

An *ex ante* evaluation of targeted fertilizer recommendations for Ethiopian cereal producers

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Abstract

Agricultural extension systems in settings with variable landscape positions, such as foot slope, mid-slope and hill slope often provide fertilizer use recommendations that do not take into account variability in landscape positions. While the limited consideration of landscape positions in agricultural extension programming may partly explain the low and variable agronomic and economic returns to fertilizer use, empirical evidence under farmers conditions is thin. In this report, we document preliminary findings from an *ex ante* evaluation of landscape-targeted fertilizer recommendations for sorghum, teff and wheat production in Ethiopia. We use data from a farm-household survey and on-farm validation trials complemented with geospatial soil, rainfall, crop and fertilizer price data from secondary sources. Results show that yield response to and profitability of fertilizer is, on average, low and varies across landscape positions. In addition, fertilizer application appears marginally more profitable on foot slopes and mid-slopes compared with hill slopes, irrespective of the cereal type. Furthermore, fertilizer application under landscape-based fertilizer recommendations seems marginally more profitable compared with fertilizer application under farmer current fertilizer application and current extension fertilizer recommendations, indicating that landscape-targeted fertilizer advisories may contribute to improving returns to fertilizer. Overall, we note that substantially improving fertilizer use efficiency and investment returns would likely require a holistic approach, involving soil health and agronomic management, market and institutional considerations, beyond landscape-targeted fertilizer advisories.

Keywords: fertilizer recommendations, fertilizer profitability, landscape positions, marginal physical product of fertilizer, sorghum, teff, wheat.

1. Introduction

Despite the crucial role of agricultural productivity growth in addressing food insecurity and rural poverty, cereal crop yields are relatively low in many parts of Sub-Saharan Africa (SSA) compared with yields in other regions (Jayne and Sanchez, 2021; Wollburg et al., 2024). Soil health challenges, including soil fertility depletion and acidity, limited application of fertilizer, and suboptimal soil and crop management practices contribute to the prevalence of low crop yields (Barrett & Bevis, 2015; Chivenge et al., 2020; Dobermann et al., 2022; Warner et al., 2023). Notably, farmer survey-based findings from different parts of SSA show that cereal yield response to inorganic fertilizer is low and highly variable (e.g., Abay et al., 2022; Assefa et al., 2021; Burke et al., 2017, 2019, 2020, 2022; Chamberlin et al., 2021, Harou et al., 2017; Liverpool-Tasie et al., 2017; Marennya & Barrett, 2009; Ragasa & Chapoto, 2017; Scheiterle et al., 2019; Sheahan et al., 2013; Theriault et al., 2018; Xu et al., 2009, etc.). This contributes to explaining the low and variable fertilizer profitability and use rates widely reported in the literature (Jayne et al., 2019).

In settings with variable agricultural landscape positions, such as Ethiopia, soil conditions vary by landscape positions, which may affect crop yields and fertilizer investment returns. For instance, empirical agronomic studies show that variability in landscape positions is strongly associated with variability in soil nutrient status, soil organic matter, soil water retention capacity and agronomic management requirements of crops (Amede et al., 2020; Bubebo et al., 2021; Desta et al., 2022; Masha et al., 2023; Seifu et al., 2020). Yet agricultural extension systems in settings with variable landscape positions “foot slope, mid-slope, and hill slope” often provide general “blanket” fertilizer use recommendations that do not take into account the variability in landscape positions (Desta et al., 2023). Such fertilizer recommendations may be suboptimal for several farmers, hampering learning and technology adoption, fertilizer responsiveness and associated farm performance (Agegnehu et al., 2023; Haile et al., 2024). In response to this challenge, the CGIAR initiative on Excellence in Agronomy (EiA) through the Fertilizer Ethiopia Use Case led by the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) in collaboration with national partners co-developed a prototype

landscape-based fertilizer advisory tool for sorghum, teff and wheat¹. The tool was validated in the 2021 main cropping season in Ethiopia and refined with the validation trial data².

Despite the large body of farmer survey-based findings on fertilizer responsiveness and profitability in SSA, the role of landscape positions has received limited attention. For instance, some studies focus on the role of soil organic carbon (Burke et al., 2019; Chamberlin et al., 2021; Marenya & Barrett, 2009), acidity (Burke et al., 2017), subsidies (Ragasa & Chapoto, 2017; Scheiterle et al., 2019), rainfall (Chamberlin et al., 2021; Theriault et al., 2018) and weed management (Burke et al., 2020; Scheiterle et al., 2019), among others. On the other hand, while there is growing agronomy literature on landscape and soil parameter nexus, and investments tailored to the development of landscape-based fertilizer advisories, empirical evidence on potential farm-level returns to landscape-targeted fertilizer recommendations is thin. Desta al. (2023) made the first attempt to document agronomic and economic gains associated with landscape-targeted fertilizer application for teff and wheat using fertilizer trial data in Ethiopia. Yet, agronomic and economic gains under on-farm trial conditions may not reflect gains under real-world farmer conditions (see Laajaj et al. [2020] for a detailed discussion). Thus, in cereal-producing areas with variable landscape positions, it remains unclear if (and to what extent) fertilizer use rates and returns under farmer current fertilizer practices and traditional extension fertilizer recommendations deviate from expected fertilizer use rates and returns under proposed landscape-targeted fertilizer recommendations.

In this report, we document preliminary findings from an *ex ante* evaluation of landscape-targeted fertilizer recommendations for sorghum, teff and wheat production in Ethiopia. Specifically, we evaluate expected fertilizer use profitability over three scenarios: farmer current fertilizer application, current extension fertilizer recommendations and proposed landscape-targeted fertilizer recommendations to better inform the scaling of targeted fertilizer recommendations. We use data from a farm-household survey and on-farm validation trials complemented with geospatial soil, rainfall, fertilizer price and crop price data from secondary sources. We estimate a flexible production function and derive the marginal and average physical product of applied nitrogen (N). The average

¹ Leveraging recent advances in data science, geospatial analysis, remote sensing, and behavioral sciences, the EIA initiative aims to deliver agronomic solutions at scale through different Use Cases, who are co-developing Minimum Viable Products (MVPs) in collaboration with demand partners in targeted geographies. The Fertilizer Ethiopia is one of the Use Cases whose MVP is a landscape-based fertilizer advisory tool.

² The prototype advisory tool is a product of machine learning-constructed fertilizer application decision rules using landscape-based on-farm trial data for teff, wheat and sorghum implemented over 2014 to 2021 period and geospatial soil, weather and topography datasets (see Desta et al. [2023] for extensive discussions on the tool development process).

physical product of applied N and relative crop output/N price ratios are used to compute the average value cost ratio (AVCR) to examine the relative profitability of fertilizer under current farmer fertilizer application. Lastly, we compute the AVCR of the recommended N application rates under current extension and proposed landscape-based fertilizer recommendations using our production function estimates, the recommended N rates and relative crop output/N price ratios.

Our findings contribute to the thin literature on the interface of fertilizer investment returns, landscape positions and locally tailored advisories. In this way, we build on previous studies that highlight low and variable returns to inorganic fertilizer in different parts of SSA stemming from variations in soil organic matter (e.g., Chamberlin et al., 2021; Marenya & Barrett, 2009), soil acidity (e.g., Abay et al., 2022; Burke et al., 2017), transaction and transportation costs (Liverpool-Tasie et al., 2017; Minten et al., 2013), agro-ecological conditions (Sheahan et al., 2013; Theriault et al., 2018), weed management (Burke et al., 2020; Scheiterle et al., 2019), among others. In particular, we add new insights by showing that the mismatch between farmer current fertilizer application and the landscape-based fertilizer requirement for sorghum, teff and wheat in areas with variable landscape positions may partly explain the observed fertilizer use returns. In this regard, targeting fertilizer recommendations based on landscape positions can partly improve returns to fertilizer use, which lends credence to R&D efforts on landscape-targeted fertilizer recommendations.

The remainder of the report is structured as follows. In section 2, we describe the data and estimation strategy employed in our study. In section 3, we present our main results and provide a detailed discussion in section 4. Section 5 concludes with a summary of the main findings and implications.

2. Methods

2.1. Data

We used data from different sources including landscape-targeted nutrient management on-farm validation trials, baseline farm-household survey and online database. The on-farm validation trials were conducted in the 2021 main cropping season to evaluate the performance of landscape-targeted nutrient management in comparison with current extension “general” recommendations for teff, wheat and sorghum. The validation trials for wheat were conducted across four districts for wheat, five districts for Teff and one district for Sorghum under the Fertilizer Ethiopia Use Case of the CGIAR EiA led by ICRISAT in collaboration with national agricultural research and extension partners. The validation trial data include current traditional extension and landscape-targeted fertilizer

recommendations for different districts, input quantities and prices, management practices, production and output prices. The baseline survey was implemented from May to June 2023 among about 1000 sampled cereal-producing households across eight districts in Amhara, Oromia and SNNP regions. The survey was conducted by both the Monitoring, Evaluation, Learning and Impact Assessment (MELIA) team and the Fertilizer Ethiopia Use Case team of the CGIAR EiA. The survey data include household level data including demographics, access to services, income, food security, etc. and detailed plot level agronomy data for teff, wheat and sorghum. Data from secondary sources include teff, wheat and sorghum market prices from Famine Early Warning Systems Network (FEWS NET), fertilizer market prices from Africafertilizer.org, geospatial soil data at 30-meter spatial resolution from Innovative Solutions for Decision Agriculture (iSDA) (Hengl et al., 2021) and rainfall dataset from the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) dataset (Funk et al., 2017).

2.2. Estimation strategy

Drawing on agronomic and economic literature, we model cereal yield as a function of fertilizer application rate, notably N application rate in our study, other farmer-controlled factors including agronomic management decisions and other exogenous factors including soil characteristics, notably landscape positions (foot slope, mid-slope, hill slope) in our study and weather variables, such as rainfall. Following empirical applications in previous studies (e.g., Burke et al., 2017; Chamberlin et al., 2021; Sheahan et al., 2013), we apply a flexible polynomial functional form, as follows:

$$Y_{ij} = \beta_0 + \beta_1 N_{ij} + \beta_2 N_{ij}^2 + \beta_3 \mathbf{LP}_{ij} + \beta_4 N_{ij} * \mathbf{LP}_{ij} + \beta_n \mathbf{X}_{ij} + \varepsilon_{ij}$$

Where: Y_{ij} is sorghum, teff or wheat yield of plot i of household j (kg/ha), N_{ij} is the amount of N applied (kg/ha)³, \mathbf{LP}_{ij} is a vector of indicator variables for landscape positions including foot slope and mid-slope with hill slope as the reference landscape position, \mathbf{X}_{ij} is a vector of plot, household and exogenous determinants of yield, To capture potential diminishing marginal returns to N, we include a quadratic term for N. β_i is the parameter to be estimated ($i=0, 1, 2, \dots, n$), ε_{ij} is the error term. In theory, a large set of interaction and quadratic terms would be desirable, but this is not always feasible in practice partly due to data limitations. In this regard, we consider a few interaction terms of interest to the focus of our study: an interaction of N with a binary indicator for plots on foot slopes and an

³ N and Phosphorus (P) nutrient rates are based on the fertilizer blends reported by farmers in the survey, which include urea (46% N), NPS (19% N, 17% P and 7% S), DAP (18% N, 20% P), NPSB (18.9% N, 17% P, 6.95% S, and 0.1% B) and NPSZnB (17.8% N, 15% P, 7% S, 2.2% Zn).

interaction of N with a binary indicator for plots on mid-slopes with hill slope as the reference landscape position. The latter allows us to model yield response to N conditional on landscape positions, which is captured by the vector of parameters, β_4 .

Estimating yield responses with farmer survey data can produce biased estimates due to plausible correlations between fertilizer use decisions and unobserved or omitted factors, such as omitted farmer managerial ability and soil quality (Burke et al., 2017; Liverpool-Tasie et al., 2017). In the absence of a panel dataset and valid instruments, we control for years of farmer education and years of farming experience as proxies for farmer ability. Leveraging geospatial datasets, we control for soil organic carbon, pH and clay content as proxies for soil quality, and. Furthermore, we control for rainfall amounts during the season, rainfall variability, and other potential yield determinants. Finally, we use region dummies to account for any unobserved region-specific factors that could affect crop yields. In general, controlling for yield determinants that are likely correlated with fertilizer use helps us to minimize potential endogeneity bias that is often associated with estimates of yield response function.

Using the estimated yield response function, we derive the marginal physical product (MPP) of applied N and the average physical product (APP) of applied N. The MPP of applied N, the change in crop output resulting from an additional unit of applied N, is estimated as the partial derivative of the yield response function with respect to applied N while accounting for quadratic N term and interactions of N with landscape positions. The APP of applied N, the average gain in crop yield per unit of applied N relative to not applying N, is calculated as the difference between predicted crop yields with N application and predicted crop yields without N application, divided by the quantity of applied N⁴. To examine the relative profitability of fertilizer use, we compute the average value-cost ratios (AVCRs) under farmer current fertilizer applications, current extension fertilizer recommendations and landscape-targeted fertilizer recommendations, as the APP of applied N multiplied by the crop output/N price ratios⁵.

Following Sheahan et al. (2013), we compute the AVCR of N fertilizer application under the current extension and proposed landscape-based fertilizer recommendations using our estimated production

⁴ In estimating APP under farmer current fertilizer applications, the predicted crop yields with N application is for the observed level of N applications. Under current extension and proposed landscape-based fertilizer recommendations, the predicted crop yields with N application is for the recommended N application rates.

⁵ While AVCR is predominantly applied in the literature, marginal value-cost ratio (MVCR) can be used to complement AVCR to gauge the profitability of fertilizer. For sake of brevity, we do not extend profitability of fertilizer using MVCR.

function, recommended N application rates and relative crop output/N fertilizer input price ratios. Traditionally, an AVCR greater than 1 is the threshold for gauging the profitability of fertilizer use, especially among risk-neutral farmers (Liverpool-Tasie et al., 2017; Burke et al., 2020). To better accommodate risk preferences (risk neutrality and risk aversion), as well as unobserved transfer costs that smallholders may face in fertilizer use, we opt for two thresholds: AVCR of 1 and 2. This aligns with previous studies that apply thresholds of 1, 2 and even 3, and considers AVCR greater than 2 as the magnitude of AVCR that can better motivate fertilizer use in high-risk production settings, where smallholder farmers are more likely risk-averse (Assefa et al., 2021; Ragasa and Chapoto, 2017; Sheahan et al., 2013; Theriault et al., 2018, etc.). We use one-way analysis of variance (ANOVA) to test whether nutrient application rates, yield and profitability vary significantly across landscape positions under farmers' current fertilizer applications, current extension fertilizer recommendations and landscape-targeted fertilizer recommendations.

3. Results

3.1. Descriptive results

Table 1 shows the summary statistics of farmer, farm and plot characteristics by crop type. Most of the farms are managed by male farmers, on average 47 years old, have about 3 years of formal schooling and with over 20 years of farming experience. Most of the teff and wheat plots are cultivated with inorganic fertilizer and herbicides compared with the sorghum plots. However, N and P application rates are higher in wheat plots compared with teff and sorghum plots. The use of improved seeds and pesticides is relatively higher in wheat plots compared with teff and sorghum plots. The use of organic fertilizer and intercropping is low across teff, wheat and sorghum plots. In terms of landscape positions, there is no considerable variation by crop type and a larger share of teff, wheat and sorghum plots are on foot and mid slopes. In general, the average yields of about 865 kg/ha, 1726 kg/ha and 1610 kg/ha for teff, wheat and sorghum, respectively are low compared with their on-farm potential yields in Ethiopia.

Table 1: Summary statistics of farm(er) and plot characteristics by cereal crop type

Variables	Teff	Wheat	Sorghum
<i>Farm(er) characteristics</i>			
Gender of farmer (1=male)	0.95	0.93	0.96
Age of farmer (years)	46.90(11.69)	47.96(12.06)	46.50(11.52)
Years of education of farmer	3.35(4.14)	3.56(4.24)	2.48(3.59)
Household size (no. of HH members)	6.38(2.26)	5.96(2.12)	6.20(2.14)
Years of farming crop	25.92(13.11)	26.13(12.76)	27.65(13.46)
Received extension advice (1=yes)	0.87	0.91	0.91
Number of plots cultivated	1.67(0.80)	1.82(0.10)	1.61(0.86)
<i>Plot characteristics</i>			
Yield (kg/ha)	864.65(655.15)	1725.79(1273.33)	1610.34(1291.39)
Use inorganic fertilizer (1=yes)	0.96	0.94	0.61
N applied (kg/ha)	71.53(64.84)	106.95(83.34)	27.24(44.84)
P applied (kg/ha)	28.26(25.46)	37.02(32.55)	4.40(8.37)
Use organic fertilizer (1=yes)	0.10	0.10	0.09
Use improved seed (1=yes)	0.27	0.54	0.12
Use herbicide (1=yes)	0.68	0.71	0.25
Use pesticide (1=yes)	0.21	0.43	0.27
Use hired labor (1=yes)	0.28	0.33	0.16
Use animal traction (1=yes)	0.75	0.78	0.70
Intercrop (1=yes)	0.06	0.001	0.02
Crop rotation (1=yes)	0.72	0.75	0.74
Bunds (yes = 1)	0.39	0.005	0.32
Terraces (yes = 1)	0.08	0.03	0.11
Plot area (ha)	0.43(0.36)	0.44(1.32)	0.48(0.38)
Plot distance (walking minutes)	20.10(20.75)	17.15(7.49)	46.36(44.74)
Own plot (1=yes)	0.75	0.70	0.74
Perception of soil fertility: high	0.18	0.12	0.15
Perception of soil fertility: medium	0.66	0.74	0.58
Perception of soil fertility: low	0.16	0.13	0.27
Landscape position: footslope	0.42	0.34	0.46
Landscape position: midslope	0.46	0.55	0.43
Landscape position: hillslope	0.11	0.11	0.11
Amhara region (1=yes)	0.62	0.66	0.79
Oromia region (1=yes)	0.11	0.03	0.08
SNNP region (1=yes)	0.27	0.30	0.13
Rainfall (mm)	830.35(135.22)	824.21(132.29)	843.93(100.23)
Rainfall variability	2.12(0.90)	1.93(0.50)	1.63(0.79)
# of HHs	806	603	246
# of plots	1114	868	329

Notes: Rainfall is the sum of total rainfall during the main agricultural season (*meher*), derived from the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) dataset (Funk et al., 2017), and matched to plot-level observations using GPS coordinates. Rainfall variability is calculated as the coefficient of variation of rainfall in the main agricultural season.

Table 2 shows that on plots where teff, wheat and sorghum are cultivated, soil fertility indicators including organic and total carbon, N total, P, K, pH, sand, silt and clay contents vary across landscape positions, except for P in teff plots. This indicates that soil nutrient status, soil organic matter, soil water retention capacity and agronomic management requirements of crops are likely to vary by

landscape positions. However, the observed variability by landscape does not align with farmers' current fertilizer use and associated yields. Table 3 shows that fertilizer use and application rates in teff, wheat and sorghum production do not vary by landscape position, except for the use of organic fertilizer in teff production. Similarly, fertilizer use, application rates and associated yields in teff, wheat and sorghum production do not vary by landscape position, except for teff yield. This suggests that farmers do not currently take into the variability in landscape positions in their fertilizer use investment decisions, which may partly explain the negligible variability in yields by landscape position. Put together, tables 2 and 3 show that regardless of the cereal type, there is a mismatch between farmers' current fertilizer use and associated yields with their soil fertility indicators across landscape positions.

Table 2: Summary statistics of soil parameters by landscape position

Variables	Footslope	Midslope	Hillslope	F value
<i>Teff</i>				
Carbon, organic (g/kg)	16.07(3.86)	17.04(3.77)	16.80(3.99)	7.85***
Carbon, total (g/kg)	24.18(2.83)	23.99(4.29)	25.19(4.08)	19.24***
N total (g/kg)	29233.46(21611.81)	27526.26(21650.92)	27409.37(21871.43)	11.41***
P, extractable (mg/kg)	11.00(2.36)	11.03(1.99)	11.24(1.50)	0.69
K, extractable (mg/kg)	226.84(27.47)	221.45(27.51)	210.41(26.76)	18.22***
pH in water	6.19(0.55)	6.10(0.52)	6.14(0.56)	3.81**
Sand content (%)	35.46(2.20)	34.89(2.96)	34.91(3.67)	4.58***
Silt content (%)	26.49(1.31)	26.22(1.30)	25.75(1.15)	16.99***
Clay content (%)	36.62(2.77)	37.10(2.63)	36.74(2.58)	4.39**
<i>Wheat</i>				
Carbon, organic (g/kg)	17.49(2.51)	18.55(2.30)	18.46(2.27)	19.00***
Carbon, total (g/kg)	24.18(2.83)	24.43(2.39)	25.81(2.73)	14.53***
N total (g/kg)	29233.46(21611.81)	36571.92(21628.03)	35720.3(19780.7)	11.03***
P, extractable (mg/kg)	11.85(2.17)	11.24(2.20)	12.53(1.45)	17.60***
K, extractable (mg/kg)	217.10(28.13)	224.97(24.01)	223.20(29.45)	8.40***
pH in water	6.06(0.35)	5.92(0.31)	5.93(0.30)	16.26***
Sand content (%)	33.40(2.05)	33.76(1.99)	32.72(1.63)	11.71***
Silt content (%)	27.13(1.37)	27.07(2.27)	26.65(1.18)	4.92***
Clay content (%)	37.94(2.17)	37.36(2.30)	37.97(1.68)	7.53***
<i>Sorghum</i>				
Carbon, organic (g/kg)	11.73(2.87)	13.07(3.96)	14.67(4.18)	11.99***
Carbon, total (g/kg)	18.75(5.59)	20.81(5.79)	24.78(4.19)	18.18***
N total (g/kg)	6215.53(11032.79)	12700.75(19206.03)	18099.14(21543.33)	10.42***
P, extractable (mg/kg)	11.35(1.37)	11.12(1.33)	10.78(1.27)	2.89*
K, extractable (mg/kg)	215.52(29.00)	207.05(30.22)	192.31(23.19)	10.10***
pH in water	6.80(0.43)	6.65(0.55)	6.46(0.57)	7.68***
Sand content (%)	36.01(3.20)	36.89(3.44)	36.99(3.42)	2.99*
Silt content (%)	26.39(1.33)	25.89(1.25)	25.44(1.13)	10.00***
Clay content (%)	36.41(2.44)	35.85(2.64)	35.08(2.24)	4.65***

Notes: F values are from one-way ANOVA tests of equality of means across the three landscape positions. * $p < .1$, ** $p < .05$, *** $p < .01$ denote statistically significant differences across landscape positions at 10%, 5% and 1% levels. Using GPS coordinates, we match the household survey data with publicly available geospatial soil data at 30-meter spatial resolution from Innovative Solutions for Decision Agriculture (iSDA) (Hengli et al. 2021).

Table 3: Summary statistics of farmer current fertilizer use and yield by landscape position

Variables	Footslope	Midslope	Hillslope	F value/ Chi-sq. value
<i>Teff</i>				
Use inorganic fertilizer (1=yes)	0.97	0.96	0.96	0.39
N applied (kg/ha)	73.43(66.98)	69.92(62.25)	70.94(67.79)	0.36
P applied (kg/ha)	28.06(25.16)	28.14(25.71)	29.45(25.81)	0.15
Use organic fertilizer (1=yes)	0.14	0.08	0.03	18.80***
Yield (kg/ha)	936.87(620.13)	840.18(696.23)	689.41(566.37)	7.71***
<i>Wheat</i>				
Use inorganic fertilizer (1=yes)	0.92	0.95	0.95	4.27
N applied (kg/ha)	108.88(83.38)	106.36(83.36)	104.03(84.13)	0.15
P applied (kg/ha)	37.61(31.45)	36.20(32.72)	41.51(34.96)	0.42
Use organic fertilizer (1=yes)	0.09	0.10	0.11	0.86
Yield (kg/ha)	1762.71(1317.13)	1718.78(1227.57)	1631.13(1374.84)	0.39
<i>Sorghum</i>				
Use inorganic fertilizer (1=yes)	0.67	0.58	0.53	2.92
N applied (kg/ha)	26.21(42.22)	27.37(44.96)	31.88(55.39)	0.23
P applied (kg/ha)	4.76(8.61)	4.59(8.20)	2.26(7.92)	1.35
Use organic fertilizer (1=yes)	0.07	0.11	0.06	2.09
Yield (kg/ha)	1688.23(1222.42)	1564.50(1344.68)	1466.55(1389.35)	0.58

Notes: N and P are based on the fertilizer blends used by farmers, which include urea (46% N), NPS (19% N, 17% P and 7% S), DAP (18% N, 20% P), NPSB (18.9% N, 17% P, 6.95% S, and 0.1% B) and NPSZnB (17.8% N, 15% P, 7% S, 2.2% Zn). F and Chi-sq. values are from one-way ANOVA and Chi-squared tests of equality of means across the three landscape positions for continuous and categorical variables, respectively. * $p < .1$, ** $p < .05$, *** $p < .01$ denote statistically significant differences across landscape positions at 10%, 5% and 1% levels.

Table 4 shows that current extension fertilizer recommendations for teff, wheat and sorghum do not vary significantly by landscape positions while the landscape-targeted fertilizer recommendations vary significantly by landscape positions in the sample districts in line with *a priori* expectation using the on-farm validation trial dataset. Similarly, teff, wheat and sorghum yields under current extension recommendations do not vary by landscape positions, but vary significantly under landscape-targeted recommendations, except for wheat yield. In terms of nutrient and yield gaps between farmers' current nutrient application rates (yields) and current extension recommended application rates (yields), we observe positive nutrient gaps and negative yield gaps across landscape positions for teff and wheat, except for the negative N nutrient gap for wheat on hillslope. This indicates that farmers' current nutrient application rates are on average larger than the current extension recommended rates, but the associated teff and wheat yields under farmers' current nutrient rates are on average smaller than the yields under current extension recommended rates. For sorghum, both nutrient and yield gaps are negative.

For nutrient and yield gaps between farmers' current nutrient application rates (yields) and landscape-targeted recommended application rates (yields), there are some variations in the direction of the nutrient gaps for teff and wheat across the landscape positions, but with negative yield gaps for both

crops. For teff, we observe negative N nutrient gaps on the foot slope and mid-slope, a positive N nutrient gap on the hill slope, a negative P nutrient gap on the foot slope, and negative P nutrient gaps on both the mid-slope and hill slope. For wheat, there are negative N nutrient gaps on the foot slope and mid-slope, a positive N nutrient gap on the hillslope, and positive P nutrient gaps across the landscape positions. For sorghum, both nutrient and yield gaps are negative. Overall, there are some variations in the magnitude of nutrient and yield gaps across landscape positions for teff, wheat and sorghum, except for the P nutrient gap for teff.

Table 4: Summary statistics of fertilizer recommendations, nutrient and yield gaps by landscape position

Variables	Footslope	Midslope	Hillslope	F value
<i>Teff: Current extension FR</i>				
N recommended rate (kg/ha)	60.26(15.64)	58.82(14.71)	55.00(15.20)	0.70
N nutrient gap (kg/ha)	+13.17	+11.10	+15.94	
P recommended rate (kg/ha)	17.04(2.58)	16.97(2.53)	17.74(2.98)	0.54
P nutrient gap (kg/ha)	+11.02	+11.17	+11.71	
Yield (kg/ha)	1206.26(505.73)	1322.10(555.43)	1239.11(288.84)	0.45
Yield gap (kg/ha)	-269.39	-481.92	-549.7	
<i>Teff: Landscape-based FR</i>				
N recommended rate (kg/ha)	110.79(23.58)	74.73(12.96)	55.22(8.37)	66.21***
N nutrient gap (kg/ha)	-37.36	-4.81	+15.72	
P recommended rate (kg/ha)	32.84(10.58)	20.82(6.44)	14.94 (4.14)	32.89***
P nutrient gap (kg/ha)	-4.78	+7.32	+14.51	
Yield (kg/ha)	1637.04(652.76)	1409.58(592.71)	1136.92(358.55)	4.40**
Yield gap (kg/ha)	-700.17	-569.4	-447.51	
<i>Wheat: Current extension FR</i>				
N recommended rate (kg/ha)	107.5(47.84)	104.54(47.90)	117.23(55.74)	0.29
N nutrient gap (kg/ha)	+1.38	+1.82	-13.2	
P recommended (kg/ha)	19.91(7.07)	19.65(6.95)	21.77(7.96)	0.40
P nutrient gap rate (kg/ha)	+17.7	+16.55	+19.74	
Yield (kg/ha)	3104.14(1174.03)	3256.84(1277.46)	4043.89(1123.08)	2.86*
Yield gap (kg/ha)	-1,341.43	-1,538.06	-2,412.76	
<i>Wheat: Landscape-based FR</i>				
N recommended rate (kg/ha)	135.1(13.25)	112.54(18.55)	59.77(9.59)	116.72***
N nutrient gap (kg/ha)	-26.22	-6.18	+44.26	
P recommended rate (kg/ha)	34.26(10.01)	28.97(2.79)	15.38(4.34)	31.26***
P nutrient gap	+3.35	+7.23	+26.13	
Yield (kg/ha)	3415.33(1241.25)	3551.82(1036.74)	3187.18(1141.14)	0.42
Yield gap (kg/ha)	-1,652.62	-1,833.04	-1,556.05	
<i>Sorghum: Current extension FR</i>				
N recommended rate (kg/ha)	41	41	41	
N nutrient gap (kg/ha)	-14.79	-13.63	-9.12	
P recommended rate (kg/ha)	15.73	15.73	15.73	
P nutrient gap (kg/ha)	-10.97	-11.14	-13.47	
Yield (kg/ha)	3121.25(1349.50)	3421.25(1510.00)	2177.50(383.43)	2.38
Yield gap (kg/ha)	-1,433.02	-1,856.75	-710.95	
<i>Sorghum: Landscape-based FR</i>				
N recommended rate (kg/ha)	94	75	60	
N nutrient gap (kg/ha)	-67.79	-47.63	-28.12	
P recommended rate (kg/ha)	20.10	16.61	10.05	
P nutrient gap (kg/ha)	-15.34	-12.02	-7.79	

Yield (kg/ha)	3645.25(1028.13)	4189.88(1476.90)	2502.50(515.88)	5.08**
Yield gap (kg/ha)	-1,957.02	-2,625.38	-1,035.95	

Notes: FR = fertilizer recommendation. N and P nutrient gaps are calculated as the differences between the means of farmers' current nutrient application rates from the baseline survey dataset (reported in Table 3) and the current extension and landscape-targeted recommended rates from the validation trial dataset. Similarly, the yield gaps are calculated as the difference between the means of yields under farmers' current nutrient application rates (reported in Table 3) and yields under the current extension and landscape-based recommended rates. F values are from one-way ANOVA tests of equality of means across the three landscape positions. F values are not reported for N and P recommended rates for sorghum because the sorghum on-farm validation trial was conducted in only one district and there is no variation in the recommended rates for all farmers in the district. * $p < .1$, ** $p < .05$, *** $p < .01$ denote statistically significant differences across landscape positions at 10%, 5% and 1% levels.

3.2. Production function estimates

Tables 5a, 5b and 5c show the production function estimation results for teff, wheat and sorghum, respectively using alternative specifications in line with the framing of our estimation strategy. In specifications (1) and (2), we do not include the interaction terms of N and landscape positions, but include them in specifications (3) and (4). In specification (1), we do not include region dummies, but include them in specifications (2), (3) and (4). In specifications (1), (2), and (3), we do not include controls for soil characteristics, rainfall and rainfall variability, but we do in specification (4).

The coefficient estimates of N application rate are positive and statistically significant across the model specifications for teff, wheat and sorghum, as expected. However, N application rate becomes statistically insignificant in specifications (2), (3) and (4) for sorghum. Similarly, the quadratic terms for N are negative and statistically significant across the specifications for teff and wheat, indicating diminishing marginal returns to applied N. As expected, landscape positions are important determinants of yield, particularly for teff. The coefficient estimates of plots on foot slope and mid-slopes are generally positive across the model specifications for all crops but statistically significant for teff, indicating that in the absence of N application, yields are higher on foot slope and mid-slope plots compared with plots on hill slope. Except for teff, the coefficient estimates of the interaction terms of N and landscape positions are statistically insignificant, indicating that under farmer current fertilizer application, cereal yield response to N application is weakly conditioned by landscape positions. For the sake of brevity, we do not interpret other significant drivers of cereal yield and focus only on the primary variables of interest to our study.

Table 5a: yield response function (Teff)

	(1) Teff Yield	(2) Teff Yield	(3) Teff Yield	(4) Teff Yield
N_rate	6.013*** (0.858)	4.966*** (0.853)	3.852*** (1.144)	2.833** (1.219)
N_rate ²	-0.013*** (0.003)	-0.011*** (0.003)	-0.010*** (0.003)	-0.007** (0.004)
N_rate x P_rate	0.004* (0.002)	0.003* (0.002)	0.002 (0.002)	0.002 (0.002)
plot_footslope	213.830*** (58.223)	214.436*** (56.306)	186.838** (75.081)	192.106*** (72.955)
plot_midslope	158.709*** (55.316)	152.479*** (54.041)	30.882 (74.878)	33.919 (74.472)
N_rate x plot_footslope			0.440 (0.800)	0.392 (0.761)
N_rate x plot_midslope			1.756* (1.008)	1.684* (0.980)
plotareaha	-321.679*** (88.823)	-286.719*** (83.461)	-278.582*** (84.097)	-240.517*** (85.399)
plotareaha ²	46.149** (19.923)	39.976** (18.986)	38.223** (18.515)	30.432* (18.423)
use_impseed	-22.210 (41.625)	13.935 (40.043)	12.769 (39.767)	34.621 (43.415)
use_orgfert	-60.407 (57.713)	-43.759 (51.739)	-39.153 (51.353)	-45.424 (52.259)
use_pesticide	222.081*** (50.538)	106.675** (50.333)	112.003** (49.395)	88.642* (49.210)
hiredlaboryes	-0.008 (0.015)	0.029* (0.016)	0.031** (0.015)	0.043** (0.020)
plot_owned	-129.267*** (46.186)	-26.060 (46.732)	-26.134 (46.493)	-2.641 (44.682)
plt_croprotection	2.972 (47.933)	-20.677 (44.760)	-22.059 (44.566)	-10.534 (47.062)
plt_draftanimals	-56.107 (54.653)	-26.425 (53.017)	-25.129 (52.539)	24.724 (48.662)
plt_intercrop	74.434 (74.336)	-30.386 (73.130)	-42.134 (72.479)	-5.992 (76.253)
education	-8.989 (5.632)	3.711 (5.737)	3.499 (5.700)	3.141 (5.864)
yrsexp	4.449*** (1.479)	-0.037 (1.544)	0.093 (1.506)	-0.444 (1.453)
hysize_adult	-78.946*** (23.582)	-8.601 (24.279)	-6.539 (24.091)	-8.888 (23.638)
amhara		449.154*** (58.536)	444.685*** (58.522)	526.558*** (83.162)
SNNP		-48.264 (56.022)	-49.805 (56.331)	-30.918 (97.135)
oc				-43.647 (26.703)
ph				-516.445** (206.822)
clay				-11.786 (8.564)
Inrain				142.618 (267.969)
rain_cv				-54.142 (47.354)
_cons	770.190*** (142.138)	333.313** (148.930)	394.306** (154.758)	3820.717 (2797.348)
N	1114.000	1114.000	1114.000	1114.000

Notes: Robust standard errors in parentheses clustered at household level, Reference level of landscape position = Hillslope, Reference level of region = Oromia, * $p < .1$, ** $p < .05$, *** $p < .01$.

Table 5b: Yield response function (Wheat)

	(1) Wheat Yield	(2) Wheat Yield	(3) Wheat Yield	(4) Wheat Yield
N_rate	11.337*** (1.458)	9.797*** (1.409)	9.683*** (2.032)	6.203*** (2.047)
N_rate ²	-0.017*** (0.005)	-0.015*** (0.005)	-0.015*** (0.005)	-0.009* (0.005)
N_rate x P_rate	-0.000 (0.003)	0.000 (0.003)	0.000 (0.003)	-0.001 (0.002)
plot_footslope	98.217 (155.075)	141.278 (147.572)	132.437 (230.890)	236.606 (221.450)
plot_midslope	99.029 (156.317)	187.445 (146.930)	169.412 (213.297)	261.892 (198.931)
N_rate x plot_footslope			0.086 (2.046)	0.490 (1.959)
N_rate x plot_midslope			0.170 (1.835)	0.244 (1.706)
plotareaha	-268.847* (141.069)	-174.746 (134.765)	-173.461 (137.105)	-307.415* (158.372)
plotareaha ²	8.450* (4.896)	4.770 (4.706)	4.719 (4.782)	9.250* (5.455)
use_impseed	132.954 (90.106)	85.694 (89.227)	86.005 (88.713)	133.916 (86.832)
use_orgfert	170.490 (127.360)	54.240 (127.204)	54.496 (127.524)	38.279 (128.410)
use_pesticide	354.606*** (96.612)	302.824*** (94.639)	302.642*** (94.604)	322.782*** (92.974)
hiredlaboryes	-0.225*** (0.080)	-0.176** (0.074)	-0.176** (0.076)	-0.058 (0.084)
plot_owned	-15.402 (86.595)	91.157 (90.931)	90.971 (92.413)	178.310** (90.390)
plt_croprotection	-35.954 (95.014)	-113.238 (98.291)	-113.411 (98.416)	-20.870 (97.512)
plt_draftanimals	107.114 (120.168)	175.772 (119.993)	176.041 (119.952)	406.308*** (125.740)
plt_intercrop	-1093.655*** (194.684)	-792.654*** (191.254)	-794.529*** (195.743)	-364.334 (253.642)
education	-16.680 (11.998)	-9.157 (11.892)	-9.217 (11.860)	0.528 (11.406)
yrsexp	-4.067 (3.328)	-12.094*** (3.679)	-12.090*** (3.681)	-11.744*** (3.470)
hysize_adult	-41.295 (48.415)	73.590 (53.670)	73.317 (53.840)	23.163 (52.085)
amhara		1090.782*** (187.178)	1089.571*** (186.881)	1294.822*** (244.908)
SNNP		500.761*** (160.280)	500.602*** (159.874)	1525.398*** (273.186)
oc				-46.158 (48.479)
ph				-759.645* (433.626)
clay				76.510** (29.951)
Inrain				2500.414*** (572.047)
rain_cv				-140.881 (119.730)
_cons	849.980*** (254.507)	-180.686 (289.122)	-167.085 (312.610)	-14641.847** (6350.582)
N	868.000	868.000	868.000	868.000

Notes: Robust standard errors in parentheses clustered at household level, Reference level of landscape position = Hillslope, Reference level of region = Oromia, * $p < .1$, ** $p < .05$, *** $p < .01$.

Table 5c: Yield response function (Sorghum)

	(1) Sorghum Yield	(2) Sorghum Yield	(3) Sorghum Yield	(4) Sorghum Yield
N_rate	12.100*** (3.914)	5.998 (4.221)	2.892 (6.372)	1.093 (7.130)
N_rate ²	-0.012 (0.017)	0.003 (0.017)	0.003 (0.016)	0.012 (0.017)
N_rate x P_rate	-0.146* (0.080)	-0.076 (0.080)	-0.069 (0.077)	-0.064 (0.081)
plot_footslope	54.192 (234.688)	-54.031 (240.611)	-190.620 (295.331)	-77.675 (318.584)
plot_midslope	26.669 (247.935)	1.818 (244.289)	-87.124 (295.038)	28.518 (318.401)
N_rate x plot_footslope			4.235 (4.204)	2.204 (4.303)
N_rate x plot_midslope			2.670 (4.852)	1.033 (5.068)
plotareaha	-657.272 (424.326)	-1596.379*** (439.158)	-1610.580*** (440.737)	-1670.762*** (458.634)
plotareaha ²	161.077 (144.345)	414.562*** (151.682)	414.858*** (152.106)	423.642*** (155.068)
use_impseed	-343.049 (247.508)	-255.868 (246.882)	-253.755 (248.640)	-216.031 (237.624)
use_orgfert	167.961 (249.378)	101.892 (219.225)	93.349 (218.765)	155.160 (226.378)
use_pesticide	647.277*** (186.978)	255.197 (205.226)	252.831 (206.349)	230.077 (218.223)
hiredlaboryes	7.105 (12.858)	18.927 (11.786)	19.813* (11.806)	17.222 (12.463)
plot_owned	64.669 (171.775)	204.096 (173.471)	207.337 (176.213)	178.394 (176.347)
plt_croprotection	-19.313 (183.800)	-122.181 (168.575)	-134.529 (168.548)	-99.548 (174.433)
plt_draftanimals	-46.413 (181.315)	5.714 (175.871)	-0.304 (176.557)	-22.131 (166.690)
plt_intercrop	-538.174 (403.486)	-427.399 (261.028)	-420.238 (265.619)	-431.094 (287.349)
education	3.654 (23.182)	19.391 (23.784)	20.232 (23.931)	18.409 (24.934)
yrsexp	3.495 (6.145)	-9.305 (6.141)	-9.132 (6.137)	-9.161 (6.028)
hysize_adult		169.762* (91.767)	176.336* (91.970)	176.135* (92.813)
amhara		1173.458*** (283.289)	1207.803*** (291.629)	1621.170 (1016.942)
SNNP		-429.642 (262.862)	-444.319* (262.204)	-561.905 (590.152)
oc				-105.964 (159.481)
ph				-1922.781* (1072.043)
clay				-54.261 (40.853)
Inrain				-261.919 (1578.779)
rain_cv				-490.465* (268.399)
_cons	1328.067*** (417.848)	767.443 (548.158)	831.736 (574.460)	19254.418 (17383.318)
N	326.000	326.000	326.000	326.000

Notes: Robust standard errors in parentheses clustered at household level, Reference level of landscape position = Hillslope, Reference level of region = Oromia, * $p < .1$, ** $p < .05$, *** $p < .01$.

3.3. Agronomic and economic returns to fertilizer use

Table 6a shows the marginal physical product of applied N (agronomic efficiency of applied N) by landscape position based on the baseline survey data and model specification (4) in Tables 5a, 5b and 5c, reflecting farmer current fertilizer practice, as well as the validation trial data, reflecting the landscape-based fertilizer recommendations. Based on farmer current fertilizer practice, the MPP of applied N for teff, wheat and sorghum, is on average, 2.78, 4.53 and 4.43 kg harvested grain per kg of N applied, respectively. This suggests that an additional kg of N is associated with about 2.8, 4.5 and 4.4 kg increase in teff, wheat and sorghum output, respectively. Except for wheat, the MPP of applied N vary significantly across landscape positions, as expected. Based on the validation trial data, the MPP of applied N for teff, wheat and sorghum, is on average, 1.48, -0.62 and 7.08 kg output per kg of N applied, respectively, and it varies significantly across landscape positions, except for sorghum. Notably, the on-average negative yield response to N for wheat masks the variability of yield response to N across the landscape positions, ranging from -13.84 kg output per kg of N applied on hill slope to 2.39 kg output per kg of N applied on foot slope.

Table 6a: Marginal physical product of applied N (agronomic efficiency of applied N) by landscape position

		Footslope	Midslope	Hillslope	F value
<i>Survey data</i>					
<i>Teff</i>					
MPP: Farmer fertilizer practice	2.78(1.13)	2.20 (0.91)	3.54(0.84)	1.84(0.93)	349.97***
<i>Wheat</i>					
MPP: Farmer fertilizer practice	4.53(1.41)	4.63(1.37)	4.51(1.49)	4.29(1.43)	1.97
<i>Sorghum</i>					
MPP: Farmer fertilizer practice	4.43(3.26)	5.24(0.86)	3.79(0.82)	2.94(0.88)	98.66***
<i>Validation trial data</i>					
<i>Teff</i>					
MPP: Landscape-based FR	1.48(4.39)	3.59(3.97)	1.22(3.86)	-1.74(3.95)	10.65***
<i>Wheat</i>					
MPP: Landscape-based FR	-0.62(10.15)	2.39(3.56)	2.23(8.64)	-13.84(13.64)	19.56***
<i>Sorghum</i>					
MPP: Landscape-based FR	7.08(7.09)	5.57(7.48)	10.25(4.53)	5.42(8.44)	1.22

Notes: Using survey data, the MPP of applied N is estimated as the partial derivative of the yield response function with respect to applied N while accounting for interactions of N with other covariates. Using validation trial data, the MPP of applied N is estimated as the difference between yield with recommended N rates of proposed landscape-based FR and yield with recommended N rates of current extension FR, divided by the amount of recommended N rates of landscape-based FR. * $p < .1$, ** $p < .05$, *** $p < .01$ denote statistically significant differences across landscape positions at 10%, 5% and 1% levels.

Table 6b shows the crop and N prices as well as the crop/N price ratios of the sampled study regions for computing the relative profitability of fertilizer use under farmer current fertilizer applications, current extension fertilizer recommendations and landscape-targeted fertilizer recommendations. We compute region-averaged prices of teff, wheat, sorghum and N prices using observed prices from

different markets in the three regions⁶. The teff/N price ratio is, on average, 0.45, ranging from 0.43 in the Oromia region to 0.47 in the Amhara region. For wheat, the crop/N price ratio is, on average, 0.39, ranging from 0.38 in the Oromia region to 0.41 in the Amhara region. In the case of sorghum, the crop/N price ratio is, on average, 0.36, ranging from 0.31 in the SNNP region to 0.38 in the Amhara region. To account for regional variation in prices of crops and fertilizer, we use region-specific crop/N price ratios in the computation of the profitability of fertilizer.

Table 6b: Crop output and N price assumptions for relative profitability calculations

	Output price (ETB/kg)	N price (ETB/kg)	Output/N price ratio
<i>Teff</i>			
Amhara region	53.46	114.67	0.47
Oromia region	52.30	120.72	0.43
SNNP region	54.66	122.76	0.45
Average	53.30	119.38	0.45
<i>Wheat</i>			
Amhara region	46.64	114.67	0.41
Oromia region	45.31	120.72	0.38
SNNP region	47.98	122.76	0.39
Average	46.44	119.38	0.39
<i>Sorghum</i>			
Amhara region	44.03	114.67	0.38
Oromia region	38.08	120.72	0.32
SNNP region	37.96	122.76	0.31
Average	39.63	119.38	0.36

Notes: Due to data limitations on input and output prices from the farmer survey, we rely on secondary sources for these prices. Output prices in the study regions are calculated from the weekly staple crop retail market prices sourced from the Famine Early Warning Systems Network (FEWS NET). We consider only prices for the months that farmers would most frequently sell their harvested grains (October 2022 to February 2023). N prices in the study regions are calculated from the average retail market prices of Urea fertilizer (the most common source of N) sourced from Africafertilizer.org. The prices are adjusted to reflect the N content of urea (46%).

Table 6c shows the APP of applied N and the AVCRs of applied N under farmer current fertilizer applications, current extension and landscape-based fertilizer recommendations⁷. Under farmer fertilizer application, the APP of applied N for teff, wheat and sorghum is, on average 3.31, 5.49 and

⁶ We note that explicitly accounting for transaction and transportation costs of fertilizer acquisition can substantially increase the farm-gate price of fertilizer in Ethiopia, as documented in Minten et al. (2013) and elsewhere in SSA (Chamberlin et al., 2021; Liverpool-Tasie et al., 2017), which may reduce the crop/N price ratios and profitability of fertilizer use.

⁷We lack current extension and landscape-based fertilizer recommendations for some of the study districts, which means that comparing the profitability of fertilizer use over the three scenarios: farmer current fertilizer application, current extension fertilizer recommendations and proposed landscape-targeted fertilizer recommendations was not feasible for some farmers. In this regard, we consider the findings as preliminary findings and should not be interpreted as precise.

2.66, respectively, and the APP values vary significantly across landscape positions for all crops. This suggests that the average gain in crop output per unit of applied N relative to not applying N is about 3.3, 5.5 and 2.7 kg output per kg N for teff, wheat and sorghum, respectively. The AVCR of applied N for teff, wheat and sorghum is, on average 1.52, 2.21 and 1.00, respectively. Assuming an AVCR threshold of greater than 1 for gauging fertilizer use profitability, N fertilizer application is, on average, profitable for teff and wheat, and can be considered profitable for only wheat, assuming an AVCR threshold of greater than 2, where transfer costs and risk aversion is taken into account. Regardless of crop type, the AVCR estimates vary significantly across landscape positions and N application appears more profitable on foot slopes and mid-slopes compared with hill slopes. Notably, assuming an AVCR threshold of greater than 1, fertilizer use is only profitable for sorghum cultivated on foot slopes. While N application is profitable on most wheat plots with an AVCR threshold of greater than 2, N application is only profitable for most teff plots irrespective of the landscape position and most sorghum plots only on foot slope assuming an AVCR threshold of greater than 1 under farmer current fertilizer applications.

Under current extension fertilizer recommendations, the AVCR of applied N for teff, wheat and sorghum is, on average 1.57, 2.20 and 0.89, respectively, and vary across landscape positions. Notably, N application is, on average, unprofitable for sorghum even when risk and transfer costs are not taken into account. However, for sorghum plots on foot slopes, fertilizer use is marginally profitable, assuming an AVCR criterion of 1. On average, N application seems slightly more profitable on foot slopes and mid-slopes compared with hill slopes. Under proposed landscape-based fertilizer recommendations, N application for teff, wheat and sorghum is profitable, with on average, AVCR values of 2.12, 2.27 and 1.04, respectively. However, N application is unprofitable for sorghum taking into account risk and transfer costs. As expected, AVCR values vary across landscape positions. Notably, the N application is profitable on all wheat plots with an AVCR threshold of greater than 2, irrespective of the landscape position. For teff, N application is profitable with an AVCR threshold of greater than 2 on a larger share of teff plots on foot slopes and mid-slopes, but not on any plot on hillslopes. Overall, N application appear marginally more profitable on foot slopes and mid-slopes compared with hill slopes, irrespective of the crop type. In addition, N application appears more profitable for wheat and less profitable for sorghum. Finally, N application under landscape-based fertilizer recommendations seems marginally more profitable compared with N application under farmer current fertilizer application and current extension fertilizer recommendations.

Table 6c: Relative profitability of fertilizer use by landscape position

		Footslope	Midslope	Hillslope	F value
<i>Teff</i>					
APP: Farmer fertilizer practice	3.31(0.82)	2.74(0.43)	4.06(0.40)	2.37(0.45)	1573.93***
AVCR: Farmer fertilizer practice	1.52(0.37)	1.27(0.30)	1.86(0.17)	1.08(0.20)	1569.59**
AVCR > 1 (%)	94	93	99	76	
AVCR > 2 (%)	10	0	21	0	
AVCR: Current extension FR	1.57(0.31)	1.31(0.06)	1.90(0.07)	1.15(0.04)	7465.33***
AVCR > 1 (%)	100	100	100	100	
AVCR > 2 (%)	0	0	0	0	
AVCR: Landscape-based FR	2.12(0.47)	2.37(0.42)	1.89(0.35)	1.63(0.24)	160.47***
AVCR > 1 (%)	99	100	100	98	
AVCR > 2 (%)	69	80	66	0	
<i>Wheat</i>					
APP: Farmer fertilizer practice	5.49(0.74)	5.64(0.71)	5.46(0.73)	5.23(0.73)	11.89***
AVCR: Farmer fertilizer practice	2.21(0.29)	2.27(0.28)	2.19(0.28)	2.12(0.29)	13.78***
AVCR > 1 (%)	100	100	100	100	
AVCR > 2 (%)	85	88	85	73	
AVCR: Current extension FR	2.20(0.17)	2.29(0.15)	2.18(0.15)	2.02(0.16)	110.82***
AVCR > 1 (%)	100	100	100	100	
AVCR > 2 (%)	75	100	66	40	
AVCR: Landscape-based FR	2.27(0.1.0)	2.21(0.04)	2.36(0.05)	2.14(0.08)	904.98***
AVCR > 1 (%)	100	100	100	100	
AVCR > 2 (%)	100	100	100	100	
<i>Sorghum</i>					
APP: Farmer fertilizer practice	2.66(0.92)	3.29(0.67)	2.16(0.63)	1.52(0.66)	99.39***
AVCR: Farmer fertilizer practice	1.00(0.36)	1.24(0.27)	0.81(0.25)	0.57(0.25)	89.73***
AVCR > 1 (%)	53	89	19	11	
AVCR > 2 (%)	1	2	0	0	
AVCR: Current extension FR	0.89(0.23)	1.05(0.00)	0.60(0.00)	0.21(0.00)	4.2e+12***
AVCR > 1 (%)	66	100	0	0	
AVCR > 2 (%)	0	0	0	0	
AVCR: Landscape-based FR	1.04(0.19)	1.18(0.00)	0.83(0.00)	0.34(0.00)	2.1e+13***
AVCR > 1 (%)	66	100	0	0	
AVCR > 2 (%)	0	0	0	0	

Notes: Following Sheahan et al. (2013), we calculate the AVCR of the recommended N rates of current extension and proposed landscape-based FRs using the production function estimates, N recommendations and relative crop output/N price ratios. To accommodate risk preferences (risk neutrality and risk aversion), as well as unobserved transaction costs that smallholders may face in fertilizer use, we opt for AVCR of 1 and 2. AVCR > 1 (%) and AVCR > 2 (%) indicate the share of plots on which expanding N application rates would be more profitable for a risk-neutral farmer and a risk-averse farmer, respectively. * $p < .1$, ** $p < .05$, *** $p < .01$ denote statistically significant differences across landscape positions at 10%, 5% and 1% levels.

4. Discussion

Regardless of the cereal type, we find that there is a mismatch between farmers' current fertilizer use and associated yields with their soil fertility indicators across landscape positions. Notably, soil fertility parameters including organic and total carbon, N total, P, K, pH, sand, silt and clay contents vary across landscape positions. This aligns with empirical studies that find that soil chemical properties and nutrient availability vary by landscape positions (e.g., Haile et al., 2024; Masha et al., 2023; Seifu et al., 2020). However, the observed variability by landscape position does not align with farmers' current

fertilizer use and associated yields in teff, wheat and sorghum production. This lends credence to the ongoing R&D efforts in landscape-targeted nutrient management in cereal farming systems.

We find that farmers' current nutrient application rates are, on average, larger than the current extension recommended rates, but their associated teff and wheat yields are on average smaller than the yields under current extension recommended rates, indicating positive nutrient gaps and negative yield gaps. This is in contrast with findings in other SSA countries where farmers' current nutrient application rates are, on average, lower than the current government extension recommended rates (Sheahan et al., 2013; Oyinbo et al., 2022). For nutrient and yield gaps between farmers' current nutrient application rates (yields) and landscape-targeted recommended application rates (yields), we find some variations in the direction and magnitude of the nutrient gaps for teff and wheat across the landscape positions, but with negative yield gaps. This implies that targeting fertilizer use based on landscape positions partly explains the variations in the direction of the nutrient gaps. Nutrient and yield gaps are consistently negative for sorghum. Overall, the observed negative yield gaps are consistent with the often-cited low crop yields on farmer's fields, which lags behind potential yields (Jayne & Sanchez, 2021; Wollburg et al., 2024).

We find relatively low MPP of applied N for teff, wheat and sorghum, on average, 2.8, 4.5 and 4.4 kg grain per kg of N applied, respectively under farmer current fertilizer application. Notably, the MPP values vary significantly across landscape positions, except for wheat, and yield responses are in general lower on hill slopes, as expected. The latter is often due to low soil organic carbon and nutrient levels on hill slopes (Haile et al., 2024). The low yield response estimates are within the range of survey-based estimates reported in previous studies in Ethiopia. For example, Rachid et al. (2013) find a yield response of 2.0 and 2.5 kg grain/kg N for teff and wheat, respectively, while a more recent study by Assefa et al. (2024) find a yield response of 4.5 kg grain/kg N for both teff and wheat. Overall, the low teff, wheat and sorghum yield responses to applied N are consistent with widely documented low cereal yield responses in other SSA countries (e.g., Burke et al., 2017, Chamberlin et al., 2021, Liverpool-Tasie et al., 2017; Sheahan et al., 2013; Theriault et al., 2018). While survey-based estimates of yield responses are often lower than estimates from agronomic trials, the yield response to applied N under landscape-based fertilizer recommendations validation trial, is on average low, regardless of crop type, but varies across landscape positions, with negative yield responses on hill slopes for teff and wheat. These findings imply that increasing fertilizer use without complementary measures aimed at improving yield response to fertilizer may limit the net benefits to fertilizer use.

Under farmer current fertilizer practice, we find that the AVCR of applied N for teff, wheat and

sorghum is, on average 1.52, 2.21 and 1.00, respectively, which indicates that N application is only profitable for wheat, assuming risk aversion and transfer costs are taken into account⁸. These AVCR values are closer to 1.55 for teff and 1.46 for wheat among fertilizer users, as reported by Rachid et al. (2013) compared with the 2.7 to 3.4 for teff and 1.8 to 3.0 for wheat, as reported by Assefa et al. (2024). The latter may be a consequence of differing crop and fertilizer prices than yield responses. Along the dimension of landscape positions, N application appears marginally more profitable on foot slopes and mid-slopes compared with hill slopes, irrespective of the crop type. More importantly, deriving profitability under current extension and landscape-targeted fertilizer recommendation scenarios provides more insights. While we find some results closely in line with the findings under farmer current fertilizer practice, we observe in general that N application under landscape-based fertilizer recommendations seems marginally more profitable compared with N application under farmer current fertilizer application and current extension fertilizer recommendations. These findings suggest that in settings with heterogeneous landscape positions, better-targeted fertilizer use advisories may contribute to improving the profitability of fertilizer use.

5. Conclusions

In this report, we document the potential of landscape-targeted fertilizer recommendations for sorghum, teff and wheat in Ethiopia by providing preliminary findings on fertilizer use profitability over three scenarios: farmer current fertilizer application, current extension fertilizer recommendations and proposed landscape-targeted fertilizer recommendations. We use data from a farm-household survey and on-farm validation trials complemented with geospatial soil, rainfall, fertilizer price and crop price data from secondary sources. Despite the variation in landscape positions in the study setting, we show that there is a mismatch between farmers' current fertilizer use and associated yields with their soil fertility indicators across landscape positions. We find a relatively low yield response to fertilizer for teff, wheat and sorghum, highlighting the need for improvement in yield response to fertilizer. In addition, we find that yield response to fertilizer varies across landscape positions and by cereal type. We show that fertilizer application appears more profitable for wheat and less profitable for sorghum. In addition, fertilizer application appears marginally more profitable on foot slopes and mid-slopes compared with hill slopes, irrespective of the crop type. Finally, fertilizer application under landscape-based fertilizer recommendations seems

⁸ Profitability may not be the only incentive for fertilizer use among some of the farmers. As highlighted in previous studies (e.g., Burke et al., 2017; 2020; Liverpool-Tasie et al., 2017), the drive for food security is one of the plausible reasons some farmers apply fertilizer in settings where it is not economically rational to apply fertilizer.

marginally more profitable compared with fertilizer application under farmer current fertilizer application and current extension fertilizer recommendations, indicating that landscape-targeted fertilizer advisories may contribute to improving fertilizer use returns. While, our preliminary findings highlight the promising potential of landscape-targeted fertilizer advisories for smallholder sorghum, teff and wheat farmers, we note that substantially improving fertilizer use efficiency and investment returns would likely require a holistic approach, involving soil health and agronomic management, market and institutional considerations.

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Data and code availability

The data and code developed for data manipulation, data analysis, and data visualization are available from the authors.

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