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REVIEW

Evolution of soil fertility research and development in Ethiopia: From reconnaissance to data-mining approaches‡

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Summary

Meeting the burgeoning global demand for both food and energy requires substantial yield increases through the efficient use of inputs like fertilizers. Prompted by the result of a soil survey expedition in the late 1950s, which signaled a widespread deficiency of nitrogen (N) and phosphorus (P), plant nutrition research in Ethiopia began in the 1960s, focusing on the response of prioritized cereals – tef (*Eragrostis tef*), wheat (*Triticum aestivum*), and maize (*Zea mays*) – to the application of N and P fertilizers. Nationwide on-farm trials conducted in the early 1970s led to a blanket recommendation of 64 kg N ha^{-1} and 20 kg P ha^{-1}, irrespective of the crop and soil types, which were applied in the form of di-ammonium phosphate (18-46-0) and urea (46-0-0), respectively. Research conducted in the 1980s across agro-ecological and edaphic spectrum recommended 30–138 kg N ha^{-1} and 0–50 kg P ha^{-1}, respectively. However, studies show that only 30–40% of the smallholder farmers use fertilizers at a rate less than recommended (on average at 37–40 kg ha^{-1}). This rate reflects limited supply, high prices, and the low and declining crop response to fertilizers. As a result, cereal yields increased only 10% despite a fivefold increase in fertilizer application since the 1980s. Owing to the limited and declining crop response and the increased price of fertilizer in the 1990s, research on the integrated application of inorganic and organic sources of fertilizers was initiated. Although the integrated use resulted in increased yield and better economic benefits, it was not mainstreamed into the national agricultural extension system. The soil survey expedition that began in 2011 culminated in the mapping of the soil nutrient status using literature-based critical limits. The maps have persistently revealed the deficiency of N, P, potassium, sulfur, zinc, and boron across the surveyed areas. Despite the above efforts, the data sets generated through the soil surveys conducted at different times during the last half-century and the agronomic research during the same period have never been fully exploited. It is believed that the recent development in data mining and machine-learning approaches creates the opportunities to use the data sets in conjunction with other covariates in order to generate evidence that helps to make better decisions both at strategic and operational levels. The development of decision support tools based on such large datasets and analytical capacity is believed to facilitate better-informed decisions that lead to increased resource use efficiency and sustainability.

Keywords: Fertilizer targeting; ISFM; Soil degradation; Soil fertility amendment; SoilScape

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Introduction

The ever-growing global demand for considerable increases in agricultural production to meet food and energy requirements, together with access to the necessary resources such as land and water, is increasingly constrained. Under current agricultural practices, rapid population growth further fuels the degradation of natural resources and diminishes agriculturally suitable lands. These challenges reinforce each other, especially in developing countries such as those in sub-Saharan Africa (SSA). Owing to such daunting challenges, Ethiopia is striving to produce more food for its 114 million population that is rapidly expanding (Tamene *et al.*, 2017; UN, 2019; Ermias and Fanuel, 2020). Increasing agriculture productivity while enhancing the resilience of the agricultural systems entails an understanding of spatial and temporal trends in the health and quality of the land, including soil fertility (Sanchez *et al.*, 2009), as well as the use of the proper technologies and practices at the right time and amount.

The judicious use of fertilizers, together with key complementary agronomic practices, is proven to increase overall agricultural productivity and thereby nutrient use efficiency (Desalegn *et al.*, 2017; Getachew *et al.*, 2019; Abdenna *et al.*, 2020; GIZ, 2020). In addition to improving economic benefits, increasing fertilizer use efficiency minimizes the negative impacts of chemical fertilizers on the agro-ecosystems and can reduce the expansion of agriculture into marginal lands (Birhanu and Chalsissa, 2019). Increasing nutrient use efficiency, however, requires proper targeting to the local contexts, which necessitate enhanced research to (1) quantify the nutrient-supplying capacity of the soils; (2) improve plant genetics and crop-management practices; and (3) improve nutrient-management approaches to include nutrient sources, rates, timing, and placement (Havlin and Heiniger, 2020).

In the 1970s, widespread on-station and on-farm trials were conducted in different parts of Ethiopia to determine the rate, sources, and methods of applications of these nutrients. These culminated in the establishment of urea (46-0-0) for nitrogen (N) and DAP (di-ammonium phosphate) (18-46-0) for phosphorous (P) as the only artificial fertilizers in the country (NFIU, 1993, 1988), which the national extension system used until 2013 (IFDC, 2015). The use of these nutrients resulted in a substantial yield increase. Inspired by the observed response, fertilizer use increased fivefold from 1980 to 2010, whereas cereal yield increased during the same period by only 10% (Zelleke *et al.*, 2010). The economic benefit of using fertilizers has also decreased over time: value-cost ratios for major crops diminished from around four in 1995 to marginally attractive levels of approximately two in 2010 (Zelleke *et al.*, 2010).

Various independent studies have shown that the soil nutrient balance in the country is negative, with an average annual depletion per hectare of 122 kg N, 13 kg P, and 82 K due to soil erosion and crop uptake (Stoorvogel and Smaling, 1993; Hailesilassie *et al.*, 2005; van Beek *et al.*, 2016). The suboptimal use of only N and P fertilizers led to a multinutrient deficiency of the soils and decreased nutrient use efficiency (Wassie and Shiferaw, 2011; Beyene, 1984). A recent national soil fertility survey revealed a widespread deficiency of sulfur (S), boron (B), and zinc (Z) in addition to N and P (EthioSIS, 2014). Some research reports also indicate a localized deficiency of potassium (K), copper (Cu), manganese (Mn), and iron (Fe) (Abera and Kassa, 2017; Fanuel *et al.*, 2018). Coupled with the widespread organic matter depletion and increased soil acidification and deterioration of physical soil properties such as compaction and clay-pan formation, the nutrient and organic matter depletion poses a major threat to agricultural productivity, rural livelihoods, and agro-ecosystem sustainability (Erkossa *et al.*, 2015; Wakgari *et al.*, 2019). A study by Erkossa *et al.* (2015) revealed that the loss of N and P through soil erosion by water has resulted in a substantial monetary loss to farmers.

Reversing the situation requires multifaceted, evidence-based interventions tailored to the local agro-ecological and socioeconomic circumstances. A robust targeting of integrated soil resources management, including fertilization, requires a thorough understanding of the system, not only at

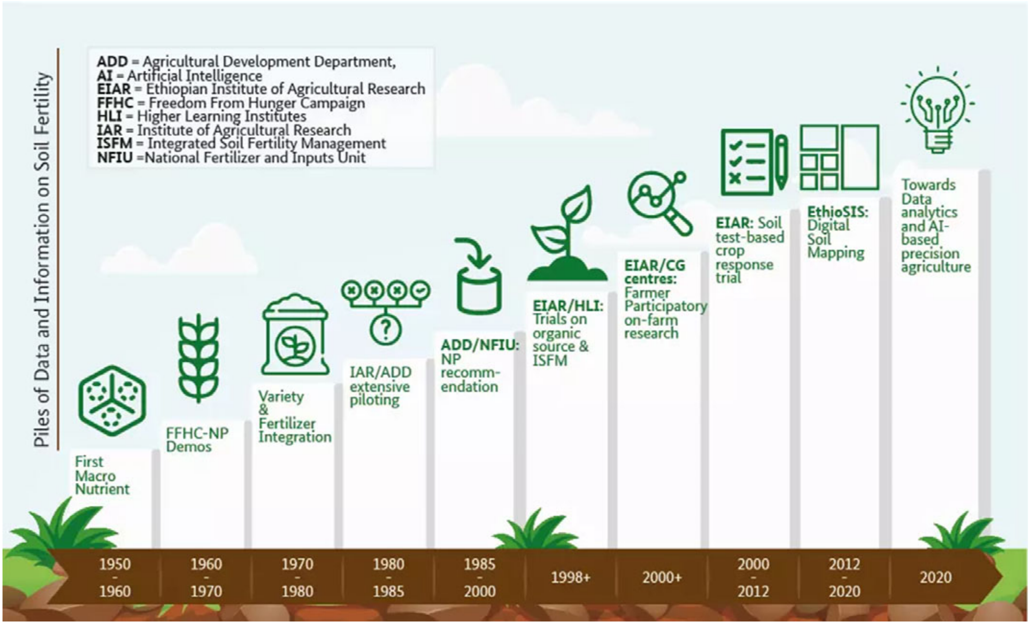

Figure 1. Timeline of key events in soil fertility researchand development in Ethiopia.

a broader scale but also at a local level including farm plots, where the actual management decisions are made. This, on the other hand, requires access to intensive biophysical and socioeconomic data and the use of rigorous analytical methods to drive relevant messages useful for land management decision-makers across the scale. At present, two key challenges to the management of agricultural soils in the country are recognized: the need for a system that focuses on integrated soil resources management (which is gaining ground) as well as the lack of a soil fertility national data repository necessary for developing the area- and crop-specific fertilizer recommendations (IFDC, 2015).

Most soil fertility and agronomy field trials were conducted in specific localities following uncoordinated approaches. Such fragmented efforts did not lead to a clear understanding of the national picture that would allow site-specific fertilizer recommendations to be generated. A systematic collation, harmonization, and mining of data from such studies and the use of advanced data-mining techniques, including machine learning, may lead to an in-depth understanding of the status and spatial distribution of the soil-related constraints and the generation of recommendations for context-specific fertilizer and other agronomic practices. The objectives of this paper are to highlight the evolution of soil fertility research and development (R&D) efforts in Ethiopia, and forward suggestions to improve the approaches to make use of the wealth of data and the advantage of emerging analytical approaches toward better targeting and efficient use of fertilizers.

Phases in soil fertility research

As shown in Figure 1, soil fertility R&D in Ethiopia has passed through key phases, starting from the initial soil survey expedition to the recently detailed soil fertility status mapping, the use of multiple fertilizer blends, and the attempt to use advanced data-mining and machine-learning approaches to target fertilizer and other agronomic management practices. In the following sections, we present a brief account of each of these phases.

Soil survey expedition

In Ethiopia land fallowing, use of dung and crop residues and crop rotation have all been used to maintain soil fertility. The increased use of dung and crop residues as a source of energy has hampered the traditional use of farmyard manure as fertilizers (Erkossa and Teklewold, 2009; Setotaw *et al.*, 2000). The continued decline in soil fertility led to the initiation of soil fertility research in the 1950s–60s with the macronutrient status survey across the country, initially by the then Alemaya College of Agriculture (now Haramaya University), which was later joined by the Institute of Agricultural Research (IAR) at Holetta, Werer, and Bako research centers (Murphy, 1968; Zelleke *et al.*, 2010). Besides, project-based soil survey expeditions have generated basic data and information related to the fertility and health of the soils (e.g. Westphal, 1975). The studies revealed a widespread N and P deficiency in soils of Ethiopia and K in some localities. These findings led to the initiation of artificial fertilization with the first two nutrients in the form of DAP and urea fertilizers.

Testing crop response to inorganic fertilizers

Based on the hypothesis that yield was limited by the deficiency of N, P, and/or their interactions, the response of major cereals (e.g. tef, wheat, and maize) to DAP and urea fertilizers was tested (Adugna and Zegeye, 2003). The studies revealed that crop response to N, P, and NP was significant. This led to the implementation of nationwide on-station and on-farm trials to determine the optimum rate of N and P application under different cropping systems. Since 1967 trials were carried out with the assistance of donor agencies and initiatives such as the Freedom from Hunger Campaign. The objectives of this programme were to (1) create awareness among smallholder farmers on the use of inorganic fertilizers; (2) determine the optimum rate of application; and (3) define sound policies, strategies, and institutional setup that would facilitate the creation of an efficient fertilizer delivery system (Adugna and Zegeye, 2003). The concerted efforts by the program led to the blanket recommendation of 100 kg DAP ha^{-1} with or without 50 kg urea ha^{-1}, irrespective of crop and soil types (NFIU, 1993), which the Ministry of Agriculture (MoA) later set at 100 kg ha^{-1} DAP and 100 kg ha^{-1} urea (Adugna and Zegeye, 2003;Yadeta *et al.*, 2001).

From 1971 to 1990, fertilizer trials were conducted at research stations and on-farm by various organizations, including the Extension and Project Implementation Department (EPID) (1971–1974); IAR/ADD since 1981; the National Fertilizer Trials Programme (ADD/NFIU) from 1986 onwards; and higher learning institutes focusing on responses of improved crop varieties to nutrient levels (FAO, 1997; ADD/NFIU, 1991). The result led to fertilizer recommendations based on soil color (black soils/red soils) (NFIU, 1993); but based on the trials conducted at a few stations from 1975 to 1990, IAR has recommended fertilizers based on specific soil and crop types, mainly in the vicinity of the research stations. Little effort was made, however, to extrapolate the results to a wider range of environments. Other studies during this period include the effect of application time on N use efficiency and the effect of cropping systems such as crop rotation and alley cropping on the N requirement of some cereals. The studies recommended the time, rate, and types of fertilizer application under different cropping systems and soil types (Erkossa and Teklewold, 2009; Taa *et al.*, 1997). Yet to date no systematic effort has been made to operationalize and scale the recommendations.

Inorganic fertilizers: piloting, consumption, and efficiency

During the 1980s–2000, extensive piloting of inorganic fertilizers, together with other technologies, was widely promoted to smallholder farmers. In the late 1980s and early 1990s, a top-down approach, known as "training and visit" (T&V) was followed by the MoA, which was not sensitive to the varied requirements of small-scale farmers (Anderson and Feder, 2007; Swanson, 2008).

In 1995, a participatory demonstration and training extension system (PADETES), which combined some aspects of T&V with the Sasakawa Global 2000 approach of bringing science-based technologies to small farms, was implemented. PADETES was aimed at accelerating the dissemination of technologies such as fertilizers, improved seeds, and cultural practices (Adugna and Zegeye, 2003). The extension approach during the period promoted monocropping and the use of agrochemicals (such as atrazine), which undermined the sustainability of the agricultural system.

From the early 1970s to 2012, only two fertilizers (DAP and urea) were imported (Adugna and Zegeye, 2003) until DAP was replaced by NPS as of 2013. The temporal data revealed that fertilizer import increased from 947 tonnes in 1971 to 1 390 535 tonnes in 2017 (ibid.); however, a proportional increase in yield and profitability was not achieved. According to Spielman *et al.* (2013), only 30–40% of Ethiopian smallholder farmers use fertilizers at an average rate of 37–40 kg ha^{-1}, which is far below the recommended rates. Studies show that fertilizer efficiency in Ethiopia is lower than in some East African countries. For instance, the nutrient use efficiency for maize in Ethiopia is 9–17 of applied N, which is less than the 7–36 and 18–43 in Kenya and Tanzania, respectively (Heisey and Mwangi, 1996). This is attributed to several factors, including limited response and low efficiency due to the absence of site-specific recommendations, lack of complementary packages, and inefficient supply system, which can all lead to high prices.

The low agronomic efficiency is related to multiple factors. These include nutrient mining due to suboptimal fertilization, nutrient imbalance, and multinutrient deficiency created due to prolonged use of only two nutrients (N and P) (Wassie and Shiferaw, 2011; Tulema, 2005; van Beek *et al.*, 2016). Other factors identified are declining soil fertility due to nutrient loss by erosion (Zelleke *et al.*, 2010; Erkossa *et al.*, 2015), leaching (Tadesse *et al.*, 2013), increased soil acidification (Getachew *et al.*, 2019), lack of site-specific recommendation and inability to target fertilizers to the diverse agro-ecology and soils, and limited knowledge of the soil fertility levels at farm-scale to guide fertilizer targeting.

Integration of organic sources

Traditionally, small-scale farmers in Ethiopia use organic sources for the rehabilitation of health and fertility of crop or grazing lands. Since time immemorial, animal manure has been the prime source of soil fertility management (Hailu, 2010). However, agricultural R&D promoted inorganic sources, including through government subsidy of inputs, which has gradually replaced such traditional systems. Following the efforts made to liberalize the input supply market in Africa since 1991 that has abolished all subsidies and price support measures to agriculture (Shikur, 2020), agricultural R&D refocused on the integration of organic sources of fertilizers both to reduce input costs and enhance the system's sustainability (Giller, 2001). Because of the high farm-level fertilizer prices, cash-constrained smallholder farmers in different parts of the country also resorted to animal manure and other organic sources (Morris *et al.*, 2007; Erkossa and Ayele, 2003; Eyasu, 2002; Fujisaka, 1997). Subsequently, in the late 1990s, several research projects on the use of organic resources or their integration with inorganic materials were initiated (Erkossa and Teklewold, 2009; Erkossa *et al.*, 2004). The private sector also has shown interest in the organic sources of fertilizers. A National Fertilizer Manufacturing plc was established in 1998 with an annual capacity of producing 10 000 tonnes of an organic fertilizer known as "Orga" from animal bones. In 2002–2003, it distributed a total of 2,762 tonnes to different users (Adugna and Zegeye, 2003). Several studies conducted in different agro-ecologies and on different crops revealed that a combined application of organic and inorganic fertilizers has significantly increased crop yield and economic profitability and improved soil quality as compared with the sole application of either source (Ermias and Fanuel, 2020; Erkossa and Teklewold, 2009; Hailu and Edwards, 2006; Wakene *et al.*, 2004; Getachew and Wondimu, 2003; Eyasu, 2002).

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The emergence of integrated soil fertility management

Integrated soil fertility management (ISFM) is a set of practices that necessarily include the use of inorganic fertilizers, organic inputs, and improved germplasm, combined with the knowledge on how to adapt these practices to local conditions, to maximize agronomic use efficiency of the applied nutrients and improve crop productivity (Vanlauwe *et al.*, 2010; Sanginga and Woomer 2009). It consists of a set of site-specific practices to increase soil fertility and reduce soil degradation; reduce input cost; and thereby improve yields, incomes, and ultimately livelihoods of farm households (Vanlauwe *et al.*, 2010; Giller, 2001).

In Ethiopia, the cereal–pulse rotation systems with strategic application of P fertilizer to legumes to maximize biological N-fixation to benefit the subsequent cereals (Amanuel *et al.*, 2000) are widely used in conjunction with complementary agronomic practices. This was further augmented with the introduction of biofertilizers and liming acid soils. The national initiatives that were largely limited to research and small projects were complemented by initiatives through international organizations in cooperation with the MoA. One such project is the "Integrated Soil Fertility Management Project," launched in Ethiopia in 2015 by the German Agency for International Cooperation (GIZ) in the three highland regions Amhara, Oromia, and Tigray. This project develops and promotes locally adapted ISFM practices via a group-based learning approach, like the well-known concept of farmer field schools (e.g., Davis *et al.*, 2012). Results from the project's field demonstrations (2016–2019) showed a yield advantage of 60% in 2016 and above 100% in 2019, as compared with the farmer's practice (GIZ, 2020). Recently, several projects, including the Wageningen-EIAR Integrated Nutrient Management project, MoARD/SG-2000 Conservation Agriculture trials, AGRA-EIAR ISFM project, GIZ-ISFM project, and N2Africa, are engaged in the promotion of ISFM options into the agricultural system of Ethiopia (GIZ, 2020). Thanks to the demonstrated success of these projects, ISFM has now been part of the national "Soil Health and Fertility Improvement Strategy" to sustainably enhance soil fertility, productivity, and livelihoods of the rural population (MoANR, 2017).

Participatory innovation approaches

While participatory research in Ethiopia goes back to the era of Farming Systems Research in the 1980s although participation was limited to its rudimental form, Farmers Participatory Research was institutionalized in early 2000 (e.g. Chimdo *et al.*, 2005). A project on Strengthening Technology Development, Verification, Transfer and Adoption through Farmers Research Group (FRG) was launched in 2004 and was implemented by Melkassa and Adami Tulu Agricultural Research Centers (JICA, 2009) focusing on ranges of topics including natural resources management. More recently, the Humidtropics project of the CGIAR has implemented the Innovation Platforms (IPs) approach in three sites in the Nile Basin where productivity and soil quality effects of integrated soil, water, and agronomic management practices were evaluated by farmers in a watershed (Jeldu), the financial cost to the farmers because of productivity loss induced by nitrogen and phosphorus loss due to soil erosion and livestock feed production due to infiltration trench and reseeding with improved fodder grass (e.g. Erkossa *et al.*, 2015; Erkossa *et al.*, 2018; Erkossa *et al.*, 2020).

Liming acid soils

Soil acidity is increasingly challenging crop productivity in the high rainfall areas of Ethiopia. According to Getachew *et al.* (2019), about 43% of cultivated land in humid and sub-humid highlands of the country is affected by soil acidity, of which about 28% are strongly acidic (ATA, 2014). Soil acidity limits the availability of essential nutrients such as P, K, calcium, and magnesium and affects the activities of essential soil organisms. The effective practice to rehabilitate acidic soil sustainably is using ISFM practices, including the application of lime. Liming acid soils improves the environment for beneficial soil microorganisms and promotes a rapid breakdown of organic

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materials in the soil, thus releasing nutrients for growing plants; however, liming should be accompanied by other agronomic practices. According to Desalegn *et al.* (2017), the combined application of 1.65 tonnes of lime ha^{-1} and 30 kg P ha^{-1} resulted in 133% more grain yields of barley than the control (without P and lime). Abdenna *et al.* (2020) reported a significant reduction in external P requirement, from 1772 to 369 mg kg^{-1} due to the application of lime. Liming also stimulates microbial activities and enhances N fixation and N mineralization. Hence, legumes benefit highly from liming (Fageria and Baligar, 2008).

Research around the year 2000 mainly by EIAR examined the liming of acid soils (Getachew *et al.*, 2006). Soil acidity has also been prioritized in the national soil fertility and health strategy (MoANR, 2017). During the last five years, the GIZ–ISFM project has supported the demonstration of liming acid soils as an integral part of ISFM, which has shown a significant increase in yield and reduced P fertilizer requirement. In 2020, the government of Ethiopia adopted an acid soil liming policy, strategy, and implementation plan. Consequently, the MoA has included agricultural lime in the list of agricultural inputs, thus allowing government agencies to allocate budgets for the promotion of lime and farmers to obtain credit for the purchase of lime.

Soil test and crop response approach

The soil-test-based fertilizer recommendations involve the development of mathematical models that integrate the soil test indices with fertilizer requirements, which can be used for the nutrient recommendations (Sala *et al.*, 2015). This approach is widely used for P fertilizer recommendations in different parts of the world. In Ethiopia, the need for a soil-test- and crop-response-based P fertilizer recommendation was recognized around 2000, and P calibration was started first for wheat and later expanded to other cereals and pulses. Studies conducted from 2012 to 2014 on P calibration for major cereal and pulse crops across different agroecology and soil types, the critical P values, and P requirement factors have been developed (http://www.eiar.gov.et/index.php/land-and-water-resources-research). For instance, in Tigray, the application of P based on soil test resulted in grain and straw yield increments of 26.4 and 35.3%, respectively, as compared with the blanket recommendation (Gidena, 2016).

Digital soil fertility status mapping

The MoA and the Agricultural Transformation Agency (ATA) of Ethiopia developed the Soil Health and Fertility Roadmap in 2011 and 2012 to address key soil fertility bottlenecks and transform the agriculture sector, by improving soil health, increasing yield, and boosting the incomes of smallholder farmers through a soil-test-based fertilizer recommendation through the Ethiopian Soil Information System (EthioSIS) programme (http://www.ata.gov.et/highlighted-deliverables/ethiopian-soil-information-system-ethiosis/). A national soil fertility status survey conducted by the ATA revealed that 96% of Ethiopian soils are either acidic or alkaline and are poor in macro-and micronutrients (e.g. S, Zn, B, Cu, and Fe) in addition to N and P (EthioSIS, 2014). Consequently, balanced fertilizers containing deficient nutrients were recommended, which heralded a significant departure from the use of N and P fertilizers for decades (http://www.fao.org/fileadmin/user_upload/GSP/docs/South_east_partnership/Ethiopia.pdf). The import of blend fertilizers was initiated, followed by the establishment of blending factories to substitute the import. The effort so far was not as successful as planned, however. Despite a consensus about the need for a new recommendation including additional macro-and micronutrients, the current widespread use of the blend fertilizers without proper validation of the proposed blends is sharply criticized by many soil scientists.

On-station and on-farm verification trials of the blend fertilizers showed mixed results. Increased crop yield and agronomic efficiency (e.g. Ishete and Tana, 2019; Bizuwork and Yibekal, 2020), as well as neutral or negative results (e.g. Eyasu *et al.*, 2020), were reported, indicating the need for refining the recommendation to fit the specific biophysical and socioeconomic context of the target sites.

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Therefore, the new recommendation requires validation and further fine-tuning following harmonized and standardized field trials. Designing site- and context-specific fertilizer recommendations requires an understanding of the fertilizer application effects on crop yield across topographic, climatic, and management conditions. Effective targeting of fertilizer recommendations centers on the ability to identify production constraints and specific niches.

The data-mining approach for targeting and scaling

The history of fertilizer research in Ethiopia shows that the approaches followed involved a few field trials that were fragmented both in time and space. The data from such trials were often not accessible to other users than their creators, necessitating new field data collection for every new research question. Recent initiatives by voluntary data generators and users to promote data sharing and access, focusing on agronomy and soil fertility, have created favorable conditions for the application of a "big data"-mining approach. Although the country lacks a formal policy on data sharing and access, the group known as the Coalition of the Willing (CoW) for data sharing and access is temporarily bridging the gap by voluntarily sharing data among themselves. Besides, the CoW has taken the initiative to map the soil and agronomy data ecosystem and has collated a large volume of data from voluntary institutions and individuals to create a data portal for use mainly by its members. The large data set covering wider environmental space can be used to develop national-level fertilizer recommendations, which will serve to showcase how enhanced data access and sharing can improve research efficiency and create an opportunity to use big data analytics and machine learning to support agricultural transformation in the country (Abera *et al.*, 2021). As outlined above, developing optimal fertilizer recommendations is challenging because it involves many variables (e.g. weather, soils, land management, genotypes, and crop diseases). With data-sharing initiatives, machine learning (ML) and artificial intelligence (AI) algorithms are provided to have extreme potential to predict site-specific optimal agronomic inputs such as fertilizer recommendations (e.g. Abera *et al.*, submitted). With the availability of high-resolution spatial layers and innovative and large agronomic data sets, ML and AI are emerging technologies that can integrate and analyze all these data sets and facilitate the development of decision-making tools.

Fertilizer recommendation at plot and individual household level is not realistic in the next few years due to the heterogeneous landscapes, diverse agro-ecological zones, different farming systems, and socioeconomically complexity of the households. Creating landscape units with a similar response to agronomic management, known as an "agronomic response unit," has been proposed to guide the targeting and scaling of fertilizer recommendations. Developing procedures for automatically classifying landscapes into functional landform or soil-landform spatial entities can be essential to define effective management units for precision farming and scaling site-specific modeling and analysis results (Fanuel *et al.,* 2018; Birhanu and Chalsissa, 2019). This can be achieved through mapping areas with similar geomorphological and soil properties and ecological potentials where similar management interventions can generate similar responses. To this end, it will be essential to develop and evaluate a practical procedure for partitioning soil landscapes into landform elements that display significant differences concerning soil properties and to management requirements for targeting recommendation and scaling.

One of the key components to creating similar "agronomic response units" is understanding yield-controlling factors and generating yield-response differential maps. Based on defined agronomic-response units, it will be possible to design management plans geared toward tackling constraints and harnessing potentials. It will also be possible to develop a dynamic system that aligns defined inputs for specific responses/outputs targeting agronomic and economic yield and efficiency. This will consider potential trade-offs (on- and off-site as well as upslope–downslope interactions) to maximize synergies. Different scenarios can be developed to assess the possibility of increasing yield and efficiency at one scale without increasing offsite/downstream effects. The recent work by Tamene *et al.*

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(submitted) provided detail and insights into how similarity units can be developed and applied for fertilizer recommendation targeting and scaling in a complex context like Ethiopia.

The way forward

Despite a long history of fertilizer R&D endeavors to improve soil fertility management practices, studies revealed that the agronomic and economic efficiency of fertilizers in Ethiopia shows mixed results. Various research results indicated that increased applications of N and P increased grain yields. High agronomic efficiency and profitability are reported in some localities, while efficiency from other locations is marginal or depressing. In explaining fertilizer use efficiency, the key question is whether the right source of fertilizer is applied to the soil at the right rate, time, and place and whether the other yield-limiting factors are also addressed. This is because variation in edaphic, climatic, and physiographic factors, together with the crop type and genotypes used, and agronomic management practices play vital roles in determining the performance of fertilizers. Ethiopia's agro-ecological system and farm management practices are highly diverse. Therefore, both the agronomic and economic efficiency of fertilizers depends on our understanding of the variations and the extent to which soil fertility management practices are in line with the local biophysical and socioeconomic circumstances.

Variation in the soil types essentially implies that different types and amounts of nutrients must be applied to maintain soil fertility and perhaps increase yield response and profitability. To address such challenges, the importance of zone- or site-specific fertilizer recommendations in the country has gained the attention of many researchers and scientists since as early as the 1990s. Consequently, the government of Ethiopia has embarked on an ambitious effort to map soil fertility status, which suggested that several macronutrients, including N, P, K, and sulfur, and micronutrients (e.g. Zn, B, Cu, etc.) might be deficient in the major agricultural areas. Although the critical values for the major crops have not yet been established through crop response, various compound or blend fertilizers containing the reportedly deficient nutrients are imported and distributed by the government. Further, the government has established fertilizer-blending facilities in the country, which led to the widespread use of the blends. However, the endeavor did not match with meaningful yield increases or the blends' performance is area specific. This entails that fertilizers and other agronomic practices should be better targeted to their ecological niches.

A wealth of soil and agronomic data have accumulated over decades through the national and international research and development institutes. Efforts to collate these data and manage them in a centralized database system is believed to pave the way for advanced statistical and data-mining approaches. Not only will these approaches help to fine-tune the type and rates of nutrients for agronomic and economic efficiency but they will also help guide their spatial targeting based on the biophysical and socioeconomic imperatives. Currently, an informal group of soil and agronomy data activists (i.e. the CoW) is championing the creation of a national soil and agronomy database, attempting to benefit from the emerging data-mining approaches to exploit the data and generate a context-specific recommendation of fertilizer and agronomic practices. Promoting the policies that encourage the sharing and access of data, encouraging the joint operation of a multidisciplinary group of scientists, and creating a conducive environment by providing necessary computational facilities will shorten the time needed to achieve context-specific fertilizer recommendations informed by decision support tools for use by decision makers across the spectrum.

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Conflict of Interest. None.

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