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Soil Nutrient Contents in East African Climate-Smart Villages: Effects of Climate-Smart Agriculture Interventions

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Abstract: Short-term and plot-level trials mostly produce data on the advantages of climate-smart agriculture (CSA) practices on food security in a changing climate. Previous studies evaluated only one or a combination of a few CSA practices that improved soil nutrients, particularly in the landscapes of East Africa; hence, it is difficult to draw general conclusions. In this study, we evaluated the effect of CSA practices portfolio on soil macronutrient (nitrogen, phosphorus, and potassium) and micronutrient (manganese and zinc) levels in climate-smart villages (CSVs) in Uganda, Kenya, and Tanzania over a six-year period across different land uses such as agroforestry, cropland, grassland, forest, and control (without CSA practices). A total of 432 soil samples were collected at depths of 0–15, 15–45, and 45–100 cm, and analyzed for macro- and micronutrients. CSA practices increased total nitrogen (TN), phosphorus (P), and potassium (K) regardless of land use type or soil depth. TN, P, and K were mainly stored in surface soil (0–15 cm), accounting for 50.8–52.5%, 47.0–79.5%, and 34.2–65.5% respectively. Concentrations of Mn and Zn were 1.5–3.6 and 5.1–15.6 times greater under CSA than those under the control, respectively, at all soil depths. Results suggest that CSA practices implemented using the landscape approach contributed to improved soil fertility, which is critical in developing more sustainable and resilient production systems among smallholder farmers.

Keywords: climate-smart agriculture; land use; macronutrients; micronutrients

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1. Introduction

Climate change is the greatest global challenge of the 21st century and it is threatening global agricultural production [1]. This problem appears to be more severe in low-income countries, where agricultural production systems are characterized by rain-fed agriculture with low farm inputs (fertilizer, agrochemicals, and improved seeds), threatening food security [2,3]. The impact is expected to be greater in these countries due to their low adaptability, ecoclimatic conditions, and socioeconomic conditions. The Intergovernmental Panel on Climate Change [1] predicted that climate change would worsen and have greater impact on the environment, economy, and society in general in the coming decades. To address this, the agricultural sector in developing countries must adapt in order to protect the poor's livelihoods and ensure food security [1,4]. High population growth rates in most African countries have resulted in increased land pressure and the intensification of agriculture without proper soil nutrient addition. As a result of these events, the vast bulk of Sub-Saharan Africa's soil nutrient reserves are being depleted. Climate-smart agriculture (CSA) practices offers significant opportunity to improve soil nutrients and livelihood for many tropical farmers who rely on the recycling of nutrients from soil organic matter for agricultural production [5]. Low nutrient gains in Sub-Saharan Africa's soils are frequently caused by mineral fertilization, nutrient deposition, and nitrogen fixation. The low mineral stocks of Sub-Saharan Africa's soils, coupled with the climatic conditions of the vast interior plains and plateaus, intensify the consequences of nutrient depletion. Additionally, the high rate of soil erosion, deforestation, overcultivation of croplands, loss of litter influx after canopy removal, and the need for sustained agricultural production in tropical countries make the adoption of CSA practices a priority. Recycling crop residues, increasing nutrient fixation through crop rotations, and using organic fertilizers are examples of CSA practices that could significantly reduce rates of nutrient depletion and the need for mineral fertilizers. Furthermore, understanding local knowledge on CSA practices assists in the advancement of relevant interventions in that specific geographical area. This aligns with Sustainable Development Goal (SDG) 2, which is one of the goals where CSA can have the greatest impact. Climate-smart agriculture (CSA) is a strategy for transforming and reorienting agricultural development in response to the new realities of climate change [1]. Farmers in climate-smart villages (CSVs) can use climate-smart agriculture (CSA) options and services [1]. Climate-smart villages are an agricultural research for development (AR4D) approach that uses participatory methods to rigorously test technological and institutional options for dealing with climatic variability and climate change [2]. CSA practices aim to (i) increase productivity, (ii) improve farmers' resilience to climate change, (iii) reduce greenhouse gas emissions (GHGs), and (iv) ensure that national food security and development goals are met in a changing climate [2]. With these assumptions in mind, the Consultative Group for International Agricultural Research (CGIAR) research program on Climate Change, Agriculture, and Food Security (CCAFS) has been implementing a portfolio of CSA practices in Lushoto (Tanzania's northeastern region), Nyando (Western Kenya), and Hoima (Western Uganda) since 2012. The CSA practices implemented in these sites were soil and water conservation (SWC) structures combined with biological measures, hedgerow planting, incorporation of crop residue into soil, grazing management, crop rotation, and perennial-crop-based agroforestry systems [6,7]. All mechanical or structural methods that reduce the velocity of runoff water, decrease soil erosion, and keep water where it is needed are considered to be soil and water conservation structures. Diversion ditches (cut-off) drains, retention (infiltration) ditches, terraces, and streams are the most common SWC structural solutions employed in croplands

Recurrent drought, prolonged dry spells, and erratic rainfall patterns are the main climate shocks in the study area [2,8]. The above-mentioned CSA practices are, therefore, expected to increase crop yield, reduce greenhouse gas emissions, and ensure farmers' resilience to climate change in the area. In the study sites, for instance, farmers planted trees such as Albizzia sp. and Grevillea sp.to protect land degradation, including soil erosion and deforestation [8]. Both Albizzia sp. and Grevillea sp. are also incorporated into the land tenure system through their usage in border delineation. Additionally, few farmers have implemented soil and water conservation structures coupled with multipurpose biological measures to reduce soil erosion in croplands. Fruit trees such as mango (*Mangifera indica*), avocado (*Persea americana*), and leguminous trees are also planted on and around croplands. Because the forest cover is undergoing a rapid conversion into agricultural land in the study sites [9–11], area closure was implemented in forest lands. The impact of a single CSA practice, such as minimal tillage, soil and water conservation structure, rotation grazing, and enclosure, on soil physical and chemical properties, and the composition and diversity of soil biological communities, was studied [12–17]. These previous studies, on the other hand, were either short-term or plot-level experiments. The number of studies on the long-term (>5 years) benefits of a portfolio of CSA practices is limited, particularly in East African landscapes, hindering drawing broad conclusions from previous research. As a result, the primary goal of this study was to quantify the effects of a portfolio of CSA practices on soil nutrient content under various land uses over a six-year period.

2. Materials and Methods

2.1. Study Area

The study was conducted in three climate-smart villages (CSVs) of East African countries (Tanzania, Kenya, and Uganda; Figure 1) in similar sites reported by Ambaw et al. [18]. The Lushoto CSV is located in Northeastern Tanzania (4°47′24″ S and 38°24′36″ E, 900–2300 meters above sea level (m.a.s.l)), the Nyando CSV is in Western Kenya (0°16′12″ S and 35°4′12″ E, 1100–2500 m.a.s.l), and the Hoima CSV is in Western Uganda (1°31′48″ S and 31°32′24″ E, 620 m.a.s.l (Figure 1). Annual precipitation in the Lushoto CSV ranges between 900 and 1300 mm, with an annual temperature range between 13.8 and 25.2 °C. The average annual temperature in Nyando ranges between 25 and 35 °C, with a minimal temperature of 9 °C and a maximal temperature of 18 °C. Average annual rainfall in Hoima is 1400 mm, with temperatures ranging from 17.7 to 31.2 °C.

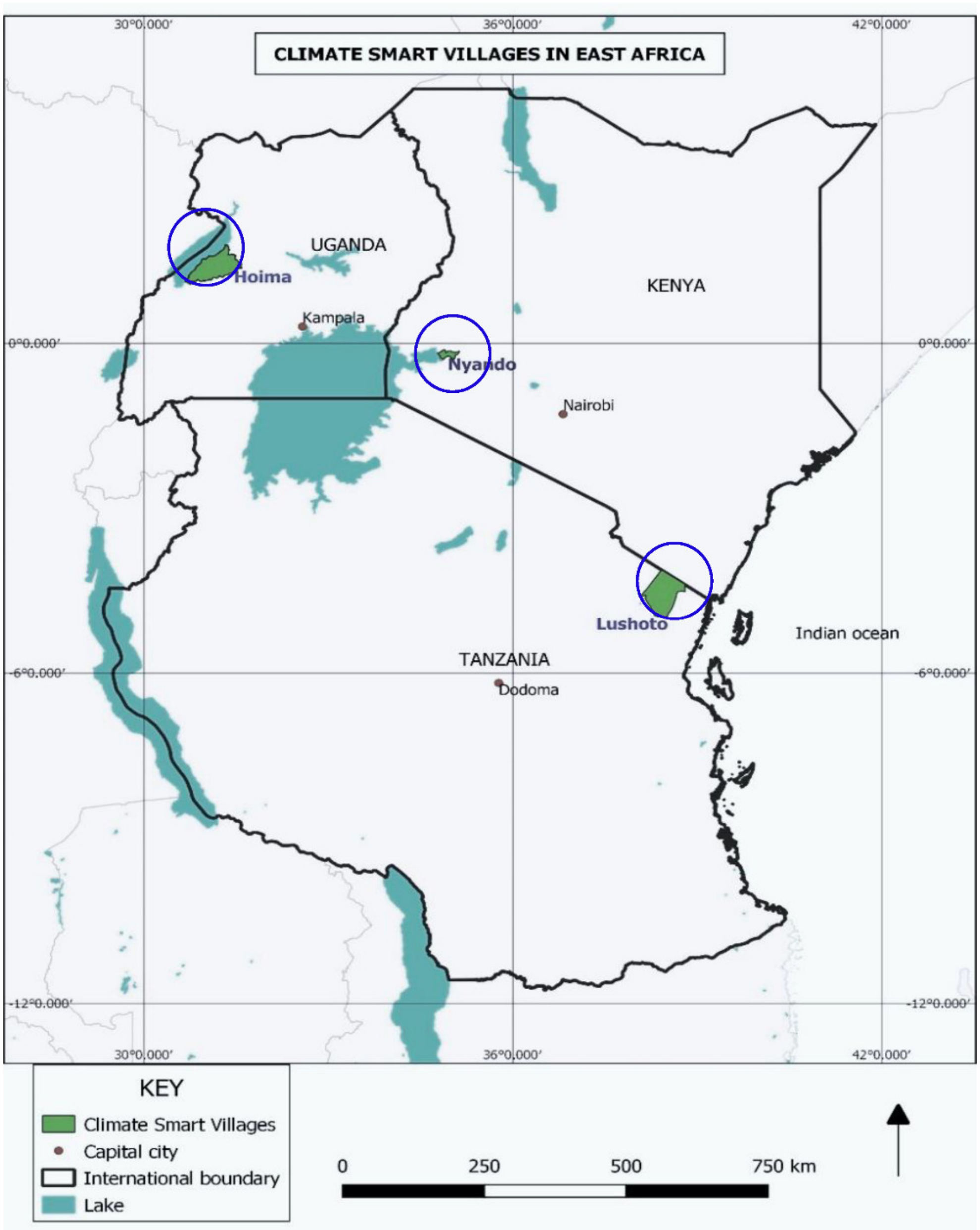

Figure 1. Climate-smart village research sites in Hoima, Nyando, and Lushoto. Source: Ambaw et al. [18].

The Lushoto CSV has a mountainous topography with overcultivated agricultural land that is experiencing extreme population pressure, increased poverty, and slow agricultural growth [19]. Lushoto CSV soil types vary along the elevation gradient, progressing from limited and shallow soils (Regosols and Lithic Leptosols) on the mountain ranges to more developed soils (Cutanic Acrisols and Ferralic Cambisols), and alluvial and wet soils in the valleys (Mollic Gleyic Fluvisols and Fluvic Gleysols) [20]. Within a relatively small area, the Lushoto CSV site contains a variety of microecological zones, including mixed crop–livestock and intensive farming systems at higher elevations, and agropastoral farming systems with patches of native forest at lower elevations. Maize (*Zea mays*), beans (*Phaseolus vulgaris*), potatoes (*Solanum tuberosum*), cassava (*Manihot esculenta*), tomatoes (*Solanum lycopersicum*), cabbages (*Brassica oleracea*), peppers (C*apsicum annuum*), avocados (*Persea americana*), and peaches (*Prunus persia*) are among the major crops grown in this area [21].

The Nyando CSV site is located in the rain shadow of the Mau Escarpment in the Nyando basin. Soil types at the Nyando CSV site range from Luvic Phaeozems (mostly above 1500 m.a.s.l.) to a complex mix of Planosols, Vertisols, Cambisols, Fluvisols, and Luvisols (below 1500 m.a.s.l.) [22,23]. Agriculture is the primary source of income and livelihood for farmers in this region. Farmers practice a rain-fed mixed subsistence farming system and livestock farming. Maize (*Zea mays*), sorghum (*Sorghum bicolor*), beans (*Phaseolus vulgaris*), cassava (*Manihot esculenta*), and sweet potatoes (*Solanum tuberosum*) are among the major crops grown in the CSV, as are livestock such as cattle, small ruminants (sheep and goats), and indigenous chicken [21].

The Hoima CSVs are located in western Uganda, on the eastern side of Lake Albert. Hoima CSV soils are mostly ferralsols (Oxisols in Soil Taxonomy), which are deeply weathered and red. On level terrain near Lake Albert, some fluvisols can be found [23]. Hoima's average elevation is 1100 m.a.s.l., but it can reach 1300 m.a.s.l. or higher on hills [23]. Farmers in the Hoima CSV practice diverse farming systems along Lake Albert, including agroforestry at the highlands, coffee or tea farming, small-scale mixed farming, and small-scale dryland agriculture. Maize (*Zea mays*), sorghum (*Sorghum bicolor*), cassava (*Manihot esculenta*), beans (*Phaseolus vulgaris*) and sweet potatoes (*Solanum tuberosum*) are the main crops grown. There is less cattle farming, and more poultry and pig farming in livestock production practices.

2.2. CSA Practices in Hoima, Nyando, and Lushoto Climate-Smart Villages

Table 1 provides a summary of CSA practices implemented in various land uses across the three CSVs. Highly degraded landscapes that are characterized by low biological and economic productivity due to limited management practices were selected in each country. Various CSA practices have then been implemented on different land uses since 2012 to reduce soil nutrient depletion and improve farmer livelihoods. Crop rotation, intercropping, physical and biological soil and water conservation measures, planting of leguminous trees integrated with various fruit trees, cereals, and legumes, and improved rotational grazing management practices are among the CSA practices implemented. In this study, control sites were also included and compared with the CSA practices. The control represents nearby landscapes with no CSA practices. In other words, the control represents degraded lands where no sustainable management practices have been implemented, and which is not used for any agricultural activity due to its very low economic and biological productivity. For forest land, conservation measures such as enclosure practice were adopted to prevent further deforestation. Enclosure results in plant regeneration, which impacts biodiversity and soil fertility through increasing organic material (litter) decomposition, and reduces soil erosion.

Table 1. CSA practices implemented in different land uses across Hoima (Uganda), Nyando (Kenya) and Lushoto (Tanzania) CSVs.

Land Uses	Implemented CSA Practices		
	Hoima	Nyando	Lushoto
Agroforestry	Use of farmyard manure, Addition of ash and household waste Integration of leguminous trees, fruit trees, crops, and vegetables	Integrated physical and biological SWC measures Use of farmyard manure. Addition of ash and household waste Integration of leguminous trees, fruit trees, crops, and vegetables Water harvesting	Integrated physical and biological SWC measures. Integration of leguminous trees with crops
Cropland	Integrated physical and biological soil and water Conservation measures. Crop rotation Improved varieties Intercropping	Integrated physical and biological soil and water Conservation measures. Crop rotation Improved varieties Intercropping	Integrated physical and biological soil and water Conservation measures. Crop rotation Improved varieties Intercropping
Grassland	Area enclosure Cut-and-carry system	Rotational grazing Area enclosure	Not sampled
Forest	Area enclosure Integrated physical and biological SWC measures	Area enclosure Integrated physical and biological SWC measures	Area enclosure Integrated physical and biological SWC measures
Control	CSApractices not implemented	CSA practices not implemented	CSA practices not implemented

2.3. Soil Sampling and Analyses

In April-May 2018, soil samples were collected from different land uses under CSA practices, including agroforestry, cropland, grassland, and forests. In Hoima and Nyando, five land uses were compared: (i) agroforestry improved through diversification and the application of organic matter; (ii) cropland improved through crop rotation, and soil and water conservation; (iii) grasslands improved through area enclosure and rotational grazing; (iv) forest lands improved through area enclosure; and (v) the control, i.e. the degraded lands. In Lushoto, all land uses were included except grassland (Table 1). In each land use type, six farmlands were randomly selected, and soil profiles were taken at depths of 0–15, 15–45, and 45–100 cm. A total of 432 georeferenced soil samples were collected, air-dried, thoroughly mixed, and sieved to pass a 2 mm sieve. Before analysis, all visible plant materials larger than 2 mm sieve size were removed. Available plant nutrients (phosphorus, potassium, manganese, and zinc) were extracted using Mehlich III extractant [24]. The Kjeldahl method was used to analyze soil samples for total nitrogen content.

2.4. Statistical Analysis

Mixed-model analysis of variance (ANOVA) was performed to test whether there were differences between different land uses improved through CSA practices and the control in terms of nutrient content. Replication was used as a random effect, whereas land use type was a fixed effect. The lem4 function in R was used to perform mixed-model analysis. Prior to data analysis, all ANOVA assumptions were checked. Shapiro–Wilk and Levene's tests were used to confirm normality and variance homogeneity. Outliers were identified using Cook distance, and the 5th and 95th percentiles were used to replace the outliers. Post hoc mean separation was carried out using Tukey's range test when significant differences were found between land use types. Some data were log-transformed to fulfill ANOVA assumptions. For variables that were not normally distributed, a nonparametric Kruskal–Wallis H test was used to determine significant differences. Statistical analyses in this study was performed using R software version 3.6.0.

3. Results

3.1. Effect of CSA Practices on Macronutrients

The effect of integrating different CSA practices on macronutrient content (nitrogen (N), phosphorus (P), and potassium (K) is presented in Figures 2–4. Findings showed that N content tended to increase under CSA practices compared with in the control irrespective of study site. The effect of CSA on macronutrient content was more pronounced at the soil surface (0–15 cm). In all CSVs, at 45–100 cm soil depth, N, P, and K were mainly stored in soil surface and accounted for 50.8–52.5%, 47–79.5% and 34.2–65.5%, respectively.

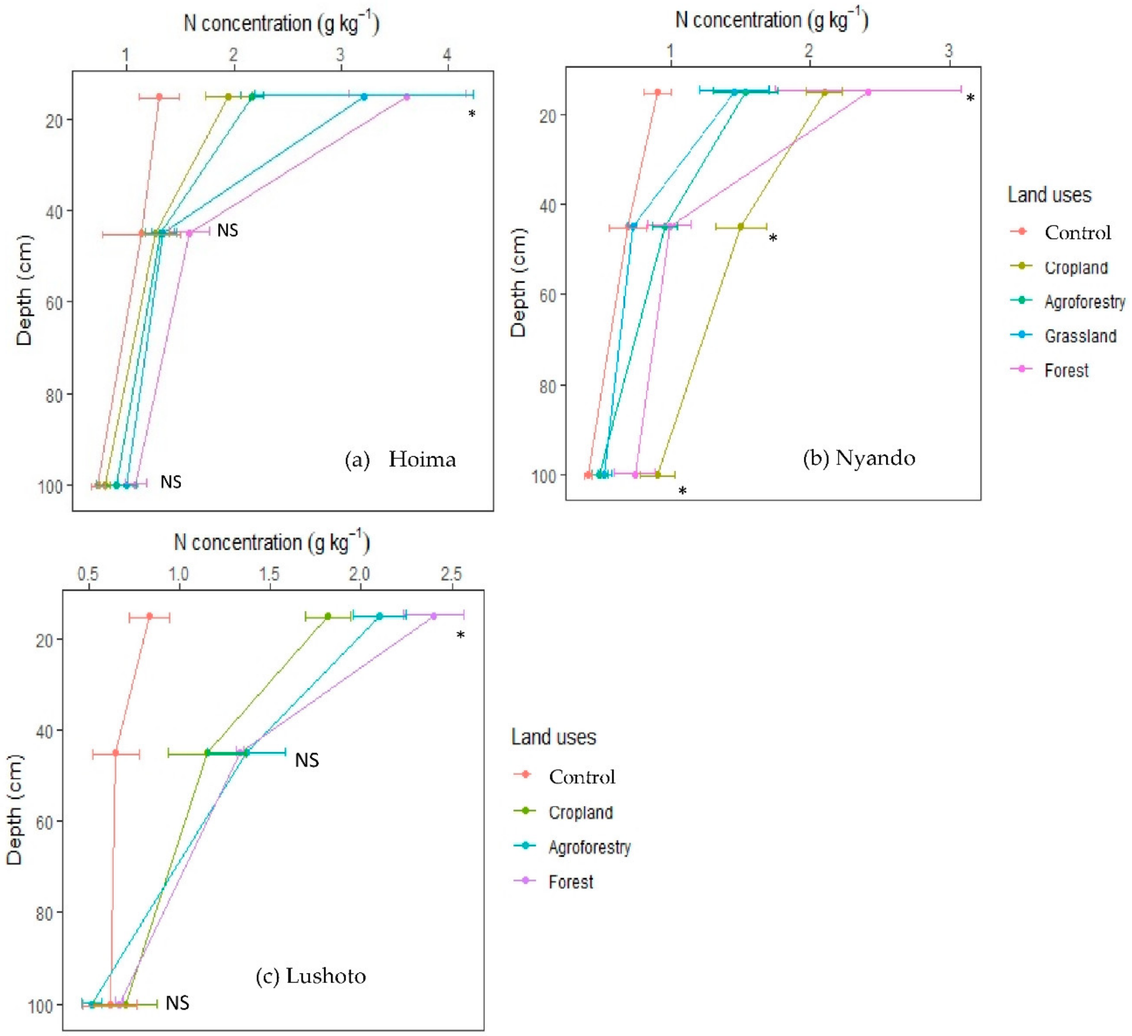

Figure 2. Nitrogen concentration in (**a**) Hoima, (**b**) Nyando, and (**c**) Lushoto at different land uses: cropland, agroforestry, grassland, forest, and control at different soil depths. Error bars represent the standard error of mean. NS denotes nonsignificant differences; * denotes significant differences at $p \leq 0.05$, respectively.

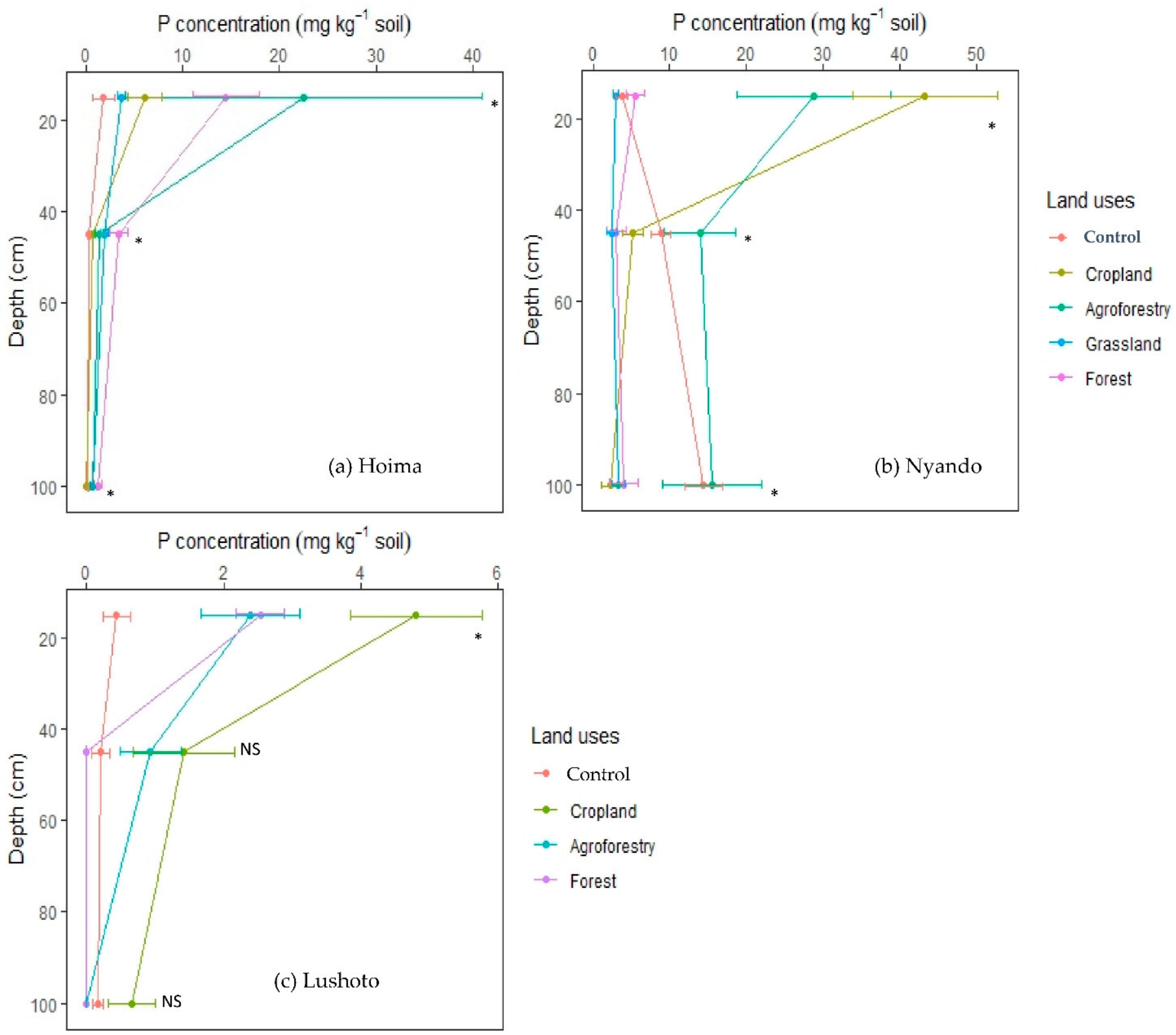

Figure 3. Phosphorus concentration in (**a**) Hoima, (**b**) Nyando and (**c**) Lushoto at different land uses: cropland, agroforestry, grassland, forest, and control at different soil depths. Error bars represent standard error of the mean. NS denotes nonsignificant differences; * denotes significant differences at $p \leq 0.05$, respectively.

In all the climate-smart villages (CSVs) in Tanzania, Kenya and Uganda, the implementation of CSA practices in cropland, agroforestry, grassland, and forestry significantly increased total nitrogen content by 66–189% at the surface soil as compared to the control (Figure 2). Forest soils in the Hoima, Nyando and Lushoto CSVs had significantly high concentrations of total nitrogen at 2.4, 3.62, and 2.42 g kg^{-1}, respectively. In Nyando, cropland had significantly higher total nitrogen content ($p < 0.05$) than that of the control at 15–45 and 45–100 cm (Figure 2). The improved land uses with CSA practices exhibited 5.7–10.9 times more phosphorus compared to the control across the CSVs (Figures 2–4). Significant differences ($p < 0.05$) in phosphorus content were observed in the Hoima and Nyando CSVs at soil depths of 15–45 cm and 45–100 cm (Figure 3). Potassium content at 0–15 cm increased by 28% and 53% in cropland and forest, respectively, in the Nyando CSVs (Figure 4).

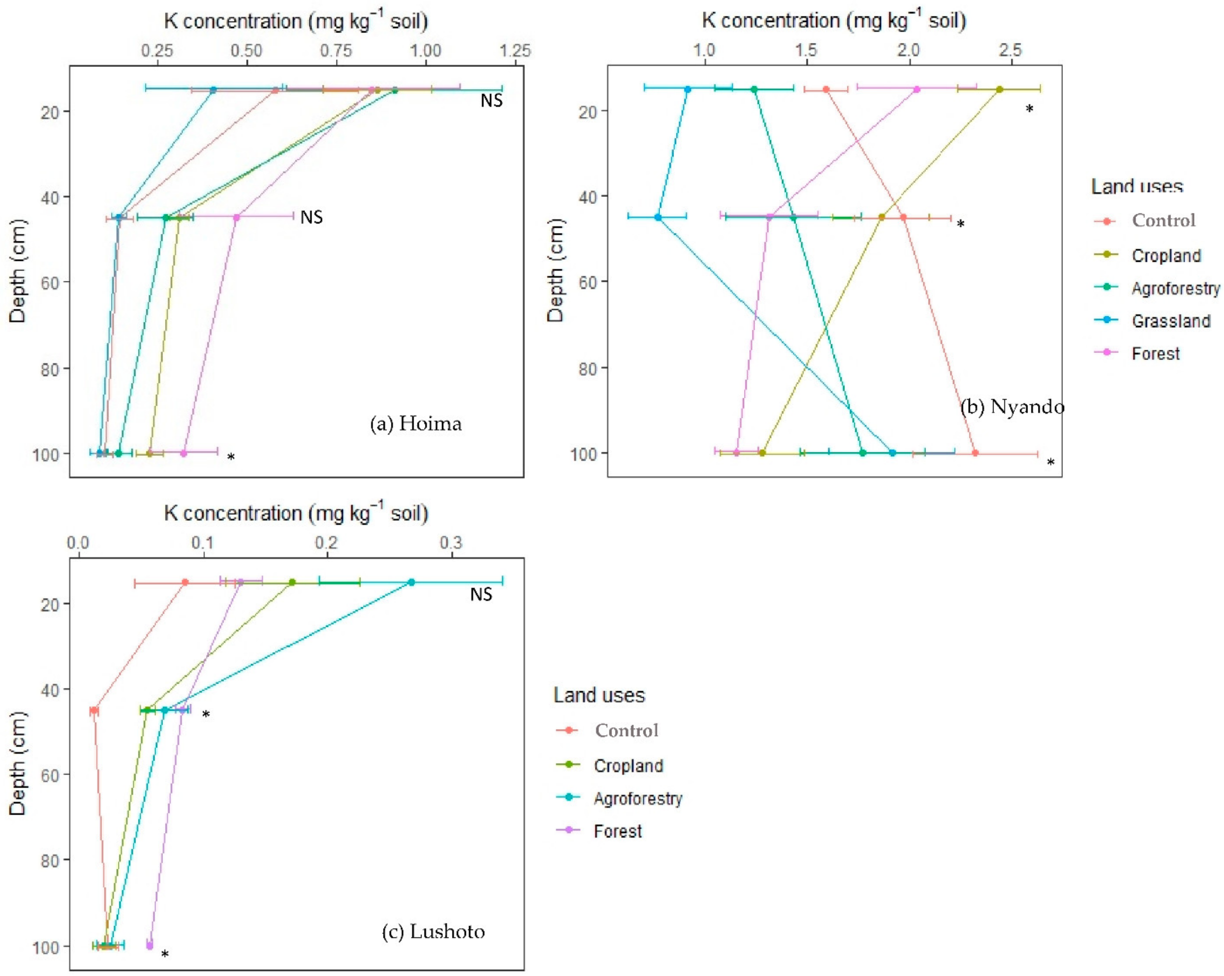

Figure 4. Potassium concentration Nitrogen concentration in (**a**) Hoima, (**b**) Nyando and (**c**) Lushoto at different land uses: cropland, agroforestry, grassland, forest, and control at different soil depths. Error bars represent the standard error of the mean. NS denotes nonsignificant differences; * denotes significant differences at $p \leq 0.05$, respectively.

3.2. Effect of CSA Practices on Micronutrients

CSA practices improved the content of micronutrients (manganese and zinc) in different land uses, as compared to the control, across all CSVs as shown in Figures 5 and 6. The adoption of CSA had an impact on the content of manganese and zinc at the surface soil in all CSVs, as well as the content of manganese and zinc in all land uses. In all CSVs, Mn and Zn availability was 1.5–3.6 and 5.1–15.6 times greater, respectively, than that in the control (Figures 5 and 6). In all CSVs, the distribution of nutrients (Mn and Zn) was greater in the topsoil (0–15 cm), with Mn and Zn accounting for 37.5–44% and 60.1–68.4% of the total across the 0–100 cm profile, respectively.

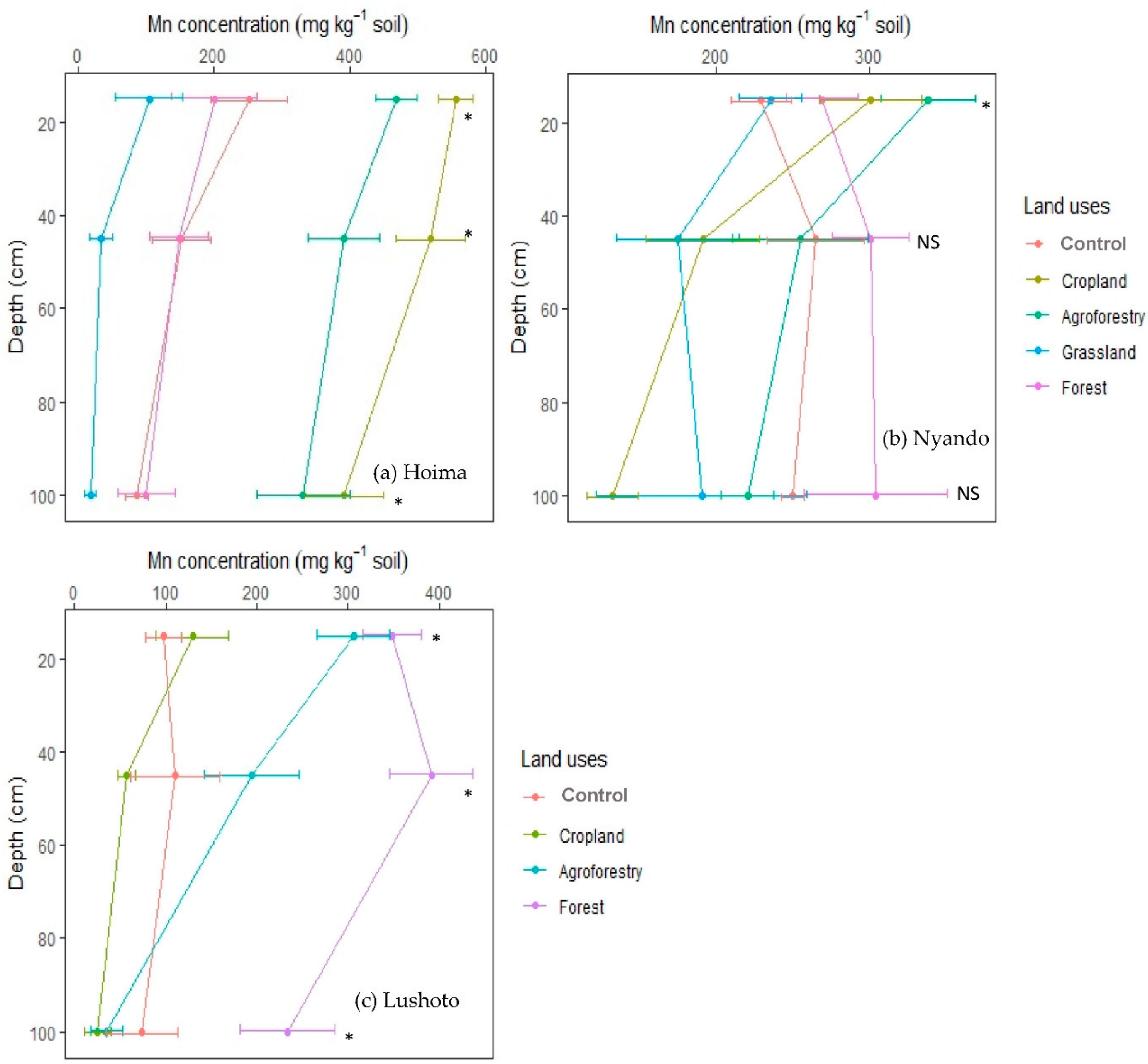

Figure 5. Manganese concentration in (**a**) Hoima, (**b**) Nyando and (**c**) Lushoto at different land uses: cropland, agroforestry, grassland, forest, and control at different soil depths. Error bars represent standard error of the mean. NS denotes nonsignificant differences; * denotes significant differences at $p \leq 0.05$, respectively.

At surface soil in Lushoto, Tanzania, forest and agroforestry showed significantly higher Mn and Zn concentrations ($p < 0.05$) than those in the cropland and control. Additionally, forest area had significantly higher ($p < 0.05$) Mn concentration in the subsoil than that of other land uses (Figure 5). Throughout the one-meter soil profile in Hoima, Uganda, the concentration of Mn in agroforestry and farmland was significantly higher ($p < 0.05$) than that in the forest, grassland, and control. Forest, agroforestry, and cropland at surface soil in the same CSV contained significantly higher ($p < 0.05$) Zn content than the control did. Agroforestry had significantly higher ($p < 0.05$) Mn concentration in surface soil in Nyando than that of the control (Figure 5), while agroforestry and cropland recorded higher concentration of Zn than that of the control.

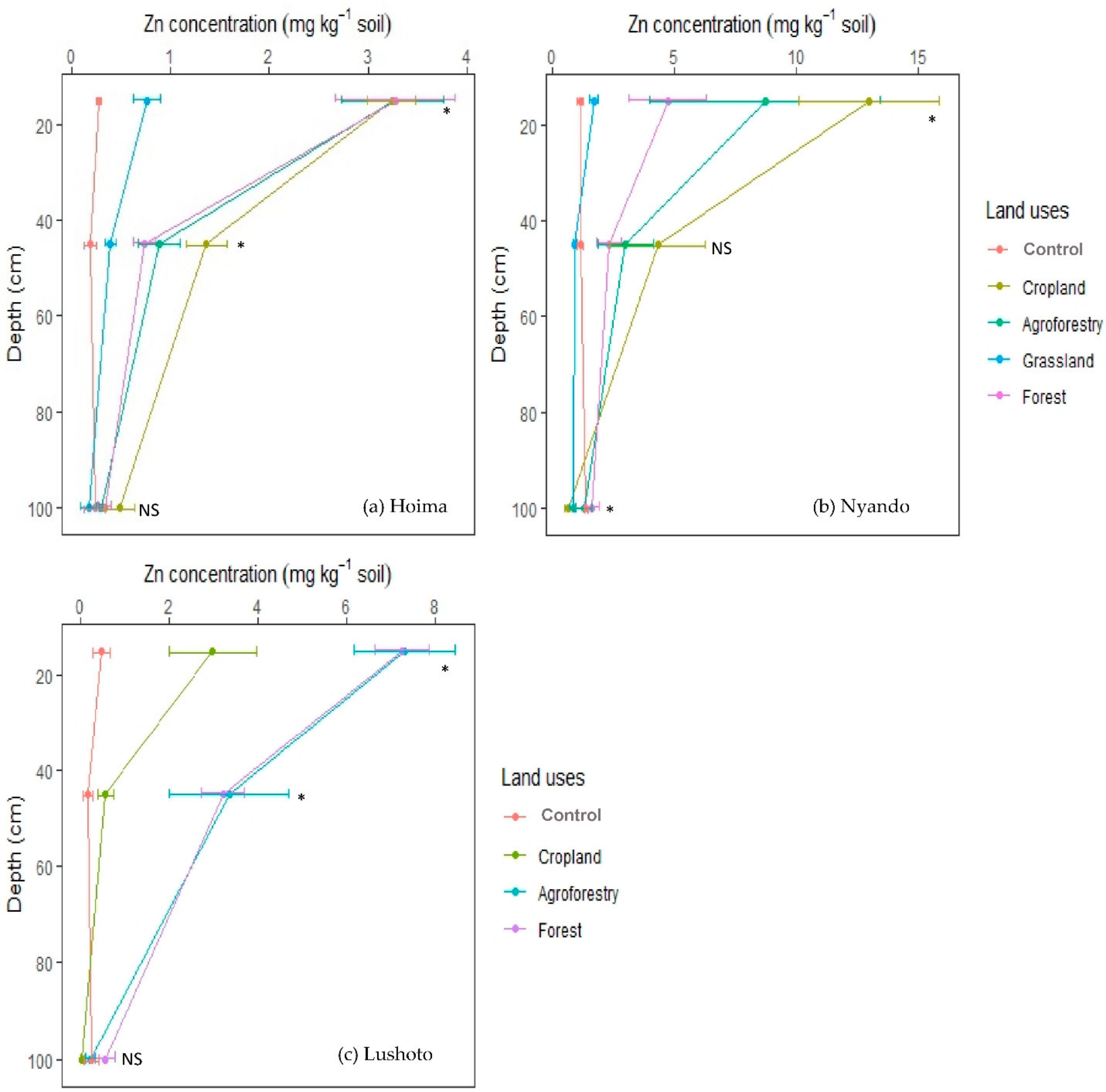

Figure 6. Zinc concentration in (**a**) Hoima, (**b**) Nyando and (**c**) Lushoto at different land uses: cropland, agroforestry, grassland, forest, and control at different soil depths. Error bars represent the standard error of the mean. NS denotes nonsignificant differences; * denotes significant differences at $p \leq 0.05$, respectively.

4. Discussion

Soil degradation, erosion, and soil fertility decline are the most significant biophysical bottlenecks to increasing agricultural productivity in Sub-Saharan Africa [25]. This presents the need for Sub-Saharan African smallholder farmers to develop more sustainable production systems [26]. As a result, climate-smart agriculture in East Africa is a viable strategy for addressing challenges that agriculture faces while ensuring food security, mitigating climate change, and adapting to the changing and varying climate. Results of this study showed that plant nutrient concentrations increased after the implementation of the CSA practices, particularly at the surface soil (0–15 cm). Thus, the rehabilitation of degraded lands through a portfolio of CSA practices such as physical and biological SWC;

the addition of farmyard manure, ash, and household waste; the integration of leguminous trees, crop rotation, intercropping, area closure, and rotational grazing, increased soil fertility, thereby improving food production in changing climate conditions (Figures 2–4).

In the study area, nitrogen and phosphorous are the most limiting nutrients for agricultural production. However, due to the high cost of mineral fertilizer and farmers' limited access to inputs and credit, its use is restricted. As a result, this study demonstrated the critical importance of CSA practices in meeting the region's high fertilizer demand while also reducing contaminations associated with mineral fertilizer production. Soil type between land uses within the country was similar [18]; hence, the observed difference between CSA practices and the control (no CSA practices) in terms of soil nutrient content could not be attributed from the variation in soil type.

The implementation of CSA practices [18,27] coupled with land use type [28,29] is expected to determine soil nutrient status. The higher amount of N concentration in agroforestry, grassland, and forest compared to that in the control is explained by a combined application of the different CSA practices, as described in Table 1. The higher N concentration in cropland could also be attributed to CSA practices such as soil and water conservation structures, which protect fine soil fractions where most of the nutrients are adsorbed. In addition, incorporation of legume crops such as beans and peas in crop rotation and/or intercropping increases nitrogen content through fixation.

Intercropping cereals and legumes helps in the maintenance and improvement of soil fertility [30]. Cereal–legume intercrops have higher nutrient use efficiency because legumes have the ability to fix atmospheric N in the soil and render it available to cereal crops [31–35], resulting in increased soil N content and greater cereal crop yield [36].

The integration of leguminous trees and addition of farmyard manure and degradable household waste has helped in N accumulation in agroforestry. Tadesse et al. [27] reported that the addition of farmyard manure and litter from plants increases the availability of nutrients through mineralization. Other studies [37,38] reported that organic inputs improve soil chemical and physical properties such as soil structure, moisture holding capacity, cation exchange capacity, and the addition of macronutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium, and micronutrients. Pieri et al. [39] concluded that soil fertility under intensive arable farming can only be maintained through efficient organic material recycling combined with N_2-fixing leguminous species rotations and chemical fertilizers. Area closure increases litter decomposition and reduces soil erosion, which improves soil nutrient content [18]. Furthermore, higher soil N content in cropland could be attributed to the recycling of N-rich residues, which returns nutrients to the soil and is crucial for maintaining soil fertility in poor soils [32].

The addition of natural organic material is higher in forest, grassland, and agroforestry. Enclosure in forest land results in forest regeneration, increase in biomass and litter accumulation. The higher P in the land uses is associated with the release of P from the decomposition of organic materials. A comparison of forest, agroforestry systems, and grassland revealed that forest and agroforestry systems contained more soil P than that of grassland, which could be attributed to tree root exudates (mostly low atomic weight organic acids), as suggested by Fisher [40]. Harcombe [41] observed variations in total phosphorus in mature upland soils as compared to the sub-humid cool temperate region, and noted that the rate of phosphorus leaching is very low. This phenomenon could also be linked to P uptake from a larger soil volume, followed by return to the soil surface via litter fall [42,43]. Grasses do not appear to have these mechanisms to the same extent as trees.

The increase in P and K concentrations in cropland is attributed to CSA practices such as soil and water conservation structures that protect soil fractions such as clay and silt from erosion, which is to where the majority of P and K is bound. Phosphorus and potassium losses are primarily caused by erosion, leaching, and surface runoff. Hence, conservation practices that prevent soil erosion and surface runoff, and improve soil structure should be implemented to reduce soil P and K losses. Recha et al. [44] also reported that the amount of exchangeable K and total N in the soil varied significantly depending on land use and soil depth. Cropland had higher K values at the soil surface (0–15 cm) compared to grassland, which had lower K values [44].

5. Conclusions

According to the findings, improving soil fertility through a portfolio of CSA practices could improve soil macro- and micronutrients in highly degraded tropical soils. Results showed that using CSA practices significantly increased macronutrient content (nitrogen, phosphorus, and potassium); similarly, micronutrient levels (Mn and Zn) were increased two- to tenfold under CSA practices compared with the land that had no CSA practices. At the soil surface, the CSA effect was more pronounced. CSA practices can thus be used to adapt to climate change in the landscape. Through this study, policy influencers and policymakers can be guided in their policy making processes in the design of agricultural programs with adaptation benefits. The study, however, was limited to Kenya, Tanzania, and Uganda. More related studies in other countries are required to reach a general conclusion on the climate change adaptation of CSA practices using the CSVs approach.

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