Validated fertilizer use at landscape scale: demand driven approach in sorghum, wheat and teff mixed farming systems in Ethiopia: A Technical Report

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Introduction

Soil nutrient management is very critical to maximize crop yield and to maintain soil health for a sustainable productivity. Decline in soil fertility and soil quality, among other factors, are major constraints to the agricultural productivity and disfunction of environmental services (Bahr, 2015). In Ethiopia, soil nutrient mining and very less replenishment of organic and inorganic resources are the recurrent problems that resulted in soil nutrient depletion. Besides, severe topsoil erosion associated with steep slope cultivation made the country one of the highest nutrient depletion rates in Africa with 41, 6 and 26 kg $ha^{-1}yr^{-1}$ of nitrogen, phosphorus and potassium, respectively (Stoorvogel and Smaling, 1990). Soil nutrient balance assessments in central Ethiopia showed that nutrient losses even worsen and reached an amount of 122 kg N, 13 kg P and 82 kg K ha^{-1} per year (Haileslassie et al., 2005). In addition to the poor nutrient and organic matter status, aluminum toxicity and phosphorous fixation are other constraints in Ethiopian soils apparent in pH less than 5.5 which enhances nutrient limitations and toxicity (Agegnehu and Amede, 2017; Agegnehu et al., 2006). The state of nutrient depletion entails context specific nutrient management and fertilizer applications.

Apart from soil depletion, the variability in rainfall condition, topographic and geomorphologic variations, cropping system and nutrient management among farmers further contribute to low productivity (Yokamo et al., 2022). Spatial and temporal soil fertility variability can occur due to natural or anthropogenic factors. Natural soil fertility variability may be as a result of complex interactions between geology and climate as well as soil use (Ayoubi et al., 2007). In addition, the topography of an area affects the storage of soil organic matter and nutrients because of a microclimate, runoff erosion, evaporation and transpiration (Raghubanshi, 1992). Changes in vegetation types and soil nutrient concentrations have often been found along the altitudinal gradient in crop-livestock mixed agricultural systems (Karaca et al., 2018). Collectively all these factors are responsible for soil fertility variability. Thus, fertilizer use is dependent upon the variability of these different factors like soil type, soil texture, soil structure, organic matter (Yoo et al., 2006). Especially, soil moisture availability and topographic gradients are the main and crucial factor in predicting optimum use of fertilizers ((Raghubanshi, 1992).

The balanced dose of fertilizer used for any crop to get the desirable yield is very much low (Yokamo et al., 2022). It is about 86, 118, 106, and 134 kg/ha of inorganic fertilizer (N and P) for teff, wheat, sorghum, and maize (CSA, 2021). The respective N and P fertilizer use is 67/19 kg/ha for teff, 93/25 kg/ha for wheat, 88/18 kg/ha for sorghum and 112/22 kg/ha for maize. However, specific household level surveys reported much low rate of N and P fertilizer use by farmers. For instance, Land and Soil Experimental Research (LASER) survey on about 1677 plot-specific soil samples from 1007 households in three zones of Oromia region reported 7 kg/ha N and 9 kg/ha P fertilizer use by farmers (Abay et al., 2021). According to Abuja's Declaration on fertilizer in African states, the current inorganic fertilizer use is much lower than the targeted threshold fertilizer use (50 Kg/ha) adopted by Africa Union in 2015. Lack of accurate information about soil nutrient requirements lead to inefficient use and management of inorganic fertilizer by farmers and could led to mismatch between soil nutrient requirements and fertilizer applications (Abay et al., 2021). Farmers applied high amounts of fertilizers to respond to perceivably poor-quality soils and acidic soils. Application of fertilizers on non-responsive and marginal lands such as hillslopes (Amede et al., 2020) and problematic soils (Abay et al., 2021), under low rainfall regimes (Martinez-Feria and Basso, 2020) affected the efficient use of fertilizers. Overall, landscape positions explained by various interrelated features (soil, slope, geomorphology, cropping system, soil moisture) respond differently to crop yield (Amede et al., 2020). A meta-analysis study on N-fertilizer use reported by Yokamo et al (2022) indicated that high price, inaccessibility, unavailability, weak extension services, limited access to credit and input at the relevant time and space are the reasons for inadequate use of fertilizers. These limiting factors for fertilizer management could explain heterogeneities in marginal returns to fertilizer and low adoption rates. This mismatch likely to have important implications for low crop productivity. It is therefore essential to implement soil nutrient management solutions tailored to varied local soil fertility needs and drivers of soil nutrient management and fertilizer use under diverse agro-ecology and farming systems and develop a fertilizer management decision tool that build on these drivers of soil fertility.

Evolution of fertilizer extension in Ethiopia

Following the introduction of fertilizer in Ethiopia in the late 1960s, fertilizer application levels remained low until the mid-1980s, when consumption increased slightly with the introduction of the Peasant Agricultural Development Program (PADEP), in the period between 1986 and 1995. Since then, a series of policies continue to reshape fertilizer supply in Ethiopia. Until these days, one of the gaps in fertilizer adoption in Ethiopia is the blanket application of fertilizer with little attention to the specific nutrient requirements based on the type of soils, climatic conditions, and crop types. As illustrated in figure 1, the need for site specific fertilizer recommendation was recognized even during the implementation of the first agricultural minimum package project in early 1970s (Tibebe and Tamene, 2017). The agricultural minimum package project was a country wide fertilizer trial initiative in Ethiopia under the third 5-year development plan. The second minimum package project was implemented between 1980 and 1984 and aimed to increase productivity through increased use of fertilizers. During PADEP, an extensive fertilizer response trials, both 2.5 ha field trials and on-farm fertilizer and integrated plant nutrition tests had been conducted with the lead by Agricultural Development Department (ADD) and National Fertilizer Input Unit (NFIU) in the MoA. These trials resulted in region and soil specific fertilizer recommendation based on an economic optimum rate of nutrients (FAO, 1997). This period was also marked with crop response studies to N and P by Institute of Agricultural Research (IAR). Participatory demonstration of inputs had continued during the Participatory Demonstration and Training Extension System (PADETES) (1993-1999). Piloting of high input approach – integrated use of seeds, fertilizer, credit, and extension- have been implemented by SG2000 to double or triple crop yields and increase profitability by two to three times (Sanchez, 2002). After this period, particularly during the GTP I, soil has gained policy focus and become priority investment areas as embedded in the agriculture Policy Investment Framework (PIF) strategic objectives. Consequently, several soil nutrient related projects such as OFRA/AGRA, EthioSIS/ATA, GiZ/ISFM, AfricaRising, CASCAPE, EIAR/EKN-WUR have been initiated. The historical fertilizer sources shifted from Nitrogen and Phosphorus to multi-nutrient or compound fertilizers including micronutrients. Large sets of trials by the national research system and agriculture offices on soil test-based fertilizer trials and fertilizer response demonstrations have been launched across the country. Now, the evolution of fertilizer management and use arrives in refining various nutrient sources and rates through validation studies and promoting integrated nutrient management through ISFM framework.

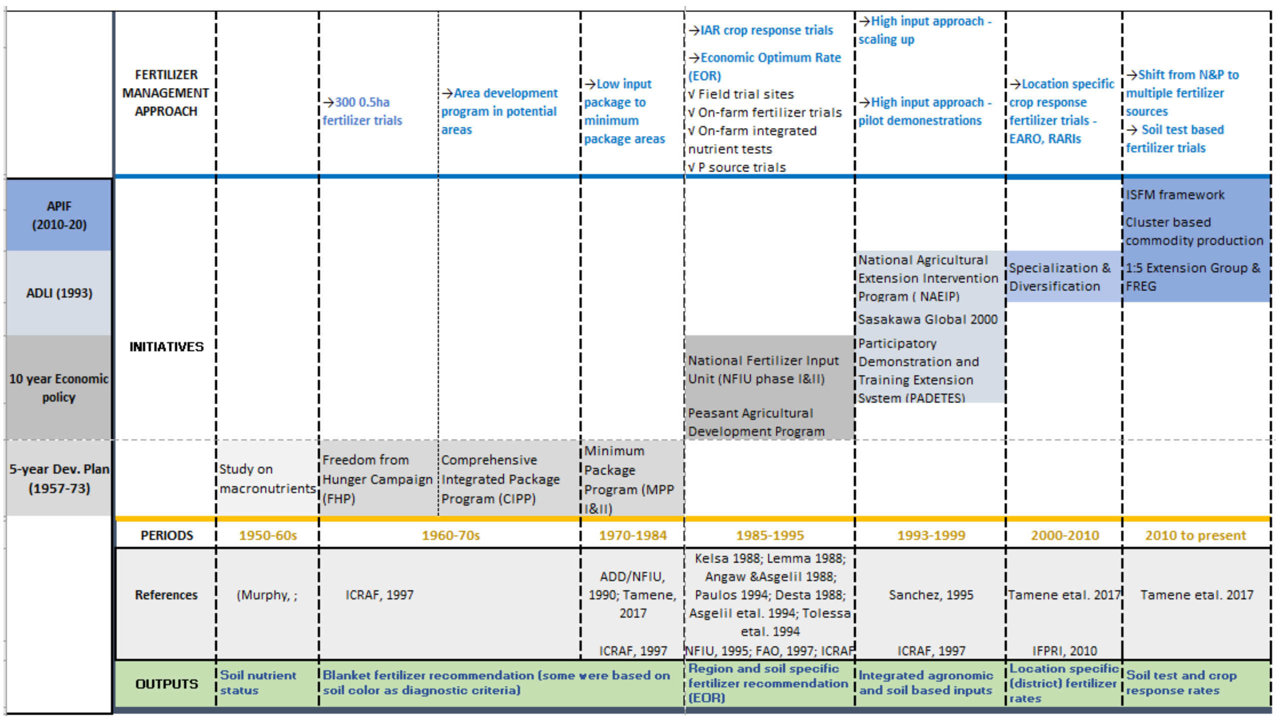

Figure 1. Illustration of evolution of fertilizer management and fertilizer rate decision methods in Ethiopia (Author own synthesis)

Why landscape specific fertilizer recommendation is relevant?

In the last decade, the national research system has involved in coordinated fertilizer trials in response to the focus on the validation of newly introduced fertilizer sources and the urgency of location specific fertilizer recommendations. Extensive evaluation and validation of different blended fertilizers, omission and rate trials have been implemented under different farming systems. However, even though the proportion of crop land uses in the country covered all ranges of slope classes, almost 90% of the fertilizer trials were implemented on fields with <10% slope gradients (figure 2). Given this context of the fertilizer research, one must question the representation of all slope gradients by the resulting fertilizer recommendations and the consequences of its adoption by the farmers. The research recommendations have thus limited representation of the actual farming systems and topographic features. The landscape specific fertilizer management approach aimed to fill the gaps of misrepresented research trials in the national research system. This entails the necessity of developing optimized fertilizer recommendations taking into consideration the variability of fertilizer responses along the landscape positions. In addition, landscape is a relevant scale where it is a decisive factor for guiding farmers' local fertilizer use and management practices. The relevance of fertilizer management along landscape positions is found relevant and useful to guide optimum and profitable fertilizer use.

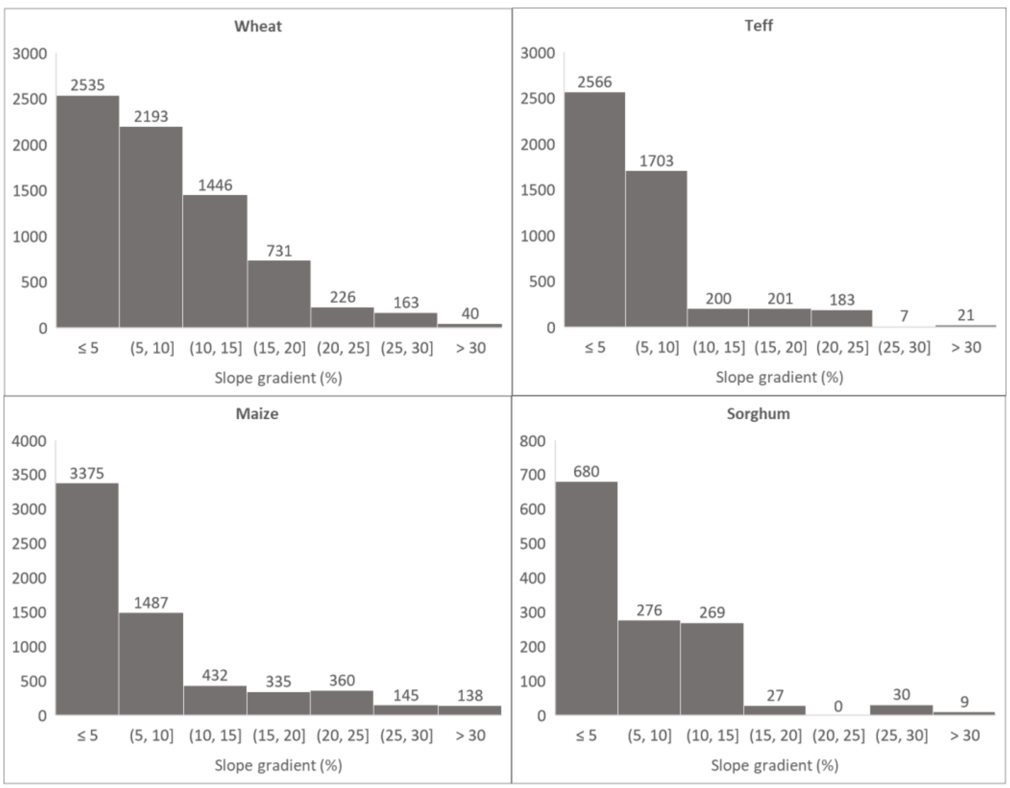

Figure 2. Slope coverage of national fertilizer research trials

Characteristics of landscapes in terms of farmers' agronomic practices

The diverse surface landforms and heterogenous soil types are associated with various cropping and fertilizer management practices (Kaizzi, et al., 2017). Farmers used to characterize their local soil types and recognize differences in land uses and crop suitability in terms of capability of soils for long term productivity, water holding capacity, and tillage and planting requirements. Understanding and characterizing farmers' fertilizer use, and management is useful to set a benchmark for targeted fertilizer application and nutrient use efficiency. A farmer participatory approach that employed focus group discussions with farmers provided context specific fertilizer use information together with the associated soil conditions, cropping systems and planting date information along three landscape positions (hillslope, midslope, footslope). Soil depth is one of the soil characteristic features and local indicator to distinguish landscape positions. Farmers used soil depth as proxy indicator to characterize the fertility status and productivity potential of their parcels. Hillslopes are characterized by shallow depths followed by mid and foot slopes (figure). The variation in soil depth determines the water holding capacity and nutrient management and the productivity levels of the landscape positions.

Moreover, the results of the focus group discussions indicated that farmers have practiced spatially explicit cropping systems, planting dates and fertilizer management along localized landscape positions relevant at specific context. Cereal-pulse rotated cropping systems are commonly observed as a characteristics of hillslope landscape positions in both wheat and teff production systems (figure 3). In teff production systems, foot slopes are dominated with cereal followed by cereal or cereal followed by pulses under residual moisture during post-rainy seasons. The cropping systems within and between landscape positions were further segmented by planting dates which is highly associated with soil type and its moisture holding capacity. Upslopes experience early planting under sub-optimal moisture condition while planting on foot slopes are taking place under wet and/or saturation moisture status. The planting dates for teff and wheat range from 1st decade of July to 3rd decade of August and 1st decade of June to 1st decade of August, respectively (figure 3). Planting dates within each landscape position vary by at least one week to one decade. Such variability in farmers cropping and planting dates along the landscape positions entail the need for variable fertilizer management. The differences in agronomic practices are attributed to soil depths and associated water holding capacity of landscape positions (figure 4). These distinct characteristics of landscape segments in terms of cropping systems and planting dates coupled with variation in soils and topographic/geomorphologic features could verify the relevance of landscape position for farmers as decision factor for fertilizer management.

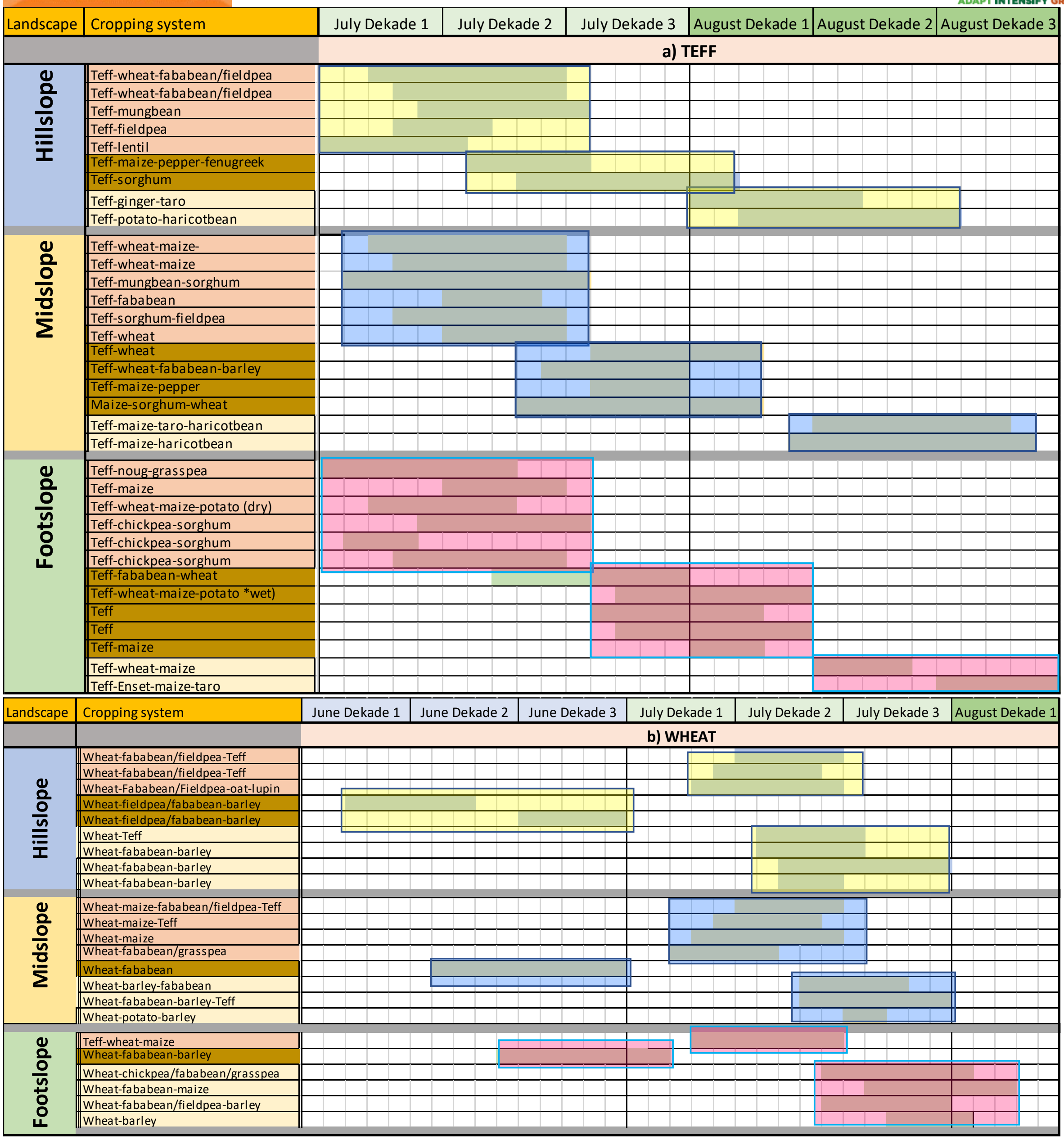

Figure 3. Farmers cropping system and planting date practices of teff, and wheat explained by localized landscape positions surveyed in 24 sampled locations of mixed farming systems. Farmer focus group discussions held during September to October 2022.

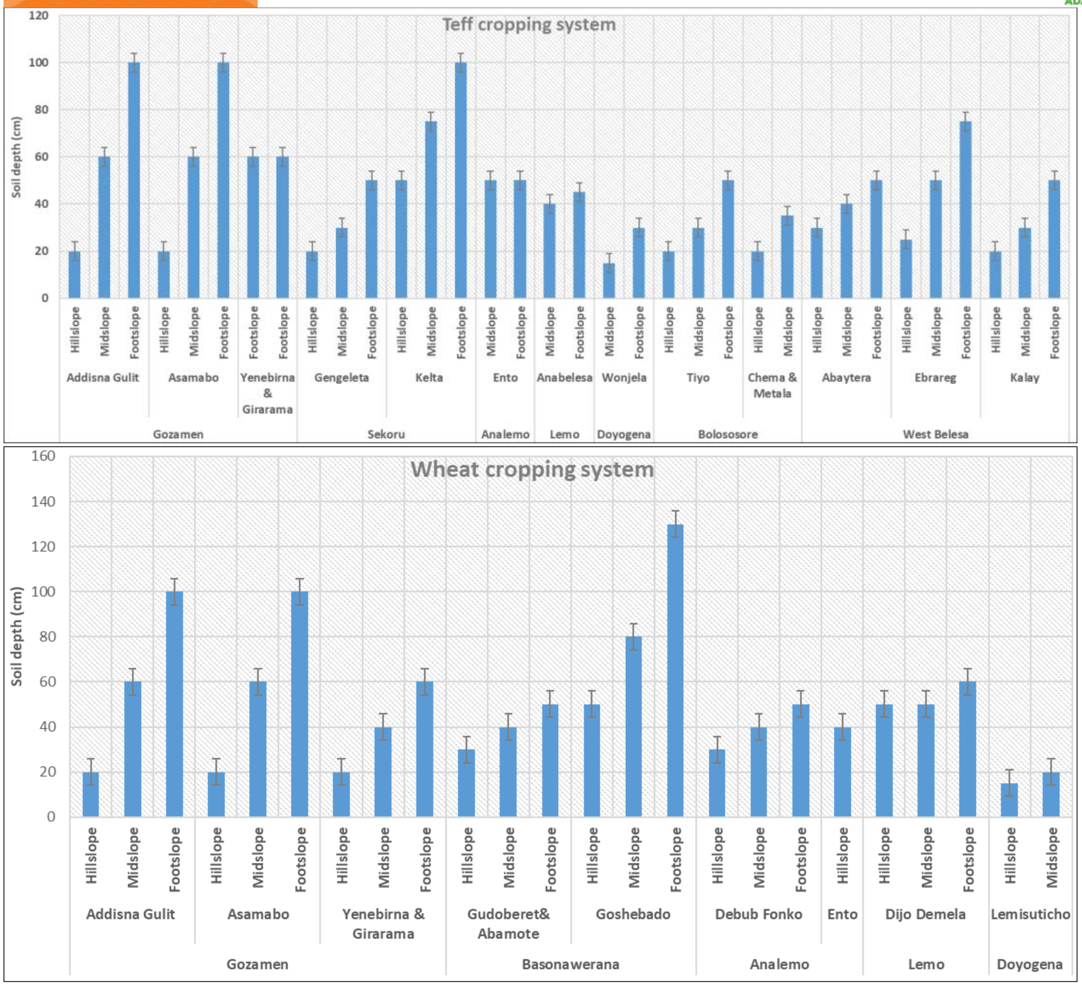

Figure 4. Soil depth variability along landscape positions of pilot districts

Farmers' fertilizer uses along landscapes

Current farmers' fertilizer use practices were discussed with group of farmers in 24 kebele administrations (lower administrative unit) where the piloting of fertilizer Advisory implemented. After thorough discussion and brainstorming with focus group participant farmers, they estimated the average nutrient application rates for each crop types (teff and wheat) considering variable use along landscape positions (figure 6). It is observed that farmers nutrient use practices vary by crop types and landscape positions. Farmers perceived to apply high amount of fertilizer for wheat than teff cropping systems. Based on farmers perceived nutrient application and regardless of the landscape positions, farmers applied 5-100 kg/ha N and 4-35 kg/ha P for teff and 50-200 kg/ha N and 10-35 kg/ha P for wheat (figure 6). Farmers applied high fertilizer rates at fields situated on hillslopes as they perceived high yield response under low fertility status and vice versa on foot slopes. Despite there is high fertilizer application by farmers on hillslopes, farmers estimated grain yield revealed a decreasing trend from foot slopes to hillslopes (figure 5). The low grain yield on hillslopes in response of applying high rate of fertilizer implies inefficient fertilizer uses leading to marginal benefit to fertilizer investment.

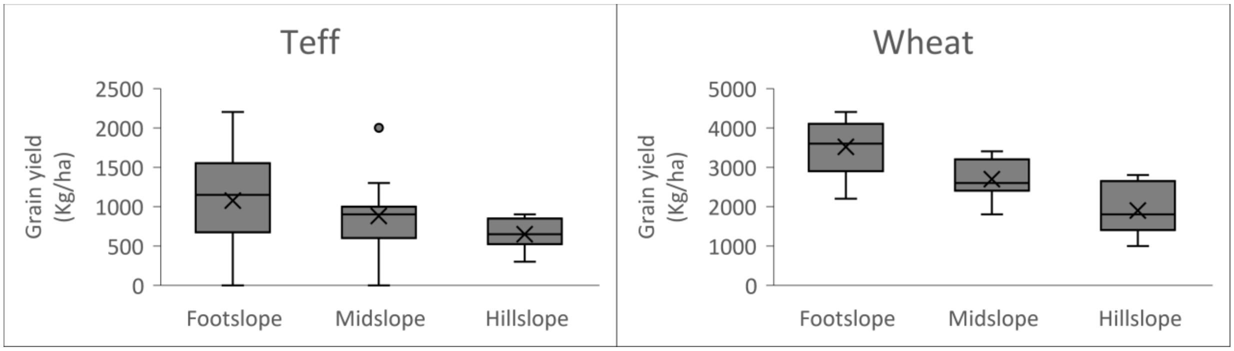

Figure 5. Grain yield information on farmers' fields which are generated from farmer focus group discussions

The resulting agronomic efficiency was found low which is attributed to inadequate farmers' knowledge of nutrient requirements at specific conditions and inefficient use. The inefficient fertilizer use was illustrated by the different trends of agronomic efficiency at three landscape positions (figure 6). Figure 6 shows the agronomic efficiency of farmers current fertilizer use for teff and wheat at three landscape segments. This farmer practice resulted in non-effective nutrient use as there is high rate of fertilizer use on hillslopes which has low crop yield response. This is unlike the expected localized nutrient requirements and associated yield response. Naturally, comparing the same rate of fertilizer application, the overall yield response is high on fields belonging to foot slopes than the hillslopes. There should be an increasing yield response per unit of fertilizer at hillslopes only for a small range of fertilizer rates. While the yield response on relatively fertile and flat lands is increasing per unit of fertilizer use for a large range of fertilizer rates. Thus, it is essential to bring change of farmers fertilizer use towards an optimized fertilizer rate over landscapes that maximize the return for a unit of fertilizer investment.

Yield gain from landscape targeted fertilizer application

Yield comparison between the landscape targeted fertilizer recommendations and the current extension recommendation (control) are indicated in figure 7. The yield response of landscape specific fertilizer rate against the yield of control varies by location and landscape positions. The yield comparison shows that the new landscape-based fertilizer innovation has shown yield advantage/gain over the blanket extension recommendation for over 65% of the tested fields for both wheat and teff crops (figure 7). Relatively, negative yield gain was observed on fields belonging to hillslopes where the yield of blanket recommendation exceeded the new recommendation. The negative yield gain was often related to locations affected by soil acidity where farmers applied more fertilizer to compensate unavailable nutrients due to the imbalance. Charts on cumulative probability of grain yield illustrated a relative yield advantage was gained from the landscape specific fertilizer recommendations against the extension recommendation and baseline yield records (figure 7). Considering observations with same cumulative probability of occurrence, higher yield was measured from landscape specific rate than extension recommendation. The yield gain was highly pronounced for teff than wheat as some wheat piloting locations affected by soil acidity. The landscape specific rate exceeded the control for those farmer fields where yield was above 1.0 ton/ha for teff and 2.5 ton/ha for wheat.

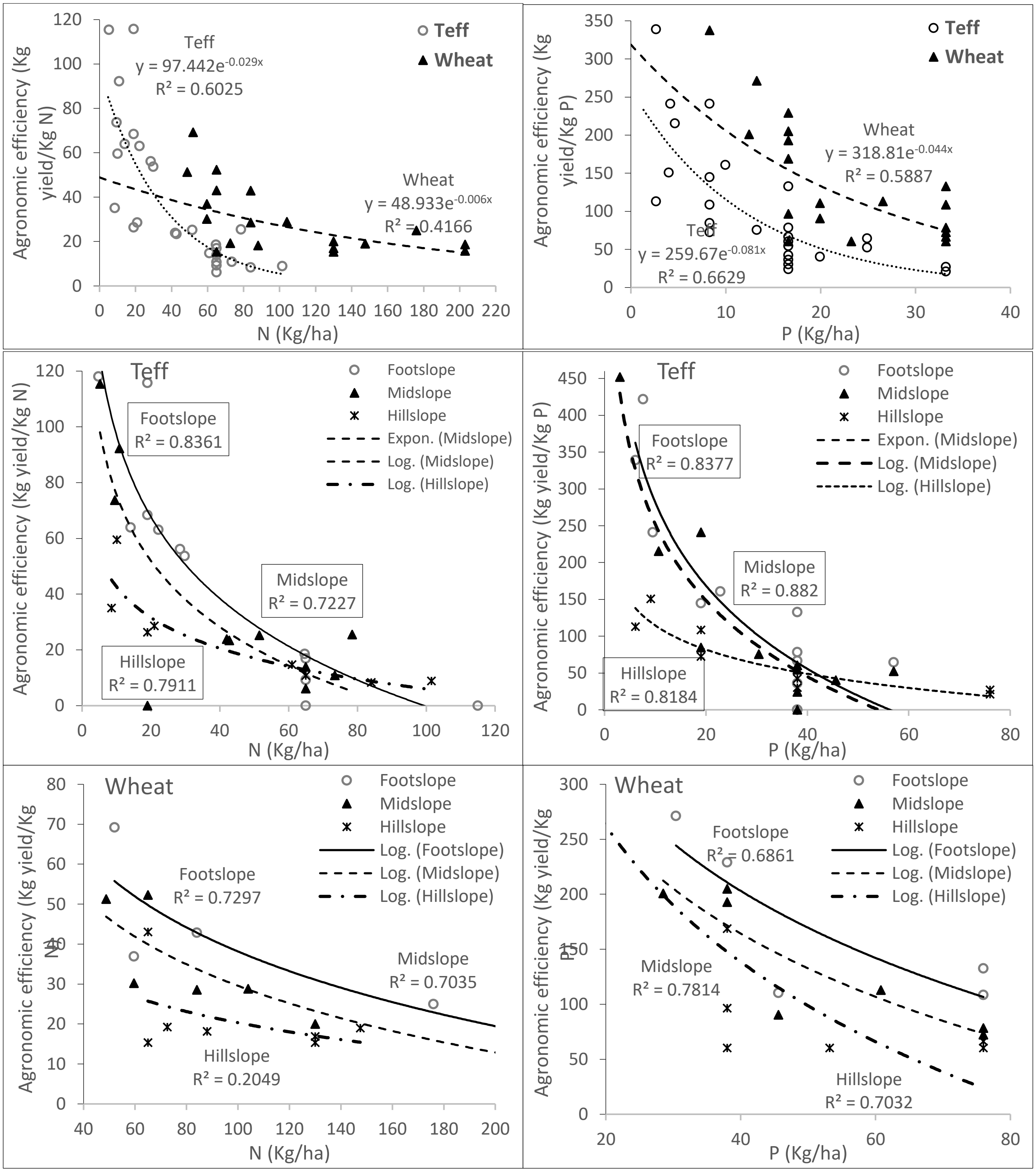

Figure 6. Agronomic efficiency of N and P fertilizers under farmer management practice of teff and wheat fields.

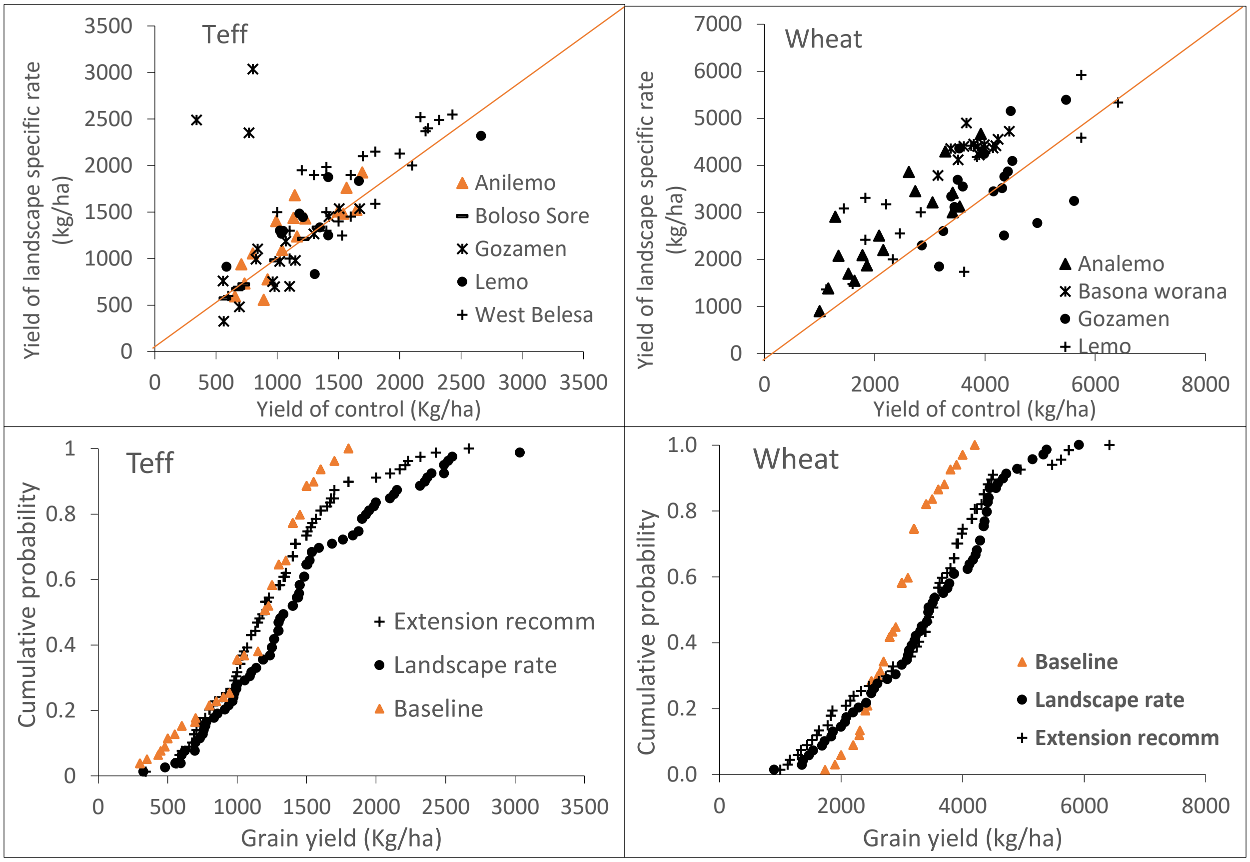

Figure 7. Comparison of yield response and cumulative probability of yield response from landscape specific rate and blanket recommendations for teff and wheat.

Economic benefits of landscape targeted fertilizer application

Apart from yield gain, the economic benefit of the landscape specific fertilizer application was evaluated in terms benefit to cost ratio and net benefit. As shown in figure 8, although only 65% of the total observations have shown yield advantage of the innovation, economic benefits have been measured in all the observations. Highly significant economic benefits over the blanket recommendation were recorded for teff. Whereas better economic gain was measured for wheat only for observations yielding high net benefit and benefit to cost ratio. Overall, optimized, and targeted fertilizer management along landscape positions at farmer relevant scales results in an increased return to fertilizer investment via reducing the cost of inputs and increasing profitability of farmers; and improving production efficiency and thereby increasing system productivity through judicious use of fertilizers and other agronomic practices.

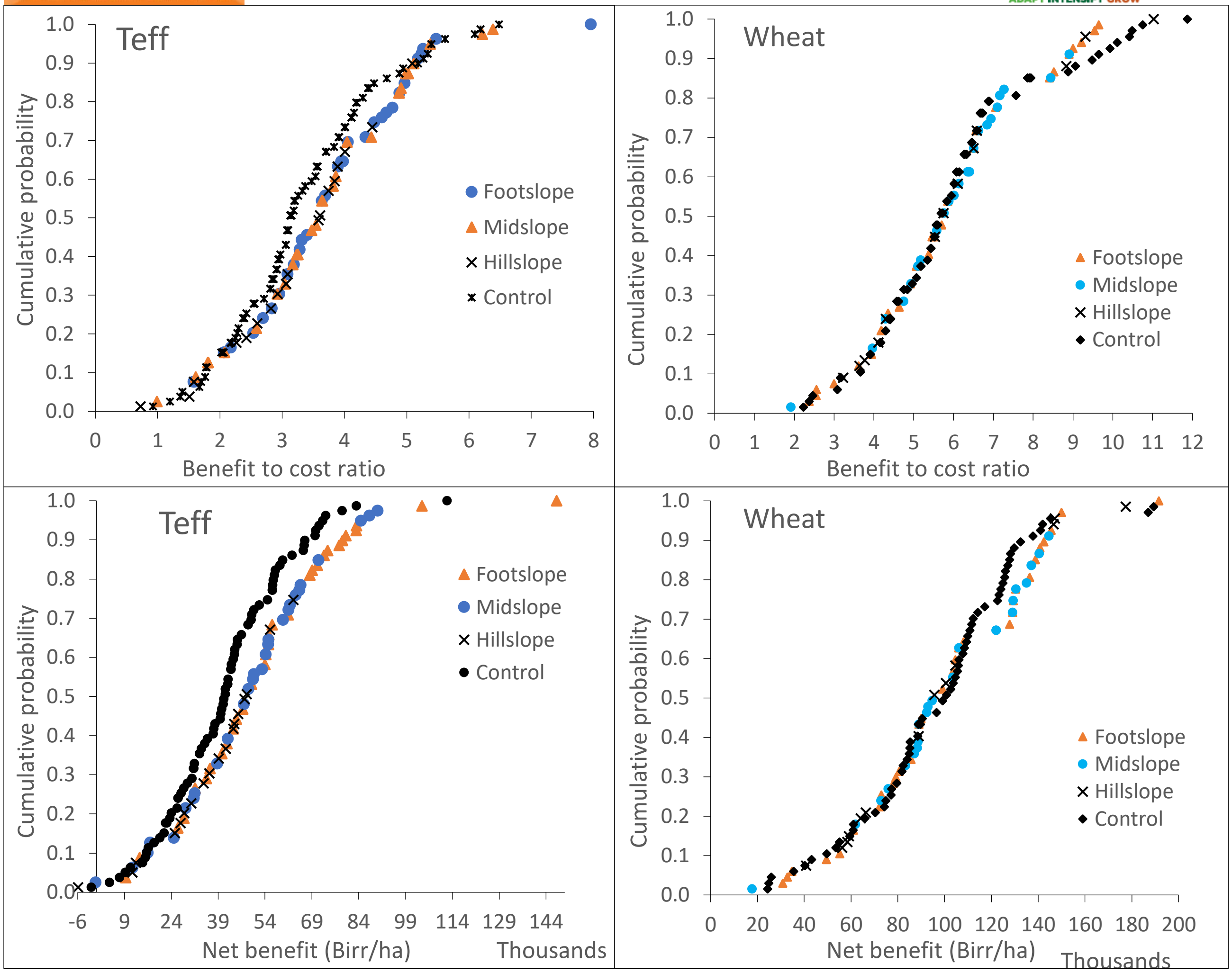

Figure 8. Comparison of economic response and cumulative probability of net benefits benefit to cost ratio from landscape specific rate and blanket recommendations for teff and wheat.

Learnings from the demand driven fertilizer advisory

Participants from different demand partners reflected on the piloting of the landscape-based fertilizer recommendations and digital advisory delivery systems. Almost all participants appreciated the landscape targeted fertilizer solution for solving the current imbalanced fertilizer use across landscape positions and farmer fields and help to address the gaps on the current blanket recommendations.

1. *Farmers* appreciated the performance of the landscape targeted fertilizer rates on pilot farmer fields with excellent crop stands, maturity, grain filling, and expected yields. They compared the performance of their fields with their previous experiences and explained the drawbacks of their practices. Farmers reflected the high performance of pilot fields by comparing with adjacent non-pilot fields. They have changed their wrong perceptions that they applied a large amount of fertilizer on

hillslopes and a small amount to foot slopes. Most farmers did not apply nitrogen fertilizer for teff and change their practice after the validation and piloting demonstrations. Because of these change in practices, farmers sought the profitability of the optimized rates of fertilizers at the landscape positions.

2. *Most farmers* realized and aware of the importance of applying Urea fertilizer for Teff and Sorghum to increase yields.
3. *Extension agents* appreciated the interventions and were interested in the digital advisory service which helps with the proper allocation of fertilizer to specific soil, cropping system, and landscape positions. Especially, they appreciated to apply right amount of fertilizer at the right time by measuring each farmers fields on the spot. It avoids overuse of fertilizers in most cases.
4. *Researchers* motivated to expand the practices and apply the bottom-up and demand driven approach in their pre-scaling demonstrations using the farmer-researcher-extension group (FREG) approach and support the community using the new landscape-based fertilizer recommendation practice.
5. *Agricultural experts* said that the piloting demonstrated an optimized fertilizer application and change the usual practice of farmers as they used to apply more fertilizer to hillslopes. This new intervention will ease their tasks and agreed to use the new landscape specific recommendation practice and are interested to use the digital delivery tool for the extension advisory services. Further consultative discussions on scaling undergone with scaling partners regarding the packaging of solutions, delivery formats and options, bundling of advisories in the existing platforms.
6. *Decision makers* are motivated to expand the new landscape targeted fertilizer recommendations to more target areas and farming systems and begin to develop scaling plans.
7. *All actors* increased localized understanding of agronomy and the relevance and impact of local scale nutrient management. Decision makers, extension agents and farmers often emphasize and give priority to variety dissemination and pest control.

8. *Creating feedback loop* with end users and contextualizing the landscape fertilizer tool with local knowledge increased the relevance of the content and maturity of the tool to scale. For example, customize the app to farmers' farming context – parcels, cropping system, planting dates and characterizing agronomy and nutrient management at farmer relevance landscape scale. *Multiple demand partner and bottom-up approach* play a key role in getting buy in and acceptance of the content and delivery formats by the end users.
9. *Enabling the delivery system*: Collaborative platforms at local and national level as well as collaboration between agronomy, extension, and research (for developing content), and extension communication (extension delivery) is found an essential process as enabling mechanism for scaling.

10. *Social media platforms* - communities of practices (researchers, extension agents, experts, decision makers) enhanced knowledge exchange and communication on DST for landscape targeted fertilizer applications and help to explore more demand requirements from farmers, extension, NARS, Input suppliers/cooperatives which will lead to integrated digital platforms and wider scaling.

11. *Setting target on the crop yield increase and NUE to fertilizer application* is an important aspect of developing a strategy of site-specific soil nutrient management and optimized fertilizer recommendation. Target optimal nutrient use efficiency that does not lead to environmental and economic cost is essential. An integrated soil health approach is thus essential to increase sustainable nutrient and will require actions across scales, sectors, and disciplines.

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