



Effects of liming and local sediment amendment on millet production and soil N₂O emission in western Kenya

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Abstract

Aim Soil acidification is a major constraint to agricultural productivity in East Africa. This study evaluated the effects of liming and local sediment amendments on millet production, soil properties, and soil N₂O emissions in western Kenya.

Methods Field experiments with liming (Ca(OH)₂, 5 t ha⁻¹) and local sediment amendments (1% and 3%) were conducted using a four-replicate block design. Soil properties, millet biomass and yield, and N₂O fluxes were measured.

Results Liming significantly increased millet biomass and yield by raising soil pH, enhancing Ca

availability, and reducing Al toxicity, while also resulting in the lowest N₂O emissions. In contrast, sediment amendments had only minor effects on soil chemistry and did not significantly improve yield or reduce N₂O fluxes compared to the control.

Conclusion By improving soil properties as soil pH and nutrient availability, liming proved to be an effective strategy to increase millet production and reduce N₂O emissions in acidic soils. In contrast, local sediment amendment offered moderate but persistent improvements in soil fertility, but did not increase millet yield significantly. These findings highlight liming as a key management practice for enhancing crop production while mitigating greenhouse gas emissions in acidified agricultural systems of East Africa.

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Introduction

Soil acidity is a global challenge for agriculture and food security, with about 50% of the world's arable land characterized as acidic (Dai et al. 2017). Acid soils occur mainly in tropical and subtropical regions, where subhumid to humid climates with high temperatures and moderate to high rainfall drive their formation (von Uexküll and Mutert 1995; Soil Survey Staff 1999; Agegnehu et al. 2021). East Africa is among the regions strongly affected by soil acidification, and in Kenya, around 13% of the total soil is acidified, which translates to approximately 63% of Kenya's arable land (Kanyanjua et al. 2002; Esilaba et al. 2023). The predominant soil types in Kenya, including Ferralsols and Acrisols, have developed through long-term and intense weathering under these climatic conditions (Nyachiro and Briggs 1987; Soil Survey Staff 1999). During this process, essential base cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+) are leached from the soil and are replaced by hydrogen (H^+) and aluminium (Al^{3+}) ions (von Uexküll and Mutert 1995; Agegnehu et al. 2021). Additionally, silicon (Si) is leached from the soil over time (Meena et al. 2014). As a result, highly weathered soils accumulate stable primary and secondary minerals, mainly iron (Fe) and Al oxides, and generally have a low pH between 4 and 5 (Kögel-Knabner and Amelung 2014). The high incidence of these acidic soils in Kenya imposes significant challenges for smallholder agriculture, because it requires integrated soil management approaches, which are not always affordable for smallholders (Bekunda et al. 2010).

Agriculture on acidic Ferralsols and Acrisols in Kenya faces two major challenges. Both challenges are linked to the fact that these soils have a low pH below 5 due to prolonged and intensive weathering and are enriched in Fe and Al oxides. The first challenge is the increased risk of Al toxicity for crops. At pH values below 5.5, aluminium hydroxide [$\text{Al}(\text{OH})_3$] gradually dissolves, releasing Al^{3+} ions into the soil solution (Li and Johnson 2016; Bojórquez-Quintal et al. 2017). These Al^{3+} ions are highly mobile and

phytotoxic (Sade et al. 2016). Their increased mobility enhances direct uptake by plants, leading to accumulation within plant tissues. Aluminium toxicity particularly inhibits root growth and root system development, thereby reducing nutrient and water uptake (Kochian et al. 2004). Consequently, plant growth and yield are limited (Lal and Singh 1998).

The second major challenge is high phosphorus (P) fixation by Fe and Al oxides in Ferralsols and Acrisols. Under acidic conditions, the surface hydroxyl groups of Fe and Al oxides, such as hematite, goethite, or gibbsite, become increasingly protonated (Li et al. 2019). This leads to a stronger positive surface charge, which enhances the retention of negatively charged phosphate species through electrostatic adsorption and ligand exchange (Kovács et al. 2020; Nkoh et al. 2021). As a result, these soils often contain considerable amounts of total P, but only a tiny fraction remains soluble and available for plant uptake (Hengl et al. 2017; Du et al. 2020). Phosphorus fixation has long been recognized as one of the major challenges for agriculture on acidic soils and is extensively discussed in the scientific literature (Kellogg 1956; Russel et al. 1974; Sanchez and Uehara 1980; Ayodele and Agboola 1981).

There are several soil management approaches to deal with these challenges for crop production on acidic soils. Most smallholders in Kenya try to compensate for the lack of P caused by P fixation by applying mineral fertilizers like diammonium phosphate (DAP) or NPK compounds (Nziguheba et al. 2016). However, Kanyanjua et al. (2002) revealed that application rates of 26 to 52 kg P ha⁻¹ in acidic soils in Kenya resulted in P recovery rates of only 9.6% to 13.5%, due to direct fixation by soil minerals. Thus, achieving sufficient yields requires large amounts of mineral fertilizers, which are mostly unaffordable for smallholders due to high costs and limited access (Minde et al. 2008). This calls for alternative approaches that reduce dependence on mineral fertilizers and are affordable to smallholder farmers.

Liming is globally applied as a strategy to mitigate the problem of Al toxicity and improve the fertility of acidic soils (Wang et al. 2021). The addition of lime materials rich in Ca^{2+} and/or Mg^{2+} to soils such as Ferralsols effectively neutralizes excess H^+ ions, thereby increasing soil pH (Wang et al. 2021). Once the pH exceeds 5.5, the toxic Al^{3+} ions are gradually transformed into less soluble and less toxic

forms such as $\text{Al}(\text{OH})_2^{2+}$, $\text{Al}(\text{OH})_2^+$ and $\text{Al}(\text{OH})_3$ (Bojórquez-Quintal et al. 2017). As a result, the concentration of toxic Al^{3+} in the soil solution decreases, alleviating its harmful effects on plants (Bolan et al. 2003; Bojórquez-Quintal et al. 2017). Additionally, the increased pH deprotonates the Fe and Al oxide surfaces, decreasing the electrostatic adsorption of negatively charged phosphate species (Fageria and Baligar 2008). Consequently, there is less P fixation and higher P availability in the soil (Fageria and Baligar 2008).

Numerous studies have demonstrated the beneficial effects of liming on acidic soils in Kenya, including reducing Al toxicity, increasing soil pH and improving the availability of essential nutrients such as Ca, Mg, N and P (Nyachiro and Briggs 1987; Kanyanjua et al. 2002; Kisinyo et al. 2014; Hijbeek et al. 2021; Scherwietes et al. 2025). However, lime is rarely used in Kenyan agricultural practices due to factors like limited access and availability, high costs and knowledge gap regarding its benefits (Kisinyo et al. 2014). Besides liming, there are other cost-effective soil management practices, such as the return of crop residues, green manuring and the application of biochar, which can improve soil fertility in smallholder farming (Mureithi et al. 2003; Okeyo et al. 2016; Kätterer et al. 2022). In this context, locally available Rift Valley sediments are of particular interest in this study because they may directly counteract soil acidity through their enrichment in base-forming cations and volcanically derived minerals, potentially providing effects comparable to liming (Scherwietes et al. 2024, 2025). Rift Valley sediments are often influenced by volcanic materials such as tuffs and tephra, which might have altered the physicochemical properties of the initial sediments (Pyle 1999; Blegen et al. 2016). As a result, these sediments can be enriched in base-forming cations (e.g., Ca^{2+} and Na^+) as well as other important nutrients such as P and Si that may benefit crop productivity (Tryon and McBrearty 2006; Blegen et al. 2016). Previous studies by Scherwietes et al. (2024, 2025) demonstrated significant increases in barley yields following both sediment application and liming. These effects were mainly attributed to increases in soil pH, which reduced Al toxicity and improved nutrient availability, while the sediment treatments may additionally have benefited from nutrient inputs such as P and Si (Scherwietes et al. 2024, 2025).

Apart from the benefits of liming and soil amendment with local sediments in enhancing crop production on acidic soils, the resulting increase in soil pH may alter microbial communities and promote the reduction of N_2O to N_2 during denitrification, thereby decreasing soil N_2O emissions (Abalos et al. 2020; Ntinyari et al. 2023). N_2O is a particularly relevant greenhouse gas because it has a high global warming potential and is a major contributor to stratospheric ozone depletion (Ravishankara et al. 2009; IPCC 2023). Since agricultural soils are one of the dominant anthropogenic sources of N_2O , understanding factors that can reduce soil N_2O emissions is essential for climate change mitigation and sustainable land management (IPCC 2023). Nutrients in the local sediments, such as amorphous silicon (ASi), may also lead to reduced soil N_2O emissions (Hoffmann et al. 2025; Madegwa et al. 2025). This is likely linked to enhanced plant growth and nitrogen uptake, which reduce mineral N availability for microbial N_2O production, as well as to improved rhizosphere conditions that may promote more complete denitrification from NO to N_2 (Hoffmann et al. 2025; Madegwa et al. 2025).

Previous investigation of the impact of liming and soil amendment with varying amounts of local sediments showed improvement in biomass production and crop yields in the Kaptagat study site in Kenya (Scherwietes et al. 2024, 2025). To further understand the implications of these practices, it was necessary to assess their impacts on soil N_2O emissions. However, despite the documented benefits of liming and local sediment amendment for crop productivity, little is known about their long-term effects on soil N_2O emissions under field conditions. In particular, it remains unclear whether the agronomic benefits of ASi-rich local sediments are accompanied by reductions in greenhouse gas emissions. Addressing this knowledge gap is essential for evaluating the potential of these amendments as sustainable soil management practices. Therefore, the first objective of this study was to investigate the extent to which a soil amendment with local sediment rich in Ca and ASi (three years after application) and liming affect soil pH, nutrient availability, biomass production and crop yield in western Kenya. The second objective was to evaluate the impact of these soil amendments on soil N_2O fluxes. We expected higher biomass and yields with liming and local sediment amendment. We also

hypothesized that soil N_2O fluxes would be lower in limed and sediment-amended soil treatments than in the control treatments because increased soil pH can promote the reduction of N_2O to N_2 during denitrification, thereby decreasing N_2O emissions.

Material and methods

Study sites and experimental design

This study was conducted at two field sites in western Kenya, with the primary experimental focus on the Eldoret site and a secondary site in Malava included to assess the robustness of the findings. The primary study site was located in Kaptagat, a village east of Eldoret in Uasin Gishu County (0.4448°N, 35.4685°E). The site is characterized by cool, temperate climate with daily temperatures ranging from 9 to 25 °C and an annual rainfall of 900–1200 mm (Tsuma et al. 2015; Werunga et al. 2022). Rainfall mainly occurs across two seasons, with long rains from March to May and short rains from October to December (Sagero et al. 2018). The experiment was carried out on cropland at 2410 m elevation. Soils at the site are classified as Ferralsols and Acrisols, which are highly weathered, acidic, and low in fertility (Nyachiro and Briggs 1987; Okalebo et al. 2005). Soil pH at the Eldoret site was 4.7. A secondary experimental site was established near Malava in Kakamega County (0.462972°N, 34.835944°E). Compared to Eldoret, the Malava site is characterized by a warmer and more humid climate, with mean temperatures of 18–20 °C and higher annual rainfall (1800–2000 mm), which is more evenly distributed throughout the year (Chepkosgei et al. 2022). The experiment in Malava took place on cropland at 1559 m elevation on ferralitic soil with pH of 4.9.

The study site in Eldoret covered an area of 30×19 m, with individual plots measuring 3×4 m (Fig. S1). Calcium hydroxide [$\text{Ca}(\text{OH})_2$] was applied in April 2024 at a rate of 0.15% by volume, equivalent to 5 t ha^{-1} . In addition, two treatments with sediment from Baringo were established at rates of 1% and 3% by volume (corresponding to 24 and 72 t ha^{-1} , respectively). The sediment, described in detail by Scherwietes et al. (2024), had been incorporated in 2022. Baringo sediment consists of a Ca-rich, aggregated matrix with Al- and Si-containing particles and

was collected west of Lake Baringo (0.574643°N, 35.984597°E).

At the Malava site, the experimental area measured 19×12 m, with plot dimensions of 4×5 m. Calcium hydroxide was applied at the same rate as in Eldoret (0.15% by volume, equivalent to 5 t ha^{-1}) in May 2024. No sediment treatments were applied at this site. Untreated control plots were included at both sites. All treatments were replicated four times using a non-randomized block design due to logistical and site management constraints. Buffer zones of 1 m were maintained between plots to prevent cross-treatment interference. All amendments were incorporated manually and mixed into the upper 20 cm of soil using hand hoes. Control plots were mixed in the same manner to ensure consistent physical disturbance across treatments.

Finger millet (*Eleusine coracana* L., cv. P224) was sown manually at both sites. Sowing took place on 15 May 2024 in Eldoret and on 16 April 2024 in Malava. Fertilizer was applied uniformly across all plots in the form of NPK (17:17:17) at a rate of 50 kg ha^{-1} before planting and an additional 50 kg ha^{-1} after germination. Harvest was conducted on 16 November 2024 in Eldoret and on 23 August 2024 in Malava.

Sampling and analyses

At the Eldoret study site, whole-plant samples were collected at four stages of the growing season: tillering, booting, flowering, and harvest. At harvest, total aboveground biomass was sampled at both sites from randomly selected 40×40 cm areas within each plot to assess yield and biomass differences. All plant material was weighed, washed, and oven-dried. In parallel, soil samples (0–15 cm depth) were taken from each plot using a small shovel and air-dried. Soil pH was measured in water (1:2.5 solid-to-solution ratio) using a WTW pH/Cond 3320 m with a Sentix41 electrode (Xylem Water Solutions, Washington, DC, USA).

Available Al, Ca, Si, and P were extracted from soils using Mehlich III solution following the method of Sparks et al. (1996). Briefly, 2 g of soil were mixed with 42 ml of Mehlich III solution in 50 ml centrifuge tubes, shaken for 5 min, centrifuged at 3,200 g for 5 min, and filtered through 0.2 µm membranes. Extracts were analyzed via ICP-OES (iCAP 6300

DUO, ThermoFisher Scientific Inc., Waltham, MA, USA).

To evaluate nutrient accumulation in plant tissues, leaves were separated and analyzed using two extraction methods. For Al, Ca, P, and Fe, microwave digestion was performed: 0.1 g of plant material was mixed with 2 H₂O₂ and 3 ml HNO₃ in closed vessels and digested in a microwave system (CEM-Mars6, CEM Corporation, Matthews, NC, USA). After digestion, extracts were diluted to 20 ml with deionized water and filtered (0.2 µm).

Amorphous Si was determined using Tiron extraction following Kodama and Ross (1991); Puppe et al. (2023). Here, 0.03 g of dried plant tissue was mixed with 30 ml of 0.1 M Tiron solution in 50 ml tubes and heated at 85 °C for 1 h in a water bath. Samples were gently shaken before heating and again after 30 min. Extracts were then centrifuged (5,000 g for 5 min) and filtered (0.2 µm). All extracts were analyzed by ICP-OES (iCAP 6300 DUO, ThermoFisher Scientific Inc.).

N₂O measurements and flux calculations

Soil N₂O concentrations were measured at the field site in Eldoret using a portable LI-7820 N₂O gas analyser (LI-COR Biosciences, Lincoln, NE, USA). The precision of the analyser is 0.40 ppb at a concentration of 330 ppb with 1 s averaging. The analyser was connected to a static, opaque polypropylene chamber (37×26×12.5 cm; length, width, height), mounted on a metal collar gently installed (about 2 cm deep) at each measurement point to minimize physical disturbances during insertion (e.g., Wangari et al. 2022). The laser-based analyzer's high sampling frequency (1 Hz) and precision (around 0.4 ppb) allowed for measurements with a short chamber-closure time of around 5 to 10 min. The chamber was fitted with a folded Teflon tube on one side to minimise pressure differences between the chamber headspace and the outside air during chamber deployment (e.g., Kong et al. 2025).

To enable temporal measurements, we focused on only the Kaptagat study site in Eldoret because it also entailed more treatments than the Malava study site. This allowed us to compare control soil, limed soil, and soil amended with local sediment. The sediment amendment trial comprised volcanic ash from Baringo at different application rates (Baringo 1%,

Baringo 3%; at 24 and 72 t ha⁻¹, respectively), carried out in April 2022 (Scherwies et al. 2024).

All treatments were established in 4 replicate plots, each measuring 4 by 3 m, with 1 m buffer strips surrounding them. Two measurement points were selected per plot, resulting in 8 points for N₂O fluxes per treatment. N₂O measurements were carried out once or twice a week for 13 weeks, from 14th March to 10th July 2024. This captured temporal aspects such as background measurements before and after planting, as well as dry and rainy periods. We calculated N₂O fluxes based on the linear changes in measured gas concentrations in the chamber headspace over time, after removing the deadband (Eq. 1).

$$N_2O_{flux} = \frac{dC}{dt} \times \frac{V}{A} \times \frac{P * M}{R * T} \quad (1)$$

where dC/dt is the change in N₂O concentration over time, V is chamber volume (m³), A is chamber area (m²), P is atmospheric pressure (atm), M is the molar mass of N₂O, R is the universal gas constant, and T is chamber air temperature (K).

Due to the limited measurement frequency conducted over only part of the growing season, seasonal N₂O fluxes were estimated by multiplying the mean measured N₂O fluxes by the duration of the growing season (248 days). Yield-scaled N₂O fluxes were then calculated by dividing the estimated seasonal N₂O fluxes (kg N ha⁻¹) by the crop yield (t ha⁻¹) and were expressed as kg N₂O-N t⁻¹ yield for each treatment.

Statistics

Comparison of soil physicochemical parameters (pH, Ca, Al, Si, and P) and millet production (yield and biomass) across treatments at the Eldoret study site was performed using a linear mixed-effects models, with block (treatment replicate) included as a random effect to account for spatial heterogeneity associated with the non-randomized block design. A two-way ANOVA was performed on the model, followed by Tukey's HSD post-hoc test using estimated marginal means (emmeans) to assess pairwise differences between treatment combinations. For data from Malava, a non-paired Welch Two Sample t-Test was conducted. For N₂O fluxes, the random effect of block was estimated to be zero; therefore, a linear model without random effects was applied. N₂O fluxes were

log-transformed to meet model assumptions. The data were analysed using R version 4.5.1 (R Core Team 2025).

Results

Effects of liming and soil amendment on millet productivity

In Eldoret, liming significantly increased millet biomass ($32.2 \pm 5.58 \text{ t ha}^{-1}$; $p=0.018$, Tukey) and grain yield ($8.12 \pm 1.17 \text{ t ha}^{-1}$; $p=0.041$, Tukey) compared to the control (Fig. 1). The Baringo sediment treatments (1% and 3%) resulted in slightly higher biomass (Baringo 1%: $27.34 \pm 7.92 \text{ t ha}^{-1}$; Baringo 3%: $25.01 \pm 0.60 \text{ t ha}^{-1}$) and yield (Baringo 1%: $7.5 \pm 3.28 \text{ t ha}^{-1}$; Baringo 3%: $6.27 \pm 1.16 \text{ t ha}^{-1}$), but these differences were not significant compared to the control (biomass: $19.94 \pm 2.27 \text{ t ha}^{-1}$; yield: $4.32 \pm 0.28 \text{ t ha}^{-1}$; $p>0.05$, Tukey). At the secondary site in Malava, liming significantly increased millet yield ($3.27 \pm 0.34 \text{ t ha}^{-1}$; $p=0.05$, $t=-2.908$, $df=3.565$, t -test), while no significant effect on biomass was observed ($15.35 \pm 1.59 \text{ t ha}^{-1}$; $p=0.116$, $t=-2.006$, $df=3.941$, t -test; Fig. S2).

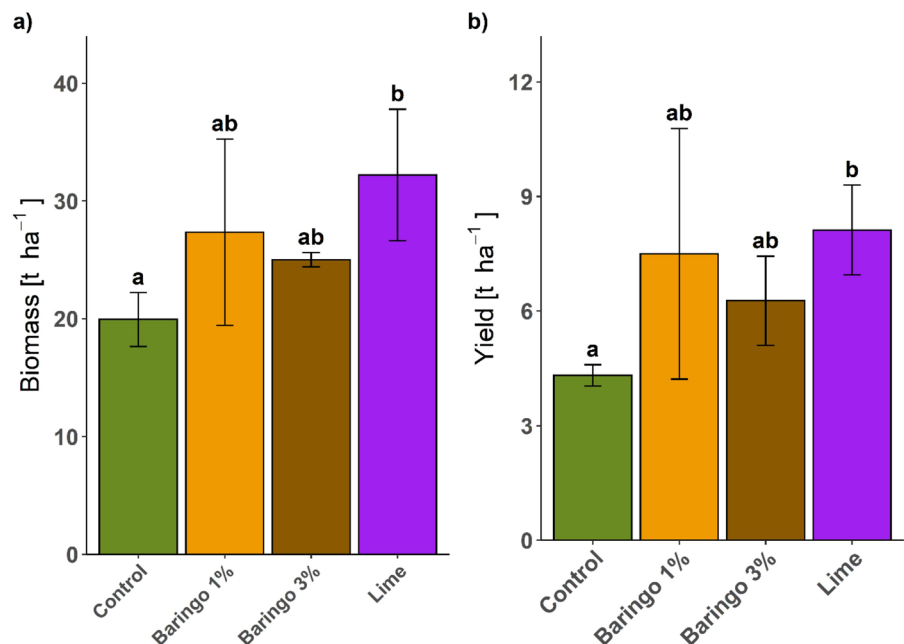
Effects of liming and soil amendment on soil pH and nutrient availability

Significant changes in soil pH and nutrient availability were observed at both study sites (Fig. 2 and Fig. S3). At the primary study site in Eldoret, liming significantly increased soil pH (6.86 ± 0.23), enhanced Ca availability (3.65 ± 0.41), and reduced Al availability ($2.65 \pm 0.04 \text{ mg g}^{-1}$ (all $p<0.001$, Tukey)). No significant effects of liming on P or Si availability were detected ($p>0.05$). The Baringo 3% treatment showed effects comparable to liming including increased soil pH (6.52 ± 0.59), higher Ca availability (3.34 ± 1.02), and reduced Al availability ($2.54 \pm 0.17 \text{ mg g}^{-1}$ (all $p<0.001$, Tukey)). In contrast to liming, Baringo 3% also significantly increased Si availability ($0.50 \pm 0.05 \text{ mg g}^{-1}$, $p<0.001$). The Baringo 1% treatment significantly reduced Al availability ($3.07 \pm 0.09 \text{ mg g}^{-1}$, $p=0.003$), but did not affect soil pH or Ca, Si, and P availability ($p>0.05$).

At the secondary site in Malava, liming likewise increased soil pH ($p=0.036$) and Ca availability ($p=0.043$) and reduced Al availability ($p=0.049$), while no significant effects on P or Si availability were observed ($p>0.05$).

Leaf nutrient contents of millet in Eldoret varied only slightly among treatments (Fig. S4). Only Ca differed significantly as liming increased Ca relative

Fig. 1 Effects of sediment amendment and/or liming on the (A) dry biomass and (B) dry yield of finger millet at the Eldoret study site. Error bars represent standard deviation ($n=4$). Different letters indicate significant differences between treatments ($p<0.05$); shared letters indicate no significant difference



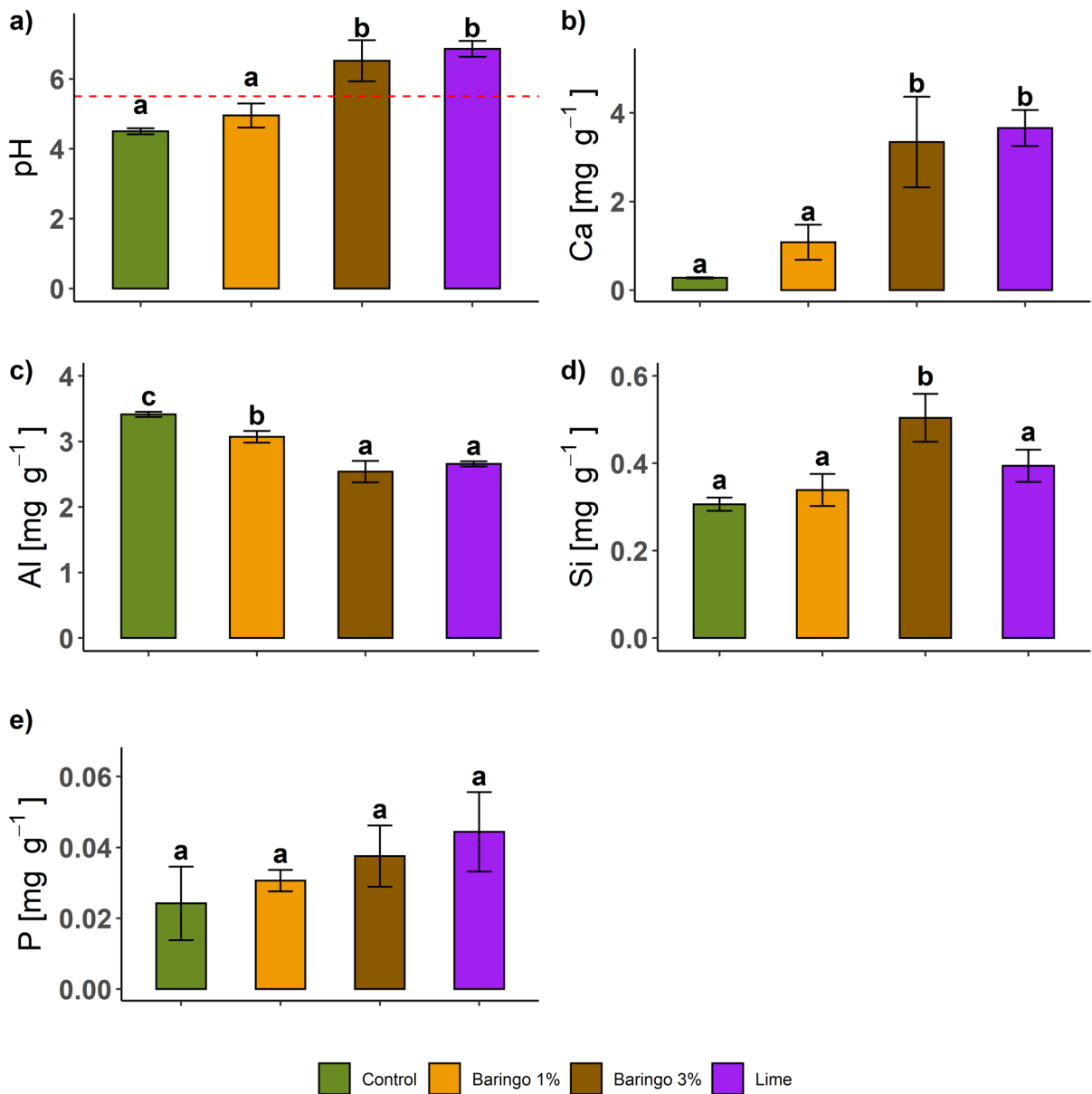


Fig. 2 Effects of sediment amendment and/or liming on (A) soil pH and soil available (B,C,D,E) Ca, Al, Si, and P at the Eldoret study site. The red dotted line indicates the pH threshold of 5.5. Error bars represent standard deviation (n=4).

Different letters indicate significant differences between treatments ($p < 0.05$); Shared letters indicate no significant difference

to the control ($p = 0.005$, Tukey) but not to Baringo treatments. For Al, P, and Si, no significant differences were detected ($p > 0.05$, Tukey), though Baringo 3% and lime tended to lower Al and raise P contents compared with Baringo 1% and the control, and both Baringo treatments generally had higher Si than the control and lime.

Effects of liming and soil amendment on soil N_2O fluxes

Spatial variability in soil N_2O fluxes was evident across treatments (Fig. 3a). Fluxes from control soils (mean: $47.5 \mu g m^{-2} h^{-1}$) were comparable to those from local sediment-amended soils

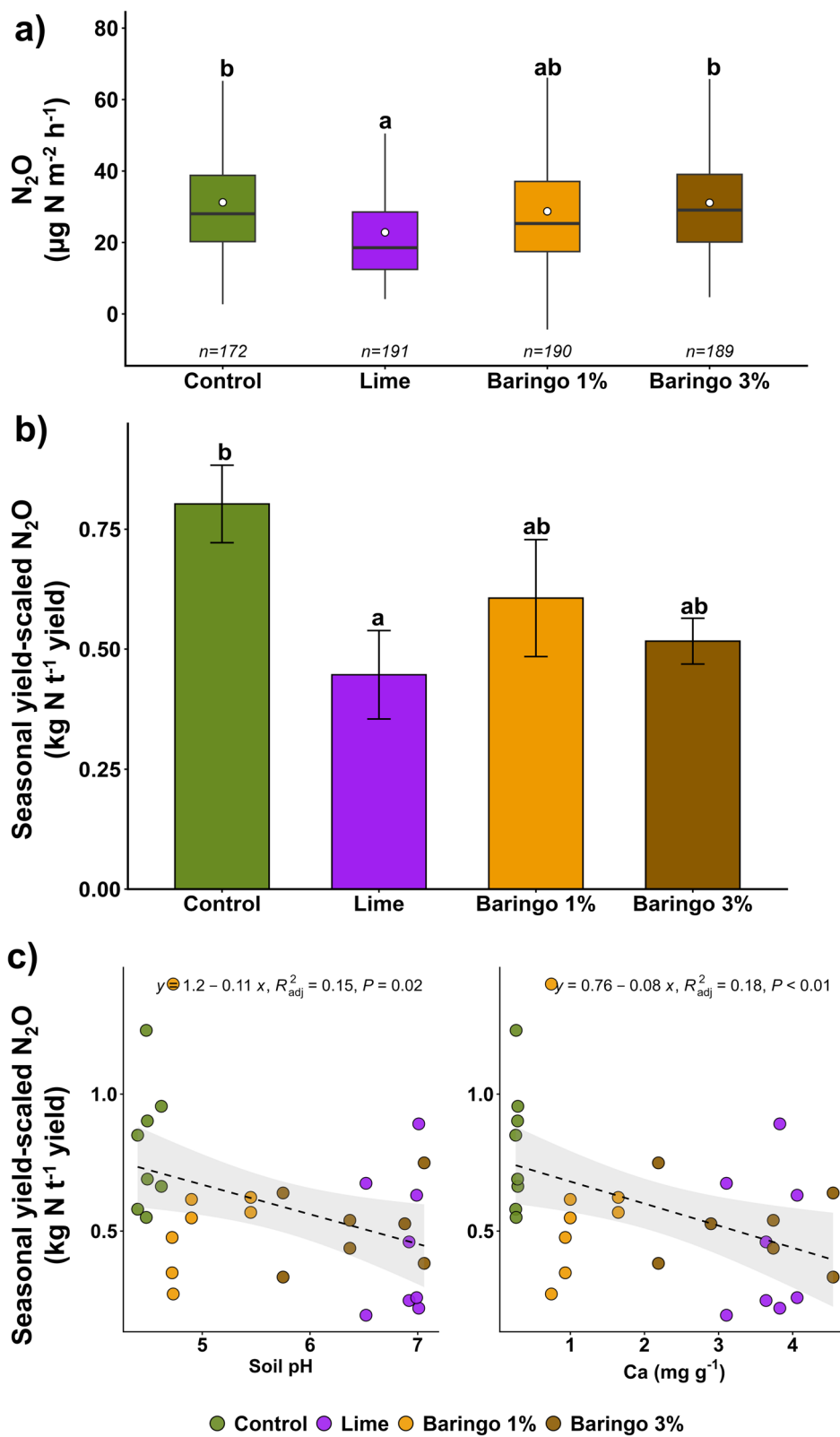


Fig. 3 **A)** Box plots showing the distribution of soil N_2O fluxes across treatments at the Eldoret study site. White dots represent the mean values, and lowercase letters above the boxes indicate significant differences ($p < 0.05$) among treatments. **B)** Bar plots comparing estimated seasonal yield-scaled N_2O fluxes across treatments, calculated by scaling mean N_2O fluxes measured over a 13-week monitoring period to the millet growing season (248 days) and dividing by the crop yield. Lowercase letters above the whiskers indicate significant differences ($p < 0.05$) among treatments. **C)** Linear regression plots showing relationships between estimated seasonal yield-scaled N_2O fluxes and soil pH and Ca

(mean: $42.5\text{--}49.6 \mu\text{g m}^{-2} \text{h}^{-1}$). Limed soils (mean: $39.3 \mu\text{g m}^{-2} \text{h}^{-1}$) exhibited the lowest fluxes across the treatments, although they were comparable with those of Baringo 1% (Fig. 3a). Similarly, average yield scaled N_2O fluxes (13 weeks of measurements) were lower in the limed plots compared to the control plots (Fig. 3b). Baringo 1% and 3% were lower than control plots, but this difference was not statistically significant ($p > 0.05$). Across the treatments, the yield-standardized N_2O fluxes exhibited significant ($p < 0.05$) negative relationships with soil pH ($r^2 = 0.15$) and Ca ($r^2 = 0.18$), with the control plots having lower pH and Ca content and higher N_2O fluxes (Fig. 3c).

Regarding temporal patterns (Fig. 4), the daily average N_2O fluxes remained relatively stable across all treatments during the pre-planting phase (the first 6 weeks of measurements). A pronounced increase in fluxes occurred following rainfall events and the sowing of finger millet. Notably, the limed soils showed the earliest increase in N_2O emissions, reaching values up to two orders of magnitude higher than the other treatments during this initial stage. The highest peak emissions were observed in the control plots the subsequent week, followed by the Baringo-sediment-amended soils and the limed soils. These peaks declined after one week to pre-planting phase levels across all treatments despite continued rainfall and remained relatively stable for the remainder of the measurement period. Similar to N_2O fluxes, the daily average soil moisture levels were lower (approximately 5% to 12%; Fig. S5) during the pre-planting phase and increased to approximately 25% to 30% following rainfall events.

Discussion

Yield increase after sediment addition and liming

It was demonstrated that the application of locally sourced sediments to acidic arable soils in Kenya can improve barley yields (Scherwietes et al. 2024). In particular, the use of calcium-rich lacustrine sediment with volcanic influence from Baringo resulted in a significant yield increase over two consecutive growing seasons (Scherwietes et al. 2024, 2025). The authors attributed these improvements to an increase in soil pH caused by calcium release through carbonate weathering (Scherwietes et al. 2024, 2025). The rise in soil pH can shift acidic soils strongly toward near-neutral conditions, thereby enhancing the availability of essential plant nutrients such as Ca^{2+} and Mg^{2+} and reducing the toxic effects of H^+ and Al^{3+} ions (Bojórquez-Quintal et al. 2017; Wang et al. 2021). When the soil pH exceeds 6, mobile and phytotoxic Al^{3+} ions are transformed into less soluble and less harmful forms, decreasing Al availability and potentially limiting its uptake by plants (Bolan et al. 2003; Bojórquez-Quintal et al. 2017). Beyond reducing Al toxicity, elevated soil pH also promotes P availability by deprotonating the surfaces of Fe oxides and thus reducing the adsorption of negatively charged phosphate ions (Fageria and Baligar 2008). The current field experiments in Kenya confirmed these mechanisms, showing reduced Al availability and toxicity alongside improved Ca and P availability following sediment application (Scherwietes et al. 2024, 2025). The present study builds upon these findings by examining the long-term effects of Baringo sediment on the soil properties of Ferralsol in Eldoret and the growth and biomass of finger millet, three years after sediment incorporation.

In contrast to previous findings obtained with barley (+1061% with Baringo 3%, Scherwietes et al. 2024), this study did not observe a significant increase in finger millet yield following the application of Baringo sediment to the soil (+45% with Baringo 3%). However, a non-significant trend towards higher yields with Baringo sediment addition was evident. Even in the third year after sediment application, the positive effects on soil properties could

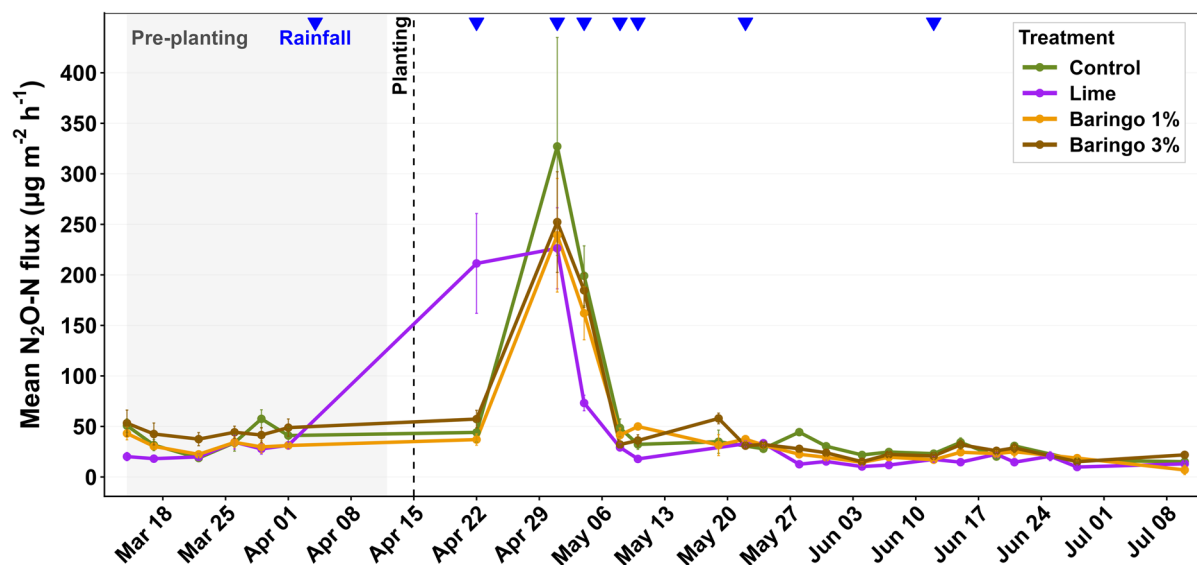


Fig. 4 Daily average N₂O fluxes (with SE error bars) across the treatments (control, lime, Baringo 1%, and 3%) from mid-March to mid-July 2024 at the Eldoret study site. The shaded

area indicates the pre-planting phase, and blue downward triangles at the top of the panel indicate days with rainfall events during the measurement period

still be confirmed. Once again, an increase in soil pH (above 6), enhanced availability of Ca, P, and Si, as well as a significant decrease in Al availability were observed. The fact that the effects on finger millet yields were less pronounced than those previously observed for barley can be attributed to the higher resilience of finger millet (Gebreyohannes et al. 2024; Srikanth et al. 2025). Unlike barley, finger millet is a C4 plant, maintaining active photosynthesis at higher temperatures and exhibiting greater water use efficiency (Srikanth et al. 2025). Combined with its deeper root system, this enables finger millet to better withstand periods of drought (Srikanth et al. 2025). Furthermore, the species is considered more tolerant to Al, enabling it to grow well even under lower soil pH conditions and higher Al availability (Brhane et al. 2022). Due to its strong adaptation to the characteristics of Ferralsols in Kenya, finger millet achieved stable yields even in the control treatment. Consequently, the sediment-induced improvements in nutrient availability and soil pH had a comparatively smaller influence on plant growth. Nevertheless, three years after sediment application, beneficial effects remained evident, resulting in higher yields compared to the control. These findings suggest that sediment amendment may be particularly beneficial for crops that are more sensitive to soil acidity and Al toxicity

than finger millet, such as barley and potentially other crops with lower tolerance to acidic soil conditions (Wang et al. 2006). In addition, sediment application may be especially relevant for strongly acidified Ferralsols with low Ca availability and high Al saturation, where increases in soil pH and nutrient availability can substantially improve crop performance. Therefore, although the yield response of finger millet was comparatively moderate, sediment amendments may still represent a valuable soil management strategy under more acidity-sensitive cropping systems or more degraded soil conditions.

Furthermore, this study examined the effects of liming on the growth and yield of finger millet at two sites in western Kenya. Numerous studies have demonstrated that liming is an effective management practice for enhancing crop production on acidic soils such as Ferralsols (Nyachiro and Briggs 1987; Kanyanjua et al. 2002; Kisinyo et al. 2014; Hijbeek et al. 2021; Scherwietes et al. 2025). Similar to the application of Baringo sediment, liming increases soil pH, thereby reducing aluminium toxicity and improving phosphorus availability (Wang et al. 2021). In this study, the application of calcium hydroxide [Ca(OH)₂] at a rate of 0.15% by volume resulted in a significant increase in finger millet yield at two locations compared to the respective controls. In Eldoret,

yields increased by 88%, exceeding those obtained with the Baringo sediment treatment, although the difference was not statistically significant. Similar results were observed at the secondary site in Malava, where yields increased by 95%, indicating a comparable directional effect. Following incorporation, calcium hydroxide dissociates and releases OH^- ions into the soil solution, which bind H^+ and thereby increase soil pH. The observed yield improvements after liming are most likely attributable to this rise in soil pH, which enhanced the availability of Ca and P while reducing Al availability, similar to the effects observed following the application of Baringo sediment.

Despite the strong positive effects of liming observed in this study, the adoption of lime amendments among smallholder farmers in Kenya remains limited due to high costs, limited availability and access, and knowledge gaps (Kisinyo et al. 2014). In this context, locally available Rift Valley sediments may represent a complementary and potentially more affordable soil management strategy for smallholder farming systems. Although the sediment treatments produced smaller yield responses than liming, beneficial effects on soil properties were still detectable three years after application, suggesting potential longer-term benefits under resource-constrained agricultural conditions and highlighting their suitability as a low-cost, long-term soil fertility management option for smallholder farming systems in Kenya.

Although the field experiment was conducted using a non-randomized block design, potential spatial heterogeneity among plots was accounted for by including block as a random effect in the statistical analyses, thereby increasing confidence in the observed treatment effects.

Effects of liming and soil amendment on soil N_2O fluxes

The lower N_2O fluxes in the limed soil compared to the control and Baringo sediment treatments in this study are consistent with findings from other studies (e. g. Abalos et al. 2020; Zhang et al. 2022). These reduced N_2O fluxes may be the result of an increase in soil pH induced by liming, which was supported by the significantly higher soil pH observed in the limed soils than in the control soils (Fig. 2) and the negative relationship between soil pH and N_2O fluxes

(Fig. 3c). Previous studies have shown that lime-induced increases in soil pH can increase the abundance and improve the stability of microbial communities involved in nitrification and denitrification, such as the ammonium oxidizers (*amoA*), nitrite reducers (*nirS* and *nirK*), and nitrous oxide reducers (*nosZ*) (Madegwa and Uchida 2021; Wu et al. 2022; Zhang et al. 2022; Mitsuta et al. 2025). In particular, soil N_2O emissions can decline with reduced soil acidity due to enhanced efficiency of N_2O reducers, which promote the reduction of N_2O to N_2 (Hénault et al. 2019; Wu et al. 2022).

Apart from the effects of pH on the microbes responsible for N cycling, liming can indirectly reduce N_2O emissions by improving plant N uptake and reducing surplus soil N availability for N_2O production (Abalos et al. 2020; Zhang et al. 2022). Lime-induced pH increase can alleviate Al toxicity and increase nutrient availability, thereby improving root and plant growth (Caires et al. 2008). This is supported by the lower Al and higher Ca and crop yields observed in the limed soils compared to control plots (Fig. 1, 2). The higher Ca availability in limed plots (Fig. 2) may also have indirectly reduced N_2O fluxes by improving soil structure and thereby favouring plant growth and N uptake, and lowering soil N availability for N_2O production. This was further supported by the negative relationship observed between soil Ca content and N_2O fluxes (Fig. 3c).

Temporal patterns, characterized by N_2O peaks following sowing and precipitation events that also coincided with fertilizer application, suggested the occurrence of hot moments of N_2O production, as the peaks were up to an order of magnitude higher than the fluxes observed in other periods (Fig. 4). Such peaks following precipitation have also been observed in other studies (e.g., Žurovec et al. 2021). The peak N_2O emissions in this study may have been enhanced by the high precipitation that occurred after a prolonged dry period, which increased soil moisture content (Fig. S5) and may have stimulated microbial activity and reduced soil aeration, creating oxygen-limited microsites that can favour denitrification. In addition, the rainfall event following fertilizer application may have enhanced the mobility and availability of mineral N substrate to the microbes, enhancing nitrification and denitrification processes (Butterbach-Bahl et al. 2013). The earlier N_2O peak observed in limed soil relative to control plots has also been

reported in other studies (e.g., Ntinyari et al. 2023). This pattern may reflect a more rapid stimulation of microbial N transformations following the precipitation event on that day. Because liming probably had already alleviated soil acidity, the resulting increase in soil moisture may have activated microbial processes more quickly than in the other treatments, consistent with evidence that liming can enhance microbial N-cycling rates (Cheng et al. 2013; Mitsuta et al. 2025). That said, due to the high temporal variability of fluxes in response to re-wetting of soils and missing measurements between April 2 and April 22, emissions may have been underestimated (Barton et al. 2015). Therefore, high-frequency measurements using automatic chambers are needed to confirm the results regarding differences in N₂O fluxes following the addition of Baringo sediments or liming.

Limitations of the study

Linking soil N₂O fluxes to rainfall events would be strengthened by paired rainfall measurements at the study site. Such rainfall data, in combination with continuous N₂O flux measurements, would allow a more detailed assessment of the effects of rainfall amount, intensity, and duration on the magnitude and persistence of N₂O fluxes. The lack of measurements of microbial functional genes and soil C and N content limited the ability to directly link the observed N₂O flux patterns across treatments to specific microbial processes and underlying changes in soil nutrient dynamics. The yield-scaled N₂O fluxes reported in this study should be interpreted as approximate estimates because they were calculated from mean fluxes measured once or twice per week over a 13-week period rather than from continuous or full-growing-season flux measurements.

Conclusion

This study demonstrated that both liming and the application of calcium-rich local sediment can improve soil chemical properties in acidic Ferralsols of western Kenya, with effects still detectable three years after sediment incorporation. Sediment application significantly increased soil pH and enhanced the availability of Ca,

P, and Si while reducing phytotoxic Al availability, confirming its long-term potential to improve soil fertility. Although these improvements did not result in a statistically significant increase in finger millet yield, a consistent positive trend indicated sustained agronomic benefits. Liming resulted in a significant increase in finger millet yields at both study sites, highlighting its effectiveness in reducing soil acidity and improving nutrient availability. In addition, liming reduced soil N₂O fluxes compared to the control and sediment treatments, supporting the hypothesis that soil amendments which increase pH can simultaneously improve crop production and reduce greenhouse gas emissions. The temporal N₂O peaks that aligned with rainfall events, sowing, and fertilization underscored the significance of these hot moments in managing soil N₂O fluxes. The cumulative reduction in soil N₂O emissions in limed soils, coupled with an increase in yield, underscored the importance of liming acidic soils.

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Author contributions Jörg Schaller and Klaus Butterbach-Bahl planned and designed the project. Elizabeth Gachibu Wangari, Ricky Mwangada Mwanake and Titus Kiplagat Bawen performed the field measurements of N₂O fluxes, Eric Scherwietes and Titus Kiplagat Bawen performed the sampling. Eric Scherwietes did the laboratory work. Eric Scherwietes, Elizabeth Gachibu Wangari and Ricky Mwangada Mwanake analysed the data. Jörg Schaller, Klaus Butterbach-Bahl and Gretchen Gettel provided laboratory access and instrumentation. Eric Scherwietes and Elizabeth Gachibu Wangari wrote the original draft with contribution of all authors. All authors read and approved the final manuscript.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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