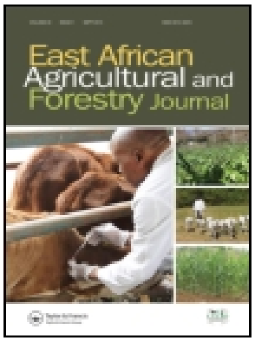

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Efforts Toward Improving Maize Yields on Smallholder Farms in Uasin Gishu County, Kenya, through Site-specific, Soil-testing-based Fertiliser Recommendations: A Transdisciplinary Approach

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ABSTRACT
This study evaluated the effects of site-specific, soil-testing-based fertiliser recommendations on maize yields using the transdisciplinary (TD) process. The TD process utilizes knowledge from science and practice. Farmers, extension officers, local financial institutions, and other practitioners collaborated with local scientists from the University of Eldoret in the process of financing, purchasing, and applying fertilisers in adequate amounts and composition. A total of 144 farmers participated in the study, which lasted for two seasons. The data sampling was based on a randomized $2 \times 3 \times 4 \times 2$ factorial complete block design, including the following factors: TD (non-participation vs participation in the TD process); ST (soil testing in the following categories: fertiliser application with no soil testing, fertiliser application following government recommendations, and application of site-specific, soil-testing-based fertiliser recommendations), and location (Kapyemit, Kipsomba, Ng'enyilel, and Ziwa). The "no soil testing" (ST_1) category refers to farmers' own practices at an average fertilisation of about 60 kg N ha^{-1} and 15 kg P ha^{-1}. The government recommendation (ST_2) calls for 75 kg N ha^{-1}, 25 kg P ha^{-1}, and 6 t ha^{-1} manure, and site-specific fertiliser recommendations (ST_3) were based on actual soil-testing results; generally, this resulted in the recommendation of 90 kg N ha^{-1}, 30 kg P ha^{-1}, 25 kg K ha^{-1}, 2 t ha^{-1} lime, and 1 t ha^{-1} manure. Highly significant effects were seen where farmers participated in the TD process (TD) for soil testing (ST). The farmers' yields in Uasin Gishu County of 4.5 t ha^{-1} increased by approximately 1.5 t ha^{-1} based on site-specific, soil-testing fertilisation recommendations and by approximately 1.0 t ha^{-1} based on participation in the transdisciplinary process. However, as indicated by a significant interaction of the variables ST and TD—and while there is a significant main effect of participating in a TD process—the latter increase occurs only if site-specific, soil-testing-based recommendations can be used in the transdisciplinary process with farmers.

KEYWORDS
transdisciplinary process; soil testing; site-specific, soil-testing-based fertilisation recommendations; phosphorus; fertiliser

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Introduction

Feeding their human populations has been a challenge for many nations (Godfray *et al.*, 2010)). Studies have suggested that crop demand may increase from 100% to 110% between 2005 and 2050. Numerous authors have suggested that increasing crop yields, rather than clearing more land for food production, is the most sustainable path to food security (Tilman *et al.*, 2011). However, this may not be possible in Sub-Saharan Africa (SSA) since maize yields have stagnated at 1.6 t ha^{-1} (FAO, 2016) as the population has continued to rise.

The average annual maize production for SSA of 1.6 t ha^{-1} falls far below the expected yield potential of 6 to 8 t ha^{-1} (Otinga, 2012). The reasons attributed to this low yield include unpredictable weather associated with drought, delayed, or especially heavy rains; soil acidity; poor agroeconomic practices; and poor crop nutrition (Sanchez, 2002). Poor crop nutrition may result from farmers being constrained by inadequate funds to purchase fertilisers, resulting in their application of low quantities of inputs and continuous cropping without replenishment. Maize is Kenya's staple food, with the area under cultivation estimated at 1.6 million hectares. Production is concentrated in the Rift Valley (Uasin Gishu, Trans-Nzoia and Nakuru Counties), a region considered the "Grain Basket of Kenya" with average yields of up to 4.5 t ha^{-1}, according to a report by the Ministry of Agriculture, Livestock, and Fisheries (MOALF, 2013). Production relies on smallholder farmers who contribute approximately 75% of the overall crop, with the remaining 25% contributed by large-scale farming operations (Guantai *et al.*, 2007). Maize production in Uasin Gishu County is practiced by both smallholder and large-scale farmers. Average farm sizes range from three hectares for smallholder farming to over 50 hectares for large-scale farming (Guantai *et al.*, 2007).

There is increasing agreement among research, development, and donor communities regarding the need to facilitate farmers' access to the right amounts and types of fertilisers at the right time (Africa Fertiliser Summit, 2006). Over time, "blanket" fertiliser applications have been implemented. These are recommendations based on regional soil surveying or on agro-ecological zoning specific to a given crop for nitrogen (N), phosphorus (P), and potassium (K) (FURP 1994). This approach of using "blanket" recommendations results in varied yields due to differences in field management and spatial topsoil heterogeneity (Vanlauwe and Giller, 2006; Wopereis *et al.*, 2006; and Zingore *et al.*, 2007).

The National Accelerated Agricultural Inputs Access Programme (NAAIAP, 2014) provided fertiliser recommendations for various crops for every county; however, limited information about nutrient requirements for specific crops and variations in soil characteristics is available to farmers. In addition, the costs of fertilisers recommended by this program are beyond the reach of most farmers. For example, the application of manure at the rate of 6 t ha^{-1} is nearly absent because of limited quantities available at the farm level (Okalebo *et al.*, 2006). Other organizations, for example the International Phosphate Institute (IMPHOS), recommend soil liming combined with conventional diammonium phosphate (DAP) use and manures for improving soil fertility (Ndung'u-Magiroi *et al.*, 2010). Despite the potential of these two recommendations, farmers have not adopted them. The current recommended rates of fertiliser application of 75 kg N ha^{-1} and 25 kg P ha^{-1} at 6 t ha^{-1} at planting time are not fully implemented (NAAIAP, 2014). Farmers instead apply 60 kg N ha^{-1} and 15 kg P ha^{-1}, which are very low levels for optimum crop production. Moreover, nutrient recovery in food crops is higher than inputs, indicating ongoing soil exploitation (Scholz *et al.,* 2014). Continuous exploitation of the soil depletes its fertility, leading to a yield gap of up to 4.3 t ha^{-1} of dry maize according to the FAO (2016). Therefore, an in-depth review of soil-testing results for farm-specific recommendations coupled with decision-making forums through a transdisciplinary (TD) process is needed.

The TD process is a reflexive approach utilizing knowledge from theory and practice to generate socially robust solutions for sustainable development. It complements other forms of science–society cooperation such as contract-based research, public participation, and participatory research (Scholz, 2011). In this context, the process aims at enabling a mutual learning process between scientists and farmers (Scholz, 2000). This process brings scientific knowledge to farmers by creating a researcher and farmer-to-farmer network. The extension and fertiliser manufacturer-supplier services play important roles in disseminating information and making the right types of fertilisers available to farmers, respectively (Scholz *et al.,* 2014). Over time, farmers have relied on recommendations (FURP, 1994) and thus have missed out on information about soil heterogeneity. Since the extension services in Kenya are farmer-driven, extension information may be limited to resource-endowed farmers. The present study investigates whether the adoption of soil-testing-based fertiliser recommendations through the TD process can improve farmers' fertilisation strategies and increase maize yields. With farming communities that have many stakeholders, this process can be utilized to bring stakeholders together. Here, the process has been executed by the interaction of soil scientists (researchers) with farmers, fertiliser traders with farmers, traders with soil scientists, and traders with farmers, i.e. with important key actors all along the supply chain.

Materials and Methods

The study was carried out in two sub-counties (Soy and Turbo) of Uasin Gishu County in Kenya. Two sites were selected from each sub-county. In the Soy sub-county, the experiments were conducted at sites in Kipsomba and Ziwa, while Ng'enyilel and Kapyemit represented the Turbo sub-county. These sites were selected because we wanted to include smallholder farmers from different counties in order to increase heterogeneity among the farmers in the TD process and because the soil type in these areas is characterised by rhodic ferralsols, the most common type of soil in Kenya. This provides some homogeneity in the soil and yield data. Kapyemit and Ng'enyilel had 12 participating farmers each, while Kipsomba and Ziwa had 17 farmers each, resulting in a total of 58 (Table 1).

Table 1. Treatment structure used for the study

	Number of farmers participating in the experiment		
Intervention	TD_1 (control group)	TD_2 (TD participants)	Total
ST_1 = soil testing without recommendation (farmers' own practice)	10 (10)	10 (10)	20 (30)
ST_2 = with soil testing and government recommendation 2014	8 (10)	10 (10)	18 (30)
ST_3 = with soil testing and site-specific recommendation	10 (10)	10 (10)	20 (30)
Total no. of farmers	28 (30)	30 (30)	58 (60)

Values indicate real and planned numbers (planned numbers in parentheses) of participants in the first year of the study.

Uasin Gishu County is 2140 m above sea level and is delineated by latitude 0° 34′ N and longitude 35° 18′ E. It receives annual rainfall ranging from 900 to 1300 mm, with a nearly unimodal rainfall distribution pattern that peaks from May to August. The average annual temperature ranges from 17 °C to 26 °C, with a maximum of 26 °C in January and a minimum of 10 °C in July. Soils in the area have developed from various parent materials (mixed igneous and metamorphic rock) as described by Jaetzold *et al.* (2007). They are well-drained, shallow and acidic, and range from rhodic ferralsols (FAO) to chromic acrisols. The experimental sites in the Soy sub-county and Turbo sub-county are in the Lower Highland 3 (LH 3) and Upper Midland 4 (UM 4) agro-ecological zones, respectively (Jaetzold *et al.*, 2007).

How the Transdisciplinary Process Was Carried Out

Here, we present only the main steps of a transdisciplinary process (Scholz *et al.*, 2014). A detailed description is provided by Njoroge *et al.* (2015).

Building partnerships

This step includes partners from science and practice, i.e. scientists, extension officers, farmers, and traders. Building partnerships are developed through meetings in which invited members are informed about the objectives of the TD process. Members are also informed about the specific aspects (e.g. soil testing as part of the process), demands (e.g. participating in a learning process and providing data), and advantages (e.g. the chance to increase yields) of participating in a TD process.

Negotiating and identifying goals

This involves a guiding question, such as, "How might site-specific fertiliser recommendations affect maize yield?" The goal is a win–win situation for all participants. After conducting soil testing and establishing fertiliser recommendations, a fertiliser trader is asked to stock the recommended fertilisers among those he or she sells. The financial institution (local bank) agrees to provide loans to farmers by financing the fertiliser inputs from the trader. Scientists will participate by discussing (depending on their assignment to different "experimental" groups) questions regarding fertiliser application, by requesting farm data and analyzing soil data with the aim of fact-finding, by utilizing the data for follow-up projects and recommendations to increase smallholder farmers' yields, and by publishing scientific information. This creates a win–win situation that will help traders to sell more fertiliser, financial institutions to provide more meaningful loans, farmers to increase their production and improve soil fertility, and scientists to conduct the study as planned and advance and disseminate knowledge for the common good.

Site-specific Soil Testing and Fertiliser Recommendations in the Study Area (ST_3)

Before any form of experimentation was undertaken, soil samples were collected from a depth of 0–20 cm from the farmers' fields in the Soy and Turbo sub-counties. The soil samples were collected from 10 auger holes, then bulked to form a composite sample per plot. The initial soil characteristics presented in Table 2 were arrived at by calculating the mean of each parameter for each site. The soil-particle analysis results were

Table 2. Initial characteristics of topsoil (0–20 cm) taken before planting for the four experimental sites in Uasin Gishu County

	Site			
	Kapyemit	Kipsomba	Ng'enyilel	Ziwa
Physical properties*				
Sand (%)	64	70	54	66
Clay (%)	20	22	25	20
Silt (%)	16	8	21	14
Textural class	Sandy clay loam	Sandy clay loam	Sandy clay loam	Sandy clay loam
Chemical properties**				
pH (H_2O)	4.96	4.97	4.79	4.72
Total N (%)	0.12	0.11	0.11	0.11
Total Organic C (%)	1.25	1.06	0.98	1.22
C:N ratio	10:1	10:1	10:1	11:1
Available P (mg kg^{-1})	11.71	9.93	8.84	8.72
Exchangeable cations				
Exch. K cmol kg^{-1}	0.23	0.23	0.19	0.35
Exch. Ca cmol kg^{-1}	0.51	0.97	1.08	1.09
Exch. Mg cmol kg^{-1}	2.11	1.75	1.53	1.95

*The analysis was done on a composite sample that was bulked from five experimental plots for each site.
**The soil samples from each experimental plot were analysed individually, and the mean result per soil property computed for each site.

obtained from the analysis of one bulked composite sample produced from bulking samples of five experimental plots from each site. This was made possible by the close proximity of the farmers to each other at every site. The farmers who participated in the study were sampled purposively according to Obare *et al.* (2010). Participants had to meet the following criteria: they had to (i) be landowners who planted maize on an area between 0.5 and 3 hectares, with a total area of not more than 20 hectares; (ii) own a herd of cattle so that they could have access to farmyard manure; and (iii) have at least a primary education or to have attended adult literacy classes so that when soil-test results were presented, they could read and understand them. Initial soil characterisation was done to determine the level of nutrients before the application of any treatments used in the experiment. The soil variables measured were pH, total organic carbon, total nitrogen, available phosphorus (Olsen method), and selected exchangeable bases, which followed the standard procedures described in Okalebo *et al.* (2002). The soil test results were carefully examined to infer possibilities of deficiencies, adequacy, and toxicities. Information on the history of each farm's management was collected so that during the evaluation of maize yields after harvests, any variability arising that was not caused by treatment application could be explained. The fertiliser recommendations were made for each farm based on the soil-testing results. The farmers were advised to follow the recommendations, for which the trader provided the inputs recommended, while the financial institution provided the cash in the form of inputs from a selected trader. Each farmer received his or her own recommendations specific to his or her farm and its soil characteristics.

Of the total number of farmers who were purposively sampled, 10 were randomly assigned to each treatment group. However, at the end of the year 2014, two farms were omitted from the analysis due to crop destruction by livestock. The transdisciplinary control-group farmers (TD_1) were those who did not participate in the transdisciplinary process; therefore, during visits to these farms, the researcher collected data but did not give farmers much information about fertiliser use or good agricultural practices. The farmers who were participants in the TD process (TD_2) followed the TD process and were visited at their farms regularly. They were given information about fertiliser use and good agricultural practices, and their farm-specific knowledge was used for developing fertilisation strategies that were then implemented. The number of farmers who participated in the experiment is shown in Table 1. One group of farmers (i.e. ST_1) had their soils tested, but the results were withheld until later in both seasons. Therefore, these farmers applied their usual fertilising practices (farmers' own practices), which included the use of 60 kg N ha^{-1} and 15 kg P ha^{-1}. In the ST_2 intervention group, the farmers' soils were tested, but they followed the National Accelerated Access to Input Acquisition Program (NAAIAP) recommendations, which consisted of using 75 kg N ha^{-1}, 25 kg P ha^{-1}, and 6 t ha^{-1} manure. In the ST_3 group, the soil-testing-based fertiliser recommendations that were developed for each farm were followed. The farm inputs applied included 2 t ha^{-1} of lime, 25 kg K ha^{-1}, 1 t ha^{-1} manure, and a range of 80–90 kg N ha^{-1} and 25–30 kg P ha^{-1}, depending on the levels of total nitrogen and available phosphorus in the soil.

Agronomic Activities

The experiment was conducted during the years 2014 and 2015. The plot size used measured 4.5 m by 5 m, resulting in a total area of 22.5 m^2. Maize seeds were planted at a spacing of 75 cm between rows and 30 cm within rows; this spacing was uniform for all the farmers regardless of the group they were in. Total plant population was 100 plants per 22.5 m^2 plot and 44 444 plants ha^{-1}. The variety of maize used in the study was H6213. This variety is adapted to the following agro-ecological zones: Lower Highlands 2, Lower Highlands 3 and Upper Midlands 4. It is also high yielding (Jaetzold *et al.*, 2007), with a potential grain yield of 6 to 8 t ha^{-1}. This variety is popular with farmers because the seed has a hard testa and is not susceptible to weevil attack. The farmers were given 5 kg of seed each as a motivation for participating in the TD process. The farmers participated in land preparation, seed planting, weeding, top dressing, and harvesting of maize. Fertiliser application was done differently for each experimental unit as described above. Hand weeding was done twice in a cropping season. Stalk borers were controlled by spraying Bulldock®, a synthetic pyrethroid with the active ingredient beta-cyfluthrin.

Data Collection

Maize harvesting was done at physiological maturity of the crop. A row of maize was removed from each side of the plot, and, likewise, one maize plant was removed from the edge of each line. A harvesting nett plot area (effective area) of $3.0 \times 4.4\ m^2$ was, therefore, considered for sampling. The total fresh weights of cobs from the nett plot and from a subsample of 10 cobs were recorded. These samples were oven-dried at 70°C to retain only 12.5% moisture content. Equations 1 and 2 show how yields per plot and per ha, respectively, were calculated from the data obtained.

$$\text{Yield per nett plot (kg)} = \text{total fresh weight of maize} \times \text{sample dry weight of maize} / \text{sample fresh weight of maize} \quad (1)$$

$$\text{Yield}\ \left(\text{t ha}^{-1}\right) = 10\,000\ \text{m}^2 \times \text{yield per nett plot (t)/nett plot}\left(\text{m}^2\right) \tag{2}$$

The weights of maize grain yield in kilograms (kg) obtained per nett plot were converted to tons (t) by dividing them by 1000.

Economic analysis

Profitability analysis of adoption of site-specific fertiliser recommendation through the TD process was done according to Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT), (1988). The procedure involved computation of gross margins, labour, capital productivity and nett change in income. The gross margin is the difference between the total costs and benefits that result from the use of technology. The nett change in income is a technique used in the evaluation of costs and benefits that varied from the control. The benefit of adopting the soil management technique was mainly the increased output of maize while the increased costs included the cost of seeds, fertilisers, labour, pest control and soil testing for the site-specific fertiliser recommendation group. Labour was paid at the prevailing wage rate while the management input was similar for all the technologies as they were subjected to the same conditions. The values for the prices of fertiliser and maize grain were set by the government through the National Cereals and Produce Board government subsidy.

The calculations (with the average maize yields for the two seasons determined as 4.66, 5.52, and 6.57 t ha^{-1}) were made after the completion of the experiment. The costs of 50 kg calcium ammonium nitrate (CAN) and nitrogen, phosphorus and potassium (NPK) fertiliser are \$15 and \$18, respectively, per the government subsidy. The maize grain-buying price is \$200 as determined by the National and Cereal Produce Board (NCPB). All dollar values refer to US dollars.

Statistical analysis

The effects on the maize yields of different fertiliser recommendations, the TD process, season, and site were subjected to an analysis of variance (ANOVA). Random variables were: the farmers in each group, the site, and the season, while fixed variables were the fertiliser treatments.

Results

Initial Soil Characterization of the Study Sites

The data (Table 2) show the initial soil characteristics for the four sites in Uasin Gishu County before fertiliser application for the 2014 and 2015 seasons. The pH ranged from 4.72 to 4.97. The soils had low available phosphorus that was below the critical value of 10 mg P kg^{-1} required for good crop growth, except for the Kapyemit site, which had 11.71 mg P kg^{-1}(Okalebo *et al.*, 2002). Organic carbon ranged from 0.98 to 1.25%. Nitrogen levels in the soil were low, ranging from 0.11% to 0.12% against a critical value of 0.25% (Okalebo *et al.*, 2002). The basic cation K was low, ranging from 0.19 cmol$_c$kg^{-1} to 0.35 cmol$_c$ kg^{-1} against a critical value of 0.45 cmol$_c$ kg^{-1} (Okalebo *et al.*, 2002).

Calcium was also low at all locations, ranging from 0.51 to 1.09 $\text{cmol}_c\,\text{kg}^{-1}$ against a critical value of 4 $\text{cmol}_c\,\text{kg}^{-1}$. Magnesium levels were adequate, ranging from 1.53 to 2.11 $\text{cmol}_c\,\text{kg}^{-1}$, since its critical value is 0.33 $\text{cmol}_c\,\text{kg}^{-1}$ (Okalebo *et al.*, 2002).

Maize Yield Data

The mean maize yields for the 2014 and 2015 cropping seasons and the results of the ANOVA are presented in Figure 1 and Table 3. For the two seasons, 144 farmers participated in the study, 58 in season 1 and 86 in season 2. There were three highly significant ($p \leq 0.001$) main effects. First, the farmers participating in the TD process had an average yield of 5.96 t ha^{-1} dry weight maize compared to 5.27 t ha^{-1} for those who did not participate in the TD process. Second, the mean yield for the soil-testing groups increased from 4.48 t ha^{-1}(ST_1) to 5.66 t ha^{-1} and finally 6.6 t ha^{-1}. Third, the mean yield of 5.43 t ha^{-1} in season 1 was lower than the 5.73 t ha^{-1} in season 2. There were no significant differences between the mean yields of the four sites.

There were two significant interactions of order, one related to soil testing (see Table 2), and the other referring to the interaction of Site × ST. There were higher yield increases at some sites than at others, which will not be discussed here. Further, as shown in Figure 1, there is a significant ($p \leq 0.01$) interaction between soil testing and TD. When no soil testing took place, there was only a low increase in yield as a result of participation in the TD process: by 0.34 t ha^{-1} under no soil testing (ST_1), by 0.77 t ha^{-1} under (ST_2), and by 0.95 t ha^{-1} under the site-specific, soil-testing-based recommendations (ST_1). There was one significant effect of the second order including the site variable, which will not be discussed here.

Farmers' Income

Table 4 shows a partial budget analysis of input/output estimates that could be made by smallholder farmers in Uasin Gishu. The profitability of different fertiliser technologies was calculated using partial budgeting. Significant additional nett benefits were obtained when site-specific fertiliser recommendations were combined with participation in the TD

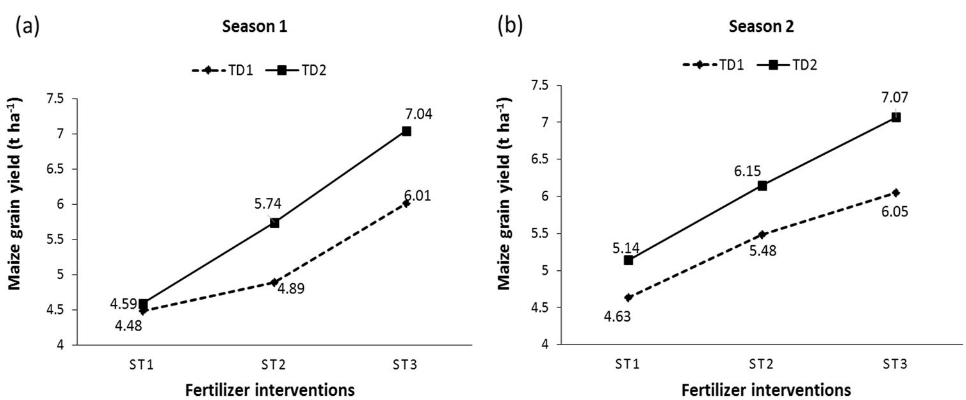

Figure 1. Mean values of maize grain dry weights under the different levels of the independent variables transdisciplinarity (TD) and soil testing (ST); see also Table 3.

Table 3. Mean maize yields (t ha-1) across the study locations for 2014 and 2015 cropping seasons as affected by treatment application with number of farmers per cell in parentheses

			Site				
Season	TD	Intervention	Kapyemit	Kipsomba	Ng'enyilel	Ziwa	Mean ST
Season 1	TD1	ST1	4.37 (2)	4.82 (3)	4.04 (2)	4.69 (3)	**4.48**
		ST2	4.94 (2)	4.91 (2)	4.78 (2)	4.56 (2)	**4.80**
		ST3	6.19 (2)	4.84 (3)	6.95 (2)	6.85 (3)	**6.14**
Mean TD1			**5.16**	**4.85**	**5.25**	**5.36**	**5.15**
	TD2	ST1	4.60 (2)	4.49 (3)	4.28 (2)	4.69 (3)	**4.51**
		ST2	5.87 (2)	5.54 (3)	5.23 (2)	5.82 (3)	**5.61**
		ST3	6.86 (2)	6.63 (3)	7.21 (2)	7.30 (3)	**7.00**
Mean TD2			**5.78**	**5.91**	**5.55**	**5.93**	**5.79**
Mean season 1			**5.43**				
Season 2	TD1	ST1	4.53 (3)	5.20 (3)	4.29 (3)	4.50 (3)	**4.63**
		ST2	5.53 (3)	5.57 (3)	5.32 (3)	5.50 (3)	**5.48**
		ST3	6.20 (3)	5.67 (3)	6.23 (3)	6.11 (3)	**6.05**
Mean TD1			**5.42**	**5.48**	**5.28**	**5.37**	**5.39**
	TD2	ST1	5.59 (4)	5.03 (4)	4.84 (4)	5.09 (4)	**5.14**
		ST2	6.19 (4)	5.63 (4)	6.45 (4)	6.33 (4)	**6.15**
		ST3	6.80 (4)	7.07 (5)	7.23 (4)	7.18 (5)	**7.07**
Mean TD2			**6.19**	**5.91**	**6.17**	**6.20**	**6.12**
Mean season 2			**5.73**				
Grand Mean			**5.59**				

Variable	SED	LSD
Site	0.110	0.218 ns
Season	0.078	0.154***
TD	0.078	0.154***
ST	0.095	0.189***
Site ×TD	0.156	0.309 ns
Season ×TD	0.110	0.218 ns
Site × ST	0.190	0.378***
TD × ST	0.135	0.267**
Site × season ×TD	0.220	0.437 ns
Site × TD × ST	0.269	0.535*
Season × TD × ST	0.190	0.378 ns
Site ×season ×TD × ST	0.381	0.756 ns
CV (%)	18.30	

***Significant at $p \leq 0.001$; **significant at $p \leq 0.01$; *significant at $p \leq 0.05$; ns: not significant; SED: Standard error of difference, LSD: Fischer's least significant difference; CV: Coefficient of variation

process. Farmers utilising the ST_3 technology received the highest income, followed by farmers adhering to the government recommendations while the farmers following their own practice had the lowest income.

Discussion

The results demonstrate highly significant effects on maize farmers' yields due to site-specific soil testing and participation of the farmers in a transdisciplinary process that included local scientists from Eldoret University. We can posit from Figure 1 (and the significant interaction of TD and ST) that the potential of a transdisciplinary process can only be fully developed if site-specific, soil-testing-based recommendations are available. Under these conditions, participation in a TD process results in a yield increase of approximately 1 t ha^{-1}, or about 17%, from six to seven tons (consistently in both seasons). Site-specific, soil-testing-based fertiliser recommendations increased yields the most for those who participated in a TD process; for those who did not participate, yields increased by almost half

Table 4. Estimated nett profit resulting from site-specific fertiliser recommendations

Intervention	Input categories	Input	Cost ($)	Yield ($/ t ha^{-1})	Nett profit ($)
ST_3 (Site-specific fertiliser recommendations based on soil testing)	NPK	250 kg ha^{-1}	90		
	CAN	150 kg ha^{-1}	54		
	Lime	2 t ha^{-1}	150		
	Manure	1 t ha^{-1}	10		
	Soil testing		20		
	Labour		50		
	Subtotal		374	1 460 (6.57 t ha^{-1})	1 080
ST_2 (NAAIAP 2014 recommendation)	NPK	250 kg ha^{-1}	90		
	CAN	150 kg ha^{-1}	54		
	Manure	6 t ha^{-1}	60		
	Soil testing		20		
	Labour		70		
	Subtotal		294	1 227 (5.52 t ha^{-1})	933
ST_1 (farmer's own practice)	NPK	150 kg ha^{-1}	54		
	CAN	100 kg ha^{-1}	36		
	Labour		50		
	Subtotal		140	1 036 (4.66 t ha^{-1})	896

NPK – Nitrogen Phosphorus and Potassium fertiliser; CAN – Calcium Ammonium Nitrate; $ – USD

(i.e. 47%), from approximately 4.5 t ha^{-1} to 6.6 t ha^{-1}. If we compare the group of farmers who were not subject to soil testing ($ST_1 \times TD_1$) to those with site-specific, soil-testing-based recommendations used in a TD process, we find an even larger increase, i.e. from 4.61 to 7.05 t ha^{-1}, or 74%. This means that the technology of soil testing alone can develop its full potential when users (i.e. the farmers) participate in a transdisciplinary dialogue in which practitioners' knowledge (from farmers and extension officers) and scientists' knowledge (local scientists) are merged.

Larger yields obtained by the TD_2 farmers were also attributed to the transdisciplinary process, including the learning from which they benefitted as a result of their interactions with local scientists. This collaboration resulted in farmers' improving their fertiliser-use practices; the application of site-specific fertiliser recommendations improved their soil's chemical properties and provided a sufficient supply of nutrients. The same results were also observed by Brar *et al.* (2015). The increased maize yield seen by farmers who participated in the TD process was also a result of farmers' accepting and modifying technology to suit them. The TD process influenced farmers' activities since the information provided to them by local scientists and extension officers resulted in their improving their fertiliser-application practices. Studies conducted in China by Pan (2014) showed that scientists' experiments on-site at farms, guided by the farmers' participation, improved nutrient management in soils.

The TD process, including the training of farmers, could have encouraged farmers to modify a learned technology to suit them. Such modification of agricultural technology has been reported by Obonyo *et al.* (2005). Farmers make modifications to align with their managerial and production systems and do not usually adopt technologies as a whole bundle or package. Instead, they tend to adopt certain principles or practices while modifying particular components or management practices. Most farmers generally act on the advice and suggestions of a person they know and trust (in our study, this was an extension officer who was collaborating with local scientists). The extension officer was in constant communication with the farmers and answered their questions concerning various agronomic practices with certainty throughout the study period. However, it is difficult to control for potential artefacts between participants and farmers in comparison groups (i.e. nonparticipants or control) because they also interact with neighbours, making it difficult to draw a definitive conclusion. We also want to note that, in some cases, the farmers of the TD_2 group provided seminal suggestions on how to improve fertilisation when discussing the results of the soil testing.

We also assessed the added value of site-specific, soil-testing-based recommendations (see Table 2). Here, we consider three scenarios that represent the typical situation of the three levels of soil testing, all material input costs including fertiliser, lime, manure, and soil testing, plus labour. These scenarios also integrate results from recent research showing that a combination of inorganic fertilisers and lime successfully increases crop production (Barasa *et al.*, 2013). Thus, we might expect even higher yields than those reported in the data presented here. Furthermore, soil testing increases not only yield but also farmers' profit margins from maize sales. Referring to Table 4, farmers are looking at a 21% increase in their income. If we add income of $200 more that would result from another ton of grain, the added values double to 43%, and the farmers' nett profits increase from $896 to $1080.

Conclusion and recommendations

The results strongly suggest that site-specific, soil-testing-based fertilisation is highly beneficial and profitable for farmers. This appears to be a robust finding, as demonstrated by the highly consistent data for the replication of season 1 data in season 2. Therefore, we can generally conclude that current Uasin Gishu's farmers' yields of 4.5 t ha^{-1} will increase by approximately 1.5 t ha^{-1} as a result of site-specific, soil-testing-based fertilisation and by a further amount of approximately 1.0 t ha^{-1} as a result of a transdisciplinary process in which farmers and local scientists jointly discuss and design how the fertiliser recommendations are best used. It must be noted that this requires an accurate, reliable, and economical service for local soil sampling, which is currently provided in Uasin Gishu County.

In summary, we recommend soil testing and consequent site-specific fertiliser recommendations for any initiative to manage soil fertility for improved maize yields. We also recommend the transdisciplinary process, which creates the adoption of effective collaborations between farmers, scientists, and stakeholders. This method provides participatory training and aligns with an extension service approach. It also relies on a high degree of farmer involvement in the extension services, which has the potential to improve farmers' fertiliser use practices and fosters their identification and welfare.

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