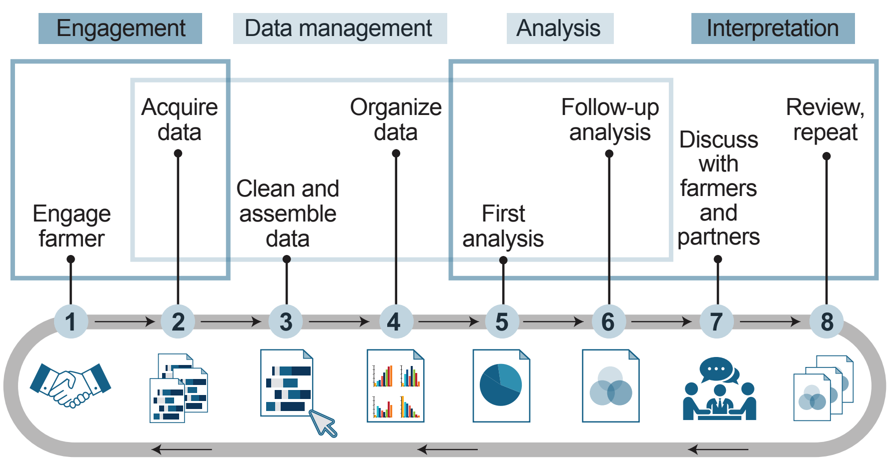


Figure 1. The OFE process for NUTCAT (adapted from Lacoste et al., 2021).

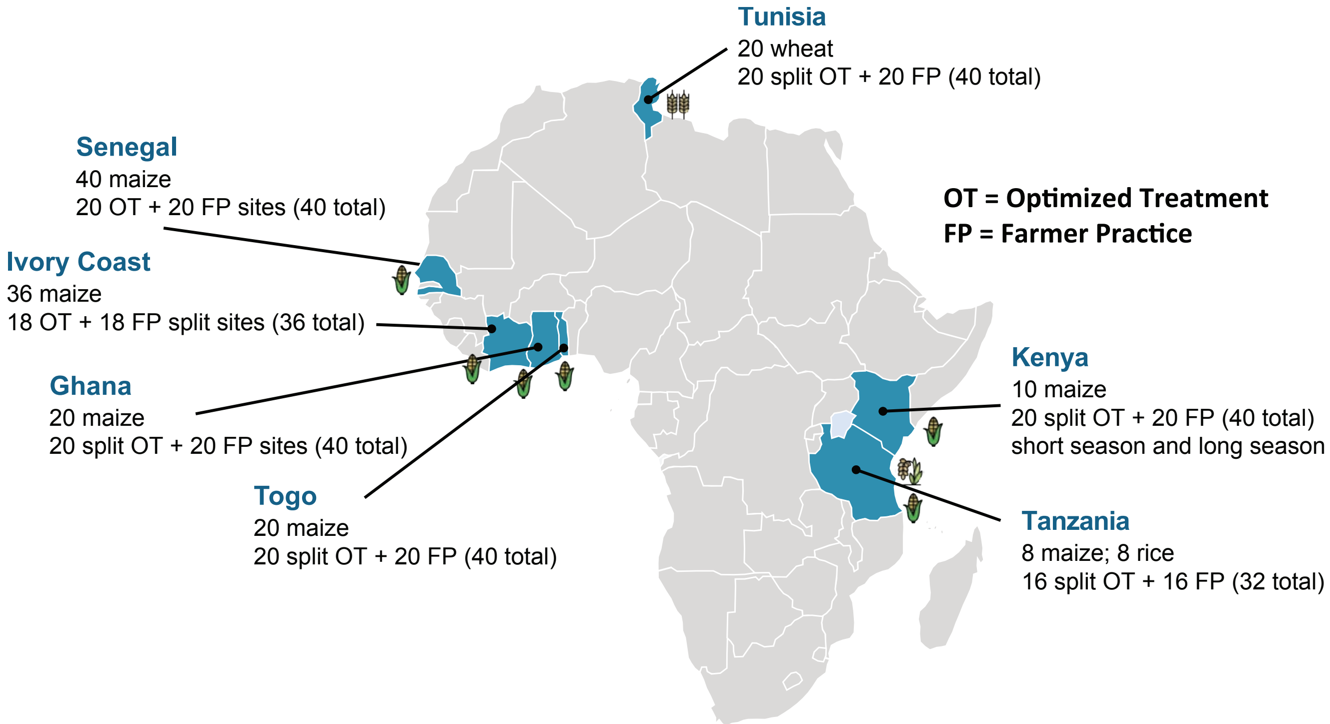


Figure 2. NUTCAT field site locations (268) during the 2021/2022 experimental season.

while providing a means to better understand the learning, decision-making and management change processes of farmers themselves. Such engagement is the goal of the **post-harvest dialogue (PHD) workshop**, which after the steps of data collection and analysis, provides a setting to share inferences made from the results achieved. The open discussion sheds light on what worked best in farmers' fields. Supporting technical and scientific advice is also sought from other project stakeholders including regional extension staff, agronomists, and APNI scientists. NUTCAT trial sites in northern Côte d'Ivoire and Kenya provide examples from contrasting biophysical, cropping and socio-cultural patterns. For instance, northern Côte d'Ivoire has a uni-modal rainfall pattern (one cropping season) representative of the cereal-root crop mixed farming system of West and Central Africa. Kenya's bimodal pattern (two cropping seasons per year) is typical of the maize mixed farming systems found in East, Central and Southern Africa. However, maize is the main cereal crop for both regions, and it is grown in association with legumes, root crops and cotton in intercrop, rotation or relay sequences.

PHD workshops for these regions gathered participating farmers as well as neighboring farmers who gained interest in the activities they observed throughout the season. Focus group discussions and in-depth interview approaches were supported by evidence drawn from agronomic and remote sensing data. Farmer engagement with extension specialists, agronomists and other agricultural stakeholders provided an opportunity to share observations and lessons learned, initiate plans for next season's plantings, and fine-tune the optimized treatment (OT) packages.

Innovation awareness and learning

The workshops uncovered a good level of awareness amongst NUTCAT farmers about cropping systems innovations such as planting in rows, recommended spacing, weed control, pest control, and fertilizer use according to the 4R Nutrient Stewardship framework.

Each workshop made it apparent that much peer-to-peer (social) learning is already taking place within the study areas. Non-NUTCAT farmers learned about good agronomic practices (GAP) from NUTCAT farmers and attained better yields after applying the acquired knowledge. There is also clear evidence of didactic learning

Post-harvest dialogue workshop in Korhogo, northern Côte d'Ivoire (top) and Siaya, western Kenya (bottom).

through NUTCAT and other projects where APNI has been an original source of GAP and 4R Nutrient Stewardship practices. Tracking how these two types of learning (social vs. didactic) are evolving is important. The PHDs provided a participatory platform to explore the role of data (digital and spatial) in accelerating such learning and making it scalable.

Management change

Dialogues helped unravel the different perspectives farmers have about variability within their fields (FP) and between fields (OT vs FP). They were also critical in deciphering some of the confounding issues arising from the data analysis including:

Why in some cases were yields so similar for the FP and OT?

As an example, Mr. Ouattara Adama, a farmer in Côte d'Ivoire, harvested three-fold the amount he usually gets on larger farm sizes from his 1 ha FP field after applying the full technological package he had observed in the adjacent OT field. This points to a move towards gradual agricultural intensification, which apart from being an effective risk-reduction strategy is highly relevant in the context of rising input costs (Bonilla-Cedrez et al. 2021; Hassen and El Bilali 2022).

Why did OT yields fail to meet the set targets?

Two cases were apparent in eastern Kenya where OT and FP yields were similar, most probably due to the combined use of inorganic and organic fertilizer. Under the conditions of an erratic rainfall regime during the short-rain season of 2021/2022, poor grain yield performance was avoided through the synergistic effects of combining mineral fertilizers and organic manures rather than reliance on mineral fertilizers alone (Mucheru-Muna et al. 2014; Mugwe et al. 2009). Given that the yield target of 7.5 t/ha was not met for the Kenyan OT treatments this was an important insight for the Kenyan CIT, which now proposes the additional application of manure at 5 t/ha in all OT plots.

Why was there very little divergence between FP and OT spectral data for the entire season?

Strong spectral signatures (NDVI, NIR, SWIR) were observed from both OT and FP fields, but there was little correlation between these signatures and yield. The confoundingly strong NDVI signatures of FP plots could have been due to weed pressure as the signatures do not distinguish between different plant species. Based on remotely-sensed imageries and their own observation, farmers recognized within-field variability of their fields, which according to them is driven by several factors. In Kenya, intercropping or mixed

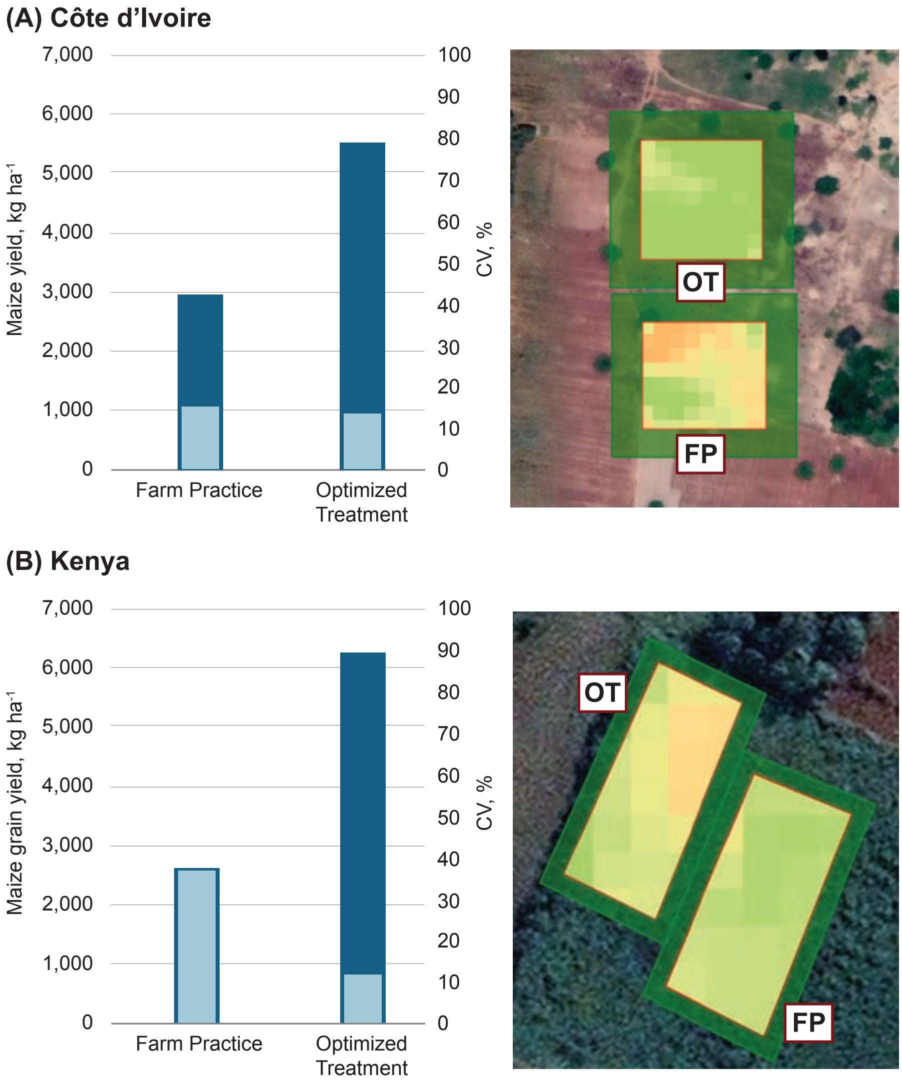


Figure 3. Agronomic and remotely-sensed results from one site in Côte d'Ivoire (A) and Kenya (B).

cropping, weed infestation (Striga), shading effects of trees, and type of germplasm used were mentioned as drivers of variability. For both countries, management aspects (e.g., manure application, herbicide use) and edaphic factors were critical.

All NUTCAT farmers expressed an intention to change their current practices in the coming season. This shift in attitude was based on the learning received from different channels and better yield performance of the OT. Most aim to adopt key elements of the 4Rs such as improved fertilizer placement and split application. Increased emphasis on recommended plant spacings, herbicide use, armyworm control, use of hybrid maize seed was noted. In Kenya, some farmers will employ practices that were not previously part of the OT package such as manure or compost application.

The next steps

Going forward, a critical step involves monitoring of how farmers implement change within their fields. In addition, a pattern of both peer-to-peer and didactic learning is emerging, which suggests the potential for enhanced social learning among farmers or farmer associations through the agency of the CIT. Therefore, the project has developed a management change and learning tracking tool, which is modelled on the Social Behavior Approach (SBA) adopted by the Catholic Relief Services (CRS, 2021). This tool is further fine-tuned using a Competency Model Approach to help us unravel learning through a skills competence assessment (CRS, 2021). Hence, the tool instils skills competency within a continuous learning and innovation cycle. This tool will be deployed to farmers at three to four key stages in the next cropping season. Similarly, a scouting protocol is in place to monitor weed and pest pressure, crop establishment, and other observations as a complement to existing data to help in explaining confounding issues.

The next steps in the OFE process entail the tracking and documentation of farmer learning and experimentation as they engage in the change process. This will be a basis for further interactions with relevant partners to capitalize the OFE process through identification of value, development of scalable business models that show how partners can invest, measuring outcomes (expected and unanticipated) and the sustained building of the process. ■

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Farmers, field technicians, and researchers conducting sites selection and initial soil sampling in northern Côte d'Ivoire.

Focus group discussion session in progress at Sindindi, Siaya in Kenya.

The use of drones helped provides insight into the performance of maize at targeted points in the growing season.

Farmers field day in Kenya reviewing the Optimized Treatment (right) and Farmer's Practice (left).

Focus group discussion session in progress at Kohrogo, northern Côte d'Ivoire.

Discussing the way forward.

Variability in Yield Response Strongly Affects Maize Productivity and Nutrient Requirements

Samuel Njoroge and Shamie Zingore

Smallholder maize productions systems in western Kenya exhibited wide spatial and temporal variability in yield responses to N, P and K application at the field level. Nutrient omission trials provide evidence of strong and ubiquitous N limitations and high vulnerability for rapid decline in P and K under continuous cropping without balanced nutrient applications.

Crop production in smallholder systems in sub-Saharan Africa (SSA) is strongly limited by poor soil fertility that results from continuous cropping with low nutrient applications (Kihara et al., 2015). Subsequently, crop yields in smallholder farming systems in SSA are far below potential yields (Van Ittersum et al., 2016). The yields of cereal crops in SSA can be readily raised (Mueller et al., 2012) when nutrient deficiencies are addressed (Adediran and Banjoko, 1995). However, profound variability of crop yield responses to nutrient applications across and within fields presents challenges for effective nutrient management.

There is limited information on how crop yield responses to nutrient applications vary over time, as most on-farm experiments are only conducted for a limited number of growing seasons. Such information is necessary to fine-tune site-specific fertilizer recommendations for improving crop productivity, fertilizer use efficiency, and profitability in the long-term. This is particularly important considering the ongoing fertilizer crisis which is severely limiting the ability of smallholder farmers in SSA to access and afford fertilizer inputs. This article outlines results from a series of on-farm nutrient omission trials conducted in the same experimental plots over six consecutive seasons to quantify variations in maize yield response to varied N, P and K applications over space and time.

Field trial description

The study was conducted within a 10 km x 10 km study site in Sidindi, western Kenya. Annual rainfall ranges between 1,600 to 2,000 mm and is distributed over two distinct seasons with a long rainy (LR) season from March to July, and a short rainy (SR) season from September to December. On-farm nutrient omission trials with maize were established in 24 sites representative of major soil units in the study area. The experiment included a set of five treatments including a control (no nutrients applied), P+K, N+K, N+P, and N+P+K

Maize growth and development in an on-farm nutrient omission trial site in western Kenya. The crop in the foreground is in an NP experimental plot (K omitted), while the crop in the background is in an NPK experimental plot. All plots were planted on the same date. S. Njoroge/APNI established in plots measuring 10 m x 10 m, with each farm serving as a complete block. Throughout the experimental period, short-season maize variety DK8031 was planted at the recommended spacing. Trial plot locations and allocated treatments remained the same throughout the study period.

Determination of yield and yield variation

At physiological maturity, all maize plants were harvested within a 2.25 m x 3 m net plot. Total cob weight and grain moisture content were determined, and grain yield calculated and expressed as 88% dry matter. The effect of treatment on grain yield was analyzed at a seasonal level using a generalized linear model, and differences in treatment means evaluated for significance using a Tukey HSD test in R software. Differences in yield variation between treatments were assessed by calculating coefficient of variation (CV) values for each treatment in each season. Scatter plots of CV values and seasons were then constructed, and regression lines fit for trend assessment. Relative yield (RY) was used as a measure of the yield responses to N, P and K and was determined as the ratio between nutrient limited yield and yield in the NPK plot (**Equation 1**). Relative yield values < 1 indicate a response to the applied nutrient, while values ≥ 1 indicate no response to the applied nutrient.

Eq. 1

$$RY_{i,j,s} = \frac{GY_{i,j,s}}{GY_{npk,j,s}}$$

Where:

$RY_{i,j,s}$ = Relative yield in treatment plot i at field j in season s

$GY_{i,j,s}$ = Grain yield in treatment plot i at field j in season s

$GY_{npk,j,s}$ = Grain yield in the NPK treatment plot at field j in season s

Effect of imbalanced and balanced nutrient applications on maize yields

Mean maize yields were consistently largest in the balanced NPK treatment, and smallest in the control treatment (**Table 1**). Yield losses resulting from nutrient omission were large and increased over time as indicated by yield differences between the NPK and control treatments of 2.7, 2.8, 3.4, 3.4, 3.5, and 4.2 t ha^{-1} in the six consecutive cropping seasons, respectively. Imbalanced nutrient applications also resulted in substantial yield losses with mean yields in the PK treatment being significantly smaller than with NPK in all seasons. While yields in the NK and NP treatments were not significantly different from NPK yields in the first season, significantly smaller yields were observed in the NK treatment in all five subsequent seasons, and in the third and last season for the NP treatment (**Table 1**). In the last season, sustained N, P and K omission resulted in mean yield losses of 3.9, 2.4 and 1.7 t ha^{-1}, respectively.

Imbalanced nutrient applications were characterized by larger variations in maize yield responses (**Fig. 1**). On average, variability was greatest in the control treatment followed by the NK treatment and was lowest in the NPK treatment. Variability remained constant for the NPK treatments but increased significantly ($P<0.05$) for the control and NP treatments.

Variations in yield response to N, P and K over space and time

Cumulative frequency plots of relative yields depict the spatial and temporal variations

Table 1. Mean maize grain yields in t ha^{-1} at 88% dry matter for on-farm (n=24) nutrient omission trials conducted over six consecutive seasons in Sidindi, western Kenya.

	Season‡					
Treatment	**LR 2013**	**SR 2013**	**LR 2014**	**SR 2014**	**LR 2015**	**SR 2015**
Control	2.8b	2.1c	2.2c	1.8c	2.2c	1.1c
PK (-N)	3.2b	2.8c	2.7c	2.6bc	2.6c	1.4c
NK (-P)	5.1a	3.7b	3.7b	3.3b	4.0b	2.9b
NP (-K)	5.1a	4.1ab	4.6b	4.4a	4.6ab	3.6b
NPK	5.5a	4.9a	5.6a	5.2a	5.7a	5.3a
HSD	**1.2**	**1.2**	**1.4**	**1.3**	**1.6**	**1.2**

Grain yield values in the same column followed by a different letter are significantly different at *P*<0.05.
‡ LR and SR refer to long and short rains seasons respectively.
HSD refers to the honest significant differences between means as per the Tukey test.

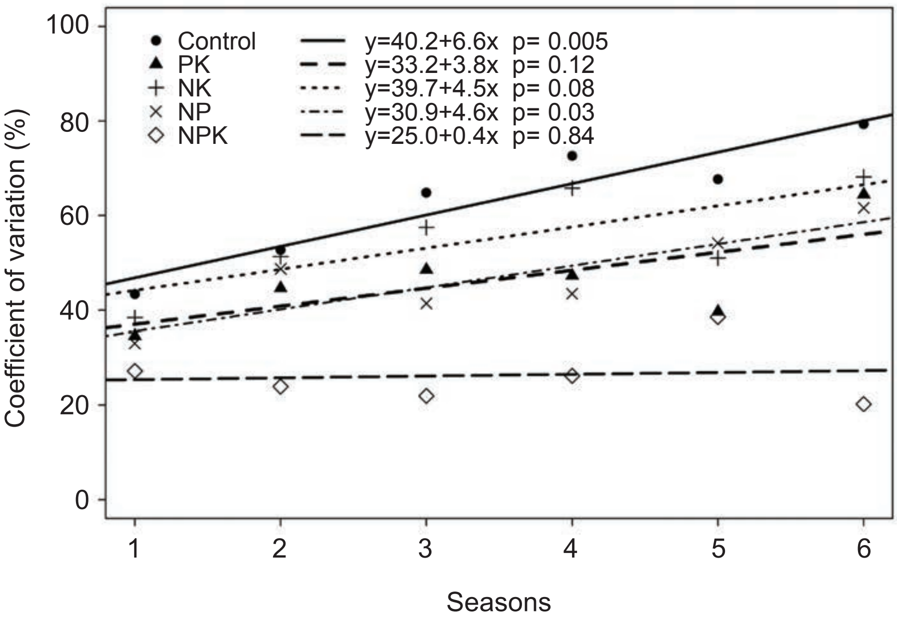

Figure 1. Scatter plots of coefficient of variation in treatment maize grain yield and seasons in nutrient omission trials conducted with a single complete replicate block per farm (n = 24) in Sidindi, western Kenya. Solid and dashed lines are fitted linear regression lines. Seasons 1-6 refer to LR 2013, SR 2013, LR 2014, SR 2014, LR 2015 and SR 2015, respectively.

in yield responses to N, P and K (**Fig. 2**). Responses to N, P and K differed between fields within a season (spatial variation) as did responses to a particular nutrient across seasons (temporal variation). The range of relative yield values for each cumulative frequency line indicates the variability in nutrient responses between fields, while a shift in of the cumulative frequency lines from one season to another indicates temporal variations in observed responses (**Fig. 2**).

In the first season, strong responses to N (RY_{PK} < 0.5) were observed in only 29% of fields. In the subsequent five seasons, the percentage of fields strongly responsive to N (RY_{PK} < 0.5) increased to 48, 57, 57, 61, and 96%, respectively. For P, only 4% of fields showed a strong response to P (RY_{NK} < 0.5) in the first season. In the subsequent five seasons, 22, 30, 35, 26, and 43% of fields were strongly responsive to P (RY_{NK} < 0.5), respectively. Lastly for K, the first season indicated that only 4% of fields where strongly responsive to K (RY_{PK} < 0.5), while in subsequent seasons this increased to 17, 13, 9, 13, and 30%. Although the proportion of fields responsive to P and K were smaller than those responsive to N, the effects of P and K omission in deficient fields were drastic, with yields losses of up to 80% relative to the NPK treatment in some of these farms, particularly from the second cropping season onwards (**Fig. 2b** and **2c**).

Findings from this study confirm the strong effects of soil fertility variability on maize productivity and nutrient requirements. Variability was largest in imbalanced treatments and least with balanced NPK applications, reflecting the potential of balanced fertilization in managing variability in crop yield responses in such smallholder farming systems. Cropping with no nutrient applications resulted in large and substantially increasing yield losses, while cropping with imbalanced nutrient applications also resulted in substantial yield losses.

Nitrogen was deficient on most farms, although the observed responses differed between farms in a season. However, these spatial differences in response to N decreased over time as illustrated by the narrower range of relative yields in the last seasons. Temporal differences in response to N were weak as illustrated by the minimal change in mean RY_{PK} over time, and by the minimal shift in the location and spread of the RY_{PK} cumulative frequency lines particularly in the first five cropping seasons.

Smaller spatial-temporal differences in response to N will limit the scope for improving nitrogen use efficiency (NUE) through targeted N application based on the spatial-temporal N response patterns. Yet N application is still critical across all farms in all seasons, and NUE can be improved by focusing on better timing and placement of fertilizer N to match crop requirements.

Large mean RY_{NK} yields indicated that maize yield response to applied P was not significant in the first season. This was likely due to residual effects of P applied in previous

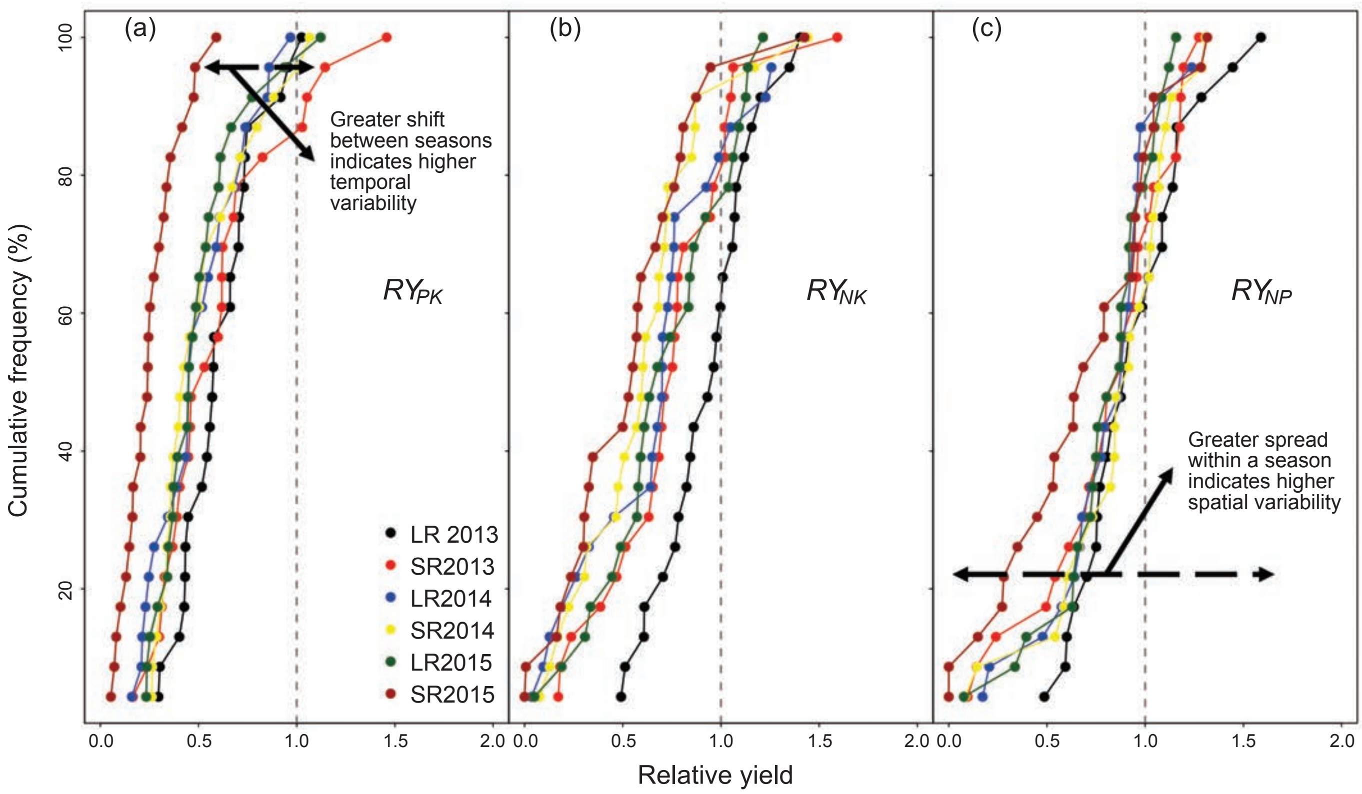

Figure 2. Cumulative frequency (%) of maize grain yield (t ha^{-1}): (a) Relative yield response to N (RY_{PK}); (b) Relative yield response to P (RY_{NK}); and (c) Relative yield response to K (RY_{NP}), across different on-farm nutrient omission trials locations (n=24), over six consecutive cropping seasons. LR and SR refer to short and long rainy seasons respectively.

seasons (Janssen et al., 1987; Kifuko et al., 2007). However, the large variability in RY_{NK} observed between farms in the first season, with about half of fields showing no response to P, indicates strong spatial variation. Differences in yield response to P can be linked to differences in the P fertility status of the soil, reflecting differences in historical field management (Vanlauwe et al., 2006). Omitting P for more than one season resulted in significant reductions in yield as indicated by the significantly smaller mean RY_{NK} values, and an increasing proportion of fields responsive to P. This indicates the need for regular application of P to sustain productivity.

Strong spatial-temporal patterns in response to K were also observed. Two out of 24 fields showed very strong response to K, while a decline in mean RY_{NP} was observed over time. The strong K deficiencies in a limited number of sites could be due to the presence of localized K deficiency hotspots (Kihara et al., 2016), and continuous removal of harvest products without application of K fertilizer (Chianu and Mairura, 2012; Zörb et al., 2014). Further, K deficiencies are expected to become more pronounced at higher N and P application rates. Fertilizer recommendations should therefore account for the need to supply K in combination with N and P, particularly in K deficiency hotspots (Kihara et al., 2016).

Given the prevailing fertilizer crisis that is limiting the ability of farmers to access and afford fertilizer applications required to attain and sustain high yields, findings from this study indicate that farmers in such smallholder settings will face yield losses of up to 50% if they drastically reduce fertilizer applications. Such yield reductions would substantially impact crop productivity, food security and farmer incomes.

Findings from this study however provide potential short-term nutrient management options that farmers can apply to mitigate severe yield losses. In low fertility soils, yield losses can be reduced by applying reduced quantities of balanced NPK applications as such soils are expected to be deficient in N, P and K. In moderate to high fertility soils that have had previous large applications of organic or inorganic fertilizers, severe yield losses can be mitigated by committing available resources to accessing and applying N fertilizers plus modest applications of P fertilizers, as such soils are expected to be mostly deficient in N. It should however be noted that these are short term (1 to 2 season) measures, and that balanced fertilization is required for long-term sustainability. ■

Summary

Strong spatial-temporal differences in maize yield responses to N, P and K were observed in smallholder farming systems in western Kenya. Fertilizer recommendations must account for such spatial and temporal differences for efficient and effective nutrient management. Improved fertilizer recommendations are critical for buffering the impact of the prevailing fertilizer crisis by improving crop productivity, nutrient use efficiency and farmer incomes, and reducing the risk associated with uncertainties in crop yield responses to fertilizer applications. Short-term measures involving reduced rates of balanced NPK applications in low fertility soils, and a focus on N and modest P application rates in moderate fertility soils can help mitigate against severe yield losses resulting from limitations in access to and affordability of fertilizer among smallholder farmers due to the on-going fertilizer crisis.

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Exploring Climate Smart Cropping System Solutions for Smallholder Farmers

By Austin T. Phiri, Sarah E. Edewor, Judith S. Kahamba, Ijeoma Nwoko, and Ulemu Chimimba

The effects of climate change are threatening the stability of smallholder farmers in Malawi. As such, most farmers are receptive to adaptive strategies such as increased adoption of drought-tolerant crops like sorghum. Here smallholders provide insight into the long-term impacts of climate change, and related field research examines nutrient management within a new grain legume-sorghum cropping system offering food security and climate resilience.

Climate change awareness is steadily increasing (Venghaus et al., 2022) and has become a major concern among most stakeholders. In Malawi, the effects of increased average global temperature that induce weather variability over years manifest as frequent droughts, floods, heat, cyclones and cold waves. Malawi's National Adaptations Programmes of Action (NAPA) report on Disaster Management for Malawi identifies Chikwawa, Nsanje, Balaka, Salima and Karonga districts as the most vulnerable districts to climate change effects (GoM, 2006).

In Malawi, sorghum is one of the major food crops for people living in the semi-arid regions of shire valley and lakeshore areas. Since the crop tolerates high temperatures and drought, sorghum can be a key adaptation strategy for the country. The bulk of sorghum production is done under rain-fed production where its productivity is very low. The average yield in Malawi is about 600 kg ha^{-1} against a yield potential of up to 3.5-6 t ha^{-1} for improved varieties available in the country (GAP, 2012). Improved varieties yield higher than local varieties like Thengalamanga, with documented grain yields of up to 2 t ha^{-1} (ICRISAT, 1995). Studies indicate that improved varieties like Pilira 1 are preferred by farmers for their early maturity, drought tolerance, white grain, and high grain yield (Nkolongo et al., 2008). Given sustainable agronomic practices, sorghum appears poised to enhance household food security among smallholder farmers and build resilience to climatic shocks and food shortages.

Climate change awareness

Table 1 presents the extent of climate variation experienced by 67 randomly selected farmers from the three targeted agro-ecological zones in Chikwawa, Salima, and Blantyre districts over the last 20-25 years. The majority of opinions tended to express either a substantial increase or decline for each indicator. In general, there is overwhelming evidence of climate variance. Very few of the respondents answered "remained the same" to the ten components of climate variation measured. When asked whether climate change has had a direct effect of their household, the majority (91%) of respondents indicated "yes".

A majority (69%) of respondents across the three districts believe average daily temperatures have increased substantially. Similarly, 58% experienced a substantial increase in the duration of dry seasons or prevalence of drought. About 49% of respondents perceived a substantial decline in average rainfall. Furthermore, 75% of the respondents reported a reduction in the length of the rainy season. A majority also perceived an increase in soil dryness during the dry season. Given the prevalence of rain-fed agriculture in Malawi, decreases in rainfall and rainy season duration significantly reduces farm productivity and increases household food shortages.

Across all regions, the largest group of respondents (41%) indicated that incidences of unusually high rainfall and thunderstorms has increased substantially. Frequency/intensity of storms and other wind-related hazards were perceived to have increased substantially by 46% of the respondents. Strong destructive winds (known as *Mphepoyankuntho*)

Table 1. Frequencies in the extent of climate variation experienced over the past 20-25 years (%).

Availably and/or service quality indicators	Community	Declined substantially	Declined slightly	Remained the same	Increased slightly	Increased substantially
Average daytime temperature	Chikwawa				16(4)	84(21)
	Salima				42(5)	58(7)
	Blantyre	5(1)			38(8)	57(12)
	Overall	**1(1)**			**29(17)**	**69(40)**
Length of dry season/prevalence of drought	Chikwawa				24(6)	76(19)
	Salima		15(2)	15(2)	38(5)	32(4)
	Blantyre	10(2)		5(1)	33(7)	52(11)
	Overall	**3(2)**	**3(2)**	**5(3)**	**31(18)**	**58(34)**
Average volume of rainfall	Chikwawa	60(15)	24(6)		4(1)	12(3)
	Salima	31(4)	46(6)		8(1)	15(2)
	Blantyre	48(10)	52(11)			
	Overall	**49(29)**	**39(23)**		**3(2)**	**8(5)**
Length of the rainy season	Chikwawa	76(19)	24(6)			
	Salima	38(5)	23(3)	31(4)	8(1)	
	Blantyre	95(20)	5(1)			
	Overall	**75 (44)**	**17(10)**	**7 (4)**	**2 (1)**	
Incidences of flood and river overflow beyond its bank	Chikwawa		28(7)	16(4)		56(14)
	Salima	46(6)			23(3)	31(4)
	Blantyre	44(4)	33(3)	22(2)		
	Overall	**21(10)**	**21 (10)**	**13 (6)**	**6 (3)**	**38 (18)**
Frequency and/or intensity of storms and other wind-related hazards	Chikwawa		9(2)	5(1)	5(1)	82(18
	Salima	8(1)	31(4)		31(4)	30(4)
	Blantyre	10(2)	5(1)	5(1)	67(14)	14(3)
	Overall	**5(3)**	**13(7)**	**4(2)**	**34(19)**	**45(25)**
Mphepoyankuntho (Strong destructive wind)	Chikwawa	4(1)		24(6)	16(4)	56(14)
	Salima	9(1)	18(2)		36(4)	36(4)
	Blantyre				76(16)	24(5)
	Overall	**4(2)**	**4 (2)**	**11 (6)**	**42 (24)**	**41 (23)**
Reliability with which rainfall supply/distribution could be predicted	Chikwawa	76(19)	8(2)			16(4)
	Salima	33(4)	17(2)	8(1)	33(4)	8(1)
	Blantyre	10(2)	52(11)		29(6)	9(2)
	Overall	**43(25)**	**26 (15)**	**2(1)**	**17 (10)**	**12(7)**
Dryness of the soil during the dry season	Chikwawa	8(2)	4(1)		28(7)	60(15)
	Salima			38(5)	31(4)	31(4)
	Blantyre	5(1)	10(2)		48(10)	38(8)
	Overall	**5(3)**	**5(3)**	**8(5)**	**36(21)**	**46(27)**
Incidences of unusually high rainfall & thunderstorm	Chikwawa	8(2)	4(1)		12(3)	76(19)
	Salima		8(1)	23(3)	38(5)	31(4)
	Blantyre	10(2)	33(7)	33(7)	19(4)	5(1)
	Overall	**7(4)**	**15(9)**	**17(10)**	**20 (12)**	**41 (24)**

Note: The figures in parentheses show the count data corresponding to the numbers.

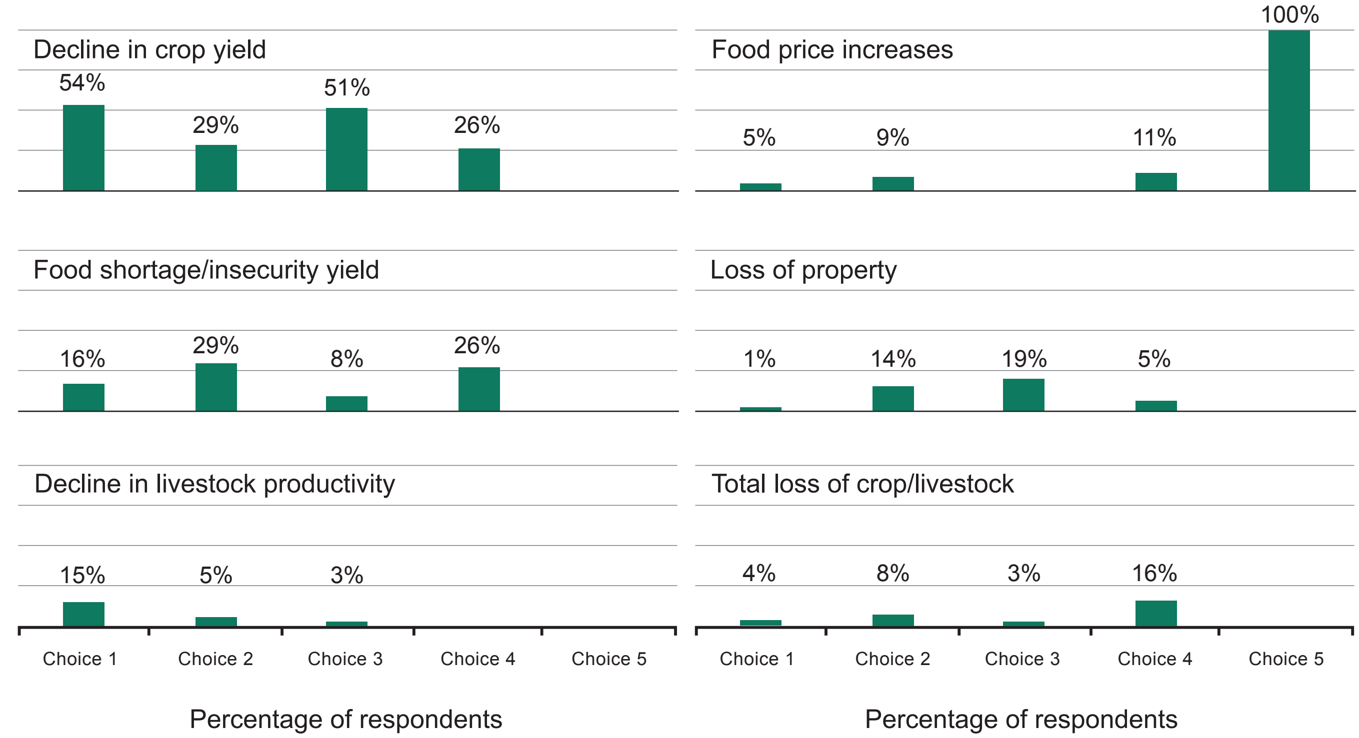

Figure 1. Respondent's top 5 ranking of most common effects of weather variation on smallholder households.

were indicated to have increased slightly to substantially by 83% of the respondents. Responses on rainfall predictability were skewed towards a substantial decline in reliability, which greatly contributes to an inability to adequately plan farm operations.

Effect of weather variation on households

Given a list of choices, respondents were also asked to rank the top five effects of weather variation affecting their households. Amongst the highest ranked effects were declines in crop yield, food security, and livestock productivity (**Fig. 1**). The impact on food price increases was not as highly ranked, but it was universally selected as a fifth most important effect. Loss of crops, livestock, or property were similarly ranked, and loss of property appeared as a significant risk.

Adaptation strategies

Respondents were also asked to state five adaptation measures used in response to their changing climate. The most popular adaptation actions included growing new crops, adopting drought-tolerant/resistant crops and consideration for new land management practices (**Fig. 2**). Household head migration to other rural areas in search of food and better lands on behalf of the other members was also a commonly listed strategy.

The surveys found a steady increase in the popularity for both maize and sorghum cropping over recent years (**Fig. 3**). It appears that growth in these two food crops has come at the expense of less extensive crops like cotton, bean, groundnut, pigeon pea, millet, and other niche crops like potatoes, cowpea, soybean and sesame.

Perhaps the current state of awareness and acceptance about the need to shift towards more resilient crops suggests an opportunity to expand the adoption of sorghum as a more drought tolerant alternative to maize? Focus group discussions in Chikwawa revealed that women consider the crop as a source of both food and economic security. However, farmers generally do not consider sorghum to require a high level of soil fertility management. So far, where they have access to fertilizer the tendency is to direct resources towards maize production.

Investigating the benefits of grain legumes

A multisite field trial is presently exploring adaptive strategies to rainfed grain production for the regions. The work hypothesizes that increased adoption of grain legumes within

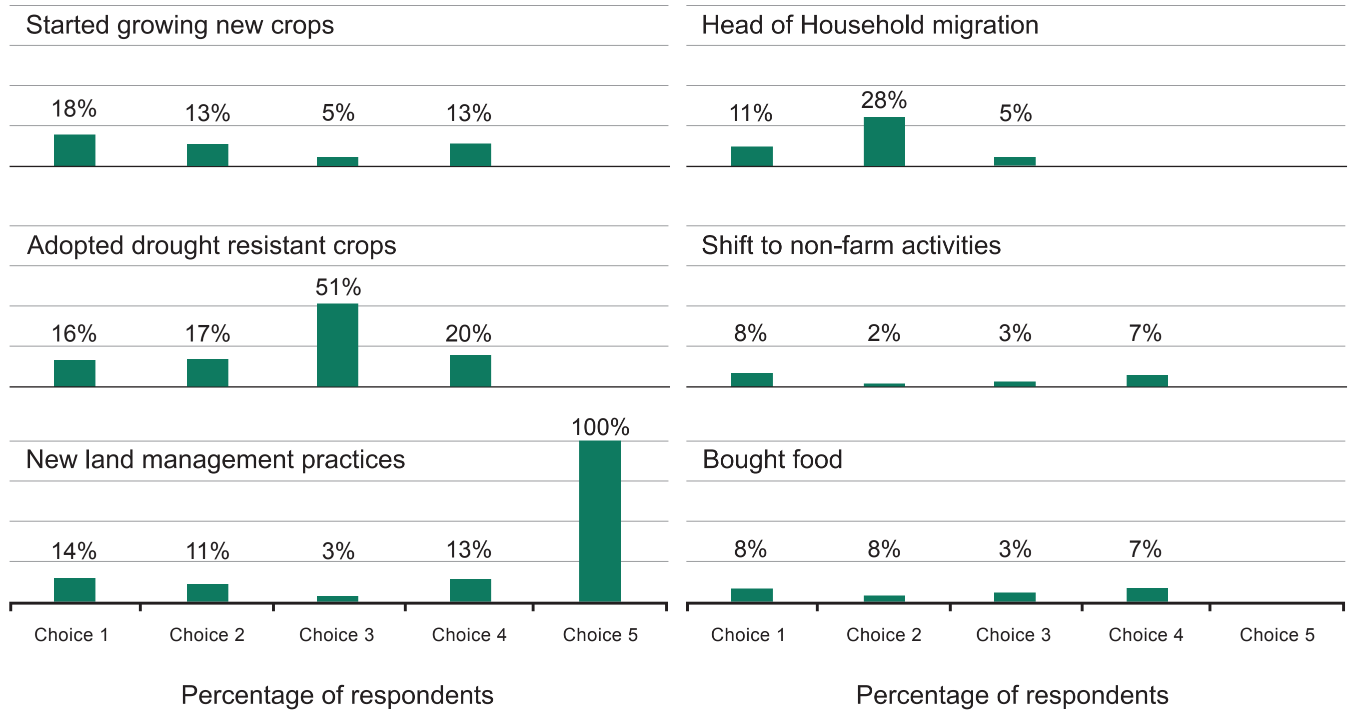

Figure 2. Participant's top 5 ranking of most common adaption strategies in response to a changing climate.

a drought-tolerant sorghum cropping system can not only generate a valued source of staple dietary protein, but it can also secure grain production through the residual benefits gained by increased access to nutrient-rich leguminous biomass.

The study's principal treatment is crop residue produced by pigeon pea-cowpea crops grown first in the rotation. This residue is recycled through a post-harvest plough down prior to growing sorghum in year two. The trials also include an assessment of different combinations of nitrogen (N) and phosphorus (P) fertilizer, and manure (data not included here), to begin to understand the impact of more balanced nutrient inputs to an otherwise under-fertilized crop.

Sorghum grain yields were collected from trials conducted between 2020 and 2021 at Chitala, Salima district and Kasinthula Agricultural Research Stations, Chikwawa district; and during 2021 and 2022 in Mikalango Extension Planning Area (EPA), Chikwawa district. **Figure 4** shows average sorghum grain yield response to different rates of N while P rate remained constant. Conversely, **Fig. 5** shows grain yield responses to different rates of P while N rate remained constant.

Of particular interest is the observation that where pigeon pea and cowpea were included in rotation with sorghum, lower N application at Mikalango EPA (23 kg N ha^{-1}) and zero N application at Chitala produced sorghum grain yields equivalent to those produced in the non-rotation system with 46 kg N ha^{-1} or more (**Fig. 4B**). This evidence suggests that farmers would be able to benefit from the N-rich legume biomass, which can offset the difference in N application and contribute to a moderated N supply that enhances nutrient uptake and use efficiency in the succeeding sorghum crop.

The plots with varying P rates but equal N input also showed site-specific responses. In the non-rotational systems the Chitala site appeared unresponsive to P, while appropriate rates were 10 kg P ha^{-1} at Kasinthula, and 40 kg P ha^{-1} at Mikalango EPA. In the rotational system, Chitala still showed little response to P, but appropriate rates appeared to be 10 kg P ha^{-1} at Mikalango EPA and 40 kg P ha^{-1} at Kasinthula. Phosphorus has relatively low mobility in the soil which may negate the benefit of increased application rates, but also sorghum is known to be particularly efficient at utilizing P (Bernardino et al., 2019), perhaps explaining the marginal to zero grain yield response to varied P application rates. More research is needed to fully understand the implications

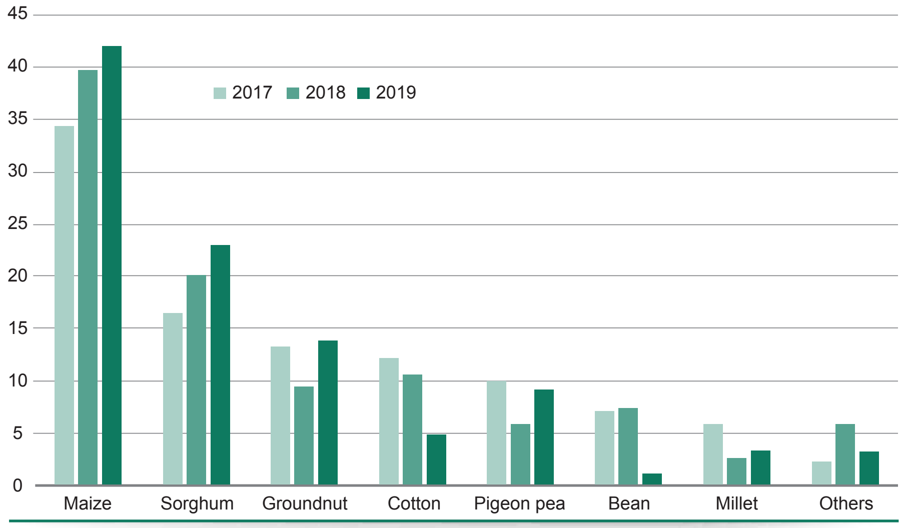

Figure 3. Proportion of crops grown within the study area during the 2017-2019 farming seasons.

of the inclusion of grain legume crops on the P balance of this novel cropping system.

Summary

Under a changing climate, drought is becoming common in Malawi, as is food shortages for Malawian households. This requires promotion and intensification of the production of drought tolerant crops like sorghum in order to enhance regional food security. Farmers, however, do not prioritize fertilizer use in sorghum. Where they have access to fertilizer, the priority crop is maize, a less drought tolerant crop. There is a need to increase awareness among farmers that like any other crop, sorghum requires more attention to soil fertility management.

A decline in the predictability of rainfall results in inability to plan for specific farm operations due to uncertainty. Future consideration is needed to develop the capacity among professionals to predict future rainfall patterns through modeling approaches. Modeled scenarios could eventually be used to develop extension messages for farmers that present most likely predictions and how they can prepare and plan their farm operations.

In general, planting new crops and adopting drought-

Sorghum productivity improvement trial in the 2020/2021 farming season at Chitala agricultural Research Station, Salima district, central Malawi.

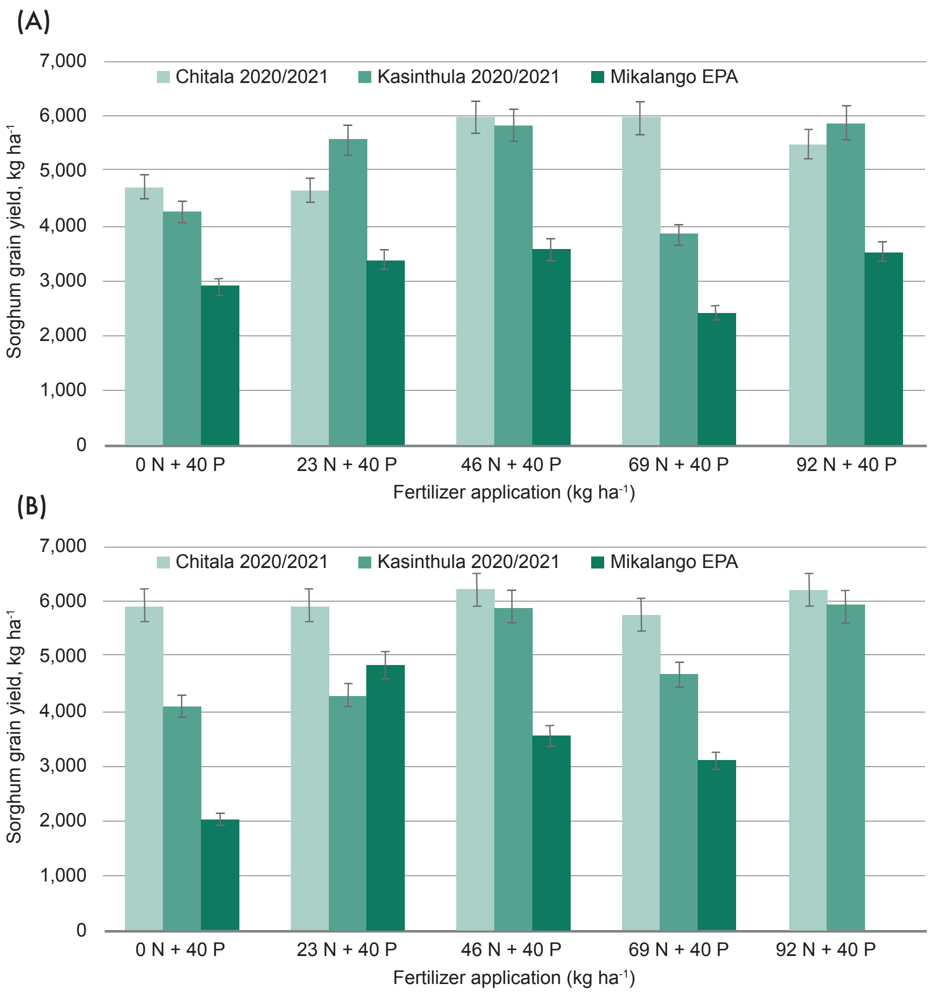

Figure 4. Sorghum grain yield response to nitrogen grown in a non-rotational system (A) and a grain legume-sorghum crop rotation (B). Note: The data from the 92 N + 40 P treatment at Mikalango EPA is not available.

tolerant crops is the most accepted adaptive action but the cost of implementation is high. Policy interventions are required to make seeds of new or drought tolerant crops readily available and affordable to the farmers. One potential strategy could be the establishment of community/village seed banks for these new crops.

The findings of the study have underscored the need for farmers to stop discounting the need for nutrient management in their sorghum crops. Mineral fertilizer alone or in combination with organic amendments coming from residual benefits of grain legume biomass in a rotation system, along with available manure sources, all combine to increase rain-fed sorghum productivity in Malawi. ■

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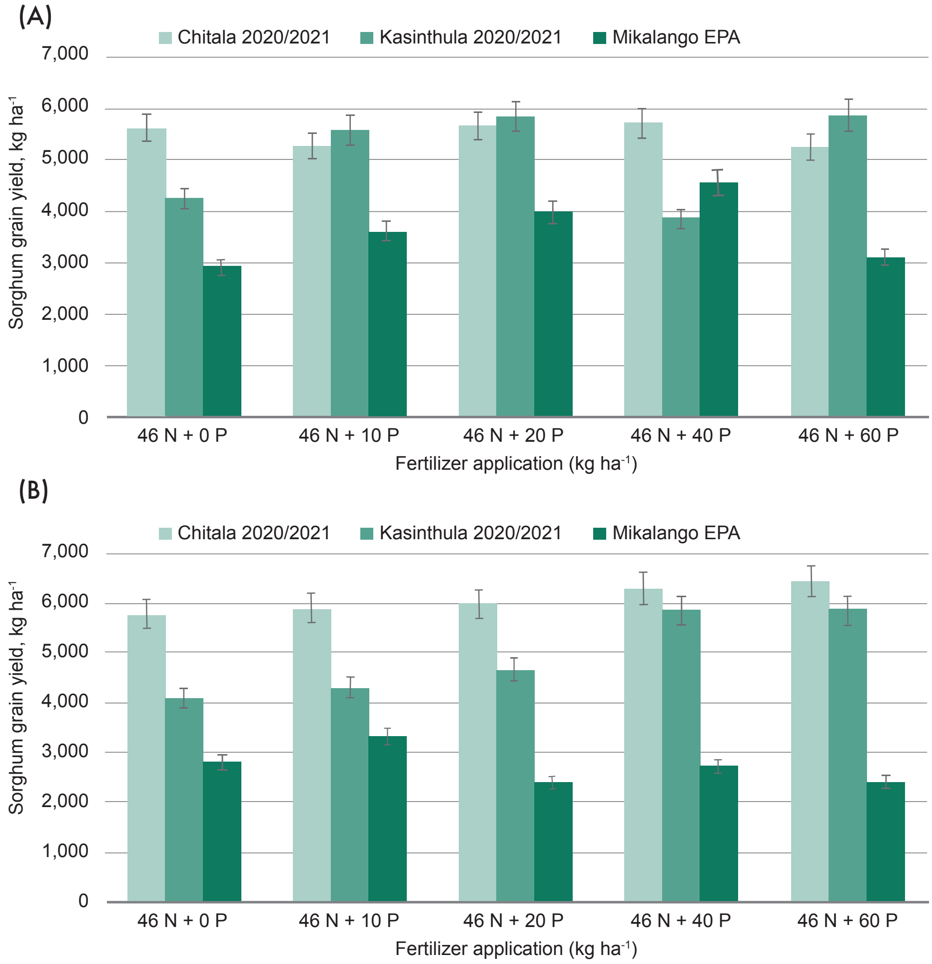

Figure 5. Sorghum grain yield response to phosphorus grown in a non-rotational system (A) and a grain legume-sorghum crop rotation (B).

Farmers and agricultural experts at a sorghum productivity improvement project field day in the 2020/2021 cropping season at Mponda village in Lunzu EPA, Blantyre District, Southern Malawi.

Grain Legumes Contribute Immediate and Residual-Effects in Rain-fed Maize Production Systems

By Esther Mugi-Ngenga and Shamie Zingore

Within-season effects of intercropping are receiving increasing attention. However, the rotational performance is rarely investigated across seasons, even though the two are complementary strategies providing spatial-temporal crop diversification.

Smallholder crop production systems in much of the East African highlands are dominated by maize (*Zea mays* L.) which is commonly intercropped with grain legumes, mainly pigeonpea (*Cajanus cajan* (L.) Millsp.), common bean (*Phaseolus vulgaris* L.), dolichos lablab (*Lablab purpureus* (L.) Sweet) and cowpea (*Vigna unguiculata* (L.) Walp) (Mugi-Ngenga et al., 2021). Beyond direct yield benefits, grain legumes can provide additional ecological benefits that may enhance the productivity of maize in the short and long-term. Within-season benefits of cereal-legume intercropping include greater ground cover and suppression of diseases and pests. Residual benefits that accrue in subsequent seasons include the supply of nitrogen (N) from N_2-fixation, improved soil health, weed (*Striga*) suppression and increased maize yields (Giller, 2001; Rusinamhodzi et al., 2012).

Productivity of intercrops depends on the balance between intra- and inter-specific competition. When the component crop species have complementary growth patterns (i.e., filling different **temporal niches** by utilizing different periods of the season, or **spatial niches** through different rooting depths or canopy sizes), inter-specific competition will tend to be weaker than intra-specific competition, and resources will be acquired more efficiently (Lithourgidis et al., 2011). This results in relatively greater yields in intercrops than in sole crops (Willey, 1979).

Within-season effects of intercropping are receiving increased attention, but the rotational performance is rarely investigated across seasons. Further, farmer management practices are critical factors that influence productivity of maize-grain legume intercrops, and a better understanding of their influence is particularly pertinent in northern Tanzania, due to the wide diversity of climatic conditions and soils. This article outlines a recent study aimed at evaluating the growth and development of maize-pigeonpea and maize-lablab intercropping systems and their interaction with fertilizer, and the assessment of their residual effects on the yields of a succeeding maize crop.

Field trial description

The study was conducted in Babati district, Northern Tanzania. Trials were conducted for three consecutive cropping seasons (2017/2018-2019/2020), on nine farms. Each farm acted as a replicate (one farm-one replicate design). In each of the selected farms, plots measuring 10 × 5 m were delineated at planting. Paths measuring 1 m wide were left in between plots. Test crops included maize Seed Co. 513 hybrid variety, dolichos lablab "Selian-Rongai" variety and pigeonpea long (ICEAP 00040) and medium-duration (ICEAP 00557) varieties. Sole maize, pigeonpea and lablab were planted at a spacing of 0.90 m × 0.50 m inter- and intra-row, respectively. Cereal legume intercrops followed an additive design, with legumes planted in the maize rows, in-between maize hills.

Three seeds were planted per hill for both maize and legumes, which were thinned to 2 seedlings post emergence to achieve the target planting density of approximately 44,444 plants ha^{-1} for each sole and intercrop. Pigeonpea were


Maize intercropped with pigeonpea (left) and lablab (right) grain legumes at on-farm trial, in Babati district, northern Tanzania.

planted simultaneously with maize, whilst lablab was relay-planted one month later.

Fertilizer was spot applied in planting holes at three levels: (i) no fertilizer, (ii) P fertilizer only and (iii) N+P fertilizer. Sole legumes did not receive the N+P fertilizer. The P fertilizer was applied at planting in the form of triple superphosphate (TSP) at the rate of 40 kg P ha^{-1} to both maize and legumes. The N fertilizer was spot-applied in the form of urea at the rate of 90 kg N ha^{-1} in three equal splits only on maize: one third at planting, one third at four weeks after planting, and one third at eight weeks after planting. The combination of cropping system (various sole and intercrops) and fertilizer (control, +P and +NP) were randomly assigned within each farm. Individual plots were maintained, and treatments (cropping systems and fertilizer) allocated to the same plots in the 2017/2018 and 2018/2019 seasons. Maize was harvested 3-4 months before the legumes.

To evaluate the residual benefits of the grain legumes on the yield of a succeeding maize crop, a third season (2019/2020) was included, where a sole maize crop was planted on all plots following a spacing similar to the sole crops of the previous seasons. No fertilizer was applied to the maize crop in the third season.

At physiological maturity of each crop, all plants within the net plot (9 m^2) were harvested. Maize cobs were manually separated from the stover and hand threshed. Legumes were also threshed manually to separate grains and haulms. After threshing, total fresh weight of maize and legume grains were separately taken in the field. Moisture content of the grains (%) was determined using a moisture meter, and grain yields corrected to 12.5% and 13% moisture content for maize and legumes, respectively.

Impacts of cropping system and fertilizer on maize and legume productivity

In most cases, maize growth was not affected by the presence of legumes as it produced similar grain yield in sole and intercrops for both seasons (**Fig. 1**). This is consistent with previous research on maize-pigeonpea systems showing insignificant effects of pigeonpea on maize (Rusinamhodzi et al., 2012). This is attributed to the fact that the growth duration of pigeonpea was 3-4 months longer than that of maize. Consequently, the greatest demand for water and nutrients in pigeonpea occurred after maize was harvested, following Dalal (1974), which is a form of temporal niche differentiation (TND). Relay-planting of lablab one month after maize planting allowed the maize crop to establish well before the closure of the lablab canopy.

Further, a significant main effect of fertilizer was found for maize grain in both seasons (**Fig. 1**). Addition of NP fertilizer significantly enhanced maize grain yield compared with the control and/or +P plots. In the 2017/2018 season, +NP plots produced more maize grain yield than +P (+0.8 t ha^{-1}) and control plots (+1.2 t ha^{-1}). In the 2018/2019 season, maize production in control plots was significantly less than +P (-0.7 t ha^{-1}) and +NP plots (-0.9 t ha^{-1}). The increase in maize yields in response to direct N fertilization indicates that although integration of legumes contributes N through atmospheric N_2-fixation, it clearly

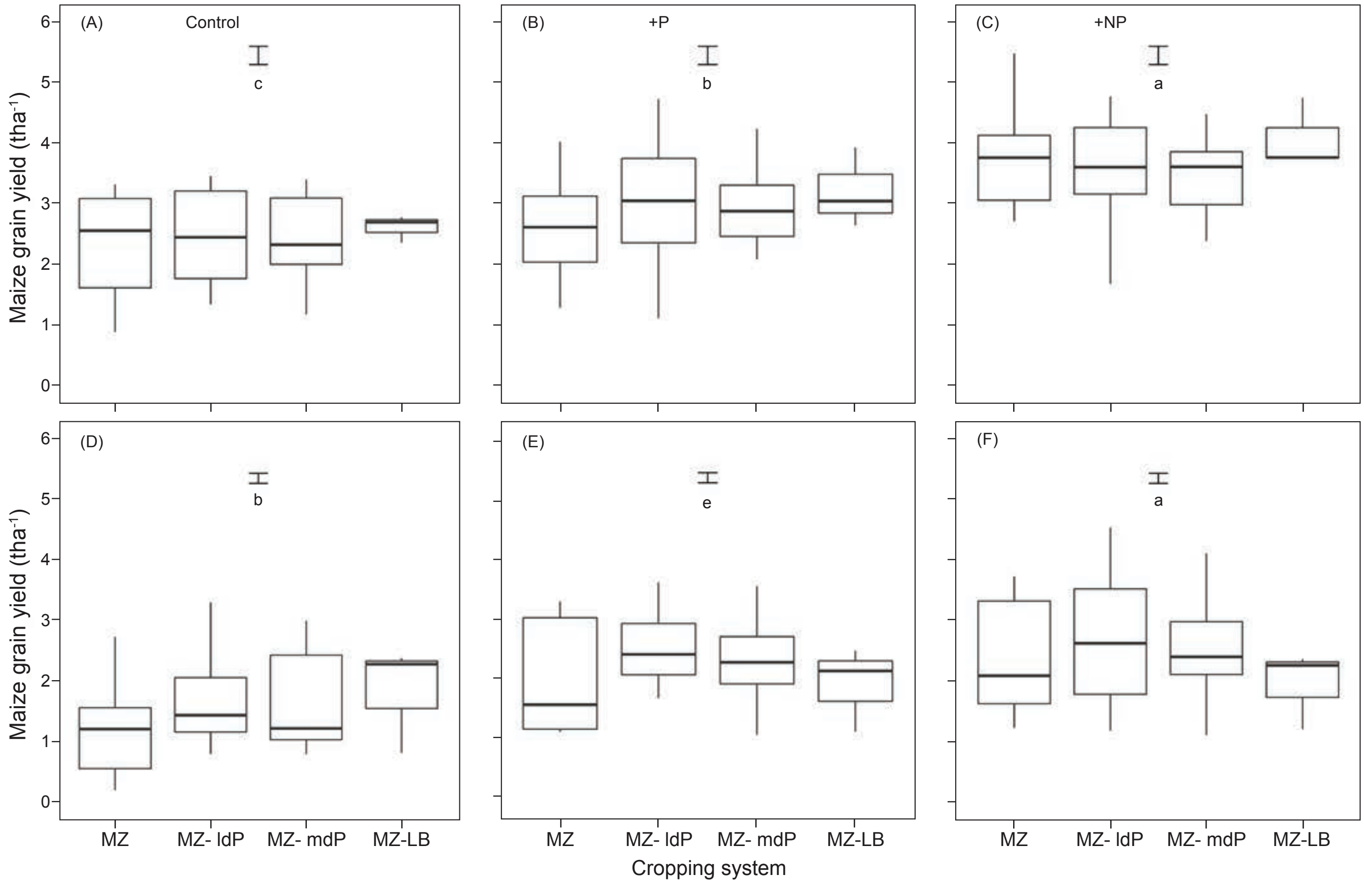

Figure 1A - F. Maize grain yield in various cropping systems as affected by fertilizer from on-farm trials during the 2017/2018 (A-C) and 2018/2019 (D-F) seasons in Babati, Northern Tanzania. MZ= maize; ldP= long-duration pigeonpea; mdP= medium-duration pigeonpea; LB= lablab. Error bars indicate the standard error of means. Mean differences of fertilizer treatments at 5% significance level in the various box plots are indicated with different small letters on the upper side of the box plot.

did not contribute enough to preclude the need for applying N fertilizer to maize (cf. Jeranyama et al., 2000; Giller, 2001).

Contrary to maize, which was hardly affected by presence of a legume, the productivity of legumes was affected by the presence of maize. Sole legumes produced significantly greater yield than in the corresponding intercrops (up to 0.6 t ha^{-1}) under almost all cases in the 2017/ 2018 season (**Fig. 2A**) and consistently in the 2018/ 2019 season (**Fig. 2B**). The smaller yields of legumes in intercrops than sole crops can partly be attributed to the reduced radiation reaching the lower part of the intercrop canopy occupied by the legumes before maize harvest. Indeed, legumes (e.g., lablab) have a high demand for light (Cook et al., 2005).

Further, significant fertilizer effects were observed in both seasons (**Fig. 2C-D**). Plots with +NP fertilizer produced significantly smaller legume grain yields (up to 0.4 t ha^{-1}) than +P plots. We attribute this to the increased maize growth with application of N fertilizer, resulting in stronger competition with the legumes. In relation to this, application of N fertilizer in cereal-legume intercrops has been reported to increase the competitiveness of cereals, very likely leading to a competitive imbalance and a failure of legumes in mixtures (Yu et al., 2016).

Residual effects of two seasons of legumes on productivity of a succeeding maize crop

In the third season of experimentation a significant main effect of cropping system was found for grain yield of the succeeding maize crop (**Fig. 3A**). Grain yield following two seasons of continuous maize was smallest and significantly less (0.8-1.9 t ha^{-1} less) than in all other systems (**Fig. 3A**). The greater grain yield in plots where a legume was included during the preceding seasons can be attributed to benefits associated with both residual N and non-N effects (Franke et al., 2018). Since we did not retain maize and legume stover in the field, we attribute any residual N effects to the decomposition of the legumes' roots, nodules, and fallen leaves (Ledgard and Giller, 1995).

Further, a significant main effect of fertilizer was found for grain yield of the succeeding maize crop. Plots that had no fertilizer applied (control plots) in the preceding seasons yielded significantly less grain yield in the succeeding maize crop than where fertilizer was applied (0.9 $t\ ha^{-1}$ less) **(Fig. 3B)**. In the control plots, the lack of fertilizer addition for three consecutive seasons could have led to soil nutrient depletion, thus reducing productivity of maize crop planted in the third season. No difference was observed between the +P and +NP fertilizer, indicating that there was no residual effect of N fertilizer from the previous seasons. ■

Summary

Maize-legume intercropping systems were superior to sole maize crops, not only for the additional grain yield from legumes, but also due to their residual effect which resulted in greater productivity of the succeeding maize crop. Significant residual benefits on maize grain yields were observed after two consecutive seasons of sole and intercropped legume crops. This implies that inclusion of legumes in maize-based cropping systems presents potential advantages especially under low input systems, and in the current environment of fertilizer shortages and high prices. Additionally, P-fertilizer applied in the previous seasons also showed strong residual

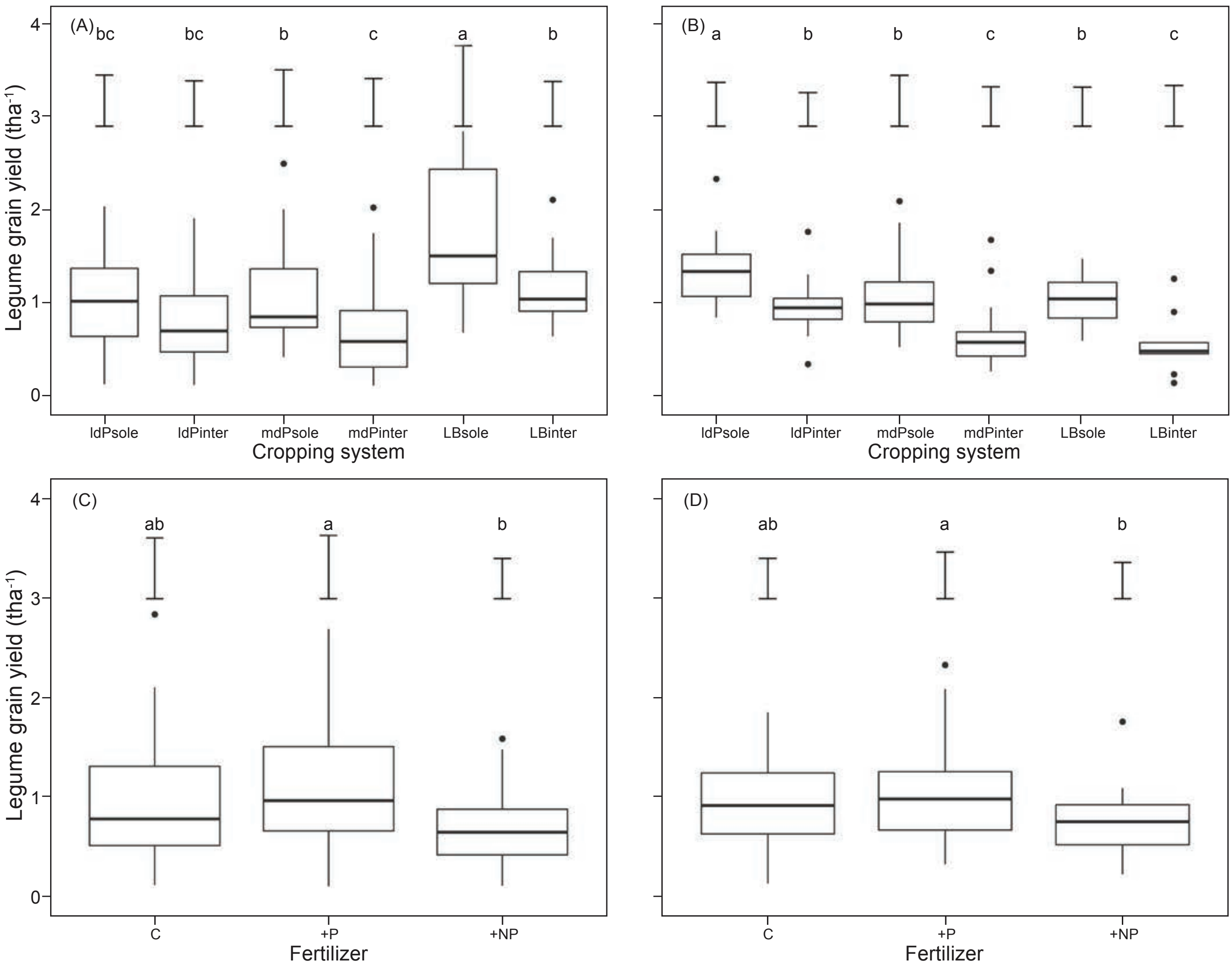

Figure 2A - D. Legume grain yields as affected by cropping system and fertilizer from on-farm trials during the 2017/2018 (A&C) and 2018/2019 (B&D) seasons in Babati, Northern Tanzania. ldP= long-duration pigeonpea; mdP= medium-duration pigeonpea; LB= lablab, inter= intercropped. Mean differences at 5% significance level in the various box plots are indicated with different small letters on the upper side. Error bars indicate the standard error of means.

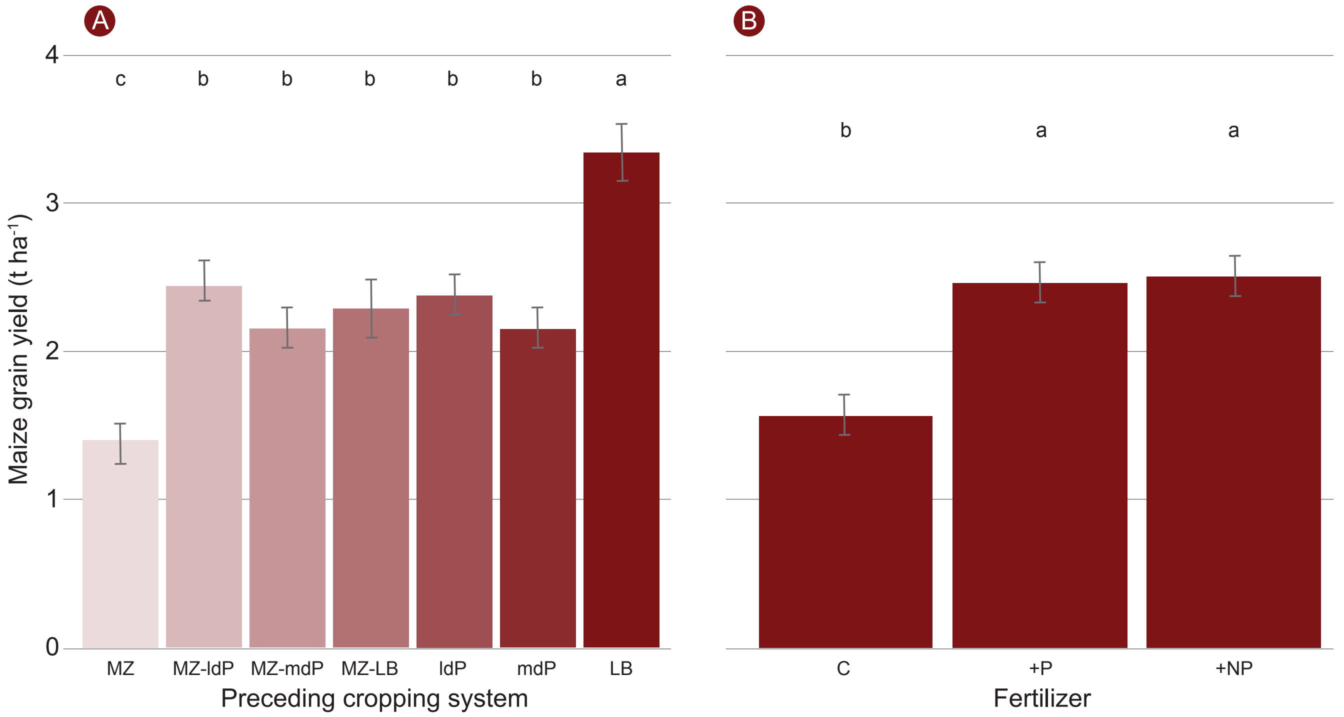

Figure 3. Grain yield of a succeeding maize crop as affected by preceding cropping system (A) and fertilizer (B) from on-farm trials during the 2019/ 2020 season in Babati, Northern Tanzania. MZ= maize; LB= lablab; ldP= long-duration pigeonpea; mdP= medium-duration pigeonpea. Mean differences at 5% significance level in the various box plots are indicated with different small letters on the upper side. Error bars indicate the standard error of means.

benefits. This is an indication that residual benefits of maize-legume intercropping are amplified by nutrient application. Assessment of the non-N effects of grain legumes to the associated or succeeding cereal crop, which was not covered in the current study, is highly recommended. Overall, our results confirm that when the component crop species in an intercrop have complementary growth patterns, temporal and spatial diversification provides a plausible pathway for ecological intensification of smallholders cropping systems.

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Building a Map of Bioavailable Phosphorus for African Soils

By Luis I. Prochnow and Artur Lupinetti-Cunha

Researchers have produced a comprehensive map of soil P bioavailability for Africa's commercial crops showing that almost the entirety of the continent's agricultural soils can be expected to have an economic response to the application of P fertilizer.

Phosphorus (P) is an essential nutrient for plant development and plant-based food production. Based on the amounts commonly needed per hectare, P is necessarily classified as a macronutrient along with nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S). The amount of P needed to achieve a high level of agricultural productivity is soil and crop specific. However, most of the world's agricultural soils are unable to supply adequate amounts of P to meet the needs of high yielding crops. The addition of P to soils is critical to produce the food, feed, fiber, and bioenergy the world requires.

In order to define the correct rate of P to apply, one must first evaluate the status of soil P bioavailability. This can be achieved by different techniques, soil chemical analysis being the most common, relying on years of agronomic studies of: 1) correlation, which defines the best soil testing methodology in the region, 2) calibration, which classifies results according to the nutrient bioavailability (e.g., very low, low, medium, high, and very high), and 3) response curve development that defines the ideal, crop specific rate of P to be applied according to soil P status and yield goals. Regions not having the basic research steps above usually rely on other studies elsewhere to define their fertilizer application programs.

Africa is a new frontier of agricultural development and accessing general information for nutrient status of African soils is crucial for guiding investments to increase continental food production. Considering this, our objectives were to produce a comprehensive map of soil P bioavailability for Africa's commercial crops based on the best dataset presently available, and to compare this status with other regions having similar information.

Mapping soil P bioavailability is important, not just at field scale to recommend fertilizer application rates, but also at larger scales to inform soil and fertilizer policies and investments, agronomic advice, and ultimately, to close crop yield gaps.

A continental map of soil P status

To capitalize on an increasing quantity of soil samples being collected by various government and/or NGO funded projects, iSDA produced detailed 30 m resolution maps for soil nutrients, including a map for soil P at the 0 to 20 cm depth [Hengl et al. (2021); https://www.isda-africa.com/isdasoil]. These maps were developed using a two-scale Ensemble Machine Learning framework implemented from the Machine Learning in R (MLR) package. The study also used coarse covariate layers of 250 m resolution (MODIS, PROBA-V and SM2RAIN products) and 30 m resolution (Sentinel-2, Landsat and DTM derivatives) images. Some important soil samples datasets included: 1) AfSIS I and II soil samples for Tanzania, Uganda, Nigeria, Ghana with ~40,000 sampling locations (Vågen et al. 2020); 2) ISRIC Africa Soil Profile Database with 13,000 legacy profiles collected across Africa and collated by ISRIC as part of the AfSIS project; 3) LandPKS with ~12,000 soil profile observations, crowd-sourced and collected via the LandPKS mobile app; 4) IFDC with 9,000 soil sampling locations across Ghana, Uganda, Rwanda, and Burundi collected from various projects; and 5) AfricaRice and the *Taking Maize Agronomy to Scale in Africa* (TAMASA) project with more than 3,000 soil sampling locations across Africa generated from on-farm trials.

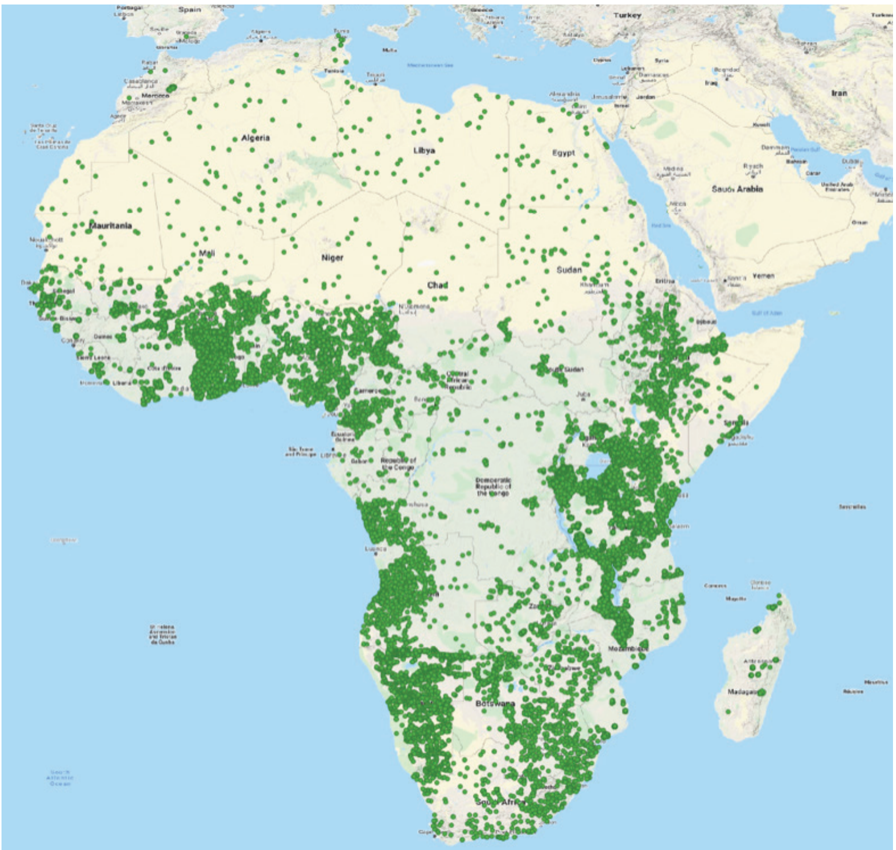

Figure 1. Location of data sample training points used for the iSDA soil maps. Adapted from: Hengl et al. (2021).

The soil sampling points collectively used in the iSDA soil P map are illustrated in **Fig. 1**. In total 53,493 soil analysis results using the Mehlich-3 soil testing methodology (Mehlich, 1984) were considered for creating the map. Mehlich-3 is a widely used procedure for evaluating P bioavailability in soils across the world. The method consists of the extraction of P from the soil samples by adding a weak acid that has the advantage of being applicable for several elements [i.e., P, Ca, Mg, K, copper (Cu), zinc (Zn), manganese (Mn), and iron (Fe)]. Mehlich-3 is well correlated with plant P uptake and is therefore considered a standard method for plant available soil P determination.

iSDA's final map for plant available P (**Fig. 2**) adopted a range scale of 0 to 125 mg P kg^{-1}, however this range has no clear connection to plant P bioavailability. Interpretations for soil tests based on thresholds linked to plant response to P vary according to the methodology and between soil types and must be preferably defined by calibration studies at the local level. However, these basic studies have not been conducted extensively for soils in Africa.

A revised map based on bioavailable P thresholds

The dataset used to create a revised version of the map was extracted from the original iSDA website data. This revision assumes Mehlich-3 thresholds [i.e., in mg P kg^{-1} very low = 0 to 5.0 (dark red); low = 5.1 to 15 (light red); medium = 15.1 to 30 (yellow); high = 30.1 to 60 (light green); and very high ≥ 60.1 (dark green)] described in the methodology and based on several different interpretations

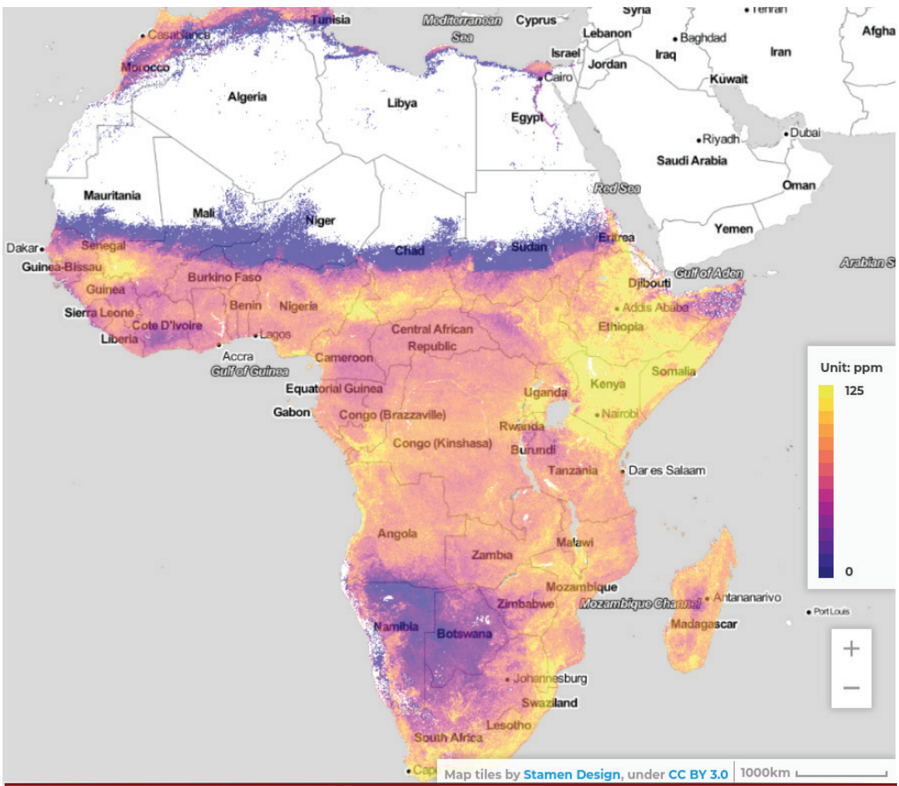

Figure 2. Original map of extractable P (Mehlich-3) for 0 to 20 cm soil samples from Africa. Adapted from: Hengl et al. (2021); iSDA website.

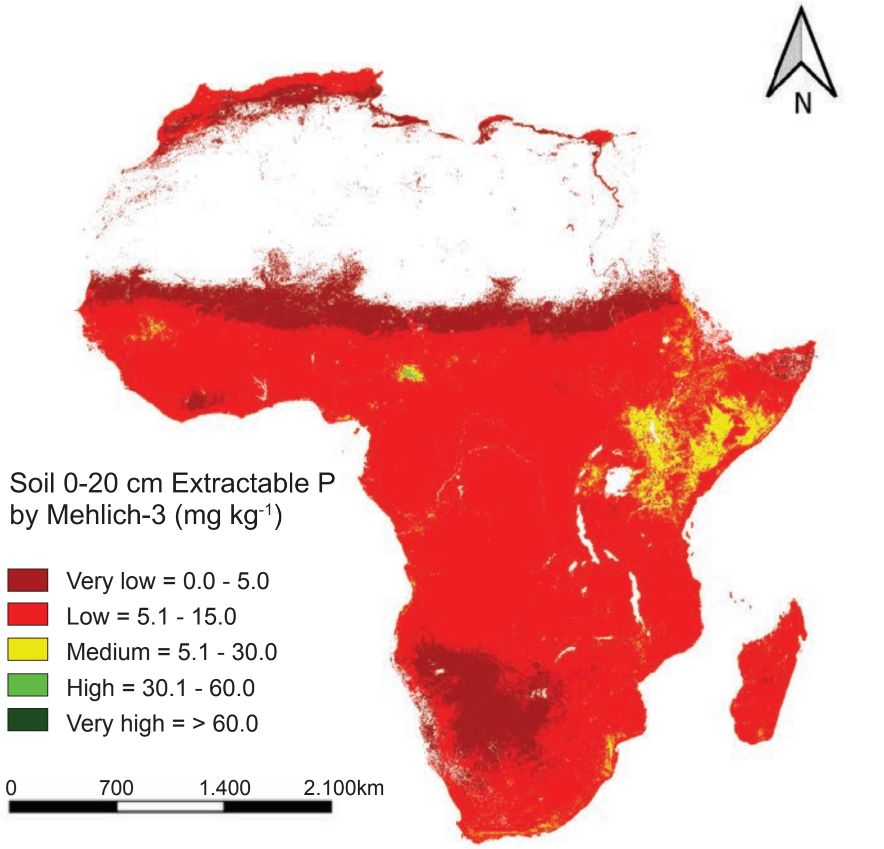

Figure 3. Map of extractable P (Mehlich-3) for 0 to 20 cm soil samples from Africa. Adapted from iSDA.

from laboratories and soils across the world. In general terms, it is assumed that the different classes of soil P bioavailability correspond to the probability of observing a response to the application of P fertilizer. Thus, the original data from iSDA was back transformed to produce a new map using thresholds recognized to reflect plant P bioavailability.

The resulting map (**Fig. 3**) shows a clear predominance of areas with low and very low bioavailable soil P in Africa. Statistics indicate 17.91%, 78.06% and 3.99% of soils have very low, low and medium amounts of Mehlich-3 bioavailable soil P, respectively (**Table 1**). Assuming that the relative yields in each of these three respective ranges would be 0 to 50%, 51 to 70% and 71 to 90% (Havlin et al., 2005), this study predicts that 99.97% of African soils would respond to P fertilization, which is remarkable if compared to other regions of the world.

Table 1. Percent distribution of P sufficiency levels in soils of Africa.

Class	Relative yield, %	Threshold, mg P kg^{-1}	% of total	Cumulative %
Very low	0 to 70	0 to 5	17.91	17.91
Low	71 to 90	5.1 to 15	78.06	95.97
Medium	91 to 100	15.1 to 30	3.99	99.97
High	100	30.1 to 60	0.03	100
Very high	100	≥ 60	0.00	100

Thresholds used to classify soil P status by Mehlich-3 do differ among regions. Some use narrower thresholds, for example 0 to 5, 5.1 to 10, 10.1 to 15, 15.1 to 30, and > 30 mg P kg^{-1} for very low, low, medium, high, and very high soil P, respectively. If this classification were to be adopted for our map, still 96% of the soil samples would be classified as P responsive.

In comparison, Ballabio et al. (2019) mapped soil chemical property datasets by interpolating 22,000 surveyed points covering the 26 European Union Member States using the LUCAS topsoil database and advanced digital soil mapping methodologies based on three classes of bioavailable P (mg kg^{-1}) including low = 0 to 25, medium = 25 to 50, and high > 50 (**Fig. 4**). Results clearly show a much lower frequency of soils low in P compared with Africa, and consequently, a smaller area expected to respond to fertilizer P. A similar trend is observed in the studies of Yu et al. (2021) for China (**Fig. 4**), Murrell et al. (2015) for the U.S., and Prochnow et al. (2018) for a portion of Brazil. The reasons for the much lower P bioavailability in Africa compared to other regions of the world are the predominance of Africa's highly weathered tropical soils and a chronically low reliance on P inputs.

It is important to note that some of these studies produced maps using soil testing methodologies other than Mehlich-3. Regardless, map interpretation should consider the sufficiency levels adapted to each methodology and region, and one should avoid using conversion factors amongst methodologies.

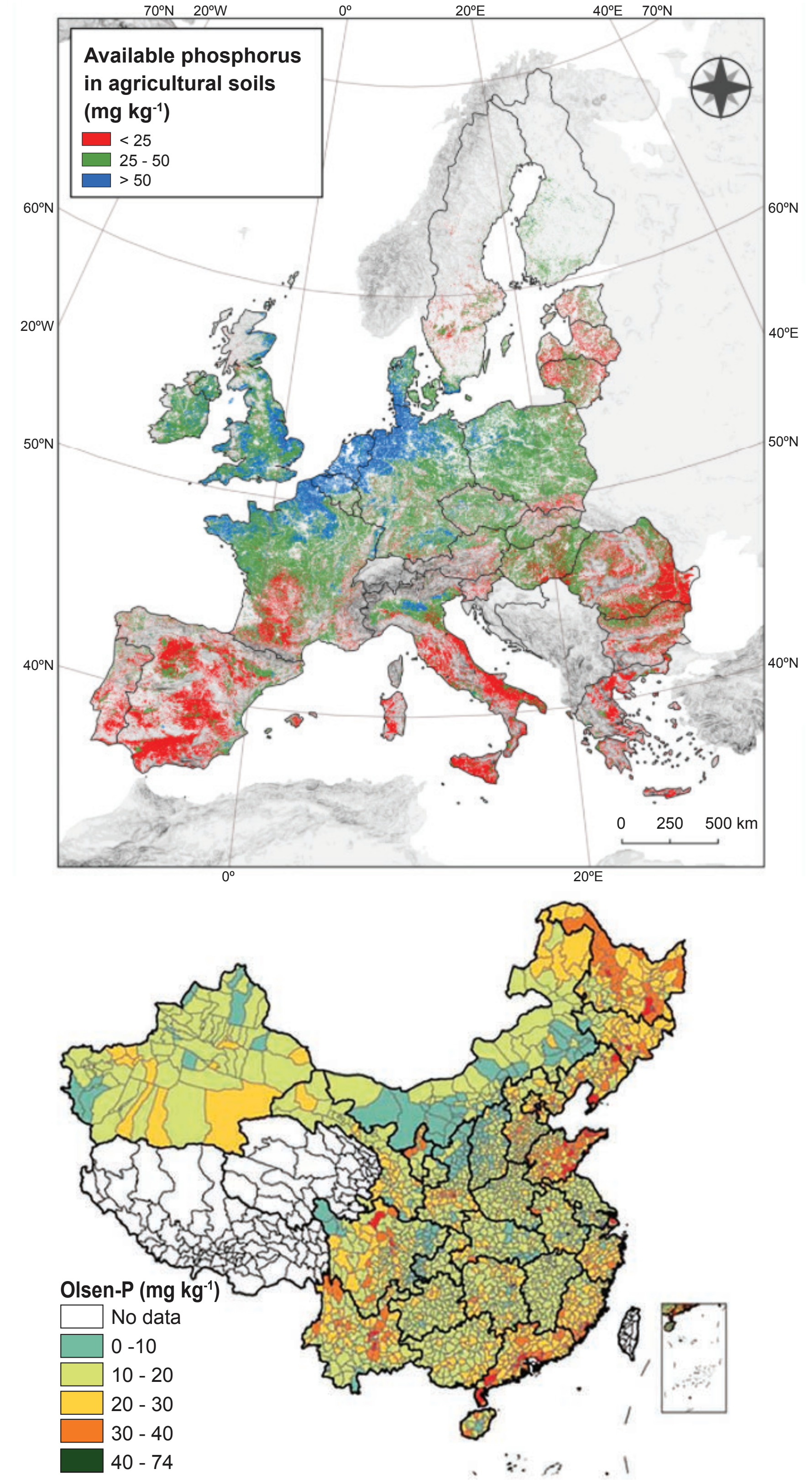

Figure 4. Bioavailable P in agricultural soils of the EU and UK (top) and China (bottom). Sources: Ballabio et al., 2019; Yu et al., 2021

Summary

The map of Mehlich-3 bioavailable P for soils of Africa clearly demonstrates, based on the best dataset presently known, that the continent's agricultural soils are extremely low in P fertility, and that in the future it will be necessary to increase soil bioavailable P through P fertilizers in order to produce the amounts of food, feed, fiber and bioenergy the continent will desperately need. ■

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Announcing Launch of the APNI Photo Contest

Join our challenge to shine a light on plant nutrition research and development in Africa through photography. Your contributions will help build a valuable forum and educational resource …plus winners are eligible for a cash prize of US$250!

Our contest is accepting entries till July 2023 after which we will announce our winners. **This year our contest is built around two categories.**

Category 1: Nutrient Deficiency Symptoms in Crops

If you find yourself scouting fields and spot a striking example of a nutrient deficiency symptom, why not take a moment to capture it for our contest. We are looking for well framed examples that we can publish with full credit to the photographer. Need help distinguishing the symptoms? Consult the general reference diagram provided on the contest website https://apni.net/photo-contest.

Ideally your images would be supported by a short description of the location and what you saw. If you have any background on how the crop was managed, or any analytical data, please include that in your description for the benefit of others, and to help our evaluation.

Category 2: Plant Nutrition Research in Action

Our contest's second theme is looking to capture images of plant nutrition in action in Africa. We are especially looking for images that describe either: 1) Climate & Weather Smart Plant Nutrition, 2) Soil Health & Improved Livelihoods, or 3) Precision Nutrient Management. Who knows? You may be featured on the next cover of Growing Africa!

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Dr. Samuel Njoroge

Researchers on-site to inspect a set of nutrient omission plots (NOTs) for wheat growing in Minjar Shenkora District, in the Amhara region of Ethiopia. The plots evaluated the effect of omitting nitrogen, phosphorus, potassium, and micronutrients on wheat growth and yield, against a plot receiving a balanced application of all nutrients.

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