Targeting travertine application in Rwanda

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Executive Summary

Soil acidity constrains crop yields across large areas of Rwanda. A key limitation of current interventions to mitigate soil acidity in Rwanda is that a blanket travertine recommendation developed and delivered at a national level does not address significant variability in soil acidity prevalence between regions and individual fields. Moreover, there is limited knowledge on the long term effects of travertine application on crop yield and profit, its interaction with fertilizer use, and the best dosage to use.

This project developed approaches to tailor travertine application recommendations at regional and field-level. The research was conducted in five AEZs across Rwanda and included:

i. On-farm trials conducted over four seasons of maize-beans rotation, with varying combinations of travertine (applied in the first season), fertilizer and compost
ii. Surveys of farmers' perceptions of their field characteristics and analysis of the extent to which these are predictive of soil pH
iii. Evaluation of rapid pH test kits in terms of their ability to measure whether soil pH is above or below a critical threshold for travertine application

Key findings were as follows:

- The current blanket recommendation for travertine application (2.5 t/ha every two years) will generally only improve yield and profit when applied to soils with pH <5.2.
- A 2.5t/ha travertine application rate did not result in statistically significant yield gains relative to a 1.5 t/ha application rate in any season
- Travertine application only resulted in significant yield and profit increases when combined with fertilizer
- Farmers' perceptions of their field characteristics can be used to predict soil pH status, or determine whether pH testing should be recommended.
- The Cornell pH Test Kit offers acceptable accuracy for determining whether soil acidity is above or below pH 5.2. Cost and relative complexity of use limit its potential to be used by One Acre Fund field officers for all fields. Still, in combination with decision trees based on farmers' characterizations of their fields, it offers a scalable way to determine where travertine application is required.

Further research is needed to determine optimal travertine application rates and interval recommendations, and how these vary by crop, soil characteristics (e.g. OM%, texture) and effective neutralising value of the liming product. The development of pedotransfer functions incorporating these variables could enable the generation of field-specific liming recommendations based on location, using soil maps such as iSDAsoil.

Trial Report

Context

Acidic soils account for approximately 45% of Rwanda's total arable land area and 60% of the highland arable areas (Beernaert, 1999). In acidic soils (pH <5.5) yields may be limited by reduced availability of essential nutrients (especially phosphorus) and increased phytotoxicity of aluminium and manganese limiting soil exploration by plant roots.

One Acre Fund Rwanda offers travertine (an uncalcined form of limestone) to farmers as a liming solution for acidic soils. Currently, One Acre Fund's travertine application recommendation aligns with the Rwanda Agriculture Board recommendation of 2.5 t ha^{-1} once for every 2 years of cropping (4 growing seasons). This recommendation is the same for all farmers and across all agro-ecological zones (AEZs). Improving the targeting of travertine application to the soils where it is most needed would allow One Acre Fund and other institutions to more effectively distribute travertine to the areas and fields where it will have the greatest impact.

Objectives

The overarching objective of this project was to develop approaches to enable One Acre Fund and other organisations to locally-tailor recommendations for travertine application in Rwanda. The specific objectives of this study were to:

- Define the soil pH threshold below which travertine application is profitable, for the current Rwanda Agriculture Board recommendation of 2.5 tons/ha.
- Evaluate the agronomic impact of travertine application over 4 seasons, and characterize its interaction with fertilizer use.
- Determine whether farmers' perceptions of their field characteristics and management history can be used to judge whether travertine should be recommended, or whether pH testing is advisable.
- Identify a simple pH test that can be used by extension workers or lead farmers to provide accurate recommendations in the field at minimal cost.

Sample and Methodology

Experimental design and treatments

On-farm trials were executed from 2019A to 2020B (4 growing seasons, 2 years). The sample was stratified across five AEZs (Table 1). In each AEZ, 56 farmers from selected cells participated in the trial and were expected to maintain the treatment plots for the next 3 continuous seasons, which would enable a total of 4 continuous seasons of crop-rotation. The number of farmers for each AEZ was determined following the method detailed in Steel and Torrie (1980). Farmers participating in the trial were randomly selected within the cells. Among the farmers who volunteered to participate in the trial, field officers selected plots of sufficient size to accommodate all treatments, with slopes inclination of <40%, without any obvious confounding factors e.g. variability in soil quality, or bordering trees or houses that could shade the plots.

Table 1. Trial locations and agroecological parameters. Alt = altitude, MAR = mean annual rainfall.

Agro-ecological zone	District	Cells	Alt	MAR

Buberuka Highlands	Burera	Musasa, Runoga	1957	1267
Congo Nile	Karongi, Nyamagabe, Nyamasheke	Banda, Kaganza, Munyege, Mutongo cya A, Tyazo, Rufungo	2058	1542
Eastern Ridges	Rwamagana, Ngoma, Kayonza	Bicaca, Ndekwe, Murundi	1575	1038
Lake Kivu	Nyamasheke, Rutsiro, Karongi	Kigarama, Kagabiro, Teba	1638	1225
Volcanic cones	Burera	Karangara, Ntaruka	1960	1317

The trial used a Randomized Complete Block Design (RCBD), with each farmer growing a rotation of maize in season A and beans in season B, in a block of five continuous plots of 5 x 10 m in dimension each. External inputs (i.e. seed, fertilizers, and travertine) were provided by One Acre Fund, and farmers collaborated by providing the land and the compost. Both crops were grown following conventional methods of land preparation, and following standard Twigire Muhinzi (Rwanda national extension system) - One Acre Fund recommendations for planting design and weed management.

Treatments were a combination of two factors; travertine (61% effective neutralizing value with a calcium carbonate equivalent of 84.5), and fertilizer; diammonium phosphate (DAP) and Urea. Travertine was applied at 3 rates: 0 kg/ha, 1,500 kg/ha and 2,500 kg/ha. Travertine was applied immediately prior to planting, in the first season only (2019A), and was broadcasted in the field and incorporated using a hoe. DAP was micro-dosed as basal fertilizer at planting at the start of both maize and bean seasons at two rates; 0 kg/ha and 100 kg/ha. In maize seasons, fertilizer treatments also received 50 kg/ha urea fertilizer micro-dosed as a topdressing at V6. Following common farmer practice, compost was applied equally to all treatments in all seasons, at rates of >2,000 kg/ha. Trial treatments are summarized in Table 2.

Table 2. 2019A-2020B Travertine Trial treatments description.

Treatment	Travertine	Compost	DAP	Urea
1	0 kg/ha	≥ 2,000 kg/ha	0 kg/ha	0 kg/ha
2	2,500 kg/ha in 19A only	≥ 2,000 kg/ha	0 kg/ha	0 kg/ha
3	0 kg/ha	≥ 2,000 kg/ha	100 kg/ha each season	50 kg/ha in maize (A) seasons only
4	2,500 kg/ha in 19A only	≥ 2,000 kg/ha	100 kg/ha each season	50 kg/ha in maize (A) seasons only
5	1,500 kg/ha in 19A only	≥ 2,000 kg/ha	100 kg/ha each season	50 kg/ha in maize (A) seasons only

Measurement and Analysis

Grain yield of each crop in each season was measured, along with the total cost of production (i.e. inputs and labor costs), revenue from selling the produce, the profitability of each treatment by season, and accumulated profit at the end of the trial. Tukey HSD post two-factor ANOVA was used to evaluate the effect of each treatment factor (i.e. travertine and fertilizer application) on yield, and their interactions. Linear prediction was used to identify the threshold of soil pH where the travertine application rates became profitable.

Farmers participating in the travertine trial were surveyed about their perceptions about the plots being used for the trial, plus two additional plots (825 plots in total). To increase sample size, 120 more plots were surveyed among farmers doing maize-variety trials with OAF in 2020A; which led to a total sample size of 945 plots.[1] The plot characteristics included: topography position (i.e., hill, radical terrace or valley), position relative to the hills (i.e., summit, shoulder, backslope, footslope, flat), slope, soil erosion, soil colour, soil texture, soil stickiness, prevalence of rocks, presence of indicator weed species, soil depth, relative soil fertility, vigor of maize, vigor of potato, and soil acidity (see more details about the variables in annexes). All these characteristics were assessed by the farmers and recorded by OAF officers while visiting the field under evaluation. For the plot-characterization assessment, tools (such as cards showing levels of rockiness, soil

[1] A further 250 plots were surveyed in 2020B for independent validation of the results, but shipping of these samples to the lab and lab analyses were delayed due to the Covid-19 pandemic and therefore results are not included in this report.

color or slope level) and short protocols (e.g. soil texture determination) were distributed and explained to farmers prior to the survey. After the survey, composite soil samples were collected from five points within each plot (20 cm depth). Soil samples were shipped to a lab for recording of pH using an electronic pH meter (Corning 340 pH meter with Hamilton glass electrode) and a soil:water ratio of 1:2.5 (Gelderman et al., 1998).

Classification-tree analysis was developed to evaluate which farmer classifications of field characteristics could be used to predict soil pH (code available here). For each AEZ, we developed classification trees to predict soil pH based on plot characteristics, after filtering for meaningful variables. This filtering was done following two rules: 1) variables were removed from an AEZ if there was >20% of the categories with < 5 data points; and 2) weed presence-variables were eliminated when they appeared in <10% of the plots in one AEZ. Classification tree analysis was performed using the *rpart* package in R.

To compare the precision and accuracy of different rapid-testing kits to assess soil pH, we used ≃10% of the samples taken for the travertine trial. We recorded the soil samples' pH using eleven rapid kits available on the market, and compared the accuracy of the readings using the electronic pH meter described before. The accuracy of rapid-testing kits was evaluated by comparing the percentage of cases in which a kit produced a pH measurement <5.2 or >=5.2, compared with the lab measurement of pH for a given sample:

- 'Correct positive' - the rapid testing kit correctly indicated pH <5.2 (lab measurement was <5.2)
- 'Incorrect positive' - the rapid testing kit incorrectly indicated pH <5.2 (lab measurement was >=5.2)
- 'Correct negative' - the rapid testing kit correctly indicated pH >=5.2 (lab measurement was >=5.2)
- 'Incorrect negative' - the rapid testing kit incorrectly indicated pH >=5.2 (lab measurement was <5.2)

Results and Discussion

Impact of travertine application, and interactions with fertilizer and compost use

There was no treatment x AEZ interaction for yield in either the first season with maize ($p = 0.12$), or the second or fourth seasons with beans ($p = 0.61$ and 0.93, respectively). In the third season (maize), treatments relative performance was slightly influenced by AEZ (interaction at $p= 0.087$). The application of travertine at a rate of 2.5 t/ha to plots with compost + fertilizer did not increase yield during the first and third seasons, in which maize was grown ($p = 0.54$ and 0.19 respectively), but did increase in the second and fourth seasons, in which beans were grown ($p < 0.01$) across all AEZ zones. It is not clear the reason why beans were more responsive to travertine. It could be due to the order of the rotation relative to the timing of travertine application (higher response expected in the second season, when beans were grown; Kisinyo et al., 2014), it is also possible that there is a genuine crop-species x travertine interaction, or a combination of both.

The use of travertine in combination with compost did increase yields relative to the use of the compost-only treatment in the second (+12%) and fourth seasons (+9%). Similarly, in plots where both compost and fertilizer was used, the yield impact of travertine application at a rate of 2.5 t/ha was significant in the second (+14%) and fourth (+8%) seasons (Table 3). In all seasons, yields in plots where travertine application was combined with fertilizer and compost were 4-14% higher than those where only fertilizer and compost was applied. As Figure 1 illustrates, there was evidence of a positive interaction between travertine application and fertilizer use in the 2019A and 2019B seasons, though this interaction was not statistically significant in either season. This suggests that farmers should be encouraged to use fertilizer and travertine in combination in acidic plots, as reported elsewhere for the region (Kisinyo et al., 2014; Opala et al., 2018).

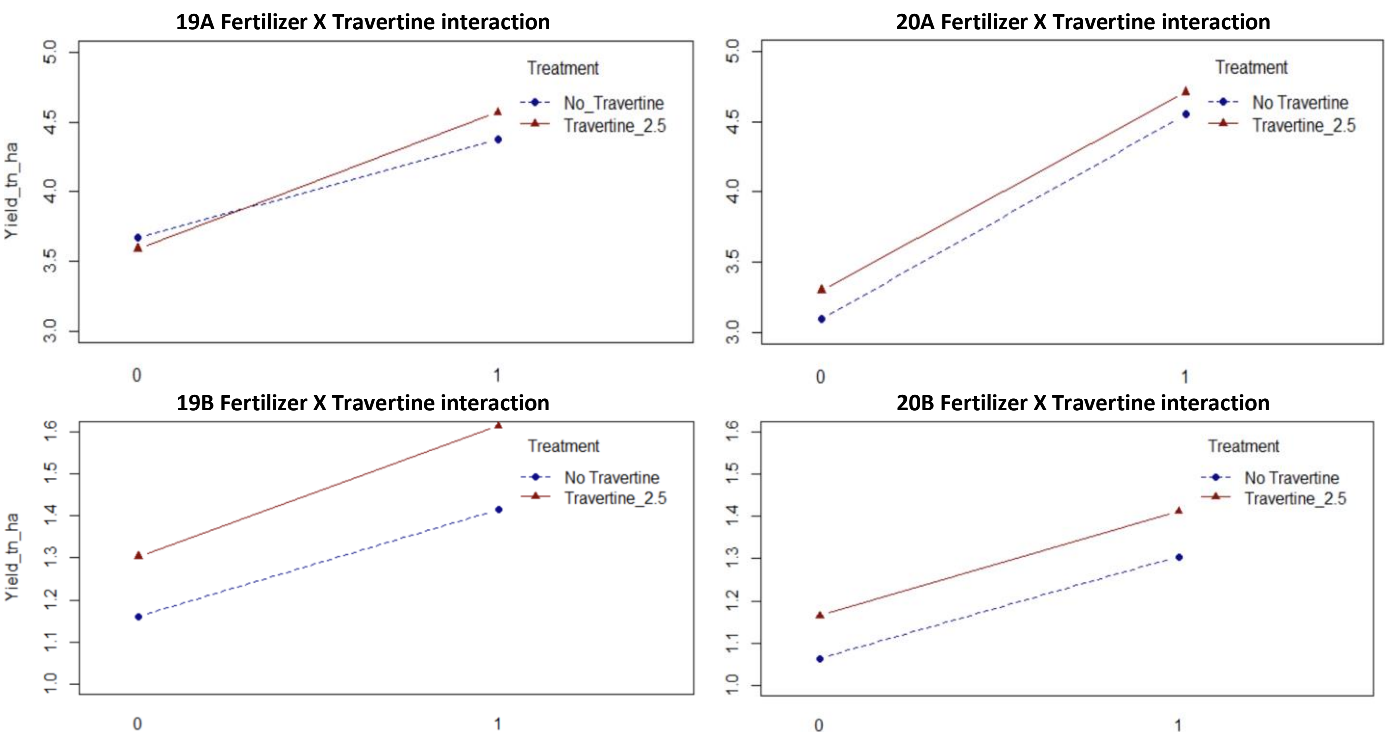

Figure 1. Yield impact of travertine application without fertilizer application (0) and with fertilizer application (1).

An application rate of 2.5 t/ha travertine (current OAF and RAB recommendation) did not result in statistically significant yield gains relative to the 1.5 t/ha application rate in any of the seasons (Table 3).

Across AEZs, in the season immediately following travertine application, profits were significantly reduced with increasing application rate (Table 3). In all subsequent seasons, seasonal profit was higher on plots where travertine was previously applied (only statistically significant in the second season for both rates and the third season for the lowest rate). However, the break-even point of the lower travertine application rate of 1.5 t/ha was not achieved until the third season after application. The cumulative profit of the higher travertine application rate of 2.5 t/ha remained below that of the compost + fertilizer treatment (no travertine) in all four seasons. This illustrates the importance of targeting travertine application to fields where there is likely to be a profitable yield response and identifying the optimal rate of application; a blanket national recommendation is not appropriate.

Table 3. Summary of countrywide yield and profit results by treatment across seasons 2019A-2020B. Cost (USD/ha) accounts for labor, fertilizers, travertine if applied, seeds cost; yield (t/ha), profit USD/ha). Figures in parentheses in black show yield increase relative to the 'Compost' treatment, figures in parentheses in blue show yield increase relative to 'Compost + fertilizer'.

Treatment	n	Cost (p<0.001)	Yield (p<0.001)	Seasonal Profit (p<0.001)	Cumulative profit
1st season, maize - 2019A					
Compost	247	14 a	3.67 a (-16%)	728 c	728
Compost + Fertilizer	254	73 b	4.37 b (+19.3%)	812 d	812
Compost + Fertilizer + 1.5 t/ha travertine	255	242 c	4.56 b (+24.5%) (+4.3%)	680 c	680 (-16%)
Compost + Fertilizer + 2.5 t/ha travertine	253	354 d	4.57 b (+24.8%) (+4.5%)	570 b	570 (-30%)
Compost + 2.5 t/ha travertine	249	296 e	3.59 a (-1.9%) (-17.8%)	430 a	430
2nd season, beans - 2019B					
Compost	243	63 a	1.16 a (-17.7%)	498 a	1226 b
Compost + Fertilizer	249	117 b	1.41 c (+21%)	572 b	1384 c
Compost + Fertilizer + 1.5 t/ha travertine	251	117 b	1.54 d (+32.7%) (+9.2%)	641 c	1321bc (-5%)
Compost + Fertilizer + 2.5 t/ha travertine	251	117 b	1.61 d (+38.7%) (+14.1%)	677 c	1263 bc (-10%)
Compost + 2.5 t/ha travertine	247	63 a	1.30 b (+12%) (-7.8%)	574 b	997 a
3rd season, maize - 2020A					
Compost	216	34 a	3.09 a (-32%)	769 a	2020 a
Compost + Fertilizer	216	114 b	4.55 b (+47.2%)	1066 b	2450 b
Compost + Fertilizer + 1.5 t/ha travertine	218	114 b	4.82 c (+55.9%) (+5.9%)	1137 c	2476 b (+0.3%)
Compost + Fertilizer + 2.5 t/ha travertine	217	114 b	4.71 bc (+52.4%) (+3.5%)	1108 bc	2372 b (-4%)
Compost + 2.5 t/ha travertine	215	34 a	3.30 a (+6.4%) (-27.4%)	822 a	1832 a
4th season, beans - 2020B					
Compost	205	87 a	1.06 a (-18.4%)	574 a	2599 a
Compost + Fertilizer	206	140 b	1.30 c (+22.6%)	635 bc	3104 b
Compost + Fertilizer + 1.5 t/ha travertine	208	141 b	1.38 d (+30.1%) (+6.1%)	681 c	3180 b (+2%)
Compost + Fertilizer + 2.5 t/ha travertine	208	141 b	1.41 d (+33%) (+8.4%)	699 c	3085 b (-1%)
Compost + 2.5 t/ha travertine	205	87 a	1.16 b (+9.4%) (-10.7%)	604 ab	2463 a

At the AEZ level, travertine application did not result in any significant yield gains relative to the application of fertilizer and compost in any season in the Volcanic Cones and Buberuka Highlands AEZs (Table 4). In the Congo-Nile AEZ, travertine application in combination with compost and fertilizer did not result in significant yield increases in maize seasons, but the higher application rate of 2.5 t/ha did result in statistically significant yield increase in bean seasons. In the Lake Kivu

AEZ, travertine application in combination with compost and fertilizer did not result in statistically significant yield increases in the first (maize) or fourth (beans) seasons, but there were significant yield increases in the second season (beans) where 2.5 t/ha travertine was applied and in the third season (maize) where 1.5 or 2.5 t/ha travertine was applied. In the Eastern Ridges AEZ, travertine application only resulted in statistically significant yield increases in the third season after application (maize).

Table 4. Summary of yield (t/ha) results by treatment across seasons 2019A-2020B, for different AEZs. Figures in parentheses show yield increase relative to the 'Compost' treatment.

1st season, maize - 2019A	**Volcanic cones (p<0.001)**	**Buberuka (p=0.059)**	**Congo Nile (p<0.001)**	**Lake Kivu (p<0.001)**	**Eastern Ridges (p=0.09)**
Compost	5.89 a	3.02 a	3.24 a	3.30 a	3.18 a
Compost + Fertilizer	6.70 c (+13.7%)	3.54 b (+17.2%)	4.48 b (+38.2%)	4.22 ab (+27.8%)	3.27 ab (+3
Compost + Fertilizer + 1.5 t/ha travertine	7.01 c (+19%)	3.63 b (+20.1%)	4.48 b (+38.2%)	4.46 b (+35%)	3.60 b (+13)
Compost + Fertilizer + 2.5 t/ha travertine	6.72 c (14%)	3.61 b (+19.5%)	4.65 b (+43.5%)	4.64 b (+40.6%)	3.57 b (+12)
Compost + 2.5 t/ha travertine	5.31 b (-9.8%)	3.09 a (+2.3%)	3.30 a (+1.8%)	3.34 a (+1.2%)	3.14 a (-1)
2nd season, beans - 2019B	**Volcanic cones (p=0.02)**	**Buberuka (p=0.04)**	**Congo Nile(p<0.001)**	**Lake Kivu p=0.006**	**Eastern Ridges (p=0.001)**
Compost	1.41 a	1.52 a	0.75 a	1.08 a	1.12 a
Compost + Fertilizer	1.73 b (+22.6%)	1.79 ab (+17.7%)	1.13 bc (+50.6%)	1.19 ab (+10%)	1.31 ab (+16.9%)
Compost + Fertilizer + 1.5 t/ha travertine	1.71 b (+21.2%)	1.84 ab (+21%)	1.36 cd (+80%)	1.43 ab (+32.4%)	1.44 b (+28.5%)
Compost + Fertilizer + 2.5 t/ha travertine	1.68 b (+19%)	1.93 b (+26.9%)	1.49 d (+97.3%)	1.52 b (+40.7%)	1.48 b (+32%)
Compost + 2.5 t/ha travertine	1.42 a (+0.7%)	1.67 ab (+9.8%)	1.03 b (+37.3%)	1.25 ab (+15.7%)	1.22 ab (+8.9%)
3rd season, maize - 2020A	**Volcanic cones (p=0.06)**	**Buberuka (p<0.001)**	**Congo Nile (p<0.001)**	**Lake Kivu (p=0.001)**	**Eastern Ridges (p<0.001)**
Compost	4.10 a	3.46 a	2.23 a	2.74 a	3.35 a
Compost + Fertilizer	5.13 b (+25.1%)	4.84 b (+39.8%)	3.86 c (+73%)	3.34 b (+21.8%)	5.74 b (+71.3%)
Compost + Fertilizer + 1.5 t/ha travertine	4.97 b (+21.2%)	5.11 b (+47.6%)	3.94 c (+76.6%)	3.95 c (+44.1%)	6.20 c (+85%)
Compost + Fertilizer + 2.5 t/ha travertine	4.91 b (+19.7%)	4.77 b (+37.8%)	3.72 c (+66.8%)	4.24 c (+54.7%)	6.07 bc (+81%)
Compost + 2.5 t/ha travertine	4.01 a (-2.2%)	3.48 a (+0.57%)	2.75 b (+23.3%)	2.85 a (+4%)	3.65 a (+8.9%)
4th season, beans - 2020B	**Volcanic cones (p=0.7)**	**Buberuka (p=0.049)**	**Congo Nile (p<0.001)**	**Lake Kivu (p=0.7)**	**Eastern Ridges (p=0.01)**
Compost	1.72 a	1.22 a	0.70 a	0.87 a	1.10 a
Compost + Fertilizer	1.84 a (+6.9%)	1.39 b (+13.9%)	1.09 bc (+55.7)	1.10 bc (+26.4%)	1.32 b (+20%)
Compost + Fertilizer + 1.5 t/ha travertine	1.92 a (+11.6%)	1.47 b (+20.4%)	1.21 cd (+72.8%)	1.10 c (+26.4%)	1.38 b (+25.4%)
Compost + Fertilizer + 2.5 t/ha travertine	1.92 a (+11.6%)	1.44 b (+18%)	1.29 d (+84.2%)	1.16 c (+33.3%)	1.42 b (+29%)
Compost + 2.5 t/ha travertine	1.74 a (+1.1%)	1.17 a (-4%)	0.98 b (+40%)	0.93 ab (+6.8%)	1.22 ab (+10.9%)

A pH of 5.2 represents a threshold below which travertine application would result in relatively higher yield and profit in the long term (i.e. cumulative of four seasons). We found that the threshold soil pH where 2.5 t/ha of travertine increases yield is approximately 5.7 (Figure 2). This coincides with the range of threshold of soil pH above which AL toxicity decreases below toxic levels (i.e., 5.0-5.2; Crawford et al. 2008). As expected, for profitability the threshold is lower, closer to 5.0 (Figure 3). We propose to use a soil pH threshold where travertine should be recommended to be 5.2; this is in agreement with existing recommendations for the region (Crawford et al., 2008).

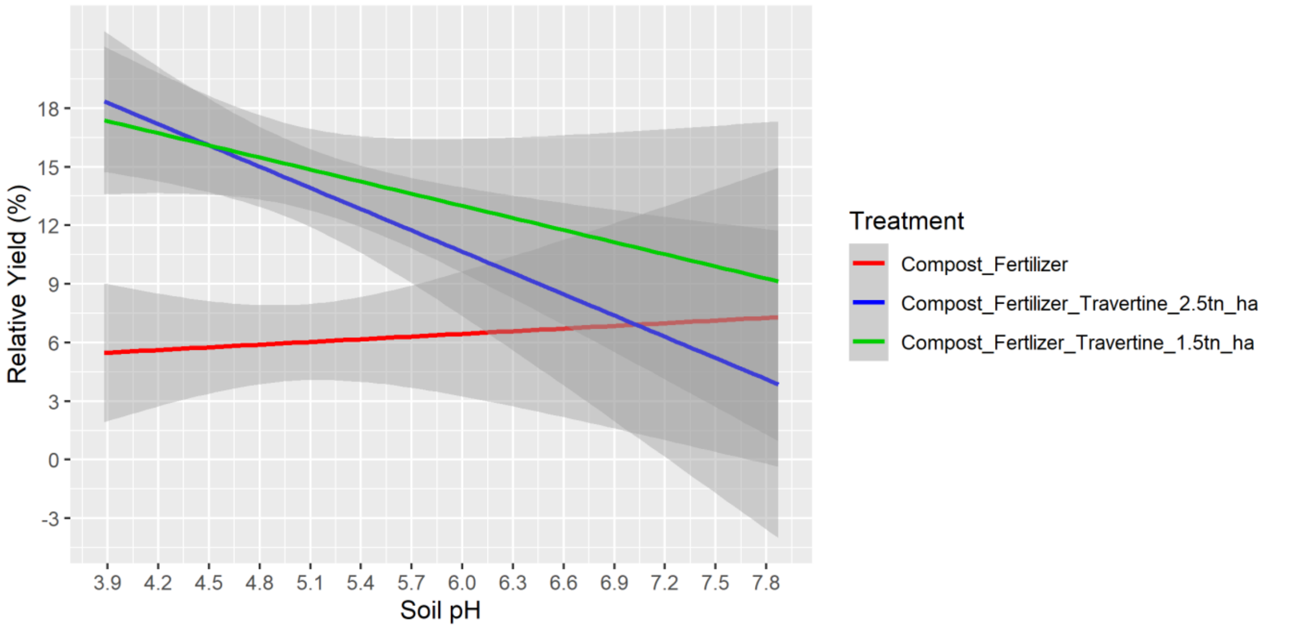

Figure 2. The relative accumulated yield of different fertilizer and travertine treatments, as a function of baseline pH (grey zones represent standard error). Relative yield was computed for each plot, each season, with its yield expressed as % relative to the average of all treatments in that block (an individual farmers' field). The relative accumulated yield of each plot was calculated as the average relative yield across the 4 seasons of the trial.

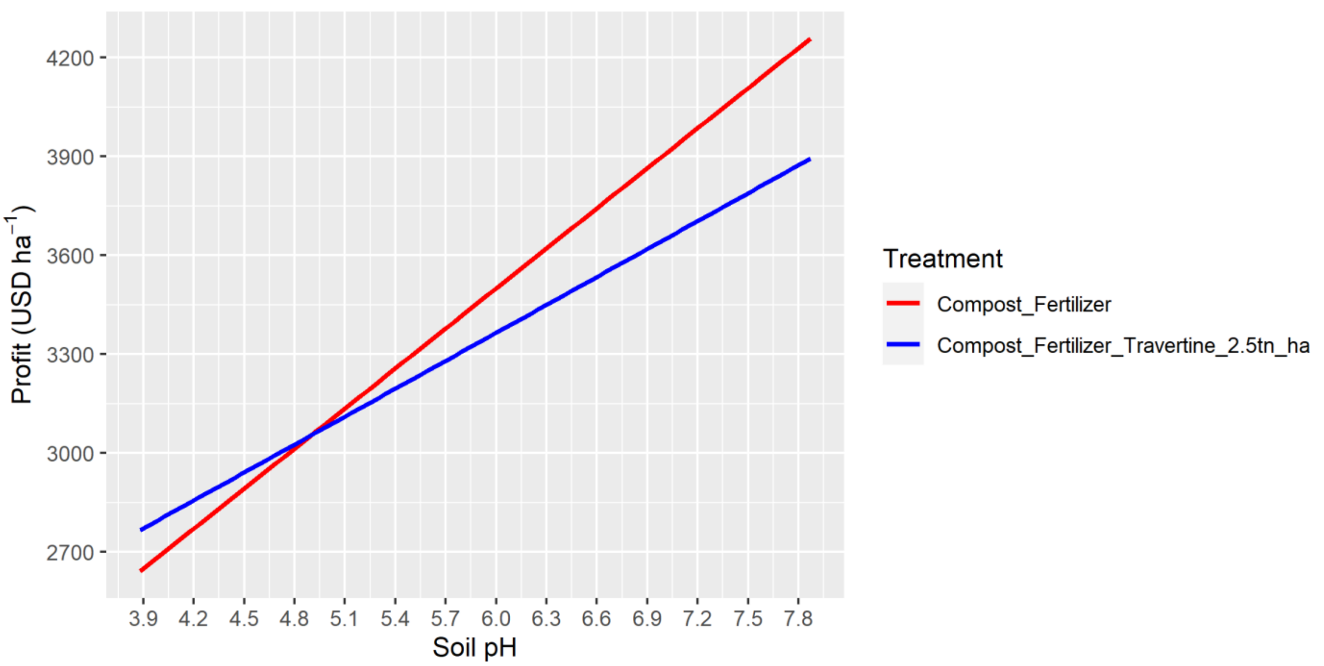

Figure 3. Cumulative profit (four seasons) of two treatments (with or without travertine applied at a rate of 2.5 t/ha) as a function of baseline pH. Crossover of linear regressions of treatments occurs at a pH of approximately 5.0.

Table 5. Summary of profit (USD/ha) results by treatments for individual seasons and cumulative across 2019A-2020B seasons.

Database was divided according to basal soil pH being < or >= 5.2. Figures in parentheses show profit increase relative to the "Compost + Fertilizer"' treatment.

1st season, maize - 2019A				
Treatment	Seasonal profit in fields with baseline pH <5.2 (p<0.1)	Cumulative profit in fields with baseline pH <5.2	Seasonal profit in fields with baseline pH >=5.2 (p<0.1)	Cumulative profit in fields with baseline pH >=5.2
Compost	594 c		894 b	
Compost + Fertilizer	713 d		937 b	
Compost + Fertilizer + 1.5 t/ha travertine	561 bc (-21%)		831 b (-11%)	
Compost + Fertilizer + 2.5 t/ha travertine	481 b (-33)		681 a (-27%)	
Compost + 2.5 t/ha travertine	325 a		564 a	
2nd season, beans - 2019B				
Treatment	Seasonal profit in fields with baseline pH <5.2)	Cumulative profit in fields with baseline pH <5.2	Seasonal profit in fields with baseline pH >=5.2 (p>0.1)	Cumulative profit in fields with baseline pH >=5.2
Compost	422 a	1017 ab	589	1485 b
Compost + Fertilizer	518 ab	1243 c	639	1594 b
Compost + Fertilizer + 1.5 t/ha travertine	623 bc (+20%)	1192 cb (-4%)	663 (+4%)	1513 b (-5%)
Compost + Fertilizer + 2.5 t/ha travertine	674 c (+30%)	1158 cb (-7%)	681 (+7%)	1399 ab (-12%)
Compost + 2.5 t/ha travertine	526 ab	841 a	632	1197 b
3rd season, maize - 2020A				
Treatment	Seasonal profit in fields with baseline pH <5.2	Cumulative profit in fields with baseline pH <5.2	Seasonal profit in fields with baseline pH >=5.2	Cumulative profit in fields with baseline pH >=5.2
Compost	631 a	1716 a	965 a	2462 ab
Compost + Fertilizer	916 b	2186 b	1281 b	2835 c
Compost + Fertilizer + 1.5 t/ha travertine	988 b (+8%)	2237 b (+2%)	1358 b (+6%)	2829 c (0%)
Compost + Fertilizer + 2.5 t/ha travertine	963 b (+3%)	2165 b (-1%)	1319 b (+3%)	2683 bc (-5%)
Compost + 2.5 t/ha travertine	758 a	1590 a	1004 a	2202 a
4th season, beans - 2020B				
Treatment	Seasonal profit in fields with baseline pH <5.2 (p<0.1)	Cumulative profit in fields with baseline pH <5.2	Seasonal profit in fields with baseline pH >=5.2 (p>0.1)	Cumulative profit in fields with baseline pH >=5.2
Compost	457 a	2186 b	759	3182 ab
Compost + Fertilizer	577 ab	2805 a	731	3588 b
Compost + Fertilizer + 1.5 t/ha travertine	630 b (+9%)	2892 a (+3%)	764 (+5%)	3621 b (+2%)
Compost + Fertilizer + 2.5 t/ha travertine	663 b (+15%)	2851 a (+2%)	755 (+3%)	3453 b (-3%)
Compost + 2.5 t/ha travertine	544 ab	2173 b	696	2891 a

As Table 5 shows, there were statistically significant differences in profitability between treatments in plots with baseline pH <5.2 in all four seasons; but in plots with baseline pH ≥5.2 there were only statistically significant differences between treatments in the first and third seasons. On plots with baseline pH <5.2, travertine application in combination with fertilizer and compost resulted in statistically significant decrease in profit in the first season, due to the added cost of production. Profitability was also reduced on plots with baseline pH ≥5.2, but to a lesser extent because their yields were higher.

On fields with baseline pH <5.2, and where compost and fertilizer was used, the break-even point tended to be reached in the third season after application for both, 1.5 t/ha and 2.5 t/ha of travertine (Table 5). On fields with a baseline pH ≥5.2 the break-even for an application rate of 1.5 t/ha tended to be reached in the third season, but for the application rate of 2.5 t/ha, a break-even point was not reached even after 4 seasons. Surprisingly, there was no difference in cumulative profit between travertine applications rates of 1.5 and 2.5 t/ha. Although profit advantage of travertine at the higher rates could be evidenced if the trial was extended beyond the 4th season, or if other crops were included in the rotation, this results suggests that in conditions where dosage is restricted (e.g., financial or labro restrictions from the farmers or logistics limitations from the organizations leading the distribution), lower dosages should be considered.

Farmer perceptions of field characteristics as predictors of soil acidity

89% of fields in the Congo-Nile AEZ had pH <5.2, and none of the field characterisation variables were included in the classification tree. This suggests that all farmers in the AEZ should be advised to use travertine. Conversely, in the Volcanic Cones AEZ, only 1% of trial fields in this AEZ had pH <5.2, and again, none of the evaluated field characterisation variables were retained in the classification tree. In this region farmers should not be advised to use travertine, unless better tools and or interventions are designed to specifically identify plots with acidic soil. Both findings were expected as reported in soil maps of the region (e.g., Söderström et al., 2016).

In the Buberuka Highlands AEZ (Figure 4), 26% of fields had pH <5.2. Fields located on a radical terrace or in a valley had only an 8% chance of having acidic soil. Such fields represent 14% of total fields, so by asking farmers in this AEZ about their field position relative to slope, we can eliminate the need for pH testing for 14% of fields. For fields located on the backslope, footslope, shoulder or summit of a slope, there was a 29% chance that soils are acidic, and therefore pH testing should be recommended.

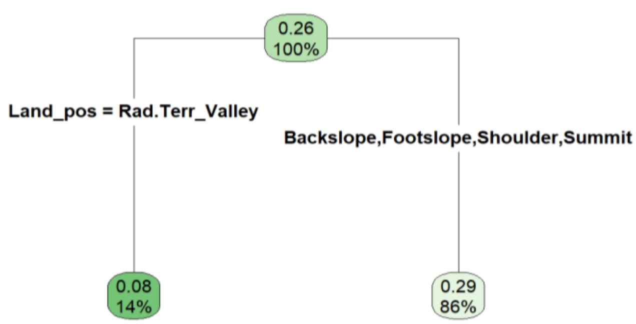

Figure 4. Classification tree for field characteristics in Buberuka Highlands AEZ. The upper decimal numbers indicate the probability of pH being <5.2, the lower % numbers indicate the proportion of trial fields in the classification.

In the Lake Kivu AEZ (Figure 5), the need for pH testing can be eliminated for 64% of plots by asking farmers about the relative fertility of their plot and the presence of the inyabarasanya weed (*Biden pilosa*). If farmers indicate that their plot has medium to low fertility, and inyabarasanya is not present, then it is 76% likely that pH is <5.2 (64% of the samples). For all other fields, soil pH should be tested. Soil stickiness (clayiness) and presence of the uruteja weed (*Cyanotis barabata*) were included in the classification tree but in practice asking farmers about these variables would not help determine whether pH testing is needed, as the confidence level for each is low.

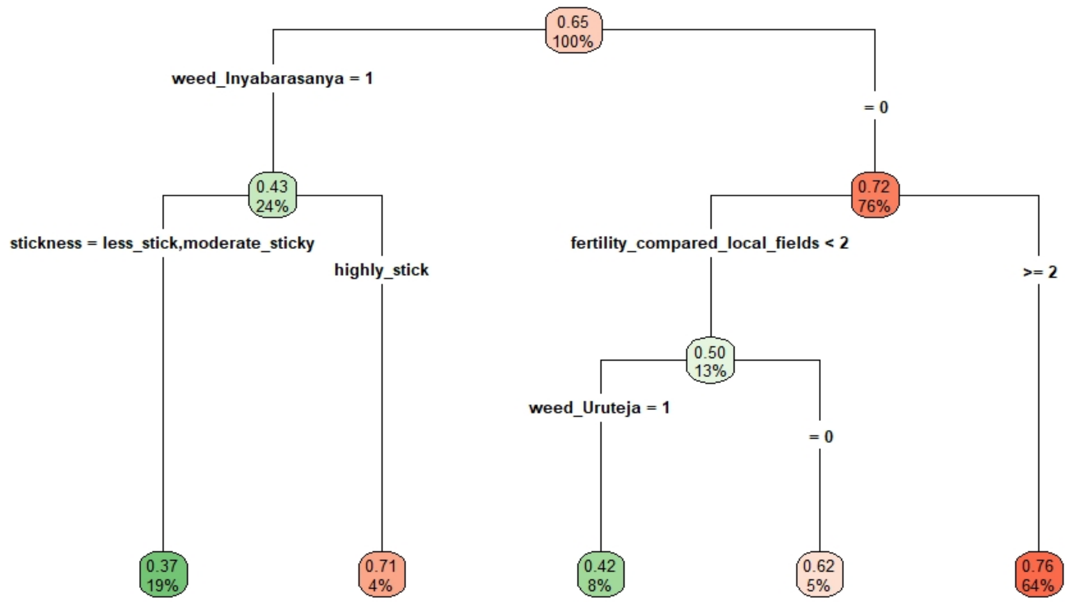

Figure 5. Classification tree for field characteristics in the Lake Kivu AEZ. In each box, the upper decimal numbers indicate the probability of pH being <5.2, the lower % numbers indicate the proportion of trial fields in the classification.

In the Eastern Ridges AEZ, three field characteristics could eliminate the need of soil pH test in 59% of the plots (Figure 6). Soil texturing was critical, with none of the 39% of clay loam soils having pH <5.2, whereas for loamy and sandy soils (61% of fields) pH was <5.2 in 46% of cases. Among the loamy and sandy soils, the ones which are not red in color and classified as mid or high fertility by the farmer, have also very low chance of being acidic (7% chances; 20% of the samples). Overall, if farmers have clay loam soil, or do have loamy or sandy soil but not red in color and classified as mid-low fertility, then they do not need to measure pH nor need to apply travertine (59% of the plots, with >97% confidence). The rest of the cases need to measure pH.

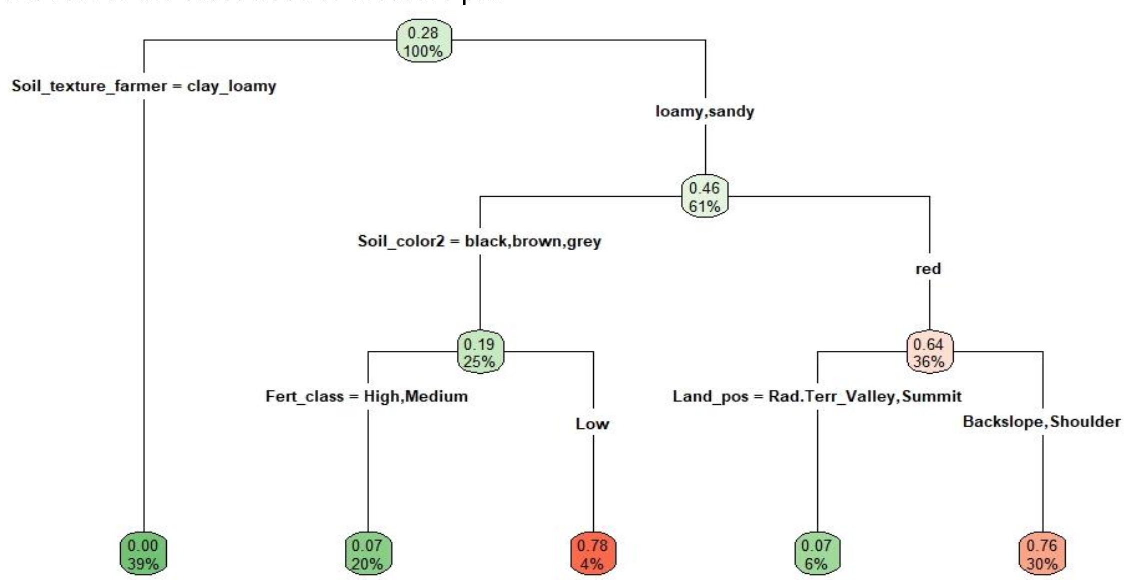

Figure 6. Classification tree for field characteristics in Eastern Ridges AEZ. The upper decimal numbers indicate the probability of pH being <5.2, the lower % numbers indicate the proportion of trial fields in the classification.

Under the assumption that the soil samples used in this analysis are representative of cultivated land in each of the 5 surveyed AEZs; results indicate that using the information generated in the decision trees, the need of soil testing would be reduced by approximately half. If using the decision trees to make recommendations, overall across regions 28% of the plots would require pH testing to determine whether soil pH is < or >= to 5.2. For the rest (72%), this could be determined on the basis of location (AEZ) and field characteristics reported by farmers. The 28% of fields that need soil testing are not distributed evenly amongst AEZs, with virtually all fields in the Congo Nile AEZ requiring travertine, none requiring travertine in the Volcanic Cones AEZ, while soil testing in needed in Buberuka Highlands (86% of the plots), Eastern Ridges (41% of the plots), and Lake Kivu (36% of the plots). On the other hand, without the use of the decision trees, soils should be tested in 52% of the plots globally for all the regions; all plots in Buberuca Highlands, Lake Kivu and Estern Ridges, and none in Volcanic Cones and Congo Nile.

Accuracy of low-cost rapid pH test kits

Five of the rapid test kits correctly diagnosed pH ≥5.2 in only ≤6% of cases. Another four kits correctly diagnosed p <5.2 in ≤11% of cases. All of these kits had low sensitivity to soil pH; the indicated pH would often not change between soils with contrasting pH values according to lab measurements. The Cornell pH test kit (which uses chlorophenol red indicator dye) had an overall diagnostic accuracy of 81%, while our self-manufactured chlorophenol red indicator dye kit had an overall diagnostic accuracy of 75%.

With subsequent improvements made to the testing protocol, the accuracy of the pH test kit was increased to 100% where pH is ≥5.2, and 25% error for pH <5.2. Cornell test kits have acceptable accuracy, with the disadvantages that it is time-consuming to use, relatively complex and expensive to distribute compared to strips, and relatively complex to train users on correct execution. As such, they can be only be used on a limited number of fields, ideally by extension officers or by well trained farmer promoters of farmer leads.

Table 6. Accuracy of rapid pH test kits in determining whether soil acidity is above or below pH 5.2

Kit	# of samples with pH ≥5.2	Correctly diagnosed pH ≥5.2	# of samples with pH<5.2	Correctly diagnosed pH <5.2	Overall diagnostic accuracy
Precision pH 4070 Test Strip 4 - 7 (Precision Europe, UK)	51	0%	29	100%	50%
Universal pH Indicator Paper 1 -14 (Precision Europe, UK)	51	100%	29	0%	50%
Hydrion pH Strip 4.5 - 7.5 (Micro Essential Lab, USA)	51	2%	29	97%	49%
Hydrion pH Strip 4.5 - 8.5 (Micro Essential Lab, USA)	23	0%	4	100%	50%
pH-Fix 4 - 7 (Marchery-Nagel, Germany)	51	98%	29	0%	49%
pH test strip 4.5 - 9 (Guangzhou Norm Scientific Instrument Company, China)	51	100%	29	0%	50%
pH Test Strips 4.5 - 9 (HealthyWiser, USA)	51	4%	29	100%	52%
MColorpHast pH Indicator Strips 4 - 7 (Merck, Germany)	51	6%	29	100%	53%
Just Fitter pH Test Strip 4.5 - 9 (Just Fitter, USA)	49	90%	26	11%	51%
Cornell pH Test Kit 5 - 6.2 (Cornell Nutrient Analysis Laboratory, USA)	51	90%	29	72%	81%
Chlorophenol red pH kit 5 - 6.2 (One Acre Fund, Rwanda)	48	73%	13	77%	75%

Conclusions

The threshold soil acidity below which application of 2.5 t/ha travertine increases yield and profit was determined to be pH 5.2. Where travertine is applied without targeting based on baseline pH, average yield is slightly increased but profitability is reduced. Travertine applied to soils with pH <5.2 at a 2.5 t/ha rate or 1.5 t/ha, in combination with compost and fertilizer, tended to increase cumulative profit after four seasons. However, if no fertilizer was used, there was no profit increase due to travertine application.

No differences in yield or accumulated profit were observed between travertine application at rates of 1.5 t/ha and 2.5 t/ha in combination with compost and fertilizer. However, greater yield differences between application rates may be possible in other crops. Travertine application tended to have a more positive effect on bean yields than maize yields. The mechanisms behind this difference are unclear and require further investigation, as it could inform the development of better travertine recommendations. Furthermore, it can be expected that the higher dosage would have an extended effect beyond the period evaluated in this study, in which case cumulative profit could be higher. However, in a context where farmers have financial or labor constraints limiting their ability to purchase or apply travertine, or distributors face logistical constraints, it would be reasonable to recommend a lower rate recommendation of 1.5 t/ha.

Based only on AEZ, pH testing would be recommended for 52% of fields. No testing would be recommended in Congo Nile and Volcanic Cones AEZs, but testing would be recommended for all farmers in other AEZs. Using decision trees based on farmers' characterizations of their fields, pH testing could be recommended for just 28% of fields. However, the contrasts in variables retained in classification trees between AEZs indicate that the decision trees developed in this project cannot necessarily be applied to AEZs that were not included in the study.

Most of the kits evaluated had unacceptably high error rates which would lead to farmers regularly being given incorrect information on their level of soil acidity and the need for travertine. The Cornell kit had the highest accuracy (80%) in initial testing. With subsequent improvements made to the testing protocol (enabling more precise volumetric measurement of soil and reagent), performance was improved to a 100% accuracy where pH ≥5.2 and 75% accuracy for pH <5.2. The self-manufactured chlorophenol kit was significantly lower cost than the Cornell version, but had lower precision, indicating that manufacturing protocol improvements are needed.

Recommendations and Next Steps

Interventions should be designed to minimize the chance of farmers apply 2.5 t/ha travertine in soils with pH ≥5.2. This can be achieved through marketing with decision trees and offering rapid pH tests using the Cornell test-kit where needed. Given that no differences in yield or accumulated profit were observed between travertine applications of 1.5 t/ha and 2.5 t/ha over two years, there should be increased flexibility on travertine rate recommendations.

Extension services should stress that travertine should be used in combination with fertilizer. Interventions should be designed to increase the adoption of travertine in combination with compost and fertilizer application. For example, this could include radio marketing campaigns, and in regions with high prevalence of soils with pH <5.2, offering travertine + fertilizer as bundled packages. Decision trees have potential to allow OAF to offer field-specific marketing of travertine and may also have relevance to the development of field-specific recommendations on fertilizer and seeding rates, crop rotation, compost targeting etc.

Congo Nile farmers should be recommended to apply travertine at a rate 2.5 t/ha every 2 years as per the current recommendation, but farmers in Volcanic Cones generally do not need it. For Lake Kivu, Eastern Ridges and Buberuka Highlands AEZs decision trees based on farmers' characterizations of their fields that have the potential to significantly reduce the number of soil tests needed for field-specific recommendations. These decision trees need to be validated on additional (independent) surveyed fields and soil samples. Data and soil sample collection for this has already been completed, with outstanding soil and statistical analyses expected to be completed in early 2021. Scale-up of AEZ-specific recommendations and decision-support tools is planned for late 2021. Given that acidification is potentially an ongoing process associated with fertilizer use, erosion and net biomass exports from fields, the conclusion that there are some zones where travertine is not required will need to be periodically revisited. Similarly, the field characteristics that relate to soil pH are expected to change with time.

The self-manufactured chlorophenol kit was significantly lower cost than the Cornell pH Test Kit (ongoing materials costs decrease from $0.35 to $0.01 per sample by refilling the kits with self-manufactured solution), and could allow more accessibility to farmers through farmer leaders or farmer promoters. Relatively trivial investments in titration equipment and calibration samples would almost certainly facilitate production of self-manufactured kits which would have equal accuracy to the Cornell kit.

Further research is needed to determine optimal travertine application rates and interval recommendations, and how these vary by crop, soil characteristics (e.g. OM%, texture) and effective neutralising value of the liming product. The development of pedotransfer functions incorporating these variables could enable the generation of field-specific liming recommendations based on location, using soil maps such as iSDAsoil.

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