








ORIGINAL ARTICLE OPEN ACCESS

Soil Property Responses to Push-Pull Cropping in East Africa

Grace Mercy Amboka¹  | Mattias Jonsson¹  | Celina Apel² | David Meinhof³ | Adomas Liepa⁴  | Frank Chidawanyika^{5,6}  | Andargachew Detebo⁷ | Felipe Librán-Embido² | Emily A. Martin²  | Ingolf Steffan-Dewenter³ | Marcell K. Peters⁸ | Jie Zhang³ | Michael Thiel⁴ | Michael Otim⁹  | James Mugisha¹⁰ | Ghebremedhin Belay Bahta⁷ | Fredah Maina¹¹ | Alice Murage¹¹ | Benjamin Feit^{1,12}  | A. Sigrun Dahlin¹³

¹Department of Ecology, Swedish University of Agricultural Sciences, Uppsala, Sweden | ²Institute of Animal Ecology and Systematics, Justus Liebig University of Gießen, Gießen, Germany | ³Department of Animal Ecology and Tropical Biology, Biocenter, Julius-Maximilians University of Würzburg, Würzburg, Germany | ⁴Department of Remote Sensing, Institute of Geography and Geology, Julius-Maximilians University of Würzburg, Würzburg, Germany | ⁵International Centre of Insect Physiology and Ecology, Nairobi, Kenya | ⁶Department of Zoology and Entomology, University of the Free State, Bloemfontein, South Africa | ⁷Institute for Sustainable Development, Addis Ababa, Ethiopia | ⁸Department of Animal Ecology, BIOM, University of Bremen, Bremen, Germany | ⁹National Agricultural Research Organisation, Kampala, Uganda | ¹⁰World Vision International, Kigali, Rwanda | ¹¹Kenya Agricultural and Livestock Research Organization, Nairobi, Kenya | ¹²Department of Forest Resource Management, Swedish University of Agricultural Sciences, Umeå, Sweden | ¹³Department of Crop Production Ecology, Swedish University of Agricultural Sciences, Uppsala, Sweden

Correspondence: Grace Mercy Amboka (grace.mercy.amboka@slu.se)

Received: 19 August 2025 | **Revised:** 1 April 2026 | **Accepted:** 10 April 2026

Keywords: context-dependence | *Desmodium* | ecological intensification | mixed cropping | soil fertility | sub-Saharan Africa

ABSTRACT

Push-pull technology is increasingly promoted in sub-Saharan Africa, particularly for pest management and enhancing crop productivity. However, its influence on soil properties remains understudied, despite its potential implications for soil health and sustainable soil fertility management. This study examines soil properties in push-pull and conventional non-push-pull cropping systems. Soil samples were collected from push-pull and conventional plots in Ethiopia, Kenya, Rwanda, and Uganda. We examined the associations between soil physicochemical properties and cropping systems, along with key components of push-pull, namely *Desmodium* coverage and plot age, and manure and mineral fertiliser application. Overall, there were a few differences in soil properties between push-pull and conventional cultivation. In Kenya and Uganda, where *Desmodium* cover varied considerably, higher cover was positively associated with soil organic matter, cation-exchange capacity, and multiple nutrients. In Rwanda, *Desmodium* cover was positively associated only with phosphorus. Plot age in Kenya was negatively associated with pH and potassium, suggesting acidification from N₂ fixation and potassium mining in the system. In Kenya, manure application was negatively associated with soil pH, CEC and several nutrients, while in Uganda, it was positively associated with calcium, sodium and zinc. In Ethiopia, manure application was positively associated with potassium and zinc, but only when testing the push-pull systems separately. Mineral fertiliser use was negatively associated with potassium and pH in Kenya, the only country with considerable use of mineral fertilisers. The data highlight a need for adaptive soil and crop management, including affordable non-acidifying N fertilisers and liming products for long-term sustainability of the push-pull system. The complexity in farmer adoption and practices, and the underlying soil and climate conditions, limit our ability to disentangle the contribution of system components to the effects of the push-pull system. Nevertheless, our findings highlight the complex and context-dependent associations of push-pull cropping and soil properties, underscoring the need for site-specific management to sustain soil health and crop productivity across sub-Saharan Africa.

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2026 The Author(s). *Food and Energy Security* published by John Wiley & Sons Ltd.

1 | Introduction

Push-pull technology (PP) has gained prominence in sub-Saharan Africa (SSA) for its role in integrated pest (stem borers and fall armyworm) and weed (*Striga*) management (Khan et al. 2000, 2002). Push-pull typically integrates cereals such as maize and sorghum with the nitrogen-fixing legume *Desmodium* to deter pests and suppress weeds—push, while *Brachiaria* or Napier grasses are planted along plot borders to trap pests—pull (Cook et al. 2007; Khan et al. 2000; Pickett et al. 2014). In recent years, PP has also been adapted to vegetable and legume production to help close the yield gap (Chidawanyika et al. 2023, 2025). While PP is widely promoted for its benefits in controlling lepidopteran pests and *Striga* weeds, some additional benefits on soil fertility have also been reported, such as increased nitrogen (N) and phosphorus (P) (Ndayisaba et al. 2021), and increased soil organism diversity (Mutiyambai et al. 2024). The long-term effects of PP on soil fertility, however, remain poorly understood.

Sustaining soil fertility is essential for long-term agricultural productivity, yet soil degradation remains a pressing challenge in SSA (Sanchez 2002; Sanchez and Swaminathan 2005). Although only a fraction of SSA's potential arable land is used for cultivation (estimated at around 20%) (FAO 2025; McIntyre et al. 2009), much of the arable land suffers from low nutrient levels and declining soil organic carbon (SOC), driven by prolonged cultivation (Jones et al. 2013; Soil Nutrient Maps of Sub-Saharan Africa 2018). Desertification, soil erosion, and the widespread burning of crop residues further degrade soil fertility (Boiko 2024; Jones et al. 2013). These factors significantly undermine productivity and food security, particularly for smallholder farmers who struggle to afford agrochemical inputs (Beegle et al. 2016). Addressing these challenges requires adopting cropping systems that enhance soil organic matter (SOM) and nutrient reserves while optimising the use of inorganic fertilisers (Vanlauwe and Giller 2006).

Many legume-based cropping systems, such as those incorporating *Desmodium*, enhance biological nitrogen fixation, enriching the soil with organic N (Chu et al. 2004; Temperton et al. 2007). In addition, legume residues and root biomass contribute to increased SOC and N levels (Amanuel et al. 2000; Lupwayi and Soon 2009, 2015), while also promoting carbon sequestration in the soil through residue decomposition (Kuyah et al. 2023; Meena et al. 2018; Ndayisaba et al. 2022). Soil C and N accumulation is, however, a gradual process, as plant material must first be deposited, decomposed, and integrated into the soil (Meena et al. 2018). In perennial legumes, these contributions depend on natural senescence and die-off unless trimmed and left as mulch. The duration of legume establishment and integration into the soil is thus a key factor influencing soil fertility improvements.

The quantity and biomass of legumes also play a significant role in soil fertility outcomes (Lupwayi and Soon 2015; Meena et al. 2018). Vigorous legume growth provides greater inputs of SOM and N, enhancing soil carbon storage and nutrient cycling. Robust legume growth, however, requires adequate supplies of other nutrients, including phosphorus (P), potassium (K), and magnesium (Mg), which must be sourced from the soil or

supplemented through mineral fertiliser or manure application (Mugwe et al. 2019; Vanlauwe et al. 2015). The influence of perennial legumes on soil stocks of these nutrients varies across studies. Previous research has suggested a potential depletion of soil P due to high legume demand for energy transformation in root nodules (Mitran et al. 2018). In contrast, another study has reported that *Desmodium* can enhance P availability (Ndayisaba et al. 2021). These findings indicate that perennial legumes can have complex and context-dependent effects on soil nutrient dynamics.

Evidence suggests that PP enhances soil health through nitrogen fixation, erosion control, enhanced carbon inputs, and beneficial soil organisms (Jalloh et al. 2024; Mutiyambai et al. 2024; Ndayisaba et al. 2021), although the underlying mechanisms and long-term effects of PP on soil health remain uncertain. While these benefits indicate potential long-term gains in SOM and nutrient availability, their effectiveness likely depends on factors such as the duration of PP cropping, *Desmodium* coverage, and interactions with different mineral fertiliser and manure inputs. Understanding these relationships is critical for optimising PP systems and soil fertility benefits in smallholder farming systems in SSA.

This study examines how twenty-two key soil properties in four East African countries are associated with PP cropping, the duration of PP cropping, *Desmodium* coverage, and mineral fertiliser and manure application. By evaluating these factors, we aim to provide insights into PP's potential as a sustainable soil fertility management strategy.

2 | Methodology

2.1 | Study Area

Our study was conducted within a year, between 2022 and 2023, across four East African countries: Ethiopia, Kenya, Rwanda, and Uganda (Figure 1). Sampling took place on smallholder farms in Ethiopia's Amhara region (districts of Dawachefa, Kalu, and Qewot, and Shewarobit City Administration), Kenya's western region (Homabay, Kisumu, Siaya, and Vihiga counties), Rwanda's northeastern Gatsibo district, and Uganda's southeastern region, in Kamuli and Namutumba districts. An overview of the climatic conditions and dominant crops in each study region is provided in Table 1.

2.1.1 | Overview of the Dominant Soil Types in the Study Region

The study regions span diverse agroecological zones, each with distinct soil types. In the Amhara region of Ethiopia, Vertisols and Leptosols are predominant, highlighting the region's varied topography and seasonal rainfall (Jones et al. 2013). In western Kenya, soils vary widely, with common types including Plinthic Acrisols and Eutric Gleysols, indicative of both well-drained and periodically waterlogged conditions. Gatsibo district in Rwanda is mainly composed of Umbric Ferralsols and Regosols, typical of weathered tropical soils with moderate fertility. In South-eastern Uganda, the dominant soil types include Acrisols,

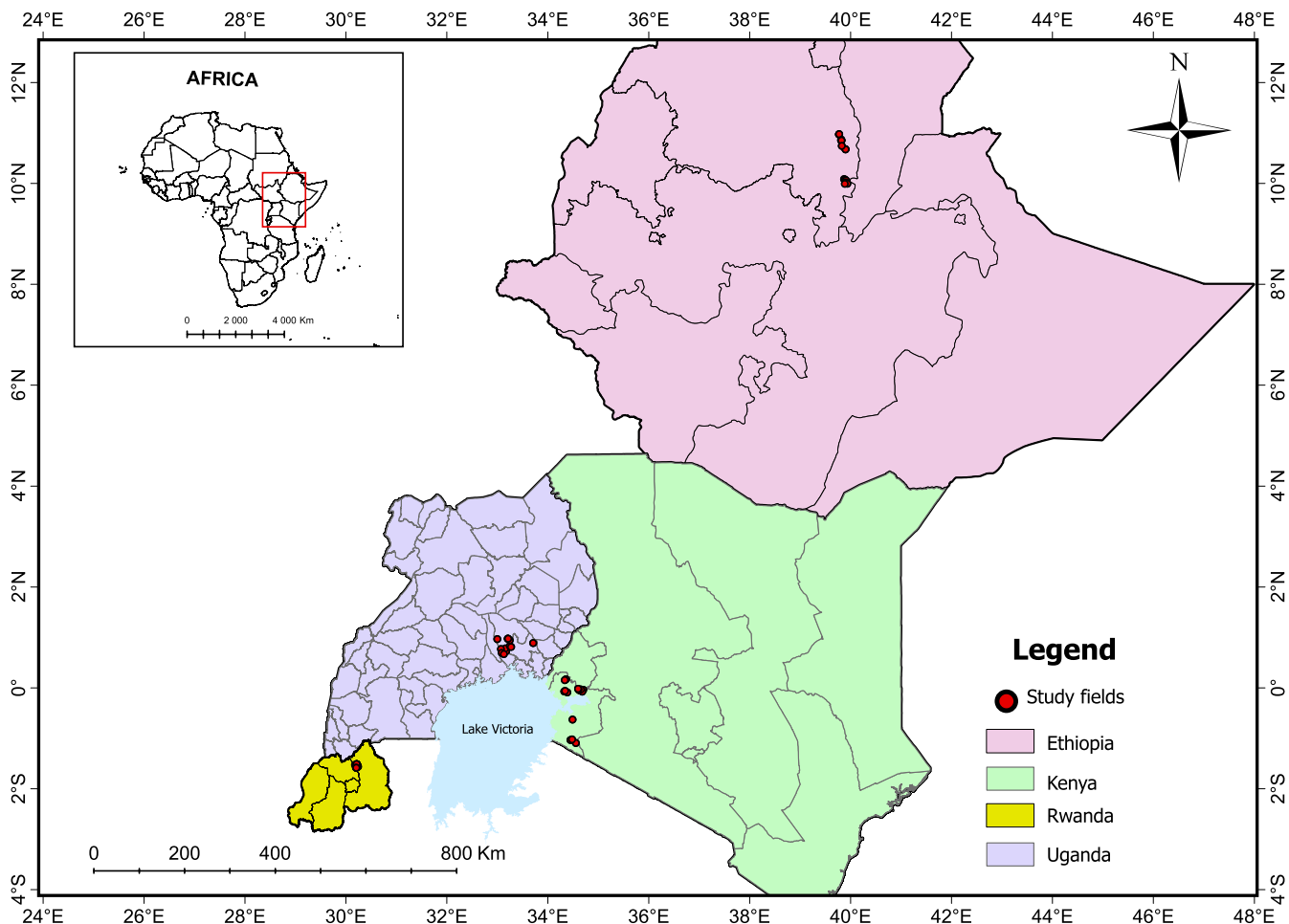


FIGURE 1 | Study plot locations in Ethiopia, Kenya, Rwanda, and Uganda.

Nitisols, and Ferralsols, which support diverse cropping systems despite limitations in nutrient availability and structure (Jones et al. 2013).

2.1.2 | Plot Selection

Plot selection was based on existing GIS databases and pedoclimatic characteristics of PP plots, which were confirmed by ground truthing and surveys. We used the Soil Atlas of Africa (Jones et al. 2013) and the African Soil Information Services maps to account for broad-scale soil differences and identify general soil type patterns. While local spatial variation exists, these maps provided a basis for selecting plot pairs with comparable soil conditions, which was further validated through ground truthing.

A total of 128 plots were selected across the four countries, with 32 plots in each country arranged in a paired design. We selected these plots based on existing PP fields and gradients of soil fertility. In each country, 16 plots were managed under the PP cropping system, consisting of maize (in Uganda, Rwanda, and Kenya) or sorghum (in Ethiopia) intercropped with *Desmodium* and with *Brachiaria* or Napier grasses planted along plot borders, while the remaining 16 plots in each country served as controls. The control plots (conventional non-push-pull, NPP) in Kenya, Rwanda, and Uganda predominantly consisted of monocropped

maize, although a few maize intercropping systems were observed, whereas in Ethiopia, it was solely sorghum. In Uganda, seven plots were intercropped: three with common beans, three with cassava, and one each with soybeans and sweet potatoes. In Rwanda, five plots were intercropped: two with bananas, and one each with cassava, beans, and potatoes. In Kenya, three plots were intercropped: two with common beans and one with groundnuts.

To help minimise potential soil variation within plot pairs, we conducted a rough test of soil texture by feel and by checking soil colour. Corresponding PP and NPP plots were placed on the same farm, or when necessary on different farms, but always within 10–50 m of each other, as recommended for minimising soil and management variability (Tittonell et al. 2005). The 128 plots varied in size across the countries from about 10 m × 10 m to about 50 m × 30 m. Notably, in Rwanda, PP plots were approximately one-third to half the size of their corresponding control plots. Overall, plots in Rwanda were also smaller than those in other countries.

2.2 | Soil Measurements

In each plot, we measured field-saturated soil-water infiltration rates, soil penetration resistance, and collected soil samples for laboratory analysis of twenty additional variables.

TABLE 1 | Climatic conditions and main crops across study regions in East Africa.

Region	Rainfall patterns	Average annual rainfall	Average annual mean temperature	Main crops	References
Amhara, Ethiopia	East Amhara: Bimodal: “Belg” (Feb-May), & “Kiremt” (Jun-Sep). West Amhara: unimodal: “Kiremt” **“Kiremt” is the main rainy season	1113 mm	20.1°C	Teff, sorghum, maize, finger millet	(Dessaegn and Akalu 2015; Tiku et al. 2025)
Western Kenya	Bimodal: long rains (Mar-May), short rains (Oct-Dec)	1500 mm	24°C	Sugarcane, maize, rice, beans	(Hession and Moore 2011; Indeje et al. 2001)
Gatsibo, Rwanda	Bimodal: long rains (Mar-May), short rains (Sep-Nov)	1170 mm	19°C	Bananas, coffee, maize, beans	(Rwema et al. 2025; Siebert et al. 2019)
South-eastern Uganda	Bimodal rainfall: long (Mar-May), short (Sep-Nov)	1197 mm	22.8°C	Millet, maize, bananas, sweet potatoes	(Hession and Moore 2011; Nsubuga et al. 2014)

2.2.1 | Field-Saturated Water Infiltration

The infiltration rate was measured at three locations per plot using a double-ring infiltrometer (20/30 cm inner/outer diameter). The measurements were conducted on level ground between maize rows, avoiding areas with previously standing water. In cases of uneven soil surface due to ridging, the infiltrometer was positioned between ridges. Readings continued for approximately 2.5 h, until the infiltration rate stabilised. The average of the three determinations was taken as indicative of the soil’s saturated hydraulic conductivity under plot conditions.

2.2.2 | Soil Penetration Resistance

Soil penetration resistance was measured once during the sampling season using a portable static cone penetrometer (Wile, Tuusula, Finland). The measurements were carried out after substantial rainfall and subsequent drainage to plot capacity, this being the simplest way to standardise the conditions across plots and countries. The depth (in half or whole sections of the rod length) at which the tip of the rod reached a resistance of 200psi (approx. border between favourable and satisfactory conditions for root penetration) and 300psi (border between satisfactory and poor conditions) was recorded, and the depth recalculated to meters. We also measured the depth at which the rod could be inserted no further, which indicates the total depth of the soil profile or an otherwise poorly penetrable layer. Any decreases in penetration resistance at larger depth and their approximate depths were also noted. The measurements were repeated 10 times across each plot, and an average penetration depth calculated.

2.2.3 | Collecting and Drying of Soil Samples

Each plot was represented by a composite soil sample (0–20 cm depth) consisting of 20 soil cores (2.5 cm diameter) collected in a zig-zag pattern across the plot. Potential organic material on the soil surface was removed before the coring (Tan 2005). The soil samples were air-dried indoors on trays, whereafter aggregates were crushed and the soil sieved through a 2 mm mesh. The fine fraction was thoroughly homogenised and subsampled through repeated halving, and subsamples dispatched for analysis.

2.2.4 | Laboratory Analyses

The samples were analysed for soil texture in the soil laboratory at Makerere University (Kampala, Uganda) using the hydrometer method (Bouyoucos 1962). Soil chemical properties were analysed at Crop Nutrition Laboratories (Nairobi, Kenya) according to their Complete Soil Analysis package, following protocols from Pansu and Gautheyrou (2006). The soil chemical properties analysed were pH, electrical conductivity (EC), soil organic matter (SOM), total nitrogen (N), and ‘plant-available’ phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S), sodium (Na), iron (Fe), manganese (Mn), boron (B), copper (Cu) and zinc (Zn). Carbon-to-nitrogen ratio (C:N ratio)

and cation exchange capacity (CEC) were calculated from the analytical data.

2.3 | Plot-Level Agronomic and Management Data Collection

Additional data collected on each plot included *Desmodium* coverage, which was scored between 20% and 100% based on visual assessment. In each field, we first identified the rows where *Desmodium* was planted and observed them at peak growth. Plots in which these rows were densely covered along their entire length were assigned a score of 100%. For plots with partial coverage, we estimated the percentage of ground within the rows visibly covered by *Desmodium*. Complementary information was also obtained from farmers through a questionnaire. This included the age of the PP plots (recorded as the number of growing seasons since establishment) and whether manure or mineral fertilisers had been applied during the current cropping season (recorded as binary variables: applied or not applied). In Ethiopia, manure application primarily consisted of cow dung, whereas in the other countries, the specific type and composition of manure were not systematically recorded and likely varied across farms.

2.4 | Data Analysis

To evaluate the association of the cropping system (PP vs. NPP), manure or mineral fertiliser use, and percentage of clay (covariate) on soil variables, we analysed each country separately using Generalised Linear Models (GLMs) with a Gamma distribution. The percentage of clay was used as a covariate since clay content directly impacts soil dynamics such as water retention, root penetrability, and nutrient retention (NCDA and CS Agronomic Division 1999) but remains independent of the cropping system. For PP plots, we further examined the association of plot age (continuous), *Desmodium* cover (continuous), and fertiliser application (treated as two separate categorical variables: manure application (Yes/No) and mineral fertiliser application (Yes/No)) with various soil variables using GLMs.

Variance Inflation Factors (VIFs) were calculated to assess multicollinearity among explanatory variables in both models: the cropping system model (clay percentage, cropping system, manure or mineral fertiliser use) and the PP model (age of plot, *Desmodium* percentage cover and manure or mineral fertiliser use). The VIFs were computed using the `vif` function from the `fmsb` package version 0.7.6 (Minato Nakazawa 2024). Only variables with VIF values less than 3 were retained for subsequent analyses. We excluded interaction terms between explanatory variables due to high correlations in the dataset. Model selection was performed using Akaike's Information Criterion ($\Delta AICc < 2$) with the `dredge` function in the `MuMIn` package version 1.48.4 (Kamil Bartoń 2024). For models meeting this criterion, model averaging was conducted using the `model.avg` function. When there were no competing models ($\Delta AICc > 2$ compared to the best model), the best model was selected as the final model, following the guidelines of Burnham et al. (2011). The goodness of fit for all models was evaluated using the `simulateResiduals` function from the `DHARMA` package version 0.4.6 to ensure

the validity of the model assumptions. All statistical analyses were conducted in R version 4.4.0 (R Foundation for Statistical Computing, Vienna, Austria 2024).

3 | Results

3.1 | Baseline Soil Characteristics and Nutrient Variability Across Study Sites

Soil texture ranged from light to heavy, with the lightest soils found in Uganda and Rwanda, and the heaviest in Ethiopia and Kenya (Table 2). Soil pH ranged from very strongly acidic to moderately alkaline; soils in Kenya varied from very strongly acidic to neutral, Ethiopia varied from neutral to moderately alkaline, Rwanda varied from very strongly acidic to slightly acidic, and Uganda varied from strongly acidic to neutral. The CEC varied widely, with levels well above what is regarded as a minimum for productive soils (15 meq/100 g) (FAO 2007; NAAIAP 2014) in Ethiopia and parts of Kenya. Lower CEC levels were recorded in Rwanda and Uganda, reflecting the differences in clay content and organic matter. Soils in Kenya and Uganda generally had the highest measured infiltration rates, while those in Rwanda and Ethiopia were lower.

Soil nutrient levels across study sites showed considerable variation, ranging from values well below agronomic recommendations to concentrations that far exceeded critical thresholds. For example, P levels were generally below the recommended 30 ppm, particularly in Uganda, Kenya, and Rwanda, but exceeded 300 ppm in Ethiopia. Nitrogen levels were generally below the critical threshold across all countries, while S levels were similarly low in Kenya, Rwanda, and Uganda. Potassium, Ca, and Mg concentrations ranged from severely deficient to highly elevated, with notably high values observed in Ethiopian and Kenyan plots and consistently lower values in Rwanda and Uganda. Copper and Mn levels were generally sufficient across all sites and countries. In contrast, B and Zn levels were generally deficient in all countries.

The age of push-pull plots varied across countries: plots in Kenya were overall the oldest (2–14 years), those in Rwanda were 3–4 years old, Uganda had plots ranging from 6 months to 4 years, and all plots in Ethiopia were 3 years old. *Desmodium* cover showed the greatest variation in Kenya and Uganda (20%–100%). Rwanda showed moderate variation (50%–100%), and Ethiopia had uniform coverage, with all plots at 75%. Manure application was most frequent in Rwanda, where all plots received manure, and lowest in Uganda (9% of the plots). In contrast, mineral fertiliser use was most common in Kenya (84%), very limited in Rwanda and Uganda (3%), and absent in Ethiopia.

3.2 | Associations Between Soil Properties and Push-Pull Cropping Systems

3.2.1 | Cropping Systems

The relationship between PP systems and soil properties varied among countries. Push-pull systems in Ethiopia were negatively associated with CEC, C:N ratio, and Cu levels, and

TABLE 2 | Minimum, maximum and median values of soil physical and chemical properties across countries.

Country	Ethiopia			Kenya			Rwanda			Uganda			Critical values ^a
	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	
Sand %	23	53	43	29	75	57	37	81	73	43	75	55	—
Silt %	18	44	28	10	38	20	11	49	23	7	45	35	—
Clay %	23	41	32	11	39	25	2	38	6	2	20	10	—
pH	6.99	8.81	7.425	4.88	7.29	5.96	4.65	6.18	5.685	5.13	6.75	6.04	> 5.5
EC (uS/cm)	34.8	209	57.3	12.5	214	35.9	13.3	65.6	36.6	17.6	68.4	34.3	> 80
CEC (meq/100g)	34.7	79.1	53.9	4.2	46.2	12.9	3.88	20.6	6.585	4.29	17.6	12.8	> 15
SOM %	1.49	4.04	2.665	1.86	4.72	3.23	1.96	3.85	2.635	2.47	4.52	3.695	—
N %	0.089	0.17	0.12	0.09	0.2	0.16	0.074	0.18	0.11	0.09	0.17	0.14	> 0.2
C:N	8.25	17.7	11.9	9.42	15.2	12.3	12.4	16	14.4	13.9	18.1	15.35	—
P (ppm)	2.64	323	24.1	1.84	76.2	13.8	4.8	88	30.05	3.12	80.2	5.655	> 30
Ca (ppm)	5010	13,700	7775	468	5810	1220	367	2320	544	290	2550	1600	> 400
K (ppm)	248	933	547.5	42.7	760	178	52.6	468	88.4	45.4	369	140	> 94
Mg (ppm)	612	1770	892.5	77.6	1140	216	53.1	476	123	51	321	222.5	> 120
Na (ppm)	19.9	817	32.35	5.73	35.9	11.5	0.82	32.4	13.45	0.6	22.5	6.615	—
S (ppm)	14.2	41.8	17.9	5.25	17.4	10.7	7.4	23.8	10.15	8.81	14.6	12.4	> 20
B (ppm)	0.46	3.72	0.885	0.09	0.95	0.43	0.2	0.7	0.2	0.11	0.75	0.42	> 0.8
Cu (ppm)	0.71	6.11	3.71	0.99	11	3.61	0.8	12.6	2.4	1.66	5.4	3.88	> 1
Fe (ppm)	55.6	173	112	98.5	272	160	69.5	399	115.5	89.3	175	129	> 10
Mn (ppm)	99.8	226	164	126	675	394	37.1	387	114	40.1	675	512.5	> 20
Zn (ppm)	1.14	3.76	1.855	3.03	13.1	6.67	0.9	12.3	3.95	0.61	24.4	4.87	> 5
Water infiltration (mm/h)	20	277	166	95	935	481	24	1188	115.5	147	1364	459.15	—
Depth to 200 psi (m)	0.302	0.628	0.457	0.095	0.438	0.186	0.015	0.685	0.361	—	—	—	—
Depth to 300 psi (m)	0.449	0.670	0.579	0.141	0.575	0.281	0.163	0.685	0.487	—	—	—	—
Depth > 300 psi (m)	0.320	0.685	0.563	0.179	0.674	0.384	0.259	0.685	0.575	—	—	—	—

^aCritical values (FAO 2007; NAAIAP 2014) refer to the threshold concentrations of extractable nutrients in the soil, above which the addition of more nutrients is unlikely to result in a significant economic yield increase. Minimum, maximum and median lowest, highest, and middle values recorded for each soil variable across all observations.

showed a marginally negative association with Fe and Mn (Figure 2 and Table S1). Although the cropping system was retained in the final models for SOM, Ca, and Mg, no significant associations were found (Table S2). In contrast, PP plots in Kenya were positively associated with soil Fe concentrations (Figure 2 and Table S3). While the cropping system was also retained in the final model for EC, no significant association was observed (Table S4). In Rwanda and Uganda, no significant associations were observed between the PP plots and any of the measured soil properties (Figure 2), although

cropping system was retained in the final model for N, S, EC, and Mg for Uganda, and for N, silt% and soil water infiltration for Rwanda (Tables S5–S8).

3.2.2 | *Desmodium* Cover

When analysing only PP plots, we found that *Desmodium* cover in Kenya and Uganda was positively associated with SOM, CEC, S and K levels (Figure 3; Tables S9 and S10). High

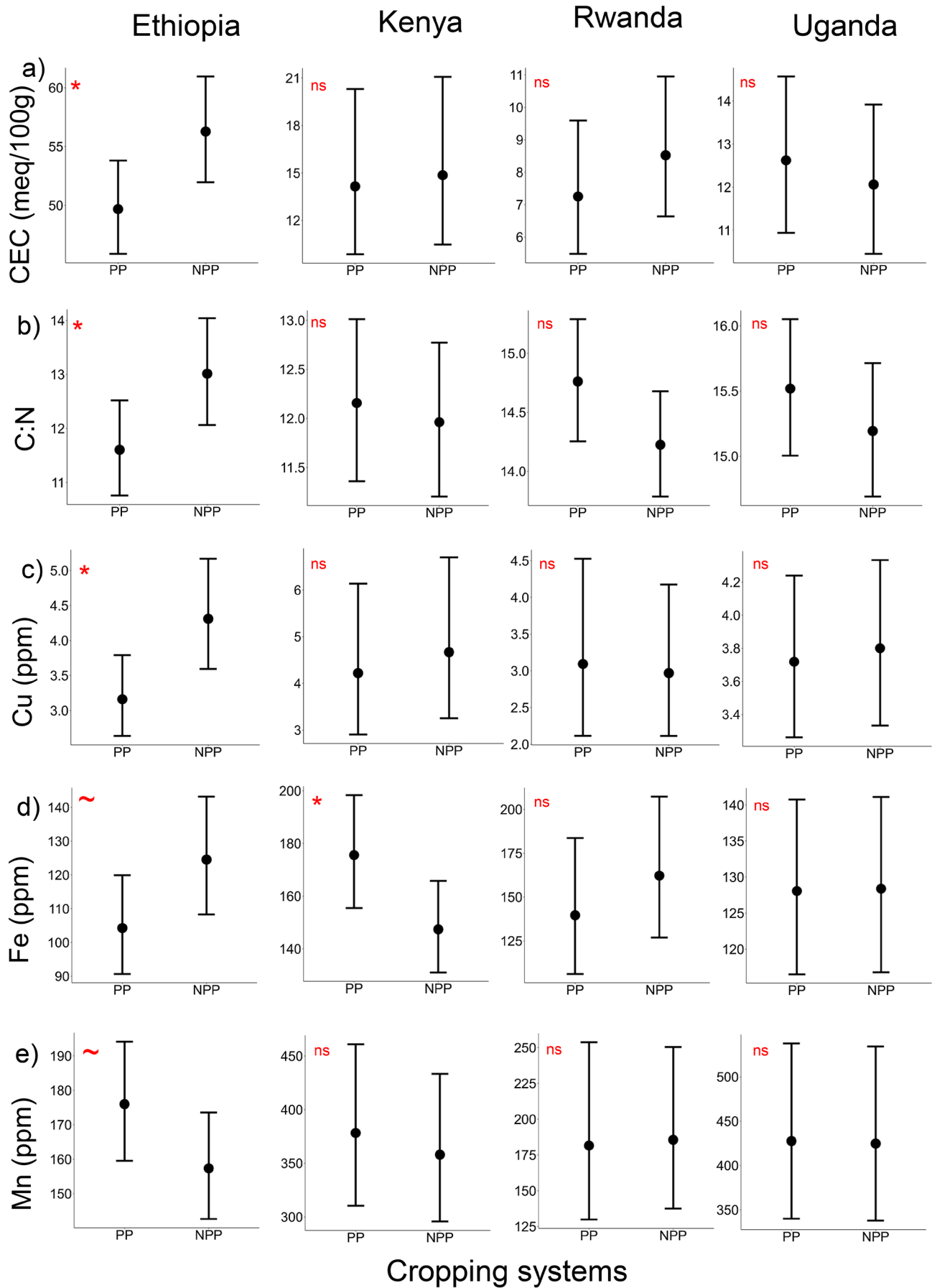


FIGURE 2 | Legend on next page.

FIGURE 2 | Model-predicted associations between cropping system and (a) cation exchange capacity (CEC), (b) carbon-to-nitrogen ratio (C: N), (c) extractable copper (Cu), (d) iron (Fe), and (e) manganese (Mn) in PP and NPP plots across Ethiopia, Kenya, Rwanda, and Uganda. Values represent GLM estimates (mean \pm standard error), with standard errors back-transformed to the response scale. Differences between cropping systems were tested using Wald z-tests. Significance levels: * ($0.01 \leq p < 0.05$), (-) marginally significant ($0.05 \leq p < 0.1$), and (ns) not significant ($p \geq 0.1$).

Desmodium cover in Kenya was also positively associated with N, and marginally with Ca levels, although *Desmodium* cover was retained in the final model for C:N ratio, EC, B, Cu, and Zn levels; no significant associations were found (Table S11). *Desmodium* cover in Uganda was positively associated with Na, B, and Cu, and marginally positively associated with Mg (Figure 3 and Table S10). Although it was also retained in the final model for N, pH, and Fe, no significant associations were observed for these variables (Table S12). In Rwanda, *Desmodium* cover was positively associated with P and marginally negatively associated with Cu levels (Figure 3 and Table S13). Although it was retained in the final model for SOM, N, K, and Na; no significant associations were found (Table S14). We did not evaluate associations between soil properties and *Desmodium* cover in Ethiopia, due to a lack of variation across PP plots.

3.2.3 | Push-Pull Plot Age

Older push-pull plots in Kenya showed a negative association with soil pH and K, and a marginally negative association with B levels (Figure 4 and Table S9). Although plot age was retained in the most parsimonious model for Fe; its association was statistically non-significant (Table S11). In Uganda, plot age was negatively associated with Cu and marginally positively associated with C:N ratio (Figure 4 and Table S10). Plot age in Rwanda did not exhibit significant associations with any soil parameters (Figure 4 and Table S13); although retained in the final model for SOM and N, no significant associations were observed (Table S14). In Ethiopia, associations between soil properties and plot age could not be evaluated due to a lack of variation across PP plots.

3.3 | Clay Content and Soil Properties

Across plots, clay content consistently emerged as an important covariate influencing soil properties. In both Kenya and Uganda, N, Cu, Mn, and Zn were positively associated with clay content (Tables S3 and S6). Sulphur was positively associated with clay in Kenya and Rwanda, while Fe and CEC were positively associated with clay content in Uganda and Rwanda; in Kenya, CEC also showed a marginal positive association (Tables S3, S5 and S6). Magnesium was positively associated with clay content in Uganda and Kenya, and marginally in Rwanda, whereas Ca was positively associated with clay in Uganda, and marginally in Kenya and Rwanda. The C:N ratio was positively associated with clay content in Uganda but negatively in Rwanda (Tables S3, S5 and S6). Additional country-specific patterns included a positive association of SOM and pH, and a marginally positive association of B with clay content in Uganda (Table S6). In Rwanda, EC was marginally positively associated with clay content (Table S5), while no significant association was found in Ethiopia.

3.4 | Associations Between Soil Properties and Manure and Mineral Fertiliser Application

3.4.1 | Manure Application

Across all cropping systems (PP and NPP) in Kenya, manure application was negatively associated with pH, K, Ca, Mg, Mn, and marginally negatively associated with CEC (Figure 5 and Table S3). Although manure application was retained in the most parsimonious models for SOM, C:N ratio, EC, Fe, B, and soil water infiltration, no significant associations were found (Table S4). Similarly, in Kenya's PP plots only, manure application was negatively associated with CEC, K, Ca, Mg, and marginally with B (Table S9). While manure use was retained in the most parsimonious models for SOM and Cu, no significant associations were observed (Table S11).

In contrast, manure application in the Ugandan cropping systems was positively associated with Ca, Na, Zn, and marginally positively associated with CEC, N, P, C: N ratio, pH, and Cu (Figure 5 and Table S6). Although no significant associations were found for SOM, Mg, Mn, Fe, B, and Na with manure application, they were retained in the most parsimonious models (Table S8). Within PP plots in Uganda, manure application was positively associated with Zn and Na (Table S10), although no significant association was observed with N, pH, P, B, and Cu; manure application was retained in the final models (Table S12).

Manure application in Ethiopia showed no significant associations with any measured soil properties across cropping systems (Figure 5 and Table S1). Although it was retained in the final models for N, Fe, Cu, Zn, and Na and water infiltration, no significant associations were found (Table S2). In PP plots in Ethiopia, manure use was positively associated with K and Zn, marginally positively associated with Ca and marginally negatively associated with P and Mg (Tables S15 and S16). Manure application in Rwanda was uniform across all plots, precluding any statistical evaluation of its association with soil properties.

3.4.2 | Mineral Fertiliser Application

The application of mineral N-P fertiliser across cropping systems in Kenya was negatively associated with soil pH, K, and marginally negatively associated with C:N ratio (Figure 6 and Table S3). Mineral fertiliser application in PP plots was also negatively associated with soil K, and marginally with Ca and CEC levels (Table S9). While mineral fertiliser application was retained in the final models for SOM, CEC, Ca, B, and explorable soil depth, no significant associations were observed (Table S11). Given the (almost) absent use of mineral fertiliser in Ethiopia, Rwanda, and Uganda, these countries were excluded from this analysis.

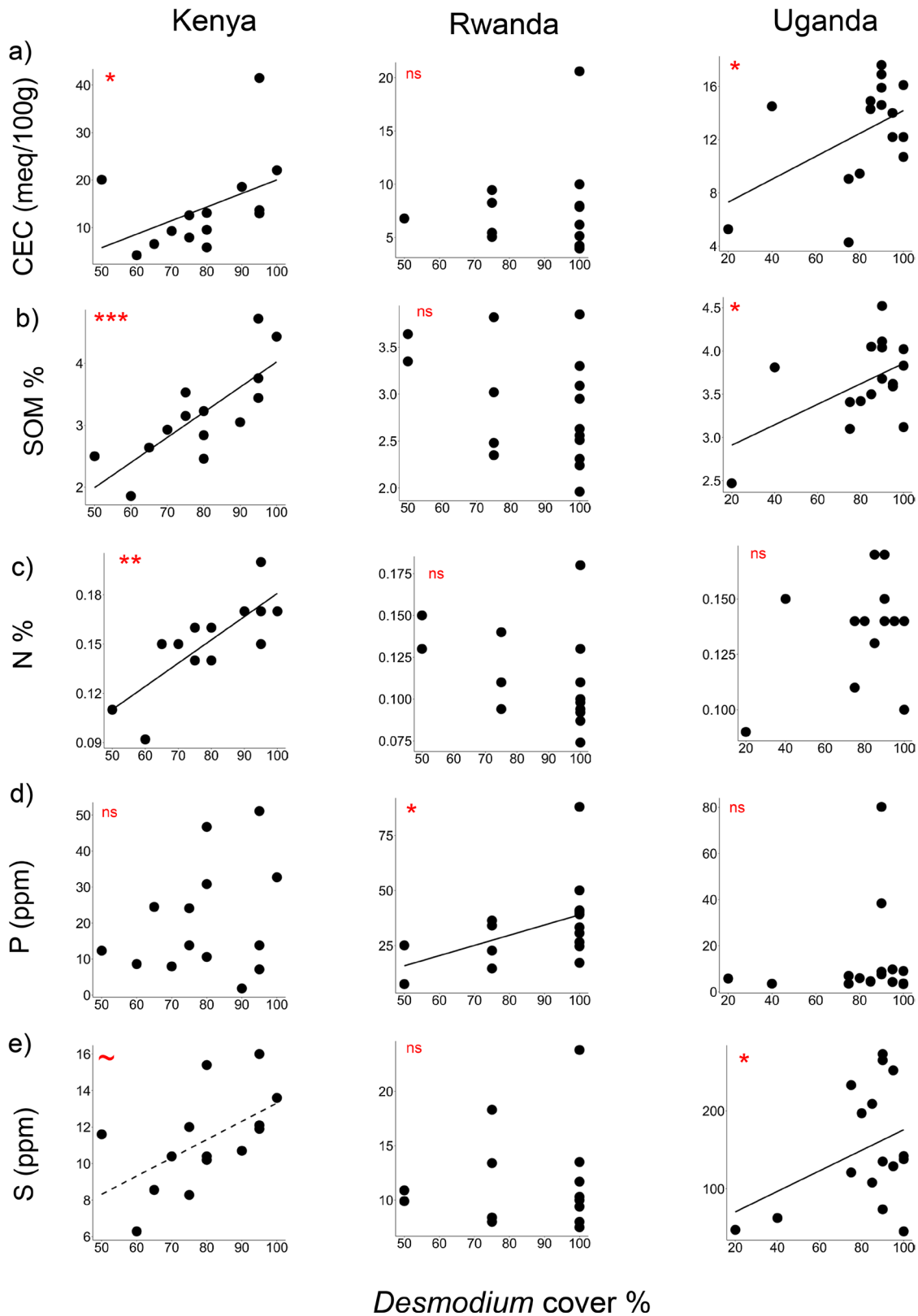


FIGURE 3 | Relationships between *Desmodium* cover and (a) cation exchange capacity (CEC), (b) soil organic matter (SOM), (c) nitrogen (N), (d) phosphorus (P), and (e) sulphur (S), (f) calcium (Ca), (g) potassium (K), (h) magnesium (Mg), (i) sodium (Na), (j) boron (B) and (k) copper (Cu) in PP plots across Kenya, Rwanda, and Uganda. Linear regression models were used to assess the associations, with fitted lines shown in each panel. Significance levels are indicated as follows: *** ($p < 0.001$), ** ($0.001 \leq p < 0.01$), * ($0.01 \leq p < 0.05$), (~) marginally significant ($0.05 \leq p < 0.1$), and (ns) not significant ($p \geq 0.1$).

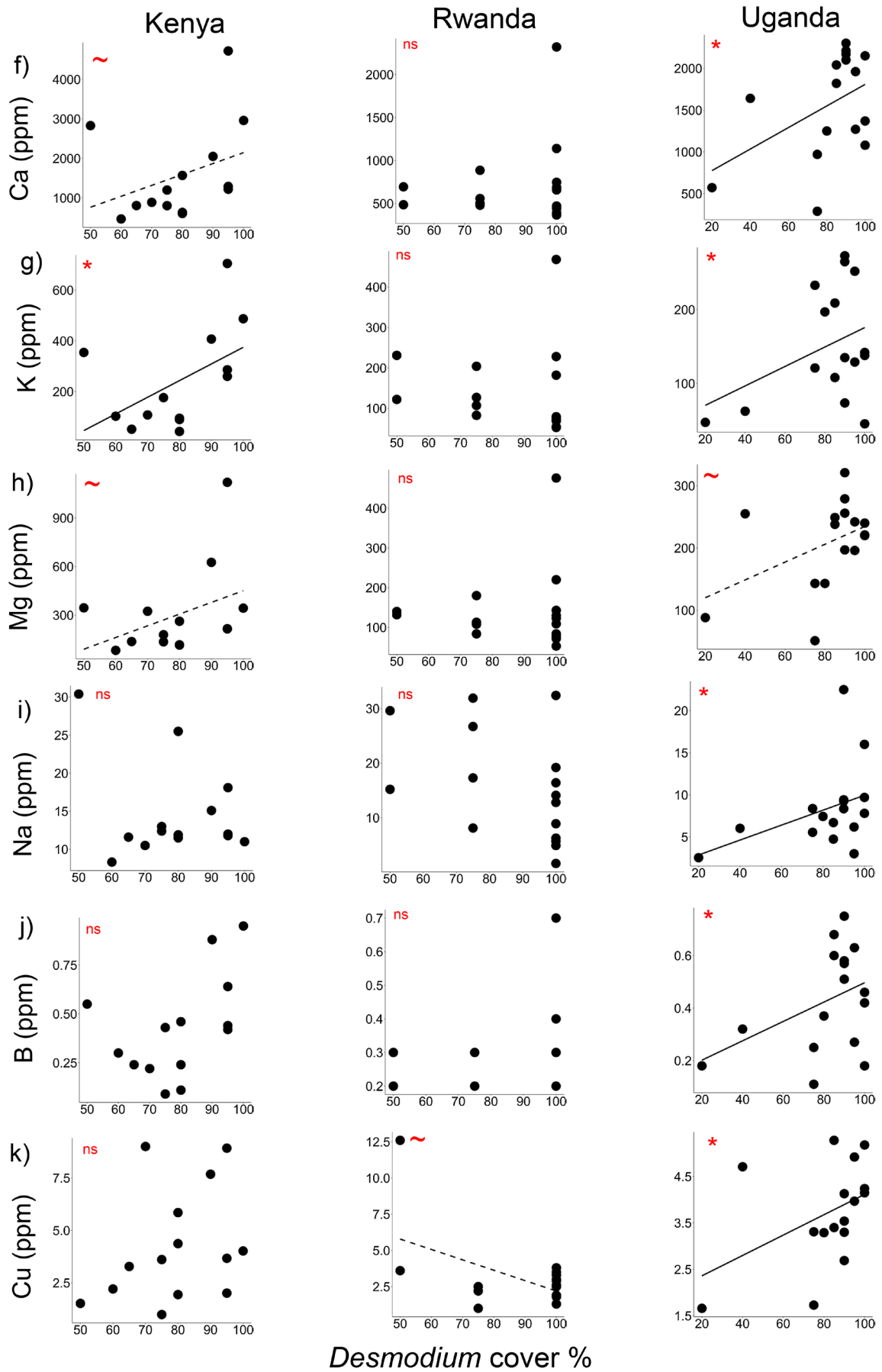


FIGURE 3 | (Continued)

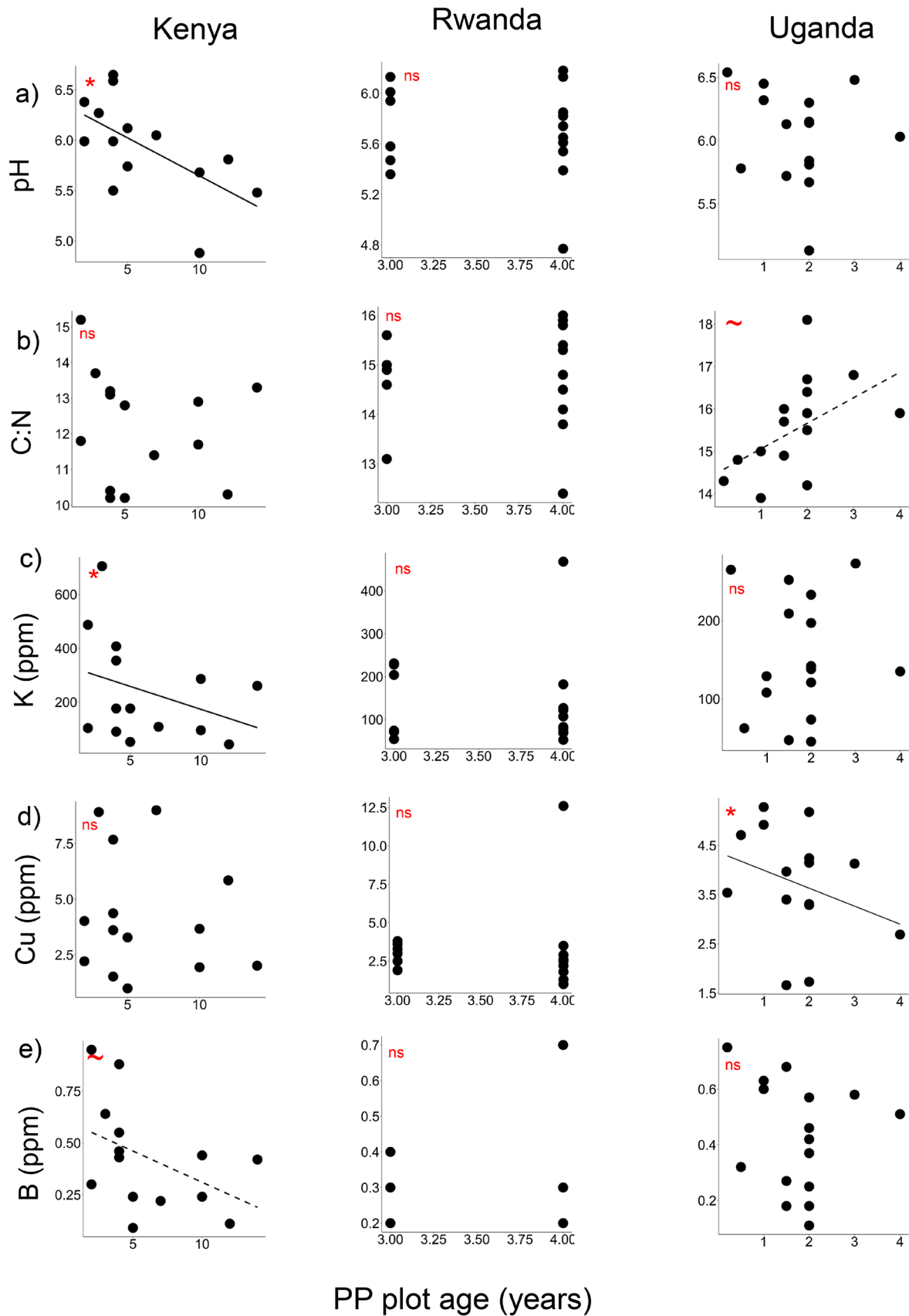


FIGURE 4 | Relationships between the age of plots and (a) pH, (b) carbon-to-nitrogen ratio (C: N), (c) potassium (K), (d) copper (Cu), and (e) boron (B) in PP plots across Kenya, Rwanda, and Uganda. Linear regression models were used to assess the associations, with fitted lines shown in each panel. Significance levels: * ($0.01 \leq p < 0.05$), (-) marginally significant ($0.05 \leq p < 0.1$), and (ns) not significant ($p \geq 0.1$).

4 | Discussion

This study provides valuable insights into how push-pull (PP) cropping systems interact with soil properties in East Africa, demonstrating how extensive *Desmodium* cover contributes to the system's capacity to improve soil health. Our findings highlight that the association is context-dependent, shaped by complex regional variations in soil conditions and cropping systems.

4.1 | Context-Dependent Effect of Push-Pull Systems

Previous studies in Kenya have reported that PP systems improve soil properties such as N, P, and C compared to NPP systems (Ndayisaba et al. 2021, 2022), but this pattern was not consistently observed in our study. Notably, Ndayisaba et al. (2021, 2022) evaluated PP systems under controlled conditions, with consistent *Desmodium* cover, standardised crop varieties and adequate soil fertility inputs. In contrast, our study captures the real world, smallholder farming systems where management practices, input use, and *Desmodium* establishment are highly heterogeneous.

Push-pull plots in Ethiopia surprisingly exhibited lower CEC and concentrations of micronutrients such as Cu, Mn, and Fe than NPP plots. Lower CEC was unexpected, given that legumes typically enhance soil organic matter and nutrient retention (Meena et al. 2018). In Kenya, PP plots had significantly higher available Fe than NPP plots. However, given the large number of soil variables tested, isolated significant results like this should be interpreted with caution. The absence of broader significant associations with other nutrients and soil properties, even in the older established plots, was unexpected. It is possible that the results observed in Ethiopia and Kenya were obscured by substantial underlying variability in soil properties. Push-pull plots in these regions may have been preferentially implemented on more degraded plots, potentially masking broader soil improvements. Similarly, the lack of significant associations in Rwanda and Uganda may also suggest that either PP plots were too young to influence soil properties or that inherent soil variability masked potential effects. These divergent patterns highlight the context-dependency of PP adoption and impacts, which are shaped not only by cropping system design but also by regional differences in soil characteristics and climatic conditions (Hession and Moore 2011; Jones et al. 2013; Nsubuga et al. 2014; Rwema et al. 2025) which may have masked the expected improvements in soil fertility.

4.2 | *Desmodium* Cover as a Key Driver of Soil Fertility

Desmodium cover emerged as a key factor influencing soil fertility in the PP plots, particularly in Kenya and Uganda, where we observed wider ranges of *Desmodium* cover. In both countries, increased *Desmodium* cover was consistently associated with higher levels of SOM, CEC, and S and K levels, and with higher levels of N in Kenya and Na, B, and Cu in Uganda. This confirms that *Desmodium* provides improved soil nutrient pools and soil health. The role of some legumes in improving soil fertility

primarily through biological nitrogen fixation, and the additional carbon inputs, is well-established, particularly when introduced as supplementary, often perennial components within a cropping system (Jackson 2000; Schutter and Dick 2002). *Desmodium* contributes to the accumulation of SOM through leaf litter and root biomass (Amanuel et al. 2000; Liebmann et al. 2020; Lupwayi and Soon 2009, 2015), which enhances nutrient availability and retention (Chu et al. 2004; Li et al. 2007; Li et al. 2018; Temperton et al. 2007). Additionally, the deep-rooted *Desmodium* may enhance nutrient concentrations in the topsoil by nutrient pumping (Peixoto et al. 2022), where deep-rooted plants extract nutrients from subsoil layers and redistribute them to the topsoil via residues and litter (Han et al. 2021).

The availability of P in Rwanda was positively associated with *Desmodium* cover, suggesting that intercropping with legumes may enhance P availability, potentially through microbial mobilisation, shifts in soil pH and organic matter decomposition (Dong et al. 2024). This finding supports previous research in SSA, which reported that PP cropping systems can improve the concentrations of plant-available P in soils compared to conventional cropping systems (Ndayisaba et al. 2021; White et al. 2021). However, the effect of *Desmodium* cover on soil P was not consistent across all countries studied, indicating that its influence is likely context-dependent (incl. differences in adoption and practices) and shaped by underlying soil conditions. These findings nevertheless highlight the importance of successfully establishing abundant *Desmodium* cover to fully realise its potential for enhancing soil fertility and reducing the reliance on external inputs in smallholder agroecosystems.

4.3 | Influence of Push-Pull Plot Age

The age of PP plots showed contrasting relationships across countries. In Kenya, where plots were the oldest and had the widest age range, older PP plots were associated with lower soil pH, K, and B. This potentially signals progressive acidification associated with dinitrogen fixation (Giller 2001), and long-term additional plant nutrient uptake and export via *Desmodium* forage without sufficient replenishment. It also suggests that long-term management of PP systems may require careful monitoring and targeted soil amendments to maintain a good nutrient balance and prevent soil acidification over time, thereby realising the full potential of PP cropping systems.

In addition, plot age in Uganda showed a negative association with Cu, and a marginally positive association with C:N ratio, suggesting an ongoing buildup of soil organic matter over time (Meena et al. 2018). The limited age variability of PP plots in Rwanda and the same age of all PP plots in Ethiopia obscured our ability to detect an association between plot age and soil properties in these countries. Strong effects are unlikely to emerge with only a one-year age difference, as in Rwanda.

4.4 | Role of Clay Content and Plot Comparability

Higher clay content was generally associated with higher levels of SOM, N, S, pH, CEC, Ca, and Mg, among other soil variables, which reinforces the well-established role of clay in enhancing

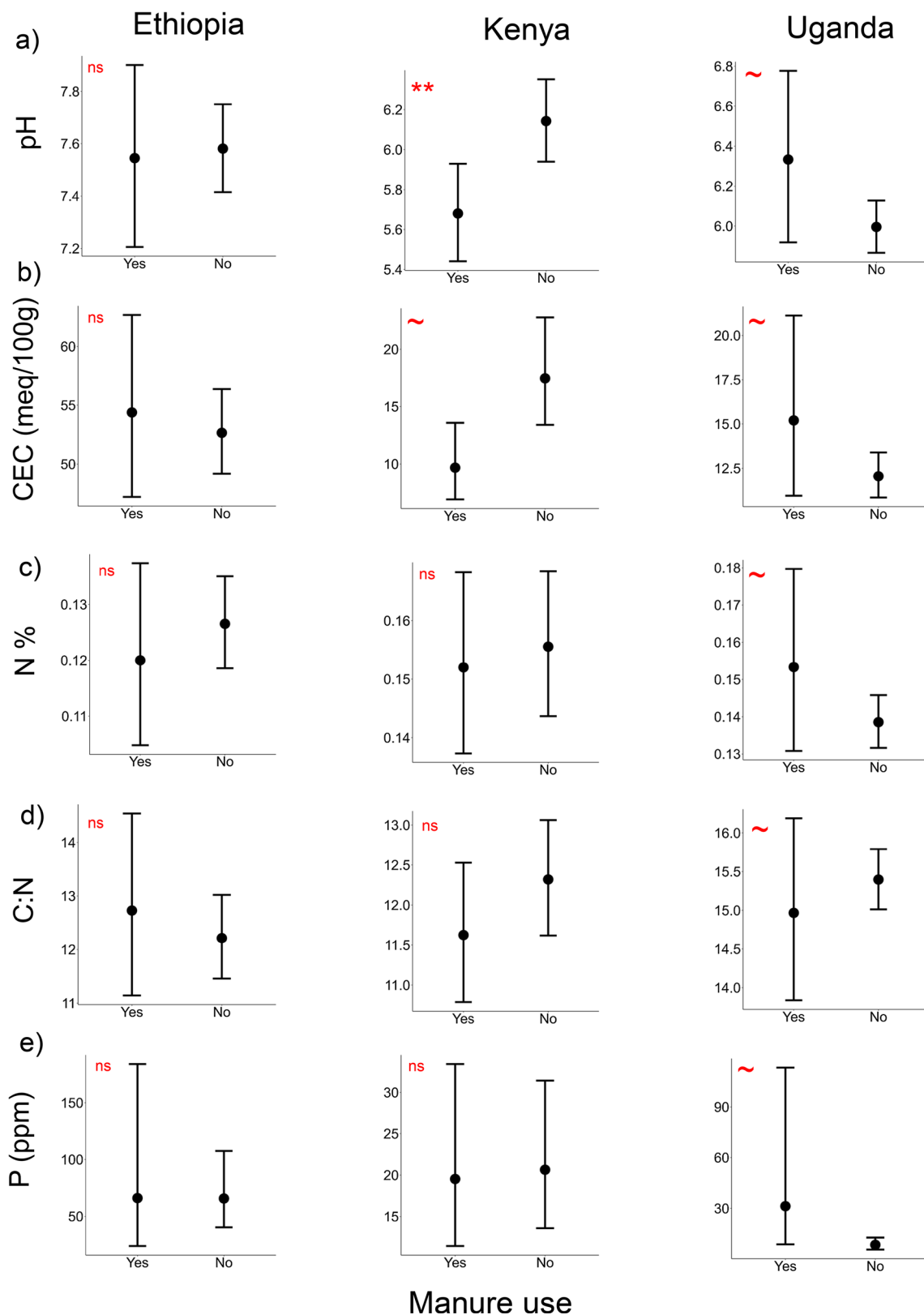


FIGURE 5 | Model-predicted associations between manure use and (a) pH, (b) cation exchange capacity (CEC), (c) nitrogen (N), (d) carbon-to-nitrogen ratio (C:N), and (e) phosphorus (P), (f) calcium (Ca), (g) potassium (K), (h) magnesium (Mg), (i) sodium (Na), (j) copper (Cu), and (k) zinc (Zn) across plots (PP and NPP) in Kenya, Uganda, and Ethiopia. Values represent GLM estimates (mean \pm standard error), with standard errors back-transformed to the response scale. Differences between manure use were tested using Wald z -tests. Significance levels are indicated as follows: ** ($0.001 \leq p < 0.01$), * ($0.01 \leq p < 0.05$), (~) marginally significant ($0.05 \leq p < 0.1$), and (ns) not significant ($p \geq 0.1$).

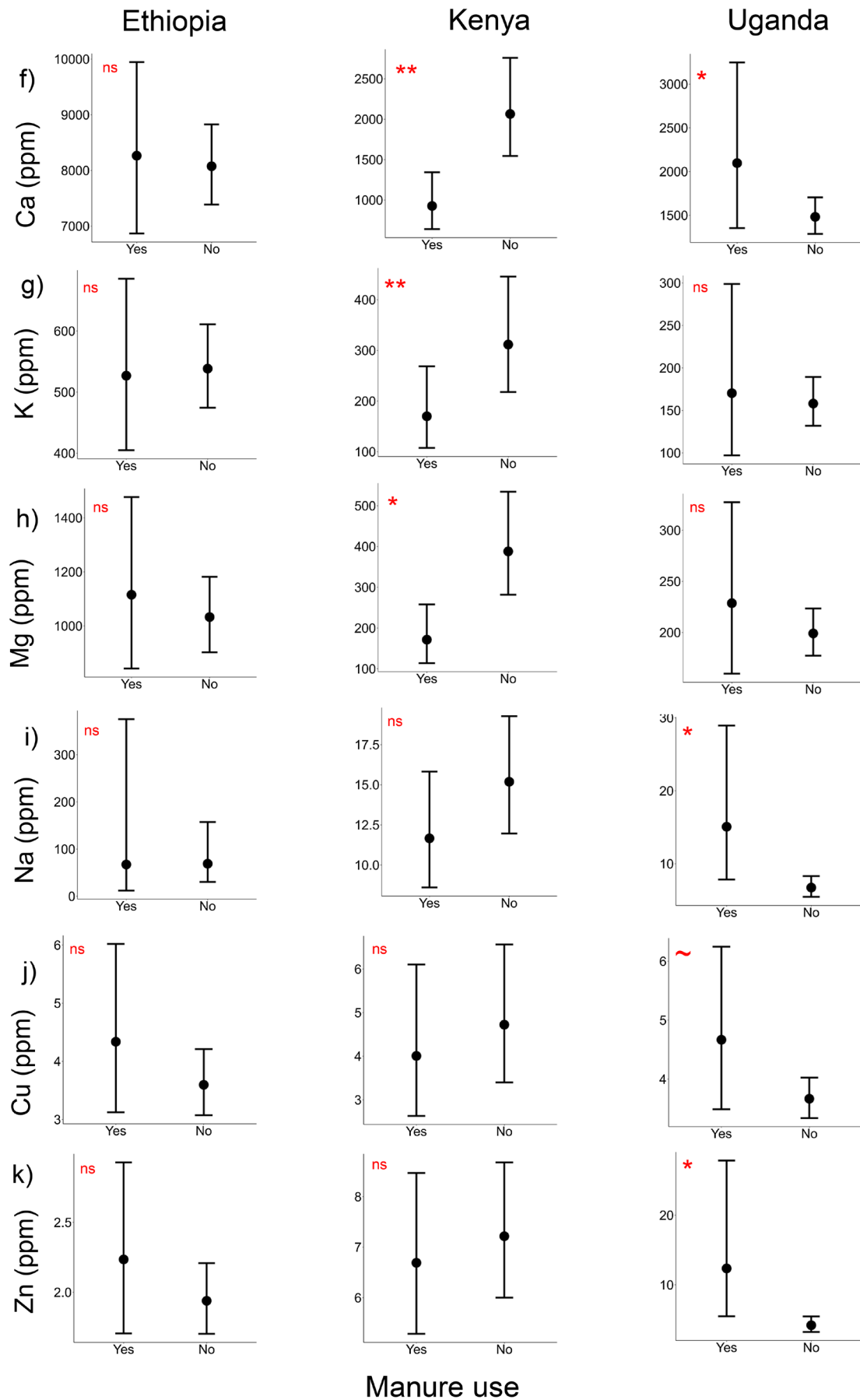


FIGURE 5 | (Continued)

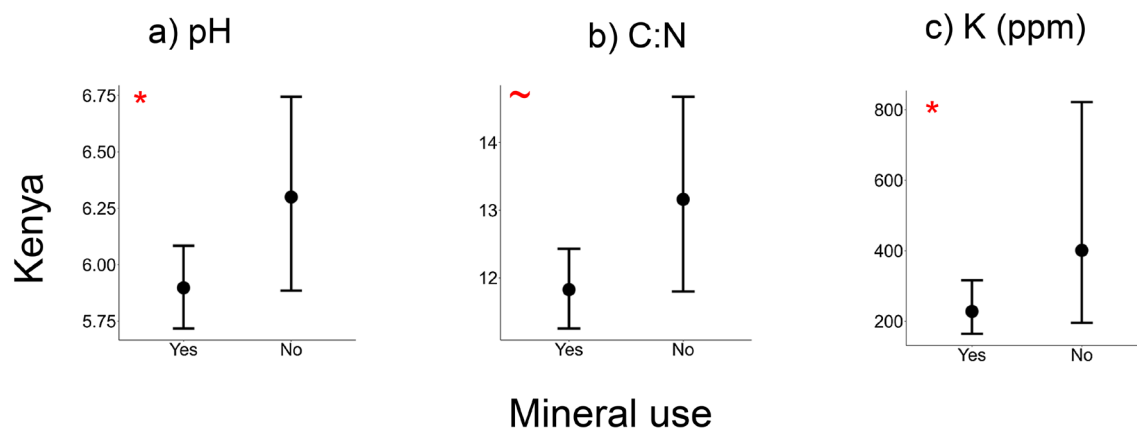


FIGURE 6 | Model-predicted associations between mineral fertiliser use and (a) pH, (b) carbon-to-nitrogen ratio (C: N), and (c) potassium (K), across plots in Kenya. Values represent GLM estimates (mean±standard error), with standard errors back-transformed to the response scale. Differences between manure use were tested using Wald z -tests. Significance levels are indicated as follows: * ($0.01 \leq p < 0.05$), and (-) marginally significant ($0.05 \leq p < 0.1$).

soil nutrient and water retention capacities (Kome et al. 2019). Notably, clay content did not differ significantly between PP and NPP plots, suggesting that the plots were reasonably well matched in terms of soil texture, which is a prerequisite for evaluating the efficacy of PP systems.

4.5 | Contrasting Effects of Manure Fertiliser Application Across Countries

Manure application yielded mixed associations with soil properties between countries. The lack of significant associations between manure use and soil properties in Ethiopia likely reflects limited manure application, as few farmers applied manure in their plots, and those who did may have applied only small quantities (Rapsomanikis 2015). Manure application across both cropping systems in Uganda was positively associated with key soil parameters, including Ca, Zn (also across PP plots only), CEC, N, P, C: N ratio, pH, and Cu. This confirms the role of manure in promoting nutrient enrichment and improving overall soil fertility (Mkhabela 2006; Sileshi et al. 2025).

In contrast, Kenyan plots receiving manure exhibited lower levels of pH (across all cropping systems), CEC, K, Ca, Mg, and B (PP plots only). The lower CEC was unexpected, as manure is typically associated with increased SOM, which in turn enhances CEC (Liu et al. 2020; Sileshi et al. 2025). Given that the soil pH range is below 7.5, an increase in pH following manure application was also expected (Liu et al. 2020; Shi et al. 2019), but this was not observed. While farmers are unlikely to have precise knowledge about fertility differences between neighbouring plots, older PP farmers often established PP systems in fields previously planted with nutrient-depleting crops such as sugarcane. This broader awareness of field history may have influenced manure application decisions. In addition, potential variability in manure quality and composition across farms likely contributed to the observed patterns. These findings should be interpreted as context-dependent associations rather than direct causal effects of manure application.

The contrasting responses of manure use between the countries may also reflect regional differences in manure availability and composition (Das et al. 2017; Silva et al. 2008; Zhang et al. 2015), application rates (Gross and Glaser 2021) and strategic considerations amongst farmers, the inherent soil buffering capacity (Eghball 2002), as well as differences in the legacy effect of past cropping on the plots (Garba et al. 2022; Mugi-Ngenga et al. 2022). It is also probable that where nutrient enhancement was observed in PP plots, it may have been enhanced by the synergistic effects of *Desmodium* on soil nutrient retention and mobilisation (Ndayisaba et al. 2021, 2022).

4.6 | Soil Acidification and Nutrient Imbalances From Mineral Fertiliser Application

Application of mineral fertilisers in Kenya, where they were commonly used, was associated with lower soil pH, K, and CEC in PP plots only. This pattern may reflect the acidifying effects of continuous mineral N input use and the potential of imbalanced nutrient uptake (Wallace 1994). The observed association only in PP plots could be related to differences in baseline soil fertility, plot history, or management practices rather than deliberate differential application by farmers. These findings align with previous research demonstrating soil acidification resulting from repeated application of ammonium-based fertilisers and urea (Sileshi et al. 2019). Additionally, the process of N_2 fixation by *Desmodium* in the PP plots also produces acid, decreasing pH and making it more pronounced (Giller 2001; Tang et al. 1999).

The observed decline in K levels may also suggest increased plant uptake and export of K from the system when N and P are applied, as this stimulates greater plant growth. This pattern is consistent with nutrient mining, whereby enhancing the availability of certain nutrients can accelerate the depletion of others that are not replenished (Dobermann 2007; Noordwijk and Cadisch 2002). In addition, *Desmodium* vines are often cut and carried as fodder for livestock (Khan et al. 2014), resulting in exporting base cations such as K from the system. This removal, combined with increased K export through harvested cereals,

may have contributed to the consistently lower K levels observed in PP plots.

These patterns highlight the importance of balanced nutrient application that extends beyond N or N-P combinations. Substituting ammonium-based N fertilisers with nitrate-based formulations could help mitigate fertiliser-induced acidification (Rivero-Marcos et al. 2025). Furthermore, wider access to affordable soil testing could enable more targeted and effective nutrient management. The success of such strategies, however, depends on the availability of suitable fertiliser options in the local markets, which is often limited in SSA countries due to higher prices (Amankwah et al. 2024; Hernandez and Torero 2013).

5 | Implications and Limitations

Our findings vary considerably across regions, with key factors such as *Desmodium* cover, system age, and fertiliser use influencing soil properties. Given that PP systems integrate multiple components, such as biological nitrogen fixation and organic matter enhancement from *Desmodium*, coupled with farmers' application of external soil amendments, it is difficult to attribute the observed soil changes to a single factor. This complexity limits our capacity to disentangle the relative contributions of each system component (e.g., *Desmodium* vs. fertiliser use) to the observed soil outcomes.

While some regions, such as those in Kenya and Uganda, show clear benefits of long-term PP adoption and through greater variation in *Desmodium* cover, others (Rwanda and Ethiopia) illustrate more nuanced responses, possibly due to having younger plots, less variation in *Desmodium* cover, or inherent soil properties. However, the potential for nutrient depletion and soil acidification in older plots as observed in Kenya underscores the need for adaptive management strategies, such as targeted soil amendments and crop rotations, to sustain long-term soil health.

Our study suggests that PP may have been preferentially implemented on less fertile or degraded plots, which in turn makes it difficult to disentangle the full effects of PP cropping on soil fertility. Relatedly, challenges in identifying well-matched control plots due to variability in land-use history, management practices, and farmer decision-making may have introduced unaccounted confounding factors, limiting the comparability between treatments. For instance, the absence of data on application rates of fertilisers and nutrient content limits our ability to assess application-response relationships or confidently attribute changes in soil properties to specific inputs. This challenge is further compounded by known regional differences in input use; for example, a smallholder farmer in Ethiopia applies four times less mineral fertiliser than one in Kenya (Rapsomanikis 2015). Furthermore, manure quality, decomposition rates, and mineral fertiliser formulation can vary widely across farms and regions, influencing their effects on soil pH, nutrient availability, and microbial activity (Bayu et al. 2005; Dahlin et al. 2021; Das et al. 2017; Kumar Bhatt et al. 2019; Sileshi et al. 2019).

6 | Conclusion

In conclusion, our findings reinforce the potential of PP systems to contribute to overall soil health, particularly through *Desmodium* cover-driven improvements in SOM and N. The relationships, however, are shaped by site-specific conditions, including soil texture, plot history, and input management, among other factors not accounted for in our study. To sustain soil health over time, PP systems must be managed adaptively, bearing in mind integrated soil fertility management that aligns with local soil conditions. Further research is needed to explore the long-term impacts of PP systems on soil health and ecosystem services, particularly in the context of climate change, local management practices, and quantitative fertiliser amendments. As efforts to upscale PP technology in sub-Saharan Africa intensify, understanding the complex, context-specific responses of soils to PP will be critical to achieving both productivity and sustainability goals.

Author Contributions

Grace Mercy Amboka: methodology; investigation; data curation; formal analysis; resources; software; validation; visualisation; writing – original draft preparation; writing – review and editing. **Mattias Jonsson:** conceptualisation; funding acquisition; methodology; resources; validation; supervision; writing – review and editing. **Celina Apel:** methodology; investigation; data curation; writing – review and editing. **David Meinhof:** methodology; investigation; data curation; writing – review and editing. **Adomas Liepa:** investigation; data curation; writing – review and editing. **Frank Chidawanyika:** conceptualisation; project administration; writing – review and editing. **Andargachew Detebo:** investigation; data curation; writing – review and editing. **Felipe Librán-Embid:** methodology; investigation; data curation; writing – review and editing. **Emily A. Martin:** conceptualisation; funding acquisition; project administration; methodology; writing – review and editing. **Ingolf Steffan-Dewenter:** project administration; methodology; writing – review and editing. **Marcell K. Peters:** project administration; methodology; writing – review and editing. **Jie Zhang:** project administration; methodology; data curation; writing – review and editing. **Michael Thiel:** project administration; writing – review and editing. **Michael Otim:** project administration; writing – review and editing. **James Mugisha:** project administration; resources; writing – review and editing. **Ghebremedhin Belay Bahta:** project administration; writing – review and editing. **Fredah Maina:** conceptualisation; project administration; writing – review and editing. **Alice Murage:** conceptualisation; project administration; writing – review and editing. **Benjamin Feit:** conceptualisation; funding acquisition; methodology; resources; validation; supervision; writing – review and editing. **A. Sigrun Dahlin:** conceptualisation; methodology; funding acquisition; project administration; resources; validation; supervision; writing – review and editing.

Acknowledgements

The authors sincerely thank all field assistants and farmers for their invaluable support during field data collection. We also gratefully acknowledge Athanase Hategekimana from the Rwanda Agricultural Board for assistance in obtaining export permits for soil samples in Rwanda, as well as Beatrice Muriithi and Dave Ireri for their support in collecting complementary farmers' information. We thank Makerere University, Kampala, for conducting the soil texture analysis, and Crop Nutrition Laboratories, Nairobi, for analysing the soil chemical properties.

Funding

Financial support for this research was provided by the European Union's Horizon 2020 research and innovation programme under grant

agreement No 861998 ‘UPSCALE: Upscaling the benefits of push-pull technology for sustainable agricultural intensification in East Africa.’

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

- Amankwah, A., A. Ambel, and S. Gourlay. 2024. *Fertilizer Price Shocks in Smallholder Agriculture: Cross-Country Evidence From High-Frequency Phone Surveys in Sub-Saharan Africa (Policy Research Working Paper No. 10842)*. World Bank. <https://openknowledge.worldbank.org/server/api/core/bitstreams/b10ebb9c-0bb1-4d1e-9f32-71b3f84ebecca/content>.
- Amanuel, G., R. F. Kühne, D. G. Tanner, and P. L. G. Vlek. 2000. “Biological Nitrogen Fixation in Faba Bean (*Vicia faba* L.) in the Ethiopian Highlands as Affected by P Fertilization and Inoculation.” *Biology and Fertility of Soils* 32, no. 5: 353–359. <https://doi.org/10.1007/s003740000258>.
- Bartoń, K. 2024. MuMIn: Multi-Model Inference (p. 1.47.5) [Data Set]. <https://doi.org/10.32614/CRAN.package.MuMIn>.
- Bayu, W., N. F. G. Rethman, and P. S. Hammes. 2005. “The Role of Animal Manure in Sustainable Soil Fertility Management in Sub-Saharan Africa: A Review.” *Journal of Sustainable Agriculture* 25, no. 2: 113–136. https://doi.org/10.1300/J064v25n02_09.
- Beegle, K., L. Christiaensen, A. Dabalen, and I. Gaddis. 2016. *Poverty in a Rising Africa*. World Bank. <https://doi.org/10.1596/978-1-4648-0723-7>.
- Boiko, M. O. 2024. “Ecological Consequences of Burning Crop Residues.” *Taurian Scientific Herald* 1, no. 135: 206–211. <https://doi.org/10.32782/2226-0099.2024.135.1.27>.
- Bouyoucos, G. J. 1962. “Hydrometer Method Improved for Making Particle Size Analyses of Soils¹.” *Agronomy Journal* 54, no. 5: 464–465. <https://doi.org/10.2134/agronj1962.00021962005400050028x>.
- Burnham, K. P., D. R. Anderson, and K. P. Huyvaert. 2011. “AIC Model Selection and Multimodel Inference in Behavioral Ecology: Some Background, Observations, and Comparisons.” *Behavioral Ecology and Sociobiology* 65, no. 1: 23–35. <https://doi.org/10.1007/s00265-010-1029-6>.
- Chidawanyika, F., B. Muriithi, S. Niassy, et al. 2023. “Sustainable Intensification of Vegetable Production Using the Cereal ‘Push-Pull Technology’: Benefits and One Health Implications.” *Environmental Sustainability* 6, no. 1: 25–34. <https://doi.org/10.1007/s42398-023-00260-1>.
- Chidawanyika, F., E. R. Omuse, L. O. Agutu, J. O. Pittchar, D. Nyagol, and Z. R. Khan. 2025. “An Intensified Cereal Push-Pull System Reduces Pest Infestation and Confers Yield Advantages in High-Value Vegetables.” *Journal of Crop Health* 77, no. 1: 40. <https://doi.org/10.1007/s10343-024-01107-3>.
- Chu, G. X., Q. R. Shen, and J. L. Cao. 2004. “Nitrogen Fixation and N Transfer From Peanut to Rice Cultivated in Aerobic Soil in an Intercropping System and Its Effect on Soil N Fertility.” *Plant and Soil* 263, no. 1: 17–27. <https://doi.org/10.1023/B:PLSO.0000047722.49160.9e>.
- Cook, S. M., Z. R. Khan, and J. A. Pickett. 2007. “The Use of Push-Pull Strategies in Integrated Pest Management.” *Annual Review of Entomology* 52, no. 1: 375–400. <https://doi.org/10.1146/annurev.ento.52.110405.091407>.
- Dahlin, A. S., M. Mukangango, F. X. Naramabuye, J. Nduwamungu, and G. Nyberg. 2021. “Effect of Grass-Diet and Grass-Legume-Diet Manure Applied to Planting Holes on Smallholder Maize Production in Rwanda.” *Field Crops Research* 263: 108057. <https://doi.org/10.1016/j.fcr.2021.108057>.
- Das, S., S. T. Jeong, S. Das, and P. J. Kim. 2017. “Composted Cattle Manure Increases Microbial Activity and Soil Fertility More Than Composted Swine Manure in a Submerged Rice Paddy.” *Frontiers in Microbiology* 8: 1702. <https://doi.org/10.3389/fmicb.2017.01702>.
- Dessalegn, O. G., and D. S. Akalu. 2015. “The Impacts of Climate Change on African Continent and the Way Forward.” *Journal of Ecology and the Natural Environment* 7, no. 10: 256–262. <https://doi.org/10.5897/JENE2015.0533>.
- Dobermann, A. 2007. Nutrient Use Efficiency – Measurement and Management. https://digitalcommons.unl.edu/agronomyfacpub/1442?utm_source=digitalcommons.unl.edu%2Fagronomyfacpub%2F1442&utm_medium=PDF&utm_campaign=PDFCoverPages.
- Dong, R., W. Hu, L. Bu, H. Cheng, and G. Liu. 2024. “Legume Cover Crops Alter Soil Phosphorus Availability and Microbial Community Composition in Mango Orchards in Karst Areas.” *Agriculture, Ecosystems & Environment* 364: 108906. <https://doi.org/10.1016/j.agee.2024.108906>.
- Eghball, B. 2002. Soil Properties as Influenced by Phosphorus- and Nitrogen-Based Manure and Compost Applications. https://digitalcommons.unl.edu/agronomyfacpub/16?utm_source=digitalcommons.unl.edu%2Fagronomyfacpub%2F16&utm_medium=PDF&utm_campaign=PDFCoverPages.
- FAO. 2007. *Mapping Biophysical Factors That Influence Agricultural Production and Rural Vulnerability*. FAO. <https://www.fao.org/4/a1075e/a1075e00.htm>.
- FAO. 2025. *Achieving Sustainable Gains in Agriculture*. Food and Agriculture Organization of the United Nations. https://www.fao.org/4/am859e/am859e01.pdf?utm_source.
- Garba, I. I., L. W. Bell, and A. Williams. 2022. “Cover Crop Legacy Impacts on Soil Water and Nitrogen Dynamics, and on Subsequent Crop Yields in Drylands: A Meta-Analysis.” *Agronomy for Sustainable Development* 42, no. 3: 34. <https://doi.org/10.1007/s13593-022-00760-0>.
- Giller, K. E. 2001. *Nitrogen Fixation in Tropical Cropping Systems*, edited by C.A.B. International. 2nd ed. CABI. <https://doi.org/10.1079/9780851994178.0000>.
- Gross, A., and B. Glaser. 2021. “Meta-Analysis on How Manure Application Changes Soil Organic Carbon Storage.” *Scientific Reports* 11, no. 1: 5516. <https://doi.org/10.1038/s41598-021-82739-7>.
- Han, E., F. Li, U. Perkons, et al. 2021. “Can Precrops Uplift Subsoil Nutrients to Topsoil?” *Plant and Soil* 463, no. 1–2: 329–345. <https://doi.org/10.1007/s11104-021-04910-3>.
- Hernandez, M. A., and M. Torero. 2013. “Market Concentration and Pricing Behavior in the Fertilizer Industry: A Global Approach.” *Agricultural Economics* 44, no. 6: 723–734. <https://doi.org/10.1111/agec.12084>.
- Hession, S. L., and N. Moore. 2011. “A Spatial Regression Analysis of the Influence of Topography on Monthly Rainfall in East Africa.” *International Journal of Climatology* 31, no. 10: 1440–1456. <https://doi.org/10.1002/joc.2174>.
- Indeje, M., F. H. M. Semazzi, L. Xie, and L. J. Ogallo. 2001. “Mechanistic Model Simulations of the East African Climate Using NCAR Regional Climate Model: Influence of Large-Scale Orography on the Turkana Low-Level Jet.” *Journal of Climate* 14, no. 12: 2710–2724. [https://doi.org/10.1175/1520-0442\(2001\)014%253C2710:MMSOTE%253E2.0.CO;2](https://doi.org/10.1175/1520-0442(2001)014%253C2710:MMSOTE%253E2.0.CO;2).
- Jackson, L. E. 2000. “Fates and Losses of Nitrogen From a Nitrogen-15-Labeled Cover Crop in an Intensively Managed Vegetable System.” *Soil*

- Science Society of America Journal 64, no. 4: 1404–1412. <https://doi.org/10.2136/sssaj2000.6441404x>.
- Jalloh, A. A., F. M. Khamis, A. A. Yusuf, S. Subramanian, and D. M. Mutyambai. 2024. “Long-Term Push–Pull Cropping System Shifts Soil and Maize-Root Microbiome Diversity Paving Way to Resilient Farming System.” *BMC Microbiology* 24, no. 1: 92. <https://doi.org/10.1186/s12866-024-03238-z>.
- Jones, A., H. Breuning-Madsen, M. Brossard, et al. 2013. “Soil Atlas of Africa.” *Publications Office*: 120–135. <https://doi.org/10.2788/52319>.
- Khan, Z. R., A. Hassanali, W. Overholt, et al. 2002. “Control of Witchweed *Striga hermonthica* by Intercropping With *Desmodium* spp., and the Mechanism Defined as Allelopathic.” *Journal of Chemical Ecology* 28: 1871–1885.
- Khan, Z. R., C. A. O. Midega, J. O. Pittchar, et al. 2014. “Achieving Food Security for One Million Sub-Saharan African Poor Through Push–Pull Innovation by 2020.” *Philosophical Transactions of the Royal Society, B: Biological Sciences* 369, no. 1639: 20120284. <https://doi.org/10.1098/rstb.2012.0284>.
- Khan, Z. R., J. A. Pickett, J. V. D. Berg, L. J. Wadhams, and C. M. Woodcock. 2000. “Exploiting Chemical Ecology and Species Diversity: Stem Borer and *Striga* Control for Maize and Sorghum in Africa.” *Pest Management Science* 56, no. 11: 957–962. [https://doi.org/10.1002/1526-4998\(200011\)56:11%253C957::AID-PS236%253E3.0.CO;2-T](https://doi.org/10.1002/1526-4998(200011)56:11%253C957::AID-PS236%253E3.0.CO;2-T).
- Kome, G. K., R. K. Enang, F. O. Tabi, and B. P. K. Yerima. 2019. “Influence of Clay Minerals on Some Soil Fertility Attributes: A Review.” *Open Journal of Soil Science* 9, no. 9: 155–188. <https://doi.org/10.4236/ojss.2019.99010>.
- Kumar Bhatt, M., R. Labanya, and H. C. Joshi. 2019. “Influence of Long-Term Chemical Fertilizers and Organic Manures on Soil Fertility A Review.” *Universal Journal of Agricultural Research* 7, no. 5: 177–188. <https://doi.org/10.13189/ujar.2019.070502>.
- Kuyah, S., T. Muoni, J. Bayala, et al. 2023. “Grain Legumes and Dryland Cereals Contribute to Carbon Sequestration in the Drylands of Africa and South Asia.” *Agriculture, Ecosystems & Environment* 355: 108583. <https://doi.org/10.1016/j.agee.2023.108583>.
- Li, L., S.-M. Li, J.-H. Sun, et al. 2007. “Diversity Enhances Agricultural Productivity via Rhizosphere Phosphorus Facilitation on Phosphorus-Deficient Soils.” *Proceedings of the National Academy of Sciences* 104, no. 27: 11192–11196. <https://doi.org/10.1073/pnas.0704591104>.
- Li, X. F., C.-B. Wang, W.-P. Zhang, et al. 2018. “The Role of Complementarity and Selection Effects in P Acquisition of Intercropping Systems.” *Plant and Soil* 422, no. 1–2: 479–493. <https://doi.org/10.1007/s11104-017-3487-3>.
- Liebmann, P., P. Wordell-Dietrich, K. Kalbitz, et al. 2020. “Relevance of Aboveground Litter for Soil Organic Matter Formation – A Soil Profile Perspective.” *Biogeosciences* 17, no. 12: 3099–3113. <https://doi.org/10.5194/bg-17-3099-2020>.
- Liu, S., J. Wang, S. Pu, E. Blagodatskaya, Y. Kuzyakov, and B. S. Razavi. 2020. “Impact of Manure on Soil Biochemical Properties: A Global Synthesis.” *Science of the Total Environment* 745: 141003. <https://doi.org/10.1016/j.scitotenv.2020.141003>.
- Lupwayi, N. Z., and Y. K. Soon. 2009. “Nitrogen Release From Field Pea Residues and Soil Inorganic N in a Pea-Wheat Crop Rotation in Northwestern Canada.” *Canadian Journal of Plant Science* 89, no. 2: 239–246. <https://doi.org/10.4141/CJPS08019>.
- Lupwayi, N. Z., and Y. K. Soon. 2015. “Carbon and Nitrogen Release From Legume Crop Residues for Three Subsequent Crops.” *Soil Science Society of America Journal* 79, no. 6: 1650–1659. <https://doi.org/10.2136/sssaj2015.05.0198>.
- McIntyre, B. D., H. R. Herren, J. Wakhungu, and R. T. Watson. 2009. Sub-Saharan Africa (SSA) Report (v. 5, p. 16). International Assessment of Agricultural Knowledge, Science, and Technology for Development.
- Meena, R. S., A. Das, G. S. Yadav, and R. Lal, eds. 2018. *Legumes for Soil Health and Sustainable Management*. Springer. <https://doi.org/10.1007/978-981-13-0253-4>.
- Mitran, T., R. S. Meena, R. Lal, J. Layek, S. Kumar, and R. Datta. 2018. “Role of Soil Phosphorus on Legume Production.” In *Legumes for Soil Health and Sustainable Management*, edited by R. S. Meena, A. Das, G. S. Yadav, and R. Lal, 487–510. Springer Singapore. https://doi.org/10.1007/978-981-13-0253-4_15.
- Mkhabela, T. S. 2006. “A Review of the Use of Manure in Small-Scale Crop Production Systems in South Africa.” *Journal of Plant Nutrition* 29, no. 7: 1157–1185. <https://doi.org/10.1080/01904160600767179>.
- Mugi-Ngenga, E., L. Bastiaans, S. Zingore, N. P. R. Anten, and K. E. Giller. 2022. “The Role of Nitrogen Fixation and Crop N Dynamics on Performance and Legacy Effects of Maize-Grain Legumes Intercrops on Smallholder Farms in Tanzania.” *European Journal of Agronomy* 141: 126617. <https://doi.org/10.1016/j.eja.2022.126617>.
- Mugwe, J., F. Ngetich, and E. O. Otieno. 2019. “Integrated Soil Fertility Management in Sub-Saharan Africa: Evolving Paradigms Toward Integration.” In *Handbook of the Historiography of Biology*, edited by M. Dietrich, M. Borrello, and O. Harman, vol. 1, 1–12. Springer International Publishing. https://doi.org/10.1007/978-3-319-69626-3_71-1.
- Mutyambai, D. M., J. M. Mutua, A. A. Jalloh, et al. 2024. “Push-Pull Cropping System Positively Impacts Diversity and Abundance of Springtails (Hexapoda: Collembola) as Bioindicators of Soil Health.” *European Journal of Soil Biology* 122: 103657. <https://doi.org/10.1016/j.ejsobi.2024.103657>.
- NAAIAP. 2014. *Soil Suitability Evaluation for Maize Production in Kenya*. Ministry of Agriculture.
- Nakazawa, M. 2024. fmsb: Functions for Medical Statistics Book with some Demographic Data (p. 0.7.6) [Data set]. <https://doi.org/10.32614/CRAN.package.fmsb>.
- NCDA&CS Agronomic Division. 1999. Clay Minerals: Their Importance and Function in Soils. <https://www.ncagr.gov/soil-fertility-note-13-clay-minerals-importance-function-soils/download?attachment>.
- Ndayisaba, P. C., S. Kuyah, C. A. O. Midega, P. N. Mwangi, and Z. R. Khan. 2021. “Intercropping *Desmodium* and Maize Improves Nitrogen and Phosphorus Availability and Performance of Maize in Kenya.” *Field Crops Research* 263: 108067. <https://doi.org/10.1016/j.fcr.2021.108067>.
- Ndayisaba, P. C., S. Kuyah, C. A. O. Midega, P. N. Mwangi, and Z. R. Khan. 2022. “Push-Pull Technology Improves Carbon Stocks in Rainfed Smallholder Agriculture in Western Kenya.” *Carbon Management* 13, no. 1: 127–141. <https://doi.org/10.1080/17583004.2022.2035823>.
- Noordwijk, M. V., and G. Cadisch. 2002. “Access and Excess Problems in Plant Nutrition.” *Plant and Soil* 247, no. 1: 25–39. <https://doi.org/10.1023/A:1021194628358>.
- Nsubuga, F. N. W., J. M. Olwoch, C. J. d W. Rautenbach, and O. J. Botai. 2014. “Analysis of Mid-Twentieth Century Rainfall Trends and Variability Over Southwestern Uganda.” *Theoretical and Applied Climatology* 115, no. 1–2: 53–71. <https://doi.org/10.1007/s00704-013-0864-6>.
- Pansu, M., and J. Gautheyrou. 2006. *Handbook of Soil Analysis: Mineralogical, Organic and Inorganic Methods*. Springer.
- Peixoto, L., J. E. Olesen, L. Elsgaard, et al. 2022. “Deep-Rooted Perennial Crops Differ in Capacity to Stabilize C Inputs in Deep Soil Layers.” *Scientific Reports* 12, no. 1: 5952. <https://doi.org/10.1038/s41598-022-09737-1>.
- Pickett, J. A., C. M. Woodcock, C. A. Midega, and Z. R. Khan. 2014. “Push–Pull Farming Systems.” *Current Opinion in Biotechnology* 26: 125–132. <https://doi.org/10.1016/j.copbio.2013.12.006>.
- R Foundation for Statistical Computing. 2024. *R Core Team (Version 4.4.0) [R Foundation for Statistical Computing]*. Vienna, Austria. <https://www.r-project.org/>.

- Rapsomanikis, G. 2015. *The Economic Lives of Smallholder Farmers: An Analysis Based on Household Data From Nine Countries*. Food and Agriculture Organization of the United Nations. <https://openknowledge.fao.org/server/api/core/bitstreams/32709b4d-ed41-4b1e-9d37-91786824cb9e/content>.
- Rivero-Marcos, M., A. Calleja-Satrústegui, and I. Ariz. 2025. "The Counteracting Role of Nitrate During Ammonium Toxicity in Plants." *Horticultural Plant Journal* 12, no. 1: 49–61. <https://doi.org/10.1016/j.hpj.2024.11.002>.
- Rwema, M., B. Safari, M. Laine, M. B. Sylla, and L. Roininen. 2025. "Trends and Variability of Temperatures in the Eastern Province of Rwanda." *International Journal of Climatology* 45: e8793. <https://doi.org/10.1002/joc.8793>.
- Sanchez, P. A. 2002. "Soil Fertility and Hunger in Africa." *Science* 295, no. 5562: 2019–2020. <https://doi.org/10.1126/science.1065256>.
- Sanchez, P. A., and M. S. Swaminathan. 2005. Hunger in Africa: The Link Between Unhealthy People and Unhealthy Soils.
- Schutter, M. E., and R. P. Dick. 2002. "Microbial Community Profiles and Activities Among Aggregates of Winter Fallow and Cover-Cropped Soil." *Soil Science Society of America Journal* 66, no. 1: 142–153. <https://doi.org/10.2136/sssaj2002.1420>.
- Shi, R., Z. Liu, Y. Li, et al. 2019. "Mechanisms for Increasing Soil Resistance to Acidification by Long-Term Manure Application." *Soil and Tillage Research* 185: 77–84. <https://doi.org/10.1016/j.still.2018.09.004>.
- Siebert, A., T. Dinku, F. Vuguziga, et al. 2019. "Evaluation of ENACTS-Rwanda: A New Multi-Decade, High-Resolution Rainfall and Temperature Data Set Climatology." *International Journal of Climatology* 39, no. 6: 3104–3120. <https://doi.org/10.1002/joc.6010>.
- Sileshi, G. W., B. Jama, B. Vanlauwe, et al. 2019. "Nutrient Use Efficiency and Crop Yield Response to the Combined Application of Cattle Manure and Inorganic Fertilizer in Sub-Saharan Africa." *Nutrient Cycling in Agroecosystems* 113, no. 2: 181–199. <https://doi.org/10.1007/s10705-019-09974-3>.
- Sileshi, G. W., Z. P. Stewart, J. Odhong, et al. 2025. "A Review of Organic Inputs to Inform Soil Health Advice for African Smallholder Farmers: Localization Matters." *Npj Sustainable Agriculture* 3, no. 1: 20. <https://doi.org/10.1038/s44264-025-00063-3>.
- Silva, G. T. A., L. V. Matos, P. D. O. Nóbrega, E. F. Carneiro, and A. S. D. Resende. 2008. "Chemical Composition and Decomposition Rate of Plants Used as Green Manure." *Scientia Agricola* 65, no. 3: 298–305. <https://doi.org/10.1590/S0103-90162008000300010>.
- Soil nutrient maps of Sub-Saharan Africa. 2018. Water, Land and Ecosystems. <https://wle.cgiar.org/solutions/soil-nutrient-maps-sub-saharan-africa>.
- Tan, K. H. 2005. *Soil Sampling, Preparation, and Analysis*. CRC Press. <https://doi.org/10.1201/9781482274769>.
- Tang, C., M. J. Unkovich, and J. W. Bowden. 1999. "Factors Affecting Soil Acidification Under Legumes. III. Acid Production by N₂-Fixing Legumes as Influenced by Nitrate Supply." *New Phytologist* 143, no. 3: 513–521. <https://doi.org/10.1046/j.1469-8137.1999.00475.x>.
- Temperton, V. M., P. N. Mwangi, M. Scherer-Lorenzen, B. Schmid, and N. Buchmann. 2007. "Positive Interactions Between Nitrogen-Fixing Legumes and Four Different Neighbouring Species in a Biodiversity Experiment." *Oecologia* 151, no. 2: 190–205. <https://doi.org/10.1007/s00442-006-0576-z>.
- Tiku, T. W., G. B. Tarekegn, D. Sahlu, et al. 2025. "Evaluating CMIP6 Precipitation Simulations Across Different Rainfall Regimes in the Amhara Region, Ethiopia." *Natural Hazards Research* 5: S266659212500023X. <https://doi.org/10.1016/j.nhres.2025.03.002>.
- Tittonell, P., B. Vanlauwe, P. A. Leffelaar, K. D. Shepherd, and K. E. Giller. 2005. "Exploring Diversity in Soil Fertility Management of Smallholder Farms in Western Kenya." *Agriculture, Ecosystems & Environment* 110, no. 3–4: 166–184. <https://doi.org/10.1016/j.agee.2005.04.003>.
- Vanlauwe, B., K. Descheemaeker, K. E. Giller, et al. 2015. "Integrated Soil Fertility Management in Sub-Saharan Africa: Unravelling Local Adaptation." *Soil* 1, no. 1: 491–508. <https://doi.org/10.5194/soil-1-491-2015>.
- Vanlauwe, B., and K. Giller. 2006. "Popular Myths Around Soil Fertility Management in Sub-Saharan Africa." *Agriculture, Ecosystems & Environment* 116, no. 1–2: 34–46. <https://doi.org/10.1016/j.agee.2006.03.016>.
- Wallace, A. 1994. "Soil Acidification From Use of Too Much Fertilizer." *Communications in Soil Science and Plant Analysis* 25, no. 1–2: 87–92. <https://doi.org/10.1080/00103629409369010>.
- White, K. E., M. A. Cavigelli, and G. Bagley. 2021. "Legumes and Nutrient Management Improve Phosphorus and Potassium Balances in Long-Term Crop Rotations." *Agronomy Journal* 113, no. 3: 2681–2697. <https://doi.org/10.1002/agj2.20651>.
- Zhang, Y., S. Yang, M. Fu, et al. 2015. "Sheep Manure Application Increases Soil Exchangeable Base Cations in a Semi-Arid Steppe of Inner Mongolia." *Journal of Arid Land* 7, no. 3: 361–369. <https://doi.org/10.1007/s40333-015-0004-5>.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Soil parameters retained in the final averaged GLM models for PP and NPP systems in Ethiopia. Estimates (\pm standard errors), z -values (or t -values), and p -values are reported for each predictor variable retained after model averaging. Significant p -values ($p < 0.05$) and marginally significant p -values ($0.05 \leq p < 0.1$) are shown in bold. **Table S2:** The results of model selection assessing the responses of soil physiochemical properties to clay %, cropping systems, and manure use in Ethiopia. AIC (Akaike Information Criterion) shows how well a model fits the data. **Table S3:** Soil parameters retained in the final averaged GLM models for PP and NPP systems in Kenya. Estimates (\pm standard errors), z -values (or t -values), and p -values are reported for each predictor variable retained after model averaging. Significant p -values ($p < 0.05$) and marginally significant p -values ($0.05 \leq p < 0.1$) are shown in bold. **Table S4:** The results of model selection assessing the responses of soil physiochemical properties to Clay %, cropping systems, manure and mineral use in Kenya. AIC (Akaike Information Criterion) shows how well a model fits the data. **Table S5:** Soil parameters retained in the final averaged GLM models for PP and NPP systems in Rwanda. Estimates (\pm standard errors), z -values (or t -values), and p -values are reported for each predictor variable retained after model averaging. Significant p -values ($p < 0.05$) and marginally significant p -values ($0.05 \leq p < 0.1$) are shown in bold. **Table S6:** Soil parameters retained in the final averaged GLM models for PP and NPP systems in Uganda. Estimates (\pm standard errors), z -values (or t -values), and p -values are reported for each predictor variable retained after model averaging. Significant p -values ($p < 0.05$) and marginally significant p -values ($0.05 \leq p < 0.1$) are shown in bold. **Table S7:** The results of model selection assessing the responses of soil physiochemical properties to clay %, and cropping systems in Rwanda. AIC (Akaike Information Criterion) shows how well a model fits the data. **Table S8:** The results of model selection assessing the responses of soil physiochemical properties to clay %, cropping systems, and manure use in Uganda. AIC (Akaike Information Criterion) shows how well a model fits the data. **Table S9:** Soil parameters retained in the final averaged GLM models for PP systems in Kenya. Estimates (\pm standard errors), z -values (or t -values), and p -values are reported for each predictor variable retained after model averaging. Significant p -values ($p < 0.05$) and marginally significant p -values ($0.05 \leq p < 0.1$) are shown in bold. **Table S10:** Soil parameters retained in the final averaged GLM models for PP systems in Uganda. Estimates (\pm standard errors), z -values (or t -values), and p -values are reported for each predictor variable retained

after model averaging. Significant p -values ($p < 0.05$) and marginally significant p -values ($0.05 \leq p < 0.1$) are shown in bold. **Table S11:** The results of model selection assessing the responses of soil physiochemical properties to *Desmodium* cover %, PP plot age, manure and mineral use in PP plots in Kenya. AIC (Akaike Information Criterion) shows how well a model fits the data. **Table S12:** The results of model selection assessing the responses of soil physiochemical properties to *Desmodium* cover %, PP plot age, and manure use in PP plots in Uganda. AIC (Akaike Information Criterion) shows how well a model fits the data. **Table S13:** Soil parameters retained in the final averaged GLM models for PP systems in Rwanda. Estimates (\pm standard errors), z -values (or t -values), and p -values are reported for each predictor variable retained after model averaging. Significant p -values ($p < 0.05$) and marginally significant p -values ($0.05 \leq p < 0.1$) are shown in bold. **Table S14:** The results of model selection assessing the responses of soil physiochemical properties to *Desmodium* cover % and PP plot age in PP plots in Rwanda. AIC (Akaike Information Criterion) shows how well a model fits the data. **Table S15:** Soil parameters retained in the final averaged GLM models for PP systems in Ethiopia. Estimates (\pm standard errors), z -values (or t -values), and p -values are reported for each predictor variable retained after model averaging. Significant p -values ($p < 0.05$) and marginally significant p -values ($0.05 \leq p < 0.1$) are shown in bold. **Table S16:** The results of model selection assessing the responses of soil physiochemical properties to manure use in PP plots in Ethiopia. AIC (Akaike Information Criterion) shows how well a model fits the data.