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Is agricultural lime a profitable investment for African smallholders? Evidence from Rwanda

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Abstract

Soil acidity is a major constraint to crop production in tropical regions. Although agricultural lime is one option to remediate acid soils, there is limited information on the potential returns on investments to liming by smallholders. Using survey data collected from 261 households in Rwanda, we estimated the crop-specific yield response to lime application and associated financial benefits. The estimated average yield gain from lime ranged from 941 kg/ha to 1 579 kg/ha for Irish potato, 562 kg/ha to 709 kg/ha for maize, and 453 kg/ha to 520 kg/ha for beans. With the existing lime and *farmgate crop prices, reliable returns on investment from lime were observed for Irish potato, while applying lime to maize and bean was only profitable at a 50% lime price subsidy. As maize and beans are the major staple crops in Rwanda, the subsidy for ag-lime use in improving crop productivity is highly justifiable. The results inform policy decisions in considering market-oriented crops and subsidies when promoting agricultural lime in acid soils under smallholder conditions.*

Key words: acid soil management, soil health, yield response, input subsidy, profitability, technology adoption

1. Introduction

Maintaining and improving soil health is critical to ensure sustainable crop productivity and the profitability of farming (Tahat *et al*. 2020). Soil acidity has been indicated as one of the key constraints on crop productivity in tropical Africa (Gurmessa 2021), as it decreases soil nutrient availability and hampers root growth due to high aluminium and manganese toxicity (Baligar *et al*. 1997; Sanchez 2019). Agricultural lime is a widely promoted soil amendment for addressing yield constraints associated with acid soils. Some on-station and on-farm research findings indicate that applying lime to acid soils increases crop yield considerably (e.g., Oliver *et al*. 2021; De Moraes *et al*. 2023). The benefits from liming typically accrue over multiple years (Sanchez 2019). Yet, estimating lime requirements to maintain soil health and crop productivity can be complex and dependent on both the soil property of interest and the crop-specific target value of that soil property that needs to be reached through liming (Merlos *et al*. 2023). The economics of lime use for smallholders is similarly complex and is not yet well understood, let alone communicated to prospective users.

Rwanda is one of the countries in sub-Saharan Africa most seriously affected by soil acidity, with soils on more than 45% of its arable land considered acidic (Nduwumuremyi *et al*. 2014; Bizoza 2021). On top of the densely populated and hilly agricultural landscape exposing farmlands to soil degradation, severe soil acidity challenges government initiatives to enhance crop productivity and ensure sustainable food and nutrition security. The government of Rwanda is committed to improving farmers' access to services, strengthening farmers' linkages to markets, and improving productivity through increased input use, irrigation and improved soil quality – including helping farmers to overcome production constraints associated with soil acidity. In pursuit of these goals, the government of Rwanda has implemented multiple rounds of its Strategic Plan for the Transformation of Agriculture (PSTA) since the early 2000s, as well as the Crop Intensification Programme (CIP), which started in September 2007 (Bizoza 2021). Lime is among the major purchased inputs considered in these programmes, next to improved seed and mineral fertilisers. Applying lime is not a new practice for some farmers in regions affected by soil acidity. Through government and partners' efforts, the promotion of lime started in the period from 2010 to 2014, when farmers in selected districts were provided information on the benefits of lime as a soil amendment and its potential yield response. The government also introduced a 50% subsidy of the lime price to facilitate lime use by smallholders in severely affected districts. However, the uptake of lime by Rwandan smallholders remains very low (Bizoza 2021). The limited adoption of lime in Rwanda, despite its promotion and subsidisation, raises questions about whether adequate economic and behavioural incentives are in place for smallholder farmers to apply it.

Although there has been field-level research to test the agronomic performance of different lime grades in Rwanda (Athanase *et al*. 2013), there is a dearth of information on the farm- and field-level profitability of lime application. Lime as a business, and its application to remediate acid soils, are recent developments in the country. Moreover, unlike seed and mineral fertiliser, the return from lime use in crop production requires multi-season agronomic experiments to assess the residual effects of liming. Given smallholders' diverse cropping systems and intrahousehold crop production dynamics, it is particularly important to assess which specific crops generate the greatest returns to investments in lime. The latter is critical to prioritise public and private investments (including subsidies) and clarify distributional and intrahousehold welfare implications, particularly with respect to male and female farmers, who often manage different crops and have different market orientations.

Using household survey data collected from four districts, we addressed this knowledge gap by evaluating the financial viability of liming acid soils under different crop types and crop management practices in the highlands of Rwanda. Specifically, we evaluated whether liming acid soils generates positive returns on investment in lime for smallholders growing maize, beans and potato in the season of lime application, especially for farms using improved seeds and mineral fertilisers. In these cases, investments in lime compete for capital with investments in these other essential inputs for crop production. In addition, we assessed the net present values of lime use under different crops and crop rotation systems over four cropping seasons to account for the accrued benefits of lime beyond the season of application. Moreover, we explored how the current government lime subsidy affects farm-level profitability, and whether lime subsidies could be targeted more deliberately to generate more benefits for smallholders and the country at large.

2. Empirical approach

Returns on investment in lime are expected through crop yield improvements in the year of application, as well as in subsequent years due to residual effects. It is assumed that smallholders have economic incentives to apply lime if the returns from yield gains exceed the investment made in lime. As the yield benefits from lime application accrue over more than a single season (Sanchez 2019), yield gains over multiple cropping seasons need to be considered in the net present value estimates by using assumed discount rates. Resource-constrained smallholders typically have short planning horizons and face difficulties in adopting technologies requiring a long-term view (Holden *et al*. 1998; Lee 2005). Relatedly, when the effective cost of borrowing is high (due to high interest rates, limited access to credit, and/or imperfect credit market functioning), the subjective discount rate for smallholders increases, reducing the incentives to invest in technologies that deliver lagged benefits (Holden *et al*. 1998; Lee 2005; Shiferaw *et al*. 2009; Llewellyn & Brown 2020). To overcome high subjective discount rates, returns from the first season of lime application should be high enough to compensate for the investment cost in that same season. Alternatively, mechanisms should be in place to make lime affordable for smallholders.

With this understanding, we modelled crop yield response to lime using both Cobb-Douglas and translog production functions. These functional forms estimate the yield response using non-linear specifications, and the coefficient estimates provide yield elasticity (percentage response) due to liming. The Cobb-Douglas functional form is more restrictive than the translog functional form, as the former assumes constant returns to scale. However, as our interest is to obtain the yield response rate to lime use, these functional forms provide a desirable outcome under smallholder production systems. As there are fields that did not receive purchased inputs, transforming these zero magnitudes to log form becomes undefined and the number of observations for the analysis could be reduced. Moreover, the coefficient estimates obtained from these observations without considering the zero application are biased (Battese 1997). Thus, following Battese's (1997) approach, we substituted the undefined values with zero and added dummy variables equal to one for those observations with no purchased input use. The Cobb-Douglas production function could therefore be specified as:

$$lnY_i = \alpha_i + \beta_1 lnL_i + \beta_2 lnF_i + \beta_3 IMV_i + \gamma X_i + \varepsilon_i, \tag{1}$$

where Y_i is yield (t/ha) of crop i, L_i is the rate of lime applied to a field allocated to crop i, and F_i is the mineral fertiliser application rate (kg/ha) on a field allocated to crop i. In the model specification, we also controlled the effect of improved varieties and other factors affecting crop yield. Accordingly, IMV is a dummy variable with a value of 1 if the field was grown to improved variety, and 0 otherwise, and X_i is a vector of farm, household and district-level covariates affecting farm management and investment decisions. These include location-specific and average acidity saturation, field-level soil fertility and slope, age, education and gender of household head, and district dummy. β_1 is the percentage change in yield due to a unit percentage change in lime applied (elasticity of crop-specific yield response to lime). Similarly, β_2 refers to yield response to fertiliser application rate (ceteris paribus). β_3 is the yield increment due to using seeds of improved varieties on the specific field. To check the consistency of the yield response estimates obtained from the Cobb-Douglas production function, we also specified a translog production function in which the functional form restrictions of the Cobb-Douglas model were relaxed and allowed for second-order terms across factors of production. In the translog functional form, normalising yield, lime and fertiliser by their mean values before taking the natural logarithms helped in obtaining elasticities (yield response to lime and fertiliser) from their first-order coefficients, viz., β_1 and β_2 (Oumer *et al*. 2020). The translog production function is defined as follows:

$$lnY_i = \alpha_i + \beta_1 lnL_i + \beta_2 lnF_i + \frac{1}{2}\beta_{11}(lnL_i)^2 + \frac{1}{2}\beta_{22}(lnF_i)^2 + \frac{1}{2}\beta_{12} lnL_i\, lnF_i + \beta_3 IMV_i + \gamma X_i + \varepsilon_i, \quad (2)$$

where the terms are defined as in Equation (1). In cases where we have field-level yield data only for those fields on which lime was used, the magnitude of yield gains from lime application (Δ_y) may be obtained from the estimated percentage change in yield due to lime application ($\widehat{\beta_1}$) and the average yield estimate from fields on which lime was used ($\bar{Y}_l$) using a backward induction approach. This can be specified as:

$$\widehat{\beta_1} = \frac{\bar{Y}_l - \bar{Y}_o}{\bar{Y}_o} = \frac{\bar{Y}_l}{\bar{Y}_o} - 1, \text{ which gives } \bar{Y}_o = \frac{\bar{Y}_l}{1+\widehat{\beta_1}}, \quad (3)$$

where $\bar{Y}_l$ is the mean yield from fields on which lime was used, and $\bar{Y}_o$ is the counterfactual mean yield if the field did not receive lime. Then the difference between the two provides the magnitude of the yield gain to lime to be used in benefit-cost ratio analysis ($\Delta_y = \bar{Y}_l - \bar{Y}_o$).

Taking the cost of lime as C_{lt} (the purchase price of lime smallholders paid in season t), and considering the yield increment due to lime application in season t (Δ_{yt}) and a decreasing effect of lime on crop yield across seasons after the first season of application, to 75%, 50% and 25% in season 2, 3 and 4 respectively (viz. $\Delta_{y2} = 0.75\Delta_{y1}$; $\Delta_{y3} = 0.5\Delta_{y1}$, and $\Delta_{y4} = 0.25\Delta_{y1}$), the net present value (NPV) of applying lime can be computed as:

$$NPV = \frac{P_{i1}\Delta_{y1} - C_{l1}}{(1+r)^0} + \frac{P_{i2}\Delta_{y2} - C_{l2}}{(1+r)^1} + \frac{P_{i3}\Delta_{y3} - C_{l3}}{(1+r)^2} + \frac{P_{i4}\Delta_{y4} - C_{l4}}{(1+r)^3} \text{ and} \quad (4a)$$

$$NPV = \sum_{t=1}^{4}\left(\frac{P_{it}\Delta_{yt} - C_{lt}}{(1+r)^{t-1}}\right), \text{ where } t = 1, 2, 3, 4, \quad (4b)$$

and where r is the interest rate (or rate of return on capital). In principle, C_{lt} should include all lime-related costs, starting from purchasing, transportation to farm, and application of lime on farm fields during season t. As transport and labour costs for lime application vary by household, we used only the purchase cost in the analysis. If lime utilisation is not economical when only purchase cost is considered, then it will also not be economical when the last-mile transportation and application costs are considered in the analysis. It is worth noting that our analysis is based on cross-sectional data that cannot address unobserved heterogeneity and bias associated with self-selection into lime use.

3. Survey data

The data used in this study was collected from four purposively selected districts in Rwanda: Nyaruguru and Nyamagabe districts in Southern province, Ngororero district in Western province, and Burera district in Northern province (Figure 1). All regions experience a bimodal rainfall pattern, allowing for two cropping seasons (denoted A and B) per calendar year and exhibit levels of exchangeable acidity above 20% of the effective cation exchange capacity (ECEC), which constrains the productivity of most cereal and legume crops (Farina & Channon 1991; Fageria & Baligar 2008). As the main goal of the survey was to assess the profitability of lime use, households that applied lime and fields that received lime were the sampling frame for the data collection. Accordingly, sample households were randomly selected from the list of households who had applied lime on their farm fields in the 2020B to 2021A[1] cropping seasons. For the selected sample households, input use and production data was collected for the fields treated with lime. As this sampling procedure could help in assessing the profitability of lime use, it is important to acknowledge that the focus on smallholders using lime as a sampling frame might cause a possible bias in yield response estimates due to the self-selection of the sample households into lime use, and the selection of the crop fields treated with lime.

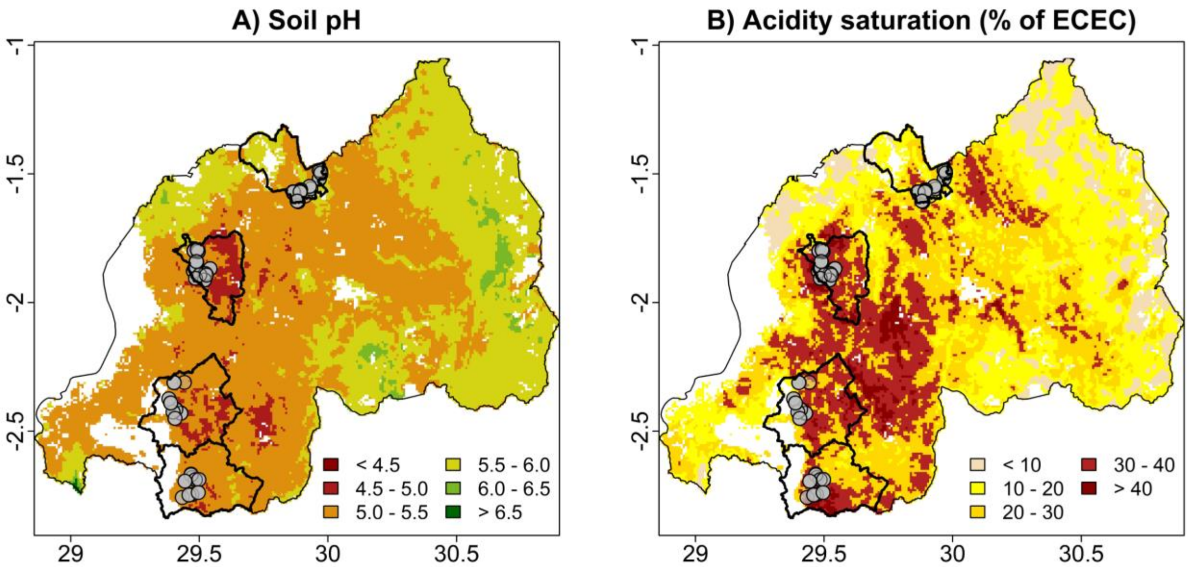

Figure 1: Map of survey districts and location of sample households overlaid on spatial predictions of (A) soil pH in water and (B) acidity saturation expressed relative to the effective cation exchange capacity (ECEC)

Experienced and well-trained enumerators administered a structured survey questionnaire and conducted interviews in the local language (Kinyarwanda) with the household head who was primarily responsible for lime-use decisions and had detailed knowledge of farm operations, including inputs used and harvests produced. The history of lime use on different fields was documented, and the inputs used per field and harvests obtained during the 2022A cropping season

[1] Rwanda has two rainy seasons, as well as two corresponding cropping seasons. Season A runs from September to February, and season B runs from March to June. Season 2020B therefore refers to March to June 2020, and 2021A refers to the period from September 2020 to February 2021.

were recorded in detail. Accordingly, a total of 261 households and 369 fields were surveyed in the four districts. Of the surveyed households, about 10% were headed by women. Data for all crops were documented, but the analyses focused only on Irish potato, maize and bean due to limited observations for some crops. Field area and production data were obtained from farmers' estimations and recall. Maize and bean production were reported in terms of dry matter, whereas potato production was reported as fresh matter. Data on acidity saturation was computed as the ratio between exchangeable acidity and the effective cation exchange capacity, and all underlying spatial layers were obtained from Hengl *et al*. (2017). Soil data was extracted for each surveyed household based on the respective GPS coordinates.

4. Results and discussion

4.1 Lime use and other management practices

The studied districts are known for growing maize, beans and Irish potato. In all four districts, farmers allocate more land to food-security crops like maize and beans than to cash crops like Irish potato (National Institute of Statistics of Rwanda [NISR] 2023). However, most of the surveyed fields in our sample targeting acid soils were allocated to Irish potato (56%). This could be due to the market-oriented nature of Irish potato production, where a larger proportion of its produce is sold out to generate cash income. The surveyed fields allocated to maize and bean were second and third in terms of frequency, respectively. Of the surveyed fields allocated to Irish potato, maize and bean, 91%, 60% and 70% respectively received lime either during the 2022A season or during any of the preceding three cropping seasons. Diammonium phosphate (DAP), urea and compound NPK were the most used mineral fertilisers, but their use varied by crop type. For instance, 85% of Irish potato fields received NPK. Compared to potato fields, the use of DAP and urea was relatively higher for maize and bean fields. During the surveyed cropping season, 65% of maize fields and 49% of bean fields received DAP. Similarly, 77% of maize fields and 31% of bean fields received urea. Farmers reported applying mineral fertilisers on fields that received lime. For instance, 79% of the Irish potato fields received both lime and NPK, 51% of maize fields received lime and urea, and 41% of bean fields received lime and DAP. On average, farmers applied 1.53, 0.86 and 0.83 t/ha of lime on fields allocated to Irish potato, maize and bean, respectively (Table 1). The cropping system and input utilisation were similar among the four surveyed districts.

Crop rotation is a common practice used by farmers for soil fertility management, and to break pest and disease cycles (see Franke *et al*. 2018). In the study districts, farmers rotate maize, beans, Irish potato, wheat, and other crops to better utilise residual nutrients from the previous season and to break the cycle of pests and diseases, which is critical for Irish potato. In the case of lime, as the benefit accrued from applying lime on a specific field in a given season could extend over three to four successive cropping seasons, the crop rotation pattern farmers use on fields treated with lime affects the level of return they can expect from their investment in lime. The history of surveyed fields shows that crop rotation between season-A and season-B was observed in a fairly large number of fields. However, there was a tendency for the same crop to be cultivated on the same field after one season. For example, only 30% of the fields allocated to Irish potato during the 2022A season were grown with the same crop during the 2021B season; the other 70% of fields were re-allocated to maize (26%), bean (15%) or other crops (29%). However, about 52% of the fields allocated to Irish potato during the 2022A season were planted with Irish potato in the 2021A season as well. Looking at the maize and bean fields, there was a clear pattern in which potato was used as a rotational crop on maize or bean fields, and vice versa. This cropping pattern was applied to generate the season-specific net present values of allocating fields treated with lime for different crops.

4.2 Lime and crop prices

The average local prices of major crops grown on limed fields (Irish potato, maize and bean) were collected from the District Offices of Agriculture, as was the fixed price of lime at local agro-dealer shops. Although the unsubsidised price of lime at agro-dealers shops was $107 per ton, the Rwandan government is currently subsidising lime by 50%, and farmers in the study area were paying a fixed price of $53 per ton of lime. Both subsidised and non-subsidised prices were used in the profitability assessment of lime to assess the sensitivity of our results to changes in lime price.

For the financial viability analysis, we used the 2022 average farmgate prices of Irish potato, maize and bean from the four districts covered in this study. The average farmgate prices for Irish potato and maize were 300 Rwandan francs per kg (RWF/kg, equivalent to 0.293 USD/kg at 2021 exchange rates). Similarly, the average farmgate price for bean was 350 RWF/kg (0.342 USD/kg). Although we considered the average prices in the computation, we also assessed how the viability changed for 50% below the average crop prices in recognition of the fact that investment in lime use is adversely affected if income from additional yield gain is lower due to low market prices. Such price sensitivity analysis indicates how lime use remains profitable under fluctuating crop prices due to unforeseen production and market dynamics.

4.3 Production levels and commercialisation

Among the three major crops grown on fields with lime applied (Irish potato, maize and bean), Irish potato was the most commercialised and most targeted crop for lime application. On average, the surveyed farmers sold 55% of the Irish potato they produced and consumed 19% at home. Meanwhile, only 30% of maize and 19% of bean produced were sold out of the farm. A larger proportion of maize (41%) and bean (35%) produced were consumed at home. The remainder was used for seed or other purposes, or lost due to post-harvest damages. Thus, among the three crops popularly grown on lime-treated fields, Irish potato was the most important crop for income generation.

Descriptive statistics for production-related variables used in the analysis are presented in Table 1. The average yield of Irish potato from the four surveyed districts was 7.2 t/ha. Average maize and bean yields were 2.2 t/ha and 1.5 t/ha, respectively. Slightly more than half of the surveyed fields were allocated to Irish potato in the 2022A cropping season. The lime application rate was highest for Irish potato (1.5 t/ha on average), whereas maize and bean fields received about half of this rate. Farmers reported that a majority of the fields allocated to Irish potato and maize were planted with improved varieties, and slightly under half of bean fields were planted with improved seed.

5. Assessment of lime profitability

Smallholders are more likely to invest their scarce capital in lime if the benefits accrued exceed the associated costs. This return on investment is first manifested in additional crop yield per unit of lime applied. Thus, accounting for observable farm inputs, we first estimated the yield response of lime for the three main crops in Rwanda (Irish potato, maize and bean) cultivated on fields to which lime was applied. Production functions, as described in Section 2, were used to obtain coefficient estimates for crop-specific conditional yield responses to lime. Different model specifications under each production function were applied to get a lower bound, conservative yield response to lime for each crop. This was done on the assumption that, if lime application yields returns, the benefit is more likely clear to smallholders even under this conservative yield response estimate.

In estimating the crop yield response to lime, we controlled for the effect of mineral fertiliser and improved seed used on the specific fields. In addition, we controlled for field, household and farm characteristics. This included slope of the field, soil fertility as perceived by the respondent, age, gender and education level of the household head who is making strategic decisions on technology choice and farm management practices, biotic or abiotic stresses on the crop grown on the specific field, and district-level variations through a district dummy. We also controlled for acidity saturation in the models, which was obtained from a secondary spatial prediction of soil properties.

Table 1: Descriptive statistics of selected variables used to determine crop yield response to lime for smallholder cropping systems in Rwanda

Variables	Irish potato fields (N = 206)		Maize fields (N = 93)		Bean fields (N = 70)	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Yield (kg/ha)	7 216.6	5 993.9	2 216.2	1 727.2	1 483.8	1 276.2
Lime applied in 2022A (kg/ha)	1 530.4	1 174.6	862.4	1 115.0	829.3	1 020.8
Fertiliser applied in 2022A (kg/ha)*	215.2	156.7	208.8	132.7	203.6	147.8
Used improved seed (dummy, 1 = yes)	0.75	0.44	0.79	0.41	0.46	0.50
Acidity saturation (% effective cation exchange capacity, ECEC)	33.66	5.19	34.59	5.58	32.43	7.59
Soil fertility of fields surveyed (as perceived by respondent farmers)						
Poor soil fertility (dummy, 1 = yes)	0.02	0.15	0.10	0.30	0.09	0.28
Medium soil fertility (dummy, 1 = yes)	0.73	0.45	0.66	0.48	0.76	0.43
Good soil fertility (dummy, 1 = yes)	0.25	0.43	0.25	0.43	0.16	0.37
Slope of fields surveyed (judged by respondent farmers)						
Flat sloped field (dummy, 1 = yes)	0.27	0.45	0.29	0.46	0.24	0.43
Medium sloped field (dummy, 1 = yes)	0.64	0.48	0.68	0.47	0.67	0.47
Steep sloped field (dummy, 1 = yes)	0.09	0.29	0.03	0.18	0.09	0.28
Sex of household head (dummy, 1 = male)	0.88	0.32	0.93	0.27	0.93	0.26
Age of household head (years)	44.04	11.65	45.30	13.01	46.27	12.97
Education of household head (years)	6.01	3.66	5.31	3.37	5.76	3.90
District						
Nyaruguru district (dummy, 1 = yes)	0.16	0.36	0.26	0.44	0.33	0.47
Nyamagabe district (dummy, 1 = yes)	0.21	0.41	0.20	0.41	0.14	0.35
Ngororero district (dummy, 1 = yes)	0.42	0.50	0.33	0.47	0.17	0.38
Burera district (dummy, 1 = yes)	0.21	0.41	0.20	0.41	0.36	0.48
Stress happened on field (dummy, 1 = yes)	0.52	0.50	0.56	0.50	0.56	0.50

Notes: Data refer to the 2022A season; * = aggregate of all mineral fertilisers applied to the field during the specific cropping season.

To obtain the effect of liming on crop yield, we estimated six different econometric models using a Cobb-Douglas functional form with different combinations of explanatory variables. We added variables in a stepwise manner to assess how the coefficient estimate of liming (i.e. the extra yield per unit of lime applied) changed when field-, farm- and district-level variations were controlled for. To evaluate the robustness of the Cobb-Douglas results, we also estimated a translog functional form with a full set of explanatory variables. Except in the case of maize, the translog model first-order coefficient estimates showed a significant yield response (elasticity) for Irish potato and bean. The results in Tables 2, 3 and 4 indicate that lime application had a positive and significant effect on the crop yield of Irish potato, maize and bean in the districts in this study. For the average rate of lime use by smallholders in the study area, the estimated average yield response to lime ranged from 15% to 28% for Irish potato (corresponding to 941 kg/ha to 1 579 kg/ha), 34% to 47% for maize (562 kg/ha to 709 kg/ha), and 44% to 54% for bean (453 kg/ha to 520 kg/ha). The bean yield response to lime is equivalent to an earlier estimate made in Ethiopia (Gurmessa 2021).

Table 2: Irish potato yield response to lime across smallholder farming systems in Rwanda

Explanatory variables	Cobb-Douglas production function						Translog
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Lime rate ln(kg/ha)	0.277*** (0.065)	0.191*** (0.065)	0.159** (0.062)	0.154** (0.063)	0.148** (0.063)	0.163** (0.063)	
Field without lime application (dummy, 1 = yes)	1.972*** (0.512)	1.512*** (0.497)	1.274*** (0.476)	1.259** (0.485)	1.194** (0.479)	1.165** (0.469)	0.151 (0.197)
Fertiliser rate ln(kg/ha)		0.364*** (0.074)	0.374*** (0.071)	0.378*** (0.072)	0.378*** (0.071)	0.365*** (0.069)	
Field without fertiliser application (dummy, 1 = yes)		1.697*** (0.500)	1.993*** (0.480)	2.006*** (0.484)	2.024*** (0.478)	1.862*** (0.475)	-0.182 (0.301)
Improved variety (dummy)			0.555*** (0.120)	0.542*** (0.121)	0.513*** (0.120)	0.526*** (0.119)	0.438*** (0.122)
Acidity saturation (% effective cation exchange capacity, ECEC)	-0.025** (0.011)	-0.027** (0.011)	-0.027*** (0.010)	-0.027*** (0.010)	-0.023** (0.010)	0.013 (0.018)	0.021 (0.017)
Soil fertility: Reference is poor							
Medium soil fertility (dummy, 1 = yes)				0.186 (0.342)	0.212 (0.335)	0.168 (0.329)	0.193 (0.322)
Good soil fertility (dummy, 1 = yes)				0.388 (0.351)	0.373 (0.344)	0.302 (0.337)	0.339 (0.330)
Slope of the field: Reference is flat							
Medium sloped field (dummy, 1 = yes)				-0.041 (0.123)	-0.037 (0.122)	-0.072 (0.123)	-0.078 (0.120)
Steep sloped field (dummy, 1 = yes)				-0.165 (0.197)	-0.148 (0.194)	-0.151 (0.190)	-0.283 (0.190)
Sex of household head (dummy, 1 = male)					0.062 (0.171)	0.131 (0.171)	0.126 (0.167)
Age of household head (years)					0.009* (0.005)	0.007 (0.005)	0.008* (0.005)
Education of household head (years)					0.045*** (0.015)	0.031** (0.015)	0.036** (0.014)
District: Reference is Nyaruguru							
Nyamagabe district (dummy, 1 = yes)						0.244 (0.232)	0.294 (0.230)
Ngororero district (dummy, 1 = yes)						-0.185 (0.163)	-0.102 (0.166)
Burera district (dummy, 1 = yes)						0.450 (0.274)	0.515* (0.275)
Stress incident happened on field (dummy, 1 = yes)						-0.148 (0.104)	-0.160 (0.101)
ln(lime_kg/ha_norm) [a]							0.342*** (0.081)
ln(fert_kg/ha_norm) [a]							0.179* (0.100)
0.5 $\ln(\text{lime\_kg/ha})^2$							0.247*** (0.081)
0.5 $\ln(\text{fert\_kg/ha})^2$							-0.302** (0.152)
ln(lime_kg/ha)*ln(fert_kg/ha)							0.155 (0.098)
Constant	7.434*** (0.639)	6.226*** (0.654)	5.980*** (0.626)	5.815*** (0.774)	5.000*** (0.831)	3.942*** (1.063)	-2.219** (0.863)
Observations	206	206	206	206	206	206	206
R-squared	0.116	0.212	0.288	0.303	0.342	0.387	0.426

Notes: Continuous variables were ln-transformed prior to the analysis. HHH = household head; standard errors are in parentheses; *** p < .01, ** p < .05, * p < .1 ; [a] normalised by its mean value before taking the natural logarithm.

Table 3: Maize yield response to lime across smallholder farming systems in Rwanda

Explanatory variables	**Cobb-Douglas production function**						**Translog**
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
Lime rate ln(kg/ha)	0.430*** (0.116)	0.428*** (0.116)	0.474*** (0.111)	0.431*** (0.113)	0.368*** (0.116)	0.338*** (0.121)	
Field without lime application (dummy, 1 = yes)	2.759*** (0.818)	2.736*** (0.823)	3.027*** (0.786)	2.839*** (0.799)	2.362*** (0.817)	2.210** (0.850)	-0.163 (0.213)
Fertiliser rate ln(kg/ha)		0.054 (0.108)	0.127 (0.105)	0.141 (0.105)	0.137 (0.105)	0.149 (0.109)	
Improved variety (dummy, 1 = yes)			0.671*** (0.205)	0.568*** (0.210)	0.534** (0.209)	0.501** (0.217)	0.475** (0.214)
Acidity saturation (% effective cation exchange capacity, ECEC)	-0.009 (0.015)	-0.007 (0.016)	-0.012 (0.015)	-0.008 (0.016)	-0.005 (0.015)	0.026 (0.023)	0.015 (0.025)
Soil fertility: Reference is poor							
Medium soil fertility (dummy, 1 = yes)				0.313 (0.299)	0.357 (0.304)	0.266 (0.308)	0.238 (0.307)
Good soil fertility (dummy, 1 = yes)				0.517 (0.341)	0.596* (0.339)	0.482 (0.349)	0.470 (0.349)
Slope of the field: Reference is flat							
Medium sloped field (dummy, 1 = yes)				-0.166 (0.185)	-0.124 (0.184)	-0.124 (0.188)	-0.152 (0.186)
Steep sloped field (dummy, 1 = yes)				-0.663 (0.491)	-0.338 (0.505)	-0.246 (0.515)	-0.334 (0.515)
Sex of household head (dummy, 1 = male)					0.462 (0.319)	0.498 (0.319)	0.506 (0.321)
Age of household head (years)					0.007	0.007	0.007
Education of household head (years)					0.050* (0.027)	0.036 (0.029)	0.039 (0.029)
District: Reference is Nyaruguru							
Nyamagabe district (dummy, 1 = yes)						0.425 (0.350)	0.247 (0.358)
Ngororero district (dummy, 1 = yes						-0.098 (0.262)	-0.222 (0.271)
Burera district (dummy, 1 = yes)						0.484 (0.352)	0.267 (0.390)
Stress incident happened on field (dummy, 1 = yes)						-0.082 (0.184)	-0.074 (0.192)
ln(lime_kg/ha_norm) [a]							0.189 (0.176)
ln(fert_kg/ha_norm) [a]							0.098 (0.189)
0.5 $\ln(\text{lime\_kg/ha})^2$							0.038 (0.221)
0.5 $\ln(\text{fert\_kg/ha})^2$							0.028 (0.204)
ln(lime_kg/ha)*ln(fert_kg/ha)							-0.304** (0.138)
Constant	4.796*** (1.034)	4.479*** (1.219)	3.461*** (1.198)	3.368** (1.337)	2.693* (1.392)	1.798 (1.564)	-2.259* (1.245)
Observations	93	93	93	93	93	93	93
R-squared	0.155	0.158	0.250	0.301	0.349	0.383	0.425

Notes: Continuous variables were ln-transformed prior to the analysis. HHH = household head; standard errors are in parentheses; *** $p < .01$, ** $p < .05$, * $p < .1$; [a] normalised by its mean value before taking the natural logarithm.

Table 4: Bean yield response to lime across smallholder farming systems in Rwanda

Explanatory variables	Cobb-Douglas production function						Translog
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Lime rate ln(kg/ha)	0.538*** (0.113)	0.499*** (0.119)	0.502*** (0.119)	0.516*** (0.119)	0.436*** (0.120)	0.452*** (0.131)	
Field without lime application (dummy, 1 = yes)	3.566*** (0.778)	3.225*** (0.832)	3.241*** (0.836)	3.307*** (0.833)	2.732*** (0.844)	2.827*** (0.941)	-0.242 (0.251)
Fertiliser rate ln(kg/ha)		0.096 (0.094)	0.088 (0.095)	0.084 (0.091)	0.065 (0.090)	0.058 (0.092)	
Field without fertiliser application (dummy, 1 = yes)		0.787 (0.674)	0.793 (0.677)	0.611 (0.667)	0.630 (0.648)	0.807 (0.659)	0.536 (0.465)
Improved variety (dummy, 1 = yes)			-0.127 (0.210)	-0.242 (0.207)	-0.325 (0.212)	-0.212 (0.228)	-0.286 (0.217)
Acidity saturation (% effective cation exchange capacity, ECEC)	-0.017 (0.014)	-0.020 (0.014)	-0.021 (0.015)	-0.022 (0.014)	-0.028** (0.014)	-0.041 (0.033)	-0.051 (0.031)
Soil fertility: Reference is poor							
Medium soil fertility (dummy, 1 = yes)				0.362 (0.356)	0.440 (0.350)	0.342 (0.367)	0.265 (0.354)
Good soil fertility (dummy, 1 = yes)				0.430 (0.429)	0.529 (0.419)	0.370 (0.436)	0.270 (0.417)
Slope of the field: Reference is flat							
Medium sloped field (dummy, 1 = yes)				-0.627** (0.251)	-0.654** (0.246)	-0.675*** (0.251)	-0.645** (0.248)
Steep sloped field (dummy, 1 = yes)				0.159 (0.422)	-0.023 (0.427)	-0.002 (0.433)	0.152 (0.417)
Sex of household head (dummy, 1 = male)					0.236 (0.384)	0.331 (0.429)	0.401 (0.411)
Age of household head (years)					0.005 (0.008)	0.004 (0.008)	0.007 (0.008)
Education of household head (years)					0.065** (0.028)	0.059* (0.031)	0.050* (0.030)
Districts: Reference is Nyaruguru							
Nyamagabe district (dummy, 1 = yes)						-0.083 (0.455)	-0.234 (0.434)
Ngororero district (dummy, 1 = yes)						0.080 (0.380)	0.087 (0.369)
Burera district (dummy, 1 = yes)						-0.242 (0.589)	-0.416 (0.566)
Stress incident happened on field (dummy, 1 = yes)						-0.439** (0.211)	-0.422** (0.202)
ln(lime_kg/ha_norm) [a]							0.851*** (0.188)
ln(fert_kg/ha_norm) [a]							0.115 (0.179)
0.5 ln(lime_kg/ha)^2							0.424*** (0.148)
0.5 ln(fert_kg/ha)^2							0.127 (0.167)
ln(lime_kg/ha)*ln(fert_kg/ha)							-0.038 (0.111)
Constant	3.883*** (1.004)	3.775*** (1.037)	3.887*** (1.059)	3.999*** (1.071)	4.002*** (1.169)	4.702*** (1.641)	1.058 (1.428)
Observations	70	70	70	70	70	70	70
R-squared	0.321	0.336	0.339	0.441	0.500	0.543	0.614

Notes: Continuous variables were ln-transformed prior to the analysis. HHH = household head; standard errors are in parentheses; *** $p < .01$, ** $p < .05$, * $p < .1$; [a] normalised by its mean value before taking the natural logarithm.

In addition to lime use and controlling for other yield-affecting variables, mineral fertiliser and improved seed had a significant effect on the yield of Irish potato. Acidity saturation showed a negative association with the yield of all the three crops, but significantly affected only the yield of Irish potato. In contrast, controlling for other variables, the yield response associated with mineral fertiliser in maize and bean production was not significant, although the use of an improved variety had a positive effect on maize yield. In all estimations, the dummy variables added for fields that did not receive lime and mineral fertiliser were significant, justifying the application of these bias-controlling variables in the estimation procedure. The R-squared values of crop-specific estimations ranged from 16% to 54% for the different models under the Cobb-Douglas model and were higher for the translog model. All these tests show the goodness of fit of these models in explaining the crop-specific yield variations. Moreover, the results of the quantile regression estimation indicated that, controlling for other factors, the effect of lime on crop yield was strongest (and significant) on fields with low productivity (Supplementary Table S1). This was consistent for the three crops considered in this analysis and underscores the potential value of targeting lime subsidies for use on low-yielding fields.

In order to measure the average crop-specific yield without lime application, the yield gain from using lime was retroactively deducted from the average yield obtained from the survey data using the estimated crop yield response to lime (Tables 2, and 4). Accordingly, Equation (3) was used to obtain the counterfactual average yield of each crop without lime applied and deduct this value from the average yield obtained from the survey data. Considering a conservative (lowest) yield response estimate, viz., 15% (0.62 kg yield per kg of lime) for Irish potato, 34% (0.65 kg yield per kg of lime) for maize, and 44% (0.56 kg yield per kg of lime) for bean, the average yield gain associated with the average rate of lime used was 941 kg/ha for Irish potato, 562 kg/ha for maize, and 453 kg/ha for bean. When considering the costs of lime purchased and the benefits from extra yield from applied lime, a 15% interest/discount rate was considered when the net present value of investment in lime use was computed (Ntaribi & Paul 2019; Miklyaev *et al*. 2020; World Bank 2023). In addition, the nationally recommended 1.5 t/ha lime application rate was considered for all crops in this analysis.

To break even on their investment in lime during the first cropping season, farmers must obtain a minimum additional yield of 547 kg/ha for Irish potato and maize and 469 kg/ha for bean after liming. Estimated yield gains from recommended lime application rates indicate this is possible for Irish potato and marginally so for maize in the first season after application, but not for bean. Without considering the subsidy on lime prices, the gross margin analysis showed a benefit of $115.3/ha on Irish potato fields, $11.4/ha on maize fields, and a loss of $0.5/ha on bean fields (Table 5). Considering the 50% government subsidy on lime, which puts the lime retailing price down to $53/t, the yield response required to break even in the first cropping season was reduced to 4% for potato, 16% for maize, and 23% for bean (Figure 2). These expected yield responses to break even the cost of subsidised lime use were much lower than the estimated minimum yield response for all three crops (viz., 15% for Irish potato, 34% for maize, and 44% for bean). Thus, the existing lime subsidy could help smallholders to absorb some level of downside risk in crop yield and/or price reduction, while generating positive returns from their investment in lime use during the first cropping season. This is more important for staple crops like maize and beans, for which the return on investment in lime use is at the margin under the actual market price of lime.

Table 5: Returns on investment in liming for the year of application for the main crops cultivated on acid soils in Rwanda

Variables	Irish potato	Maize	Beans
Estimated average yield (with lime) *(kg/ha)*	7217	2216	1484
Yield response to lime (%)	15	34	44
Adjusted average yield without liming *(kg/ha)*	6276	1654	1031
Estimated yield response to lime *(kg/ha)*	941	562	453
Farmgate crop price *(RWF/kg)*	300	300	350
Crop price *(USD/kg)*	0.293	0.293	0.342
Gain from liming *(USD/ha)*	276.1	164.9	155.0
Cost of liming *(USD/ha)* at a rate of 1.5 t/ha			
- Without subsidy *($107/t)*	160.5	160.5	160.5
- With 50% subsidy *($53/t)*	79.5	79.5	79.5
Gross margin *(USD/ha)*			
- Without subsidy *(USD/ha)*	115.6	4.4	-5.5
- With 50% subsidy on lime price *(USD/ha)*	196.6	85.4	75.5
Yield gain from liming needed to break even in season 1 (expected additional yield gain due to liming)			
- Without subsidy *(kg/ha)*	547.8	547.8	469.6
- With 50% subsidy on lime price *(kg/ha)*	271.4	271.4	232.6
Percentage additional yield needed to break even in season 1			
- Without subsidy *(%)*	8.7	33.1	45.6
- With 50% subsidy on lime price *(%)*	4.3	16.4	22.6

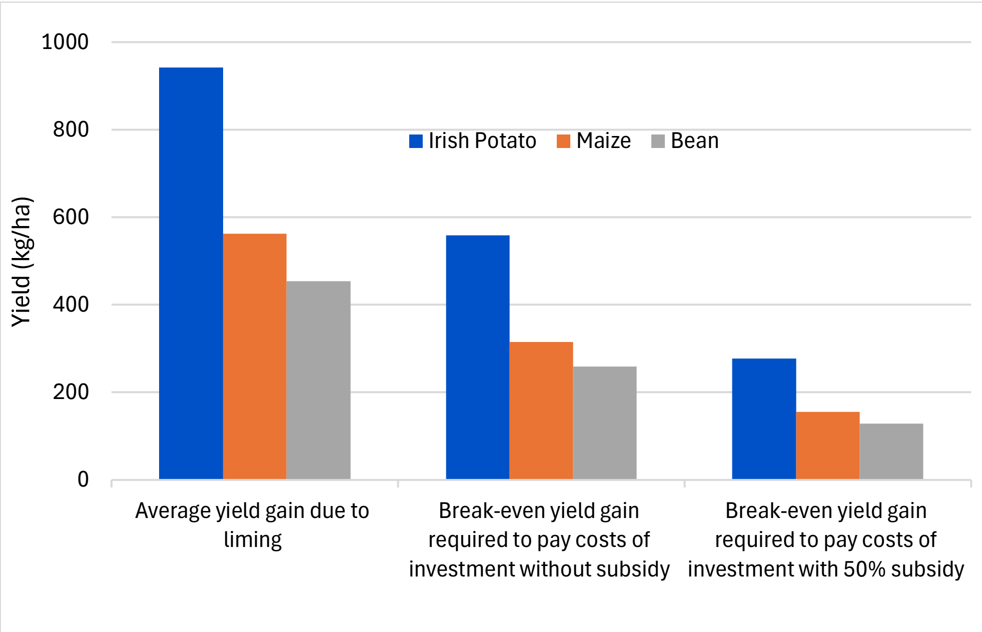

Figure 2: Yield gains required to break even on investments in lime in the year of application based on the current average lime rate used by farmers on fields with different crops (1 530 kg of lime per ha for Irish potato, 862 kg/ha for maize, and 829 kg/ha for bean)

It is worth noting that these net benefits would likely be reduced if lime transportation costs and labour costs associated with application were included in the analysis. Thus, we are cautious in interpreting net benefits at a narrow positive margin as a rewarding practice. To address this gap, we conducted a sensitivity analysis to check the maximum and minimum limits on prices and yield response to lime required to maintain positive returns on investment to smallholders. Accordingly, considering the estimated yield response to lime for the three crops, and the subsidised lime price as given, potato prices could drop a maximum of $0.09/kg before farmers fall below the break-even point, which is a 71% reduction from the price considered in this analysis. Similarly, the prices of maize and bean could drop by 51% and 48%, respectively, before farmers fall below the break-even point during the first cropping season after the lime is applied. These results show that the application of lime is reasonably profitable for smallholders under the subsidised lime price, and under the estimated yield response to lime.

As yield response to lime extends beyond one season, the anticipated benefits in subsequent seasons further justify investments in lime for the districts in this study. Studies confirm that liming could help ameliorate acidity for three to four seasons (Sanchez 2019). As such, after assessing the returns in the first season, we computed the net present values (NPV) of liming for four subsequent cropping seasons, with a possible reduction in crop-specific yield response to lime by 25% each year. As yield gains for potato covered lime investment costs during the first season (even without a subsidy on lime price), our focus in computing NPV based on four cropping seasons in two years was on maize and bean. On fields to which lime had been applied, we considered the different patterns of crop rotation that farmers follow, ultimately assessing NPV for maize or bean rotated with potato in each consecutive season. Considering the 15% discount rate on capital (Ntaribi & Paul 2019; Miklyaev *et al*. 2020; World Bank 2023) and the existing yield response to lime as fixed, it was evident that bringing potato into the rotation with maize and bean pays off farmers' investments within the first two cropping seasons. Accordingly, in two cropping seasons, rotating Irish potato with bean on a field treated with lime could generate a net present value of $163.9/ha without subsidy, and $244.9/ha with the 50% subsidy on lime price. Similarly, by rotating Irish potato after maize, farmers could generate – on average – a net present value of $173/ha and $254/ha without and with subsidy on lime price, respectively.

6. Conclusions and implications

To facilitate the uptake of agricultural lime by smallholders to deal with soil acidity and to benefit from the associated improvement in crop yield, it is important to show evidence that lime application generates a net profit, both in the short term (in the year of application), and in the medium term (in subsequent years). Therefore, extension advice on lime use provided to smallholders for acid soil management needs to consider smallholders' capital constraints and to prioritise the most yield-improving inputs to be purchased.

In this study, which used survey data from four districts in Rwanda, we assessed the financial viability of applying lime to the commonly produced crops in Rwanda (Irish potato, maize and bean). Our results indicate that Irish potato showed the greatest returns on investment in lime, and indeed, most fields to which lime was applied during the survey year or earlier were allocated to potato. Although the estimated percentage yield response to lime for Irish potato was far below the estimated yield response to lime for maize and bean, the actual yield response to lime was larger. This made Irish potato the most economically attractive crop to grow on limed fields, as it could generate positive returns on investment to lime in the season of application, unlike maize or bean alone. This implies that crop choice is an essential consideration for lime investments, and that rotating maize and bean with cash crops like Irish potato may be helpful in boosting the revenue of lime-treated fields and generating returns on investment to lime.

The findings also have implications for the effective targeting of lime subsidies. Currently, the government of Rwanda subsidises lime use in selected districts, regardless of the specific crop farmers grow on lime-treated fields or the soil fertility status of the field. Considering existing farmgate crop prices and estimated yield response to lime, smallholders growing maize and bean on lime-treated fields might not generate a significant financial benefit from maize and bean production in the first season to justify investments in lime. Thus, investing in lime to grow maize and bean is not economically attractive to smallholders under the prevailing conditions. Reducing the cost of investment through lime subsidies increases farmer incentives to apply lime, but the cost to the government could be reduced through more deliberate targeting. As the Irish potato yield leads to positive returns to lime, even without price subsidies, the government could consider lifting lime subsidies for fields allocated to Irish potato and providing more incentives for farmers to use lime on fields allocated to maize and bean. This could be done to the point where the estimated benefits from additional grain yield (income) from maize and bean are higher than the subsidy cost to the government. The ongoing lime subsidy efforts by the government of Rwanda need to be strengthened through agricultural development programmes to encourage smallholders to apply lime to acid soils and thereby to ensure better soil health.

This study provides strong evidence of the potential economic benefits of lime application for Rwandan smallholders, particularly for cereal, legume and tuber crops. However, farmer demand for lime is a complex issue. The decision by farming households to use lime relates not only to the price farmers pay for lime (included in our analysis), but to labour and transportation considerations, livelihood priorities, and intrahousehold decision-making and input-use dynamics. As lime is bulky to transport, and its application in the field is laborious – especially at the recommended application rates – the costs of transportation and application may merit further research. Such hidden costs (as farmers use family labour to transport and apply) might often be much higher than the actual cost of lime, especially in cases where lime is obtained at a highly subsidised price. Future analysis could consider the wider cost components of the application of lime to farmers' fields – from purchase and transport to its final application on the farm – as well as the social and behavioural dynamics that could influence farmer uptake beyond simple cost-benefit analysis.

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Supplementary Table

Table S1: Quantile regression on yield responses to liming in Irish potato, maize and bean production _ln(kg/ha)

Explanatory variables	Irish potato				Maize				Beans			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
	q25	q50	q75	q90	q25	q50	q75	q90	q25	q50	q75	q90
Lime rate ln(kg/ha)	0.288*** (0.088)	0.137 (0.111)	0.111 (0.077)	0.047 (0.070)	0.638*** (0.214)	0.424* (0.247)	0.114 (0.133)	0.129 (0.139)	0.773*** (0.205)	0.700*** (0.239)	0.181 (0.316)	0.021 (0.407)
Fertiliser rate ln(kg/ha)	0.357*** (0.100)	0.481*** (0.114)	0.389*** (0.088)	0.393*** (0.114)	-0.123 (0.221)	0.024 (0.190)	0.221 (0.173)	0.317 (0.204)	0.095 (0.146)	0.014 (0.147)	0.078 (0.109)	0.063 (0.166)
Field is not treated with lime (dummy, 1 = yes)	1.731** (0.705)	0.920 (0.844)	1.048** (0.505)	0.588 (0.510)	4.503*** (1.471)	2.696 (1.758)	0.673 (1.102)	0.977 (1.037)	5.070*** (1.572)	4.537** (1.768)	0.615 (2.339)	-0.561 (3.076)
Field is not treated with fertiliser (dummy, 1 = yes)	1.140* (0.687)	3.350*** (1.183)	2.497*** (0.725)	2.120*** (0.706)	-	-	-	-	1.240 (0.901)	0.783 (1.001)	0.732 (0.902)	0.911 (1.380)
Improved variety (dummy, 1 = yes)	0.760*** (0.149)	0.596*** (0.192)	0.475* (0.250)	0.369** (0.179)	0.472 (0.304)	0.331 (0.391)	0.676* (0.373)	0.416 (0.319)	-0.499 (0.419)	0.037 (0.337)	-0.053 (0.306)	0.087 (0.259)
Medium soil fertility (dummy, 1 = yes)	-0.025 (0.526)	0.067 (0.420)	0.521 (0.337)	0.385* (0.232)	0.222 (0.638)	0.390 (0.698)	0.846 (0.807)	-0.010 (0.751)	0.356 (0.995)	-0.122 (0.957)	0.144 (0.886)	0.488 (0.800)
Good soil fertility (dummy, 1 = yes)	0.182 (0.596)	0.347 (0.392)	0.664** (0.298)	0.428 (0.279)	0.693 (0.677)	0.330 (0.732)	1.014 (0.759)	0.309 (0.723)	0.486 (1.252)	-0.177 (0.934)	0.024 (0.880)	0.294 (0.850)
Medium sloped field (dummy, 1 = yes)	-0.204 (0.212)	-0.099 (0.206)	0.055 (0.156)	0.051 (0.156)	-0.260 (0.228)	-0.200 (0.223)	0.081 (0.239)	0.002 (0.278)	-0.228 (0.444)	-0.532 (0.320)	-0.444 (0.312)	-0.514 (0.333)
Steep sloped field (dummy, 1 = yes)	-0.150 (0.251)	-0.134 (0.268)	-0.232 (0.225)	-0.145 (0.242)	-1.277 (0.770)	-0.386 (0.793)	0.664 (0.719)	-0.391 (1.011)	0.862 (0.547)	-0.007 (0.498)	-0.321 (0.486)	0.143 (0.502)
Sex of HHH (dummy, 1 = male)	0.278 (0.265)	0.151 (0.171)	0.126 (0.172)	0.298 (0.288)	0.489 (0.415)	0.921* (0.467)	1.009 (0.632)	0.607 (0.748)	0.121 (0.424)	0.077 (0.581)	-0.370 (0.734)	-0.219 (1.065)
Age of HHH (years)	0.001 (0.008)	0.016* (0.009)	0.009 (0.008)	0.015* (0.009)	-0.006 (0.015)	0.015 (0.017)	0.011 (0.011)	-0.004 (0.015)	0.015 (0.011)	0.008 (0.011)	0.006 (0.010)	0.013 (0.014)
Education of HHH (years)	0.015 (0.019)	0.050** (0.020)	0.026 (0.028)	0.025 (0.028)	0.008 (0.050)	0.034 (0.050)	0.040 (0.043)	0.039 (0.058)	0.045 (0.053)	0.044 (0.051)	0.101* (0.055)	0.123** (0.059)
Nyamagabe district (dummy, 1 = yes)	-0.161 (0.295)	0.244 (0.253)	0.159 (0.222)	0.293 (0.209)	-0.053 (0.330)	-0.157 (0.351)	0.261 (0.404)	0.610 (0.544)	-0.087 (0.526)	-0.099 (0.535)	0.663* (0.394)	1.110*** (0.391)

Ngororero district (dummy, 1 = yes)	-0.256 (0.181)	0.040 (0.242)	-0.149 (0.204)	-0.426** (0.178)	-0.175 (0.358)	-0.251 (0.305)	-0.058 (0.394)	-0.191 (0.416)	0.104 (0.639)	0.021 (0.553)	0.225 (0.556)	0.556 (0.759)
Burera district (dummy, 1 = yes)	0.348 (0.251)	0.538** (0.257)	0.200 (0.277)	-0.100 (0.222)	0.071 (0.437)	0.159 (0.339)	0.291 (0.271)	0.214 (0.294)	0.362 (0.429)	0.257 (0.329)	0.605** (0.285)	0.787* (0.401)
Stress incident happened on field (dummy, 1 = yes)	-0.019 (0.175)	-0.111 (0.144)	-0.172 (0.142)	-0.097 (0.137)	-0.056 (0.271)	-0.162 (0.266)	-0.107 (0.244)	0.199 (0.303)	-0.315 (0.407)	-0.582* (0.309)	-0.333 (0.291)	-0.312 (0.382)
Constant	3.471*** (1.043)	3.397*** (1.059)	4.715*** (0.969)	5.369*** (0.925)	2.380 (2.271)	2.421 (1.822)	2.962** (1.165)	4.489*** (1.489)	-0.189 (2.163)	2.132 (2.576)	5.495** (2.206)	5.730** (2.219)
Observations	206	206	206	206	93	93	93	93	70	70	70	70

Notes: HHH = household head; standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$