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Liming agricultural soils in Western Kenya: Can long-term economic and environmental benefits pay off short term investments?

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ABSTRACT

Context: Soil acidification affects crop yields which can diminish farmers' incomes. Whilst soil pH can easily be increased by application of lime, in practice application must be economically viable with yield benefits offering an acceptable return on investments. Liming is a long-term investment with benefits becoming apparent over multiple years. Long-term economic strategies can be problematic for farmers who lack investment capital and who may have short-term decision time frames, such as most smallholder farmers in sub-Saharan Africa. In addition, application of lime causes substantial greenhouse gas (GHG) emissions (especially CO_2). It is currently unclear how liming affects GHG emissions per tonne of maize, in cases where liming increases crop yields.
Objective: In this study, we assessed if liming acid soils is economically and environmentally viable at different levels of intensification for maize cultivation in Western Kenya.
Methods: First, a meta-analysis using a regression analysis was conducted to quantify effects of lime application on soil pH and maize yields based on 26 field experiments. Related effects on farm profit and and returns on investment were estimated for a period of five years for soils with varying levels of initial soil pH and fertiliser application. Finally, synergies and trade-offs were assessed between maize yields, economic benefits and GHG emissions.
Results and conclusions: Liming consistently increased maize yields on soils with an initial soil pH between 4.0 and 5.7 in Western Kenya, with or without fertiliser use. For a soil pH of 5, applying 2 t ha^{-1} lime resulted in a significant increase in maize yields of 57% (from 2.3 to 3.6 t ha −1) in the first year after application. Despite these positive effects on yield, associated profits – when including costs of labour - were only positive when liming was combined with fertiliser (N,P) application. While liming causes substantial GHG emissions per tonne lime applied, these were offset when expressing GHG emissions per tonne of grain maize, due to the observed yield increases. The pay-back period for lime investments was at least two years.
Significance: Our analysis shows that liming has potential co-benefits for food security and the environment in tropical acid soils, but we expect uptake by farmers to be unlikely without external incentives, at least in Western Kenya.

1. Introduction

With the human population growing and diets changing in East Africa, regional food production will need to increase to keep up with growing food demands (Alexandratos and Bruinsma, 2012). To meet projected national cereal demands, between 2015 and 2050 cereal production has to increase more than threefold in Kenya (updated - van Ittersum et al., 2016). Currently maize yields - the most important cereal crop in Kenya - are relatively low, being on average only 24% of their yield potential, indicating scope for improvements (yieldgap.org, 2020). Furthermore, yield trends for maize have been stagnating recently in Kenya (FAO, 2020). Clearly, agronomic improvements are needed, supported by socio-economic incentives.

The relatively low maize yields currently observed in Kenya can be attributed to a diverse range of factors, such as low use of nutrient inputs (IFDC, 2012; Ten Berge et al., 2019), lack of infrastructure, poor access to markets and limited agricultural extension services (e.g., Vanlauwe et al., 2014). In addition, poor soil fertility might also limit yield

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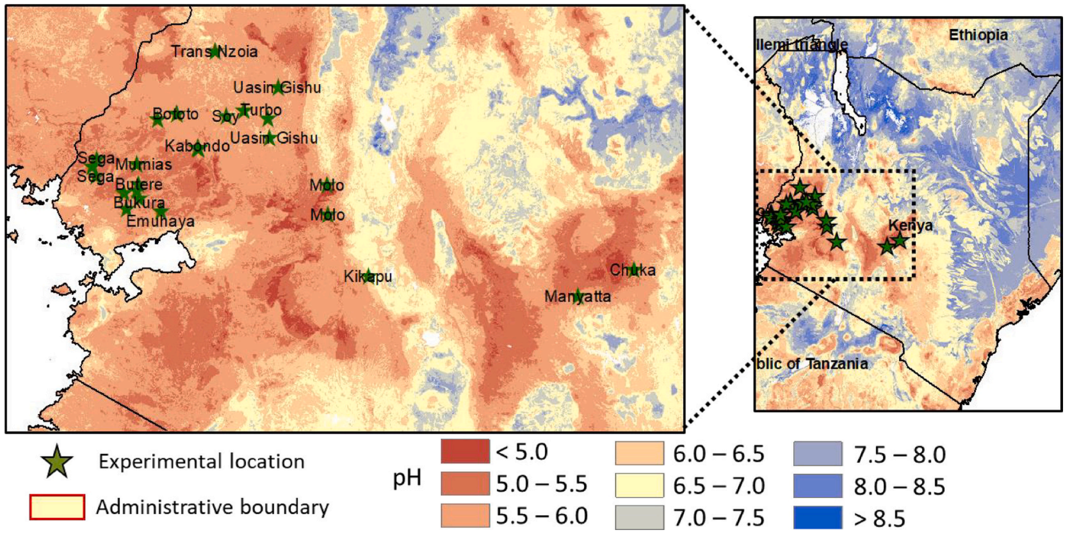

Fig. 1. Map of (Western) Kenya showing soil pH (Hengl et al., 2015) and locations of the field experiments used in this study (red indicates acid, yellow indicates neutral and blue indicates alkaline soils) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

responses to inputs (Tittonell et al., 2008) due to poor soil structure, limited soil supply of nutrients and/or acidity of soils. Soil acidity causes an increase in the amounts of exchangeable aluminium (Al). Al toxicity can prevent uptake of phosphorus (P), calcium (Ca) and magnesium (Mg) and inhibits root growth (Fageria and Baligar, 2008).

Soil pH can be increased by soil amendments with alkalifying effects, such as manure, biochar or lime. The most effective amendment to raise soil pH is lime. Currently, less than 3% of smallholder farmers use lime in Western Kenya (One Acre Fund, 2015; Kenya Market Trust, 2019). To raise soil pH, relatively large quantities of lime are needed, in the range between 1 and 16 t ha^{-1} (Godsey et al., 2007). Such amounts, even at the lower end, require substantial logistics for transportation to remote rural areas (One Acre Fund, 2015). This might be one of the explanations for the low uptake of liming among smallholder farmers in Kenya presently (Kisinyo et al., 2013). Other barriers include high initial investment costs for farmers, combined with uncertainties on yield benefits in later years. While liming gives benefits over multiple years, the costs are to be incurred in the first year (at application). Liming therefore requires scarce capital devoted to a long-term investment, while farmers with limited resources are unlikely to have such financial manoeuvre space.

Soil acidity thresholds have been estimated previously and differ per crop type. For maize, a soil pH of 5.6 is considered a common threshold (Cranados, 1993). In Kenya, substantial parts of agricultural soils have a soil pH below this value, especially in Western Kenya (i.e. 17% and 24% of the cultivated maize area respectively; Fig. 1). Currently, impacts of these low soil pH values on maize yields and profitability are unknown. To assess if measures to increase soil pH are justified, improved insights are needed on impacts on crop yields and return on investments.

Besides affecting crop yields and returns on investments, liming also has environmental consequences. The main component of lime is $CaCO_3$ and decomposition (after application to the soil) results in CO_2 emissions. Some of these CO_2 emissions may be offset if liming leads to more efficient use of fertiliser (causing less nutrient losses to the environment) and/or if the yield increases are sufficient to balance the GHG emission per tonne maize yield produced. Such environmental benefits of liming can add justification to public investments in soil liming besides other motivations such as safeguarding long-term soil fertility and improving farmers livelihoods.

In summary, whilst substantial shares of agricultural soils in Western Kenya have soil pH values below a common threshold value (Fig. 1), investments in lime are only justified if these make for increased yields, higher returns on investments and/or reduced environmental impacts. In this study, we therefore address the following three research questions:

1. What is the impact of liming on soil pH and maize yields in Western Kenya?
2. Is liming an economically viable option for smallholder farmers in Western Kenya?
3. What are the synergies or trade-offs between maize yields, return on investments and GHG emissions of liming?

To answer the research questions, we performed a trade-off analysis, in which we combined a regression analysis of emprical field data with economic and environmental modelling. While economic or environmental analyses for liming have been conducted previously in temperate climates (Abalos et al., 2020; Gibbons et al., 2014; Holland and Behrendt, 2020), such integrated analysis seems more rare, especially for tropical conditions.

2. Methodology

To answer the research questions, data from 26 maize field experiments conducted in Western Kenya were compiled (Sections 2.1 and 2.2). Based on these data, liming effects on soil pH and maize yields were modelled through time (Section 2.3). Thereafter, returns on investments were calculated to assess under which conditions liming is an economically viable option in Western Kenya (Section 2.4). Finally, trade-offs and synergies between maize yields, return on investments and GHG emissions were explored and uncertainties were quantified (Sections 2.5 and 2.6).

2.1. Data compilation on field experiments with lime application

A literature search was conducted using Google Scholar and Web of Science to find suitable field experiments. Our study interests were fourfold: 1) to quantify the effect of lime application on soil pH in the first year after lime application; 2) to quantify the change in soil pH in the second to fifth year after lime application; 3) to quantify the effect of lime application on maize yields; 4) to quantify the effect of soil pH on maize yields. If data from a field experiment could provide insight into at least one of these four interests, it was included in our database.

Based on our study interests, the selection criteria for inclusion of experimental data were as follows: 1) maize was included as a crop; 2) the experiment was conducted in East Africa; 3) at least two of the following variables were reported: maize yields, initial soil pH and/or -

Table 1
Overview of field experiments used in the analysis (data points used after outlier removal; i.e., a data point is a unique combination of site, year, season, liming rate, and fertiliser rate).

Publication	Sites	Year(s)	Seasons (#)	Liming rates (#)	N rates (#)	P rates (#)	FYM[a] rates (#)	Experiment type[b]	Data points available		
									Soil pH in the first year (#)	Soil pH in years 2 to 5 (#)	Maize yield (#)
Ademba (2009)	Bototo, Kabondo	2007	2	2	2	1	0	F	0	0	10
Ademba et al. (2014)	Boboto	2007	2	2	2	1	0	F	0	0	5
Kihanda et al. (2013)	Manyatta	2 years	1	2	2	2	1	F	0	0	8
Kiplagat et al. (2014)	Ugenya, North Kakamega	2010	2	4	1	1	0	F	8	6	8
Kisinyo et al. (2014)	Sega	2005–2008	2	4	1	3	0	F	10	24	16
Kisinyo et al. (2015)	Busia	2008	2	3	2	2	0	F	3	0	0
Kisinyo (2016)	Uasin Gishu	2005–2008	1	2	3	2	0	F	5	6	2
Lelei et al. (2014)	Molo	2009–2010	1	2	1	2	2	R	0	0	8
Mochoge et al. (2010)	Molo	1 year	1	2	2	1	0	R	0	0	4
Mucheru-Muna et al. (2007)	Chuka	2000–2003	2	0	1	2	0	R	2	2	0
Mungai et al. (2009)	Kikapu	2006–2007	1	1	1	1	0	F	0	0	2
Ndung'u-Magiroi et al. (2010)	Trans Nzoia, Uasin Gishu	1 year	1	2	2	2	0	F	0	0	8
Njoroge, 2019	Sidindi	2014–2018	2	0	2	2	0	F	4	4	0
Nekesa et al. (2011)	Kuinet	2005	1	4	4	4	0	F	0	0	16
Okalebo et al. (2009)	Mabanga, Sega	2005	1	2	1	2	0	F	14	10	10
Onyango (2013)	Shianda	2011	2	2	1	2	0	F	4	0	4
Opala et al. (2010)	Bukura	2006–2007	2	0	2	2	0	F	8	4	4
Opala et al. (2018)	Butere, Emuhaya, North Kakamega, Mumias	2015–2016	2	2	2	2	0	F	6	4	16
Tabu et al. (2007)	Shitirira	1 year	1	2	1	1	0	F	0	0	2
Total data points									**64**	**60**	**123**

[a] FYM, farm yard manure.
[b] Type of experiment: F = on-farm, R = research station.

if applied - the amount of liming. Initially, our geographical scope was East Africa, especially focussing on Ethiopia, Tanzania and Kenya, but with an interst in any East African country. After the literature search however, we found almost all suitable field experiments being located in Western Kenya. For consistency purposes, we therefore delineated our research to this area.

Twenty-six suitable field experiments were found in Western Kenya, conducted between the years 2000 and 2018, published in 19 articles (Fig. 1; Table 1). The experimental sites cover three agro-ecological zones (the humic, sub-humid and semi-humid zones) as initially defined by Sombroek et al. (1982) and further described by Karanja (2006). Together, the experiments are located in the former provinces Nyanza, Rift Valley and Western Kenya. For readability, we use the term 'Western Kenya' in further text.After extracting data from the publications, outliers were removed. Data was considered an outlier if reported values on maize yields and change in soil pH were above or below the mean plus or minus three times the standard deviation. In addition, reported soil pH values from Ademba et al. (2014) and Mwangi et al. (2002) were excluded from analysis because all treatments without lime application showed an increase in soil pH, which was deemed unlikely and an indication of (potential) measurement errors (either in the laboratory or in the field).

2.2. Quantifying the effect of liming in the first year of application using yield pairs

At 23 experimental sites, at least one pair of treatments could be identified in which all characteristics (e.g. mineral and/or organic fertiliser application, tillage) were similar and only the amount of lime applied differed. These paired treatments were used to calculate the relative yield increase due to liming. For some experimental sites, multiple yield pairs could be constructed (i.e. different fertilisation levels, each repeated with and without lime). In total, 54 pairs of yield data were formed from 16 publications.

2.3. Modelling changes in soil pH and maize yields through time

The analysis of yield pairs (Section 2.2) provided insights into the relative effect of liming on maize yields in the first year of application. However, a lack of data prevented the construction of further correlations between liming, soil pH and maize yields in the years following, based on these pairs. Yet, tracking effects of liming on maize yields through time is indispensable for assessing economic viability. Therefore, additional statistical analyses were conducted to relate maize yields to liming and change in soil pH for up to 5 years after application, as explained below.

In the first year after lime application, soil pH increases, after which

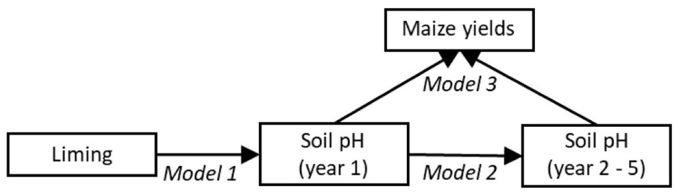

Fig. 2. Modelled relations between liming, soil pH and maize yields through time.

Table 2
Initial levels of soil pH and fertiliser application used to assess effects of liming on farmers' income and GHG emissions.

Fertiliser application level	Initial soil pH	Mineral fertiliser N (kg N/ha)	Mineral fertiliser P (kg P/ha)
No	4.5	0	0
Low	4.5	50	25
Medium	4.5	100	50
No	5.0	0	0
Low	5.0	50	25
Medium	5.0	100	50
No	5.5	0	0
Low	5.5	50	25
Medium	5.5	100	50

it decreases again over time. As such, benefits of liming to farmers will last for more years, but the magnitude will differ, depending on time passed since lime application, initial soil pH and amount of lime applied. Ten publications in our data set contained information on maize yield responses in relation to the change in soil pH in the first year, and eight of those provided maize yields and change in soil pH beyond the first year. As such, we first assessed the effect of liming on soil pH (Models 1 and 2) and then assessed the relation between maize yields and soil pH (Model 3), based on available data (Fig. 2). Each model was based on a subset of the entire data set, with Model 1, 2 and 3 having respectively 64, 60, and 123 underling measurements (Table 1). In this manner, we could fully utilize the available data on liming, soil pH and maize yields to answer our research questions.

In summary, three statistical models were constructed to link liming, soil pH and maize yields through time using the nls function (R v3.6.1) of the 'stats package. For each model, relevant co-variables such as fertiliser application, liming rate and initial pH were included (Tables S2 to S4).

2.4. Assessing effects of liming on farmers' income at different initial soil pH and fertiliser schemes

The benefits of liming were assessed for varying degrees of intensification (i.e. fertiliser schemes) at different levels of soil acidity. To this end, three levels of initial soil pH (4.5, 5.0 and 5.5) were modelled with three levels of fertiliser application (no, low or medium; Table 2). For each situation, the effect of liming on soil pH and crop yields was assessed using Models 1 to 3. For each fertiliser scheme and soil pH level, farm profit and GHG emissions were estimated, based on the cop yield models (the latter as described in more detail in Section 2.5).

Analayis of the experimental data indicated that effects of liming on soil pH generally occurred up to five years after application. This timeframe was therefore used to assess liming effects on profits and return on investments (ROI). Profits were calculated as earnings from maize yield minus costs of inputs and labour. Maize yield was estimated from Model 3 based on the experimental data (Section 2.1, Fig. 2). Costs consisted of input costs (i.e., liming and/or fertiliser) and labour costs (i.e., liming and/or fertiliser and fixed labour costs for land clearing, ploughing, weeding, planting and harvesting). The return on investment for liming was calculated using Eq. 1. Note that lime is only applied in the first year.

$$ROI = \left(\frac{profit\ with\ lime - profit\ without\ lime}{total\ costs\ with\ lime - total\ costs\ without\ lime}\right)*100 \quad (1)$$

Annual profits over time and the pay-back period were calculated for the lime application with the greatest ROI. Sources of the economic data used can be found in Table 3.

2.5. Exploring synergies and trade-offs between maize yields, return on investments and greenhouse gas emissions

Synergies and trade-offs of liming on farm income and GHG emissions were assessed for a five-year period. GHG emissions included emissions related to production of lime and fertiliser and emissions related to application of lime and fertiliser. Emissions from transportation were not included (see Discussion Section for an elaboration). All emissions were converted to CO_2 equivalents.

GHG emissions from lime application were estimated based on the IPCC tier 1 approach. The amount of lime applied was multiplied by the emission factor of lime application (i.e., 0.12 CO_2-C t lime^{-1} for $CaCO_3$ (IPCC, 2006, 2019), as this type of lime was the most common type used in the experiments (Table S1) and in Western Kenya (Kenya Market Trust, 2019)). GHG emissions from the production of lime were estimated as the amount of lime applied multiplied by the emission factor (i.

Table 3
Data and data source of input, output, and labour prices and of labour requirement.

Category		Unit	Average	Standard deviation	Number of observations	Source
Input prices	CAN	KES/kg	50.40	0.83	15	Africafertiliser.org
	DAP	KES/kg	68.00	1.50	15	Africafertiliser.org
	NPK	KES/kg	60.73	2.55	15	Africafertiliser.org
	TSP	KES/kg	72.50	6.36	2	Oseko and Dienya (2015)
	Urea	KES/kg	59.00	4.36	3	Oseko and Dienya (2015)
	Lime	KES/kg	5643.28	504.49	2	One Acre Fund (2015) and personal communication S. Njoroge
Output prices	Maize	KES/kg	27.60	6.72	104	Jindo et al. (2020)
Labour prices[a]	Fixed labour[b]	KES/day	383.34	407.99	835	Jindo et al. (2020)
	Fertiliser application[c]	KES/day	241.18	324.38	835	Jindo et al. (2020)
	Lime application	KES/day	269.34	240.39	7	Kiplagat et al. (2014); Kisinyo et al. (2014)

[a] Assuming that a working day consists of 8 h.
[b] Fixed labour includes land clearing, ploughing, weeding, planting and harvesting.
[c] The fertiliser application consists of two applications.

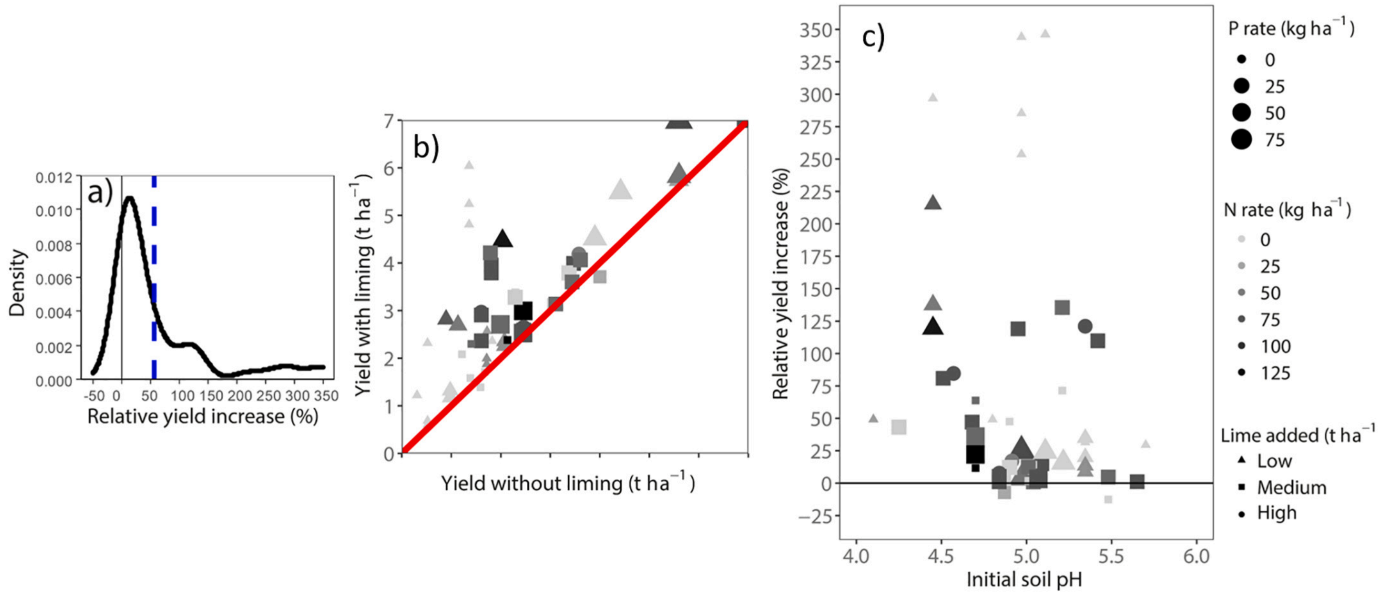

Fig. 3. a) Density plot of relative yield increase due to liming; blue dashed line indicates the average increase b) Maize yield with lime applied versus without lime applied; red line indicates the 1:1 line. c) relative yield increases due to liming versus the initial soil pH. Symbol gradient from small to large indicates the P rate, from grey to black indicates the N rate, triangles, circles and squares indicate respectively low (< 2 t ha^{-1}), medium (< 4 t ha^{-1}), high amount of lime added (> 4 t ha^{-1}). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

e., 0.06, Feliciano et al. (2017)).

GHG emissions from fertiliser application were composed of the direct N_2O-N emission from applied fertiliser, indirect N_2O emission through NH_3 and NO_x volatilization, and indirect N_2O-N emission from leaching and run-off (IPCC tier 1). The CO_2 emissions from the production of fertiliser were calculated as the amount of a specific mineral fertiliser multiplied by the emission factor for that type of fertiliser (Tables S5 and S6). All GHG emissions were translated into CO_2 equivalents and expressed in GHG emissions per tonne of maize, as recommended by Van Groenigen et al. (2010).

2.6. Uncertainty analysis

For each fertiliser scheme and level of initial soil pH, uncertainties in the estimated maize yield, profits and GHG emissions were estimated. Uncertainty in maize yield was estimated using the predictNLS function of the 'propagate' package in R. Uncertainties on profit estimates and GHG emissions were assessed using a replicated Latin hypercube design (Pleming and Manteufel, 2005) and drawing 625 (25 × 25) samples from the parameter space (Tables 3, 4, S1 and S2 from van Loon et al. (2019)). For each individual sample, model predictions were made for profit and GHG emissions, after which the mean and standard deviation of all model predictions were calculated. This facilitated the testing of the significance of observed differences in yields, GHG emissions and profits between fertiliser schemes and soil pH levels, which depends partly on the size of the sampling strategy.

3. Results

3.1. Relative yield increases due to liming in the first year after application

Based on 54 treatment pairs - with an average lime application of 2.0 t ha^{-1} - maize yields increased 57% ($P < 0.01$; Fig. 3) in the first year after application. Type of N or P fertiliser used, as well as amount of N or P applied did not significantly influence the yield effect of liming ($P =$ 0.38; 0.49; 0.68 and $P = 0.07$ respectively). However, N rate was significantly confounded with liming rate ($P < 0.01$) and P rate was significantly (positively) confounded with N rate ($P < 0.01$; Fig. S1a).

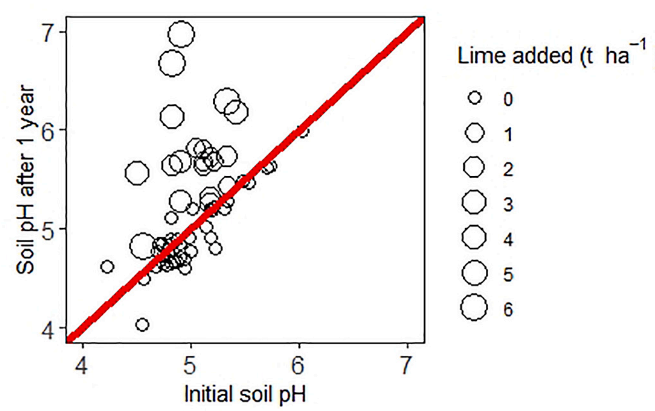

Fig. 4. soil pH after 1 year after the start of the experiment versus the initial soil pH at the start of the experiment. The symbol gradient from small to large indicates the amount of lime added. The red line indicates the 1:1 line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Liming and soil pH through time

Based on 64 observations from 16 experimental sites, an average lime application of 2.77 t ha^{-1} increased soil pH from 5.00 to 5.57 in the first year after application ($P < 0.01$; Fig. 4). This increase in soil pH depended on the amount of lime applied ($P < 0.01$; Fig. 5a) and was significantly positively correlated to the soil pH at the start of the experiment ($P < 0.01$; Fig. S1c). The addition of fertiliser had a negative effect on the soil pH (Table S1). With no lime application after the first year, soil pH decreased on average with 0.13 units pH per year in the following two to five years (Fig. 5b).

3.3. Soil pH and maize yields

Maize yield was positively correlated with soil pH, levelling off at a soil pH value of ca. 6. The actual response curve of maize yield to soil pH

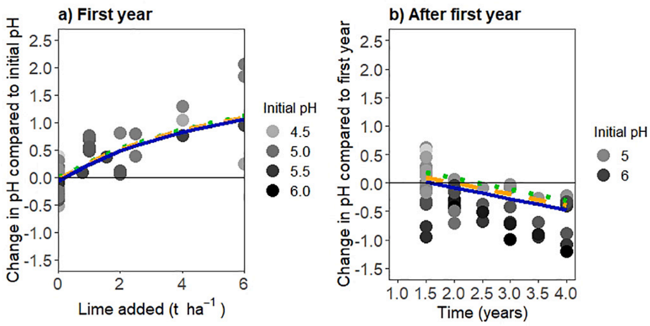

Fig. 5. A) Change in soil pH one year after lime application related to the amount of lime added as observed (dots), and as estimated (lines) (see Table S2 for model parameter values). B) Change in soil pH 1 to 5 years after lime application, as observed (dots), and as estimated (lines) (see Table S3 for parameter values). The symbol gradient from grey to black indicates the initial soil pH from low to high. The green dotted, orange dashed, and blue continuous lines represent no, low and medium fertiliser application (for specific amounts see Table 2) for an initial soil pH of 5.0. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

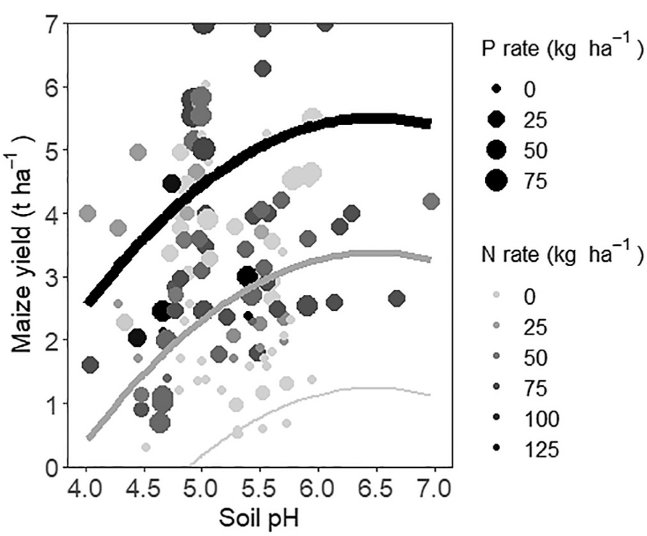

Fig. 6. Maize yield versus soil pH at the end of the first year as observed (dots) and as estimated with the quadratic regression model (lines) (see Table S4 for parameter values). The symbol gradient from small to large indicates the P rate, from grey to black indicates the N rate. The light grey, dark grey and bold black lines represent, respectively, the scenarios of no, low and medium fertiliser (for specific amounts see Table 2).

depended on the amounts of N and P applied (both $P < 0.01$; Fig. 6). No significant interaction was found between the effects of soil pH and nutrient supply on maize yields ($P = 0.11$).

3.4. Liming and farmers' income

Connecting the three regression models (Sections 3.1 to 3.3) with economic variables (Table 3) shows that for farmers with a soil pH of 4.5 or 5 and a capital of below 187,000 KES ha^{-1} or 169,000 KES ha^{-1} over 5 years respectively (dotted vertical lines Fig. 7a,b), investing capital in liming instead of mineral fertilisers gives better economic results, but profits are still negative. With more capital available and/or at higher soil pH (5.5), investing capital only or mostly in fertiliser gives better economic results than investing only in lime and it creates a positive profit.

When comparing the ROI for lime or fertiliser over a five-year period in Western Kenya (Fig. 8), a number of features become apparent. Increasing fertiliser application always increases the ROI (at least for the analysed range of 0 to 100 kg N/ha and 0 to 50 kg P ha^{-1}), whilst for liming, an optimum can be observed, after which the ROI starts to decrease. For most combinations of soil pH and fertiliser application, the economic optimum amount of lime application is between 1.5 and 2 t ha^{-1} (Fig. 8). Interactions between liming and fertiliser application on ROI are also apparent. Increasing fertiliser application consistently increases ROI of liming. For example, for a situation with an initial soil pH of 4.5 and 1 t lime/ha, the ROI for liming is negative without fertiliser application but becomes positive when 10 kg N and 5 kg P per ha are applied. By contrast, liming only increases the ROI from fertiliser application at lower soil pH (Fig. 8d,e).

Annual profits in the five consecutive years show that the pay-back period at optimal lime application (with the highest ROI) is in most cases two years (Table 4).

3.5. Modelled synergies or trade-offs between maize yields, farmers' income and greenhouse gas emissions

Adding lime at an economic optimal amount (corresponding with the highest ROI; Table 4) results in significantly higher yields across all soil pH levels and fertiliser schemes investigated (Fig. 9a,b,c). These increases in yield however do not translate into significantly increased farm profits (Fig. 9d,e,f).

Without fertiliser application, farm profits are zero or negative at all investigated levels of soil pH, be it with or without liming (when taking labour costs into account). Only at medium fertiliser application (i.e. 100 kg N per ha) farm profits are consistently positive (with and without liming; Fig. 9d,e,f).

For most fertiliser schemes and soil pH levels, liming does not alter GHG emissions per tonne maize because the increase in maize yield compensates for the additional emissions from liming. At a soil pH of 4.5 and low fertiliser use, adding lime decreases GHG emissions per tonne of maize (Fig. 9g).

4. Discussion

4.1. Strengths and weakness of a meta-analysis based on field experiments

The basis for this study was a meta-analysis of published data from field experiments on liming in maize fields in Western Kenya (Fig, 3 to 6). Such an aggregation of data from multiple experiments in a meta-analysis gives more confidence on wider applicability of experimental results, beyond data from only one location or one year. Moreover, this approach enabled a deeper investigation into the yield benefits of liming across a range of initial soil pH levels and fertiliser schemes. In practice, liming effects may however depend on a larger array of factors, such as soil structure or management history (One Acre Fund, 2015). As we relied on published data we could not account for these additional factors, which are likely to cause at least some of the observed variation in the yield effect of liming.

The field experiments in our study were conducted between 2000 and 2018 (Table 1), being most likely representative of current cultivars and management of the last two decades. New cultivars could be associated with higher yield potentials, thereby changing the yield responses to nutrients, and possibly lime, especially at higher input use. The mean N application of the treatments was however relatively low (49 kg N/ha), meaning the observed yield responses are most likely in the linear part of the yield-nutrient response curve, and little affected by yield potentials. While our findings therefore have validity for low input farming systems (< 100 kg N/ha), other dynamics might come at play for more intensive farming systems (> 100 kg N/ ha).

Meta-analyses are prone to confounding effects. In our study, field

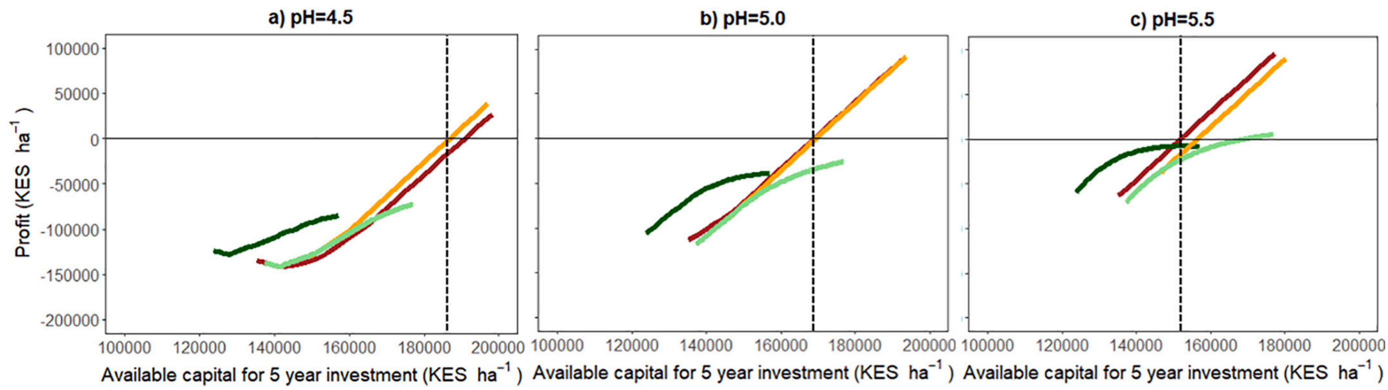

Fig. 7. Profit related to the available capital for investment in liming and/or fertiliser with different initial soil pH's. All profits are summed over five years of maize cultivation (after lime application in year 1). Dark green line: 100% investment in liming; light green: 50% lime, 50% fertiliser; orange: 25% lime, 75% fertiliser; brown: 100% investment in fertiliser. Vertical dotted lines indicate the available capital needed to create a positive profit. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

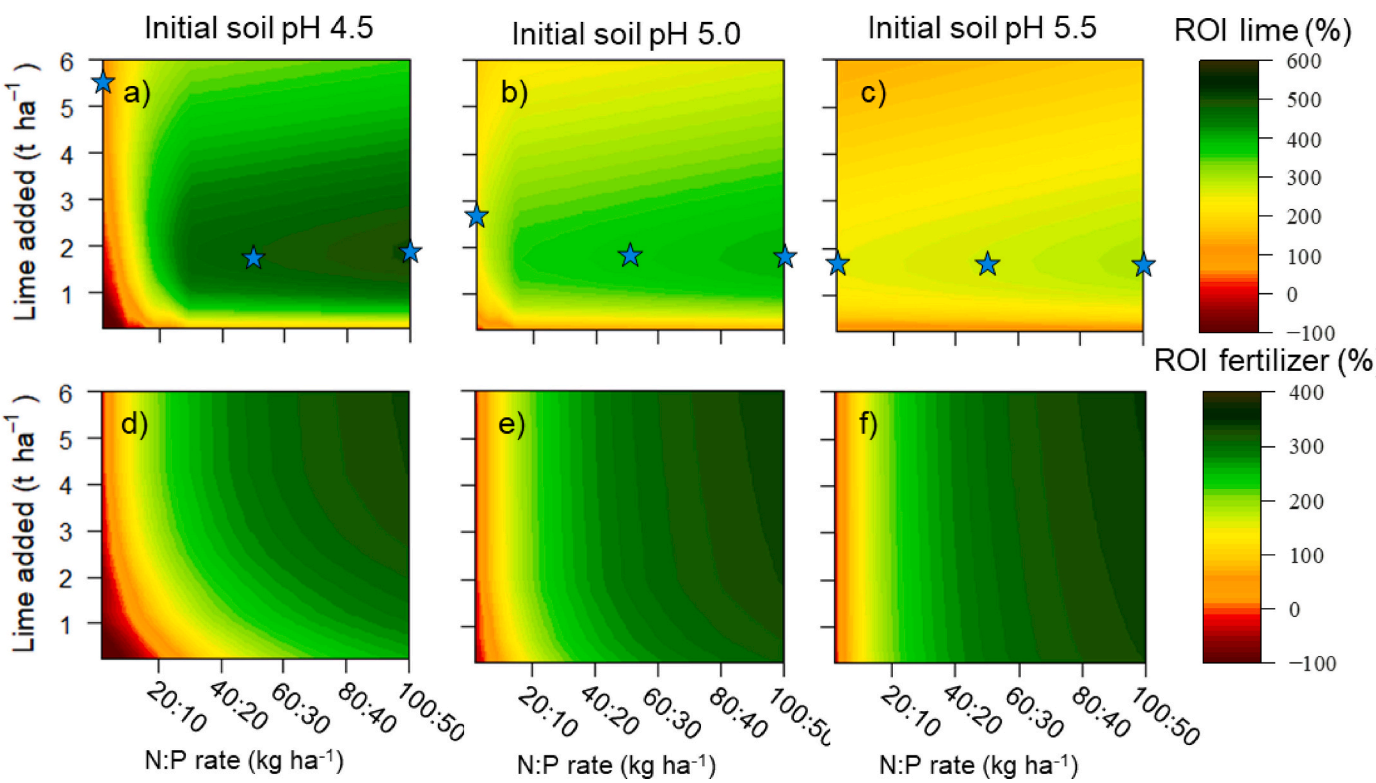

Fig. 8. Return on investment (ROI) over a five year period, for liming (a – c) and for fertiliser (d – f) ((extra profit due to liming or fertiliser addition / extra costs due to liming or fertiliser addition) * 100) for different amounts of lime and fertiliser added with an initial soil pH of 4.5 (a, d), 5.0 (b, e), and 5.5 (c, f). Stars indicate the optimal amount of lime for maximum ROI at three levels of fertiliser application (No, Low, Medium).

experiments with higher amounts of lime application also tended to include higher amounts of N and P application, leading to potential confounding effects between lime on the one hand and N and P on the other. By using a multiple regression analysis, we aimed to disentangle these factors.

4.2. Uncertainties in the trade-off analysis

Based on the aggregation of the maize experiments, our trade-off analysis focussed on the economic effects of liming on maize cultivation only. In Western Kenya, maize is the most important staple crop, occupying approximately 50% of the agricultural area (pers. comm. Wytze Marinus). Western Kenya has two cropping seasons, and as our study included one maize crop per year, this leaves room for a rotation with another crop. The liming effect on soil pH may therefore have more benefits than highlighted in this study. These additional benefits remain uncertain, but would most likely be positive. Further research could investigate liming effects for crops other than maize. Our meta-analysis showed that application of lime did not increase GHG emissions per tonne maize as the yield benefits compensated for increased emissions from liming. At a soil pH of 4.5 and low fertiliser use, adding lime even decreased GHG emissions per tonne of maize. However, if dolomite would be used instead of $CaCO_3$ for liming, this would result in an average increase of 18 kg CO_2 eqv. per tonne of maize (+3%) due to its higher emission factor (0.13 instead of 0.12 CO_2-C t lime^{-1};IPCC, 2019).

Another source of uncertainty is the GHG emission from

Table 4
Return on investment (ROI) for optimal liming at three levels of fertiliser application (No, Low, Medium) and three initial soil pH values, compared to the ROI of only applying fertiliser, summed over 5 years of maize production.

Initial soil pH[a]	Fertiliser level	Highest ROI for lime application			ROI fertiliser (%)[b]
		Lime added (t ha^{-1})	ROI value (%)	Pay-back period (years)	
pH = 4.5	No	5.6	93	3	
	Low	1.8	480	2	173
	Medium	1.9	504	2	258
pH = 5.0	No	2.7	239	2	
	Low	1.8	377	2	252
	Medium	1.8	401	2	305
pH = 5.5	No	1.7	246	2	
	Low	1.7	274	2	274
	Medium	1.7	298	2	320

[a] For low and medium fertiliser application amounts, see Table 2.
[b] ROI for fertiliser without lime application.

transportation of fertiliser and lime, which was not included as distances between farms and fertiliser and lime production sites differ through time and the focus of our study was on field emissions. Nonetheless, we tried to gain more insight whether inclusion of tranport emissions could change our main findings. In Western Kenya, most of the lime is currently mined in Koru, Kisumu by Homa Lime Company Ltd. (Table S1). We assume that the average distance for transport of lime is about 50 km. Fertiliser is imported from abroad and then shipped to the harbour in Kenya (on average 9421 km; Kabiri, 2020), from where it is transported to Eldoret (800 km) to be blended and packed, and finally transported to local agro-dealers (50 km). Based on ranges in transport emissions (Cefic and ECTA., 2011), transport emissions from fertiliser are 3.88 and 3.21 kg CO_2 per tonne maize in the low and medium fertiliser schemes. Transport emissions from lime range between 1.37 and 7.07 kg CO_2 per tonne maize produced (in the optimal ranges). Considering the sizes of the GHG emissions (Fig. 9g,h,i), including transport emissions is thus unlikely to change our results (see Table S7 for more details).

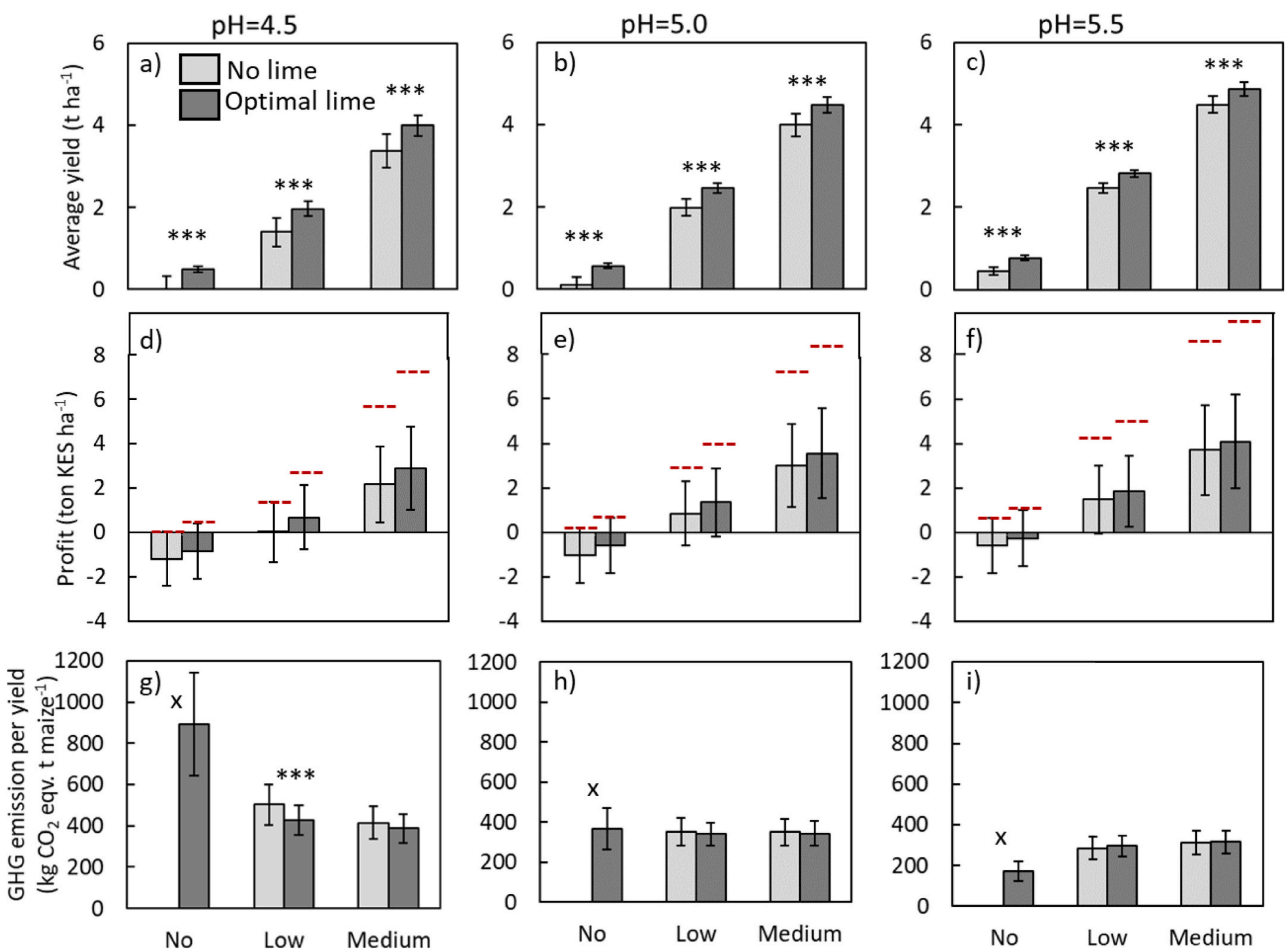

Fig. 9. Average yield across five years (a – c), total profit over five years (red dashed lines indicate total profit without labour costs) (d – e), and total GHG emission per unit maize produced (g – i) if no lime (light grey bars) or the optimal amount of lime (dark grey bars) is applied (see Table 4 for optimal liming amounts) combined with no fertiliser, low fertiliser and medium fertiliser (see for specific amounts Table 2). Error bars represent the standard deviation, the error bars of profit and of GHG emission per unit maize produced do not include the uncertainty of yields (as this is already presented in panels a – c). Stars indicate a significant difference between no lime and optimal lime applied (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, x not applicable). An X indicates no emissions related to liming or fertiliser use.

Emerging evidence shows that N fertiliser application on soil with a lower soil pH leads to more N_2O emissions than the same fertiliser N application on soil with a higher soil pH (Wang et al., 2018). In our study we followed current IPCC guidelines to compute GHG emissions, which do not account for this potential mechanism. Nevertheless, liming either reduced or did not alter GHG emissions per tonne of grain maize in our study. If the findings from Wang et al. (2018) have general applicability, liming would most likely reduce GHG emissions per tonne of grain maize yield at lower soil pH, enlarging co-benefits of liming for food security *and* the environment. This would provide additional rationale in favour of public support for liming.

4.3. Relevance and recommendations

Our meta-analysis revealed liming consistently increased maize yields on soils with an initial soil pH between 4.0 and 5.7 in Western Kenya, with or without fertiliser use (Fig. 3c). Following, our study went beyond a biophysical assessment of liming by including farm profits and ROIs. In this manner, our study sheds new light on the economic feasibility for smallholder farming to follow common threshold values for soil pH (i.e. 5.6; (Cranados, 1993). Our analysis shows that – at least in Western Kenya – when including costs of labour, associated profits across a period of five years were only positive when liming was combined with fertiliser (N,P) application (Fig. 7 and Fig. 9). Further research is needed to see if these findings are also valid elsewhere.

Our analysis did not include the scale of farming or resource endowment. Larger farms might have more capital available to invest in lime or fertilisers. On the other hand, management practices might differ between small and large farms, e.g. caused by differences in labour availability or use of locally available organic inputs. These differences could affect the effectiveness of liming and the associated GHG emissions. Further research (e.g. based on farm surveys, on-farm experiments or through partcipatory workshops) could shed more light on these dynamics.

Currently, lime is not abundantly available to smallholder farms, especially in remote rural areas. In these cases, alternative options exist to increase the pH of a soil, such as applying biochar or crop residues. Jeffery et al. (2017) found the yield effect of biochar on crop yields to be more pronounced in tropical than temperate regions and linked this to lower soil pH. While the effects of biobased materials on soil pH might be similar to lime (Haynes and Mokolobate, 2001), these materials might not be available or under pressure of competing claims (such as fodder for livestock or biomass for cooking) and economic feasibilities are also unknown. Future research could therefore compare economic viability of different liming substances.

Based on our analysis, liming can be one of many tools to improve food security with potential environmental benefits. In the shorter term (upto five years) increasing fertiliser application gives more stable returns or investments, while returns on investments for liming depend on the amount applied. Moreover, liming only gives positive profits when combined with fertiliser (N, P) application and at higher investment capacities. Therefore, in the current context, uptake of liming seems unlikely to happen without external incentives or facilitation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2021.103095.

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