Variability in soil quality among smallholder macadamia farms in Malawi

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Research Article

Keywords: Malawi, soil fertility, smallholder farmers, macadamia, soil organic matter, cation exchange capacity

Posted Date: December 29th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2418801/v1

Abstract

Declining soil fertility limits smallholder macadamia productivity in Malawi. In order to reverse this trend, it is essential to apply organic and inorganic fertilisers in an efficient and effective manner. Yet, fertiliser recommendations for smallholder macadamia (*Macadamia integrifolia*) production in Malawi are not site-specific. Nutrient imbalances can occur if fertilisers are applied without a clear understanding of whether they are required or not. This may lead to yield losses, unnecessary costs, and other environmental issues associated with excess fertiliser application. To address this knowledge gap, our study examined the current soil fertility status among smallholder macadamia farms in Malawi. Specifically, the objective was to establish an evidence base for promoting soil fertility restoration interventions for smallholder macadamia production. One hundred and eighty nine soil samples at a depth of 0–15 cm were collected from sixty three smallholder macadamia farms belonging to the Highlands Macadamia Cooperative Union Limited members in central and southern Malawi. We found that the majority of the soils were sandy loams (52%), strongly acidic (mean $\mathrm{pH} \leq 5.1$), and deficient in essential nutrients required for the healthy growth of macadamia. The soils had an average low cation exchange capacity of 1.67 cmol (+) kg^{-1}, which is inadequate for macadamia cultivation. Over half of the sampled soils had very low organic matter content ($\leq 1\%$). The low soil organic matter content, coupled with the sandy texture and high acidity, contributed to the observed low concentrations of essential nutrients and cation exchange capacity. Poor agronomic practices and the long-term uptake of nutrients by macadamia trees and annual crops are responsible for this low soil fertility. Altogether, our findings underscore the urgent need to identify and implement more sustainable and effective soil nutrient management practices that help to improve the soil fertility of macadamia farms under smallholder systems.

1. Introduction

Fertile and productive soils play a key role in agricultural production and crop yield (Ngwira et al., 2012; Asfaw et al., 2018). Globally, particularly in Africa, soil fertility is declining due to intense and mismanaged farming. This has resulted in significantly lower crop yields in the region relative to other continents. For example, the average yield productivity of maize in southern Africa increased from 1.6 metric tonnes per hectare (t ha^{-1}) in 2016 to 2.0t ha^{-1} in 2020, whereas in South America and Asia, yields increased from 3 to 4.5t ha^{-1} during the same period (The World Bank). In Malawi, declining soil fertility has been identified as a major factor limiting crop production (Snapp, 1998; Ligowe et al., 2017). Continuous cropping and lack of agricultural inputs are the common sources of this problem in the country (Nájera et al., 2015; Asfaw et al., 2018). Studies conducted in Malawi show that long-term cultivation of a single crop, especially maize and tobacco, depletes soil fertility (Ngwira et al., 2013; Stevens & Madani, 2016; Bouwman et al., 2021). Further, soil fertility loss is linked to weathering, erosion, and blanket fertiliser applications (Asfaw et al., 2018; FAO, 2022). Understanding the soil fertility status of previously cultivated arable lands where high-value perennials such as macadamia are currently grown is essential for Malawi's long-term agricultural productivity.

Macadamia (*Macadamia integrifolia, M. tetraphylla*, and hybrids) is one of the world's most profitable export nut crops (Zuza et al., 2021a). The crop is native to the highly weathered acidic soils of north-eastern Australia but grows productively in subtropical climates (Moncur et al., 1985). Over forty countries are actively engaged in the cultivation of macadamia nuts, with a market value of over $1.14 trillion (INC, 2021). The crop is essential to the economies of producing countries as it contributes to income generation and revenue from foreign exports (Barrueto et al., 2018; Zuza et al., 2021b). The growing public knowledge of the health benefits of consuming macadamia nuts has led to a 45% increase in macadamia nut production over the past decade compared to the previous decades (INC, 2021). Because of this, the international retail market prices for first-grade macadamia nuts are higher than those for other nut crops ($\geq$ \$25 kg^{-1}) (INC, 2021).

Macadamia nuts have high socio-economic value for smallholder producers in rainfed agricultural economies of the world, including Malawi. Producing two percent of total global production, Malawi is ranked the world's eighth-largest producer of macadamia nuts (INC, 2021). The nuts are a high-value export crop with an estimated value of over $30 million. As a result, Malawi's macadamia industry is rapidly expanding. Additionally, the Malawi government's *Vision 2063* commercialisation programme on strategic crops like macadamia is expected to facilitate a further increase in the production and marketing of the crop (Malawi National Planning Commission, 2022).

Macadamia production in Malawi is divided into two distinct subsectors: commercial estate (highly intensive with hectarages above 100 hectares) and smallholder (small-scale production with limited use of mechanization and usually no more than two hectares for production), and a growing intermediate scale of growers between these two. Production is dominated by the commercial estate subsector accounting for more than 90% of overall output (Evans, 2020; Zuza et al., 2021a). However, smallholder production has rapidly increased, particularly during the past decade, starting from a low base. This expansion has provided many smallholders with a unique option to support their livelihoods. In addition, with an estimated net carbon sequestration potential of 3 t CO_2e ha^{-1} year^{-1} (Murphy et al., 2012), macadamia is attractive for contributing to both economic development and decarbonisation.

Despite the expansion of the smallholder macadamia subsector in Malawi, smallholder crop yields are substantially lower ($\leq$ 8 kg tree^{-1}) than those of commercial estate producers ($\geq$ 20 kg tree^{-1}) (Toit et al., 2017). The low input context of smallholder farmers on already nutrient-deficient soils has led to these massive yield reductions (due to inherent fertility issues and land mismanagement) (Evans, 2021). On top of the general scarcity and suboptimal management of organic fertilisers (i.e., farmyard manure, mulch, and crop residues), the lack of adequate replenishment of soil nutrients is one of the factors for the low macadamia yields among the smallholders (Zuza et al., 2021a).

The importance of soil fertility for macadamia production and productivity cannot be over-emphasized, as it impacts nut retention, quantity, and quality, all of which determine the yield and market value of the nuts produced (Bright, 2019; Evans, 2021). For optimal growth and quality yields, macadamia trees require a soil pH between 5.5 and 6.5, adequate amounts of soil organic matter (SOM), and essential nutrients, especially during the sensitive phenological stages of flowering, nut development, and oil accumulation (Cull et al., 1986; Bright, 2018). For example, a study indicated that an insufficient supply of essential nutrients results in nutrition deficiencies in macadamia trees (Aitken et al., 1990). A related study showed that nutritional imbalance promotes floral abortion and contributes to macadamia yield losses (Stephenson et al., 1997). Zhao & Dong (2019) found that excessive application of phosphorus (P) inhibits the development of cluster roots and rhizosphere processes, thereby decreasing the P-use efficiency and inducing iron deficiency. Research undertaken in Malawi has revealed that the majority of the soils lack soil organic matter (SOM) and many of the essential nutrients, including nitrogen (N), potassium (K^+), boron (B), and zinc (Zn) (Matabwa & Rowell, 1997; Njoloma et al., 2016; Gashu et al., 2021). Consequently, these nutritional deficiencies limit the production potential of macadamia in Malawian soils.

Soil micronutrients are essential to the global functioning of ecosystems and food production (Jiménez et al., 2022). Soil micronutrients, primarily B and Zn, are crucial for macadamia nut set, yields, and quality (Stephenson et al., 1986). Boron is required for the development of new tissues and nut set (Trueman, 2013). Zinc is essential for the fertility of the female parts of the macadamia flowers and for auxin metabolism, both of which contribute to fruit quality and disease resistance (Nagao & Hirae, 1992). As such, a thorough understanding of soil limiting factors among Malawian smallholder macadamia farms is essential to creating site-specific soil fertility management strategies and fertiliser recommendations for the crop. This is because applying fertilisers without knowing whether they are needed or not may lead to excessively low or high levels of some nutrients, which may negatively impact macadamia tree growth, yields, and quality. Moreover, available fertilisers high in N:P:K and without the correct mix of micronutrients are usually targeted for maize production and can be less appropriate for macadamia nutrition.

To date, soil fertility studies on smallholder macadamia farms in Malawi are still lacking. Because of this, smallholders still adhere to early recommendations provided in the 1990s for sustaining soil fertility on their macadamia farms. Assessing the soil fertility status of smallholder macadamia farms to identify underlying nutritional deficiencies is key to determining soil improvement recommendations. Furthermore, the lack of quantitative knowledge prevents smallholders from taking cost-effective corrective actions, thereby reducing the crop's potential yields. Realising the severity of these challenges, the present study was undertaken to better understand the soil fertility status among smallholder macadamia farms throughout Malawi and to compare the results to actual macadamia tree requirements. This should allow the first steps for effective nutrient management resulting in more efficient land use for sustainable smallholder macadamia production.

2. Materials And Methods

2.1. Study sites

The study was conducted in Malawi, a country located in southern Africa. The country has a subtropical climate with two distinct seasons, the rainy season from November to April and the dry season from May to October. Soil samples were collected from beneath age uniform trees (10-year-old macadamia orchards) at 63 locations among Highlands Macadamia Cooperative Union Limited (HIMACUL) members. These were Nachisaka (NSA) in Dowa district, Chikwatula (CTA), Malomo (MLM), Mphaza (MPA), and Tithandizane (TZE) in Ntchisi district, Mwanza (MA) in Mwanza district, and Neno (NN) in Neno district (Fig. 1). These cooperatives represent the country's primary smallholder macadamia production areas in terms of the number of growers and area under production (Zuza et al., 2021a).

2.2. Soil sampling procedure

Soil samples were collected from all study sites during the dry season in 2019 between August and September. Three undisturbed soil cores of 7 cm diameter were sampled from macadamia farms with an 8 m by 8 m tree-spacing (the middle and two other random locations) at 0 – 15 cm depth. A total of 27 soil samples were collected from nine locations in each cooperative, making an overall total of 189 soil samples. The study only focussed on the topsoil because macadamia has a shallow taproot and draws the majority of its nutrients through fibrous proteoid root systems near the soil's surface. Soil cores were trimmed at both ends immediately after collection, covered with plastic caps, and transferred to the Lilongwe University of Agriculture and Natural Resources (LUANAR) Plant and Soil laboratory situated in Lilongwe city. After air-drying, the soil samples from each core were sieved using 2 mm sieves to remove large particles, debris, and stones. A composite soil sample was generated by combining the three soil samples from each macadamia farm. Using soil standard preparation techniques outlined by Njoloma et al. (2016), 10 g of the composite soil sample was weighed and used for each analytical method.

2.3. Soil analysis

The soils were analysed for pH in a 1:2.5 soil to water slurry (McLean, 1982) using a calibrated electrode pH meter at room temperature (OrionVersaStar®), particle size distribution (texture) using the Bouyoucos hydrometer method as described by Bouyoucos (1962) at the LUANAR Plant and Soils laboratory, and soil electro-conductivity (EC) using the method outlined by Wanda et al. (2013) at The Open University's, Ecosystems and Geobiology Laboratories (EGL). The cation exchange capacity (CEC) was determined by the ammonium acetate method (Metson, 1956), and available P was measured using the Olsen P method (Hodges & Sharpley, 2004) also at EGL.

Soil organic carbon (SOC) was assessed by wet digestion and colorimetric scale using the Elemental Vario EL Cube® analyser. Total N (TN), available K^+, and other nutrients (B, Zn, sulphur/S, calcium/Ca^{2+}, magnesium/Mg^{2+}) were analysed using the Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES)®, Agilent 5110 at EGL. The soil's physical and chemical properties were analysed over several analytical sessions, with three replication runs for each element, and mean values were used for the statistical analyses.

2.4. Statistical analysis

Analysis of variance (ANOVA) and mean comparisons were carried out using the general linear model (GLM) procedure in R® Statistical Computing Software version 4.2.0 (R Core Team, 2018). The assumptions of the ANOVA were tested by ensuring that the residues were random, homogeneous, and with normal distribution. Based on Bartlett's test, all soil properties exhibited a homogeneous variance. Shapiro's test revealed normal distributions for the soil's physical and chemical properties. When the *F-test* showed statistical significance at $p \leq 0.01$ or $p \leq 0.05$, the Tukey Honest Significant Difference (HSD) post hoc test was used to evaluate the significance of differences between pairs of group means (Tukey, 1949). Pearson's correlation coefficient matrix was further used to describe relationships among the soil properties.

3. Results

3.1. Soil texture

Using the USDA classification system, six distinct soil texture classifications were identified among the study sites (Table 1). The textural classes were principally sandy loams (52%) to sandy clay loams (15%), with some soil layers subtending clay loams (13%), loams (12%), and silty clay loams (5%). However, site-specific soil assessment revealed substantial variation within and between the farms among the cooperatives. For example, we observed that some farms in Tithandizane cooperative had silty clay loams with a silt content of less than 2%, while others had silt contents of more than 25%.

Soils in Nachisaka cooperative contained a high concentration of sand (57–81%) (Fig. 2a), followed by clay (13–29%) (Fig. 2b) and some low proportions of silt ranging from 2–14% (Fig. 2c). These soils have thus been categorised as sandy loams. Sandy clay loams (11.7%) were the most common type of soil in Tithandizane cooperative as they had considerable concentrations of clay and silt (Fig. 2b and Fig. 2c). Similar to Nachisaka, Malomo and Mphaza cooperatives had sandy loam soils (Fig. 2d).

3.2. Soil pH and Cation exchange capacity

Soil pH is a measure of soil acidity or alkalinity. The pH of the soil sites did not differ significantly ($p > 0.05$) across the study sites. The soil pH ranged from 4.6 to 5.88, with a mean value of 5.10, indicating strongly acidic soil (Fig. 3a). Despite not being statistically different, we observed that Tithandizane soils had the highest mean pH values (5.26). Similar mean values were found for Mwanza (5.15), Mphaza (5.13), Neno (5.05), Malomo (5.02), Chikwatula (5.01), and Nachisaka (5.00) cooperatives.

The cation exchange capacity (CEC) indicates the ability of soil to hold onto and exchange cations, including plant nutrients such as Ca^{2+}, $Mg^{2+,}$ and K^{+}. In the current study, the mean CEC values did not differ significantly ($p > 0.05$). In general, the cation exchange capacity CEC in the smallholder macadamia farms evaluated was very low and ranged between 0.34 cmol (+) kg^{-1} and 3.77 cmol (+) kg^{-1}, with an average of 1.67 cmol (+) kg^{-1} (Fig. 3b). This showed that the CEC of the sampled soils were below (3–8 cmol (+) kg^{-1}) the global averages commonly reported for macadamia soils (Table S1). The relationship between CEC as the dependent variable and soil pH as the explanatory variable was significant at $p \leq$

0.001, and the adjusted R-square was 0.55 (Fig. 3c); that is, soil pH explained 55% of the variation in CEC. This showed that the soil pH among the sampled macadamia farms influenced the cation exchange capacity.

3.3. Soil organic matter

Soil organic matter primarily consists of organic carbon, which is commonly used to assess soil fertility. Our study has revealed that the SOM content among the sampled smallholder macadamia soils in Malawi is lower (Fig. 4) than the critical (2–5%) required level for healthy functioning of soil. Minimum and maximum values across the farms ranged from 0.26 to 2.96%, with an average of 1.13%. More than half of the study sites had soil organic matter content lower than one percent, 36.7% had less than 1.8% SOM content, and only 7.9% had a SOM content greater than 2%. Moreover, Chikwatula (1.31%) and Malomo (1.25%) cooperatives had the highest mean SOM content, whereas Mwanza (0.87%) cooperative had the lowest mean SOM content, suggesting that land management factors may be responsible for the SOM content on the farms.

3.4. Soil macronutrients

The findings of our study indicate that the levels of total nitrogen (TN) and available potassium did not differ significantly across the sampled smallholder macadamia farms. In 70% of the study sites, the TN levels ($\leq 0.08\%$) were below the values considered optimal ($\geq 3\%$) for macadamia growth. We found that the TN content ranged between 0.065% and 0.102% (Fig. 5a). The total soil K^+ concentrations were sufficient (Fig. 5b) in four of seven sites compared to the recommended range (200–300 mg kg^{-1}) for macadamia production. Mwanza cooperative recorded the highest mean concentration of K^+ (237 mg kg^{-1}), whereas Chikwatula cooperative had the lowest mean concentration of K^+ (176 mg kg^{-1}). Significant differences ($p \leq 0.01$) were observed regarding available P among the sampled smallholder macadamia farms. Mean comparisons showed that Mphaza cooperative had the highest mean phosphorus value of 46.1 mg kg^{-1}, while Chikwatula cooperative had the lowest mean P value of 9.82 mg kg^{-1} (Fig. 5c). Overall, only 17% of the sampled soils met or exceeded the recommended threshold of 30 mg kg^{-1}, indicating a general deficiency in soil available P.

Available sulphur concentrations significantly varied ($p \leq 0.02$) between macadamia farms among the study sites. The available S concentrations ranged from 2.06 mg kg^{-1} to 27.03 mg kg^{-1}, with an average of 10.9 mg kg^{-1} (Fig. 5d). Five of the seven cooperatives had farms with available S concentrations within the recommended range (10–300 mg kg^{-1}) for macadamia production. No significant differences ($p > 0.05$) were observed in the concentration of available Ca^{2+} among the study sites (Fig. 5e). Nearly all of the farms under the study had lower Ca^{2+} levels than desirable for macadamia production. Further, the average calcium concentration of the soils examined (417.9 mg kg^{-1}) was threefold lower than the minimum optimal level ($\geq$ 1200 mg kg^{-1}). Nachisaka cooperative had the highest average concentration of Ca^{2+} (677 mg kg^{-1}), while Mphaza had the lowest concentration of the nutrient (267 mg kg^{-1}). Only one farm in the Mwanza cooperative had optimal Ca^{2+} concentrations (1300 mg kg^{-1}) Ca2+, out of all the sampled farms.

Significant differences were observed in terms of the concentrations of magnesium among the sampled macadamia cooperative farms ($p \le 0.024$). Tithandizane cooperative had the highest average of Mg^{2+} (84.9 mg kg^{-1}). Mwanza, in contrast, had the lowest average of Mg^{2+} (38.5 mg kg^{-1}). Despite these differences, available Mg^{2+} levels at all the study sites were deficient, with an average of 60.4 mg kg^{-1} (Fig. 5f) below the optimal level of 170 mg kg^{-1} required for the healthy growth of macadamia trees.

3.5. Soil available boron and zinc

The total available boron concentrations among the smallholder macadamia farms ranged from 0.02 to 0.29 mg kg^{-1}, with none exceeding the lower threshold concentration ($\ge$ 1 mg kg^{-1}) recommended for macadamia production (Fig. 6a). Compared to the recommended ranges, we observed that 95% of the soil samples in this study were deficient in B. Zinc, next to boron, is often the most limiting nutrient for macadamia production. Our study has shown that Zn exhibited similar patterns as those of boron, with very low concentrations in all the study areas ($\le$ 0.4 mg kg^{-1}) than the optimal ($\ge$ 3 mg kg^{-1}) (Fig. 7b). Additionally, 98% of the sampled soils were below the threshold for Zn.

3.6. Relationships among soil physical and chemical parameters

This study has shown significant negative relationships between sand content with soil nutrients, cation exchange capacity ($R^2 = -0.48$), and organic matter content ($R^2 = -0.33$) (Fig. 7). This suggests that the higher sand concentrations impact the availability of soil nutrients in the soil. Correlations among soil nutrients were negatively significant for available S versus available P, and Ca^{2+}, implying that these nutrients were affected by different factors. We also found significant positive relationships for soil pH with available B, Ca^{2+}, K^{+}, P, Zn, total N, and CEC. In contrast, a strong negative correlation ($R^2 = -0.48$) was found between available sulphur and soil pH. This suggests that the soil pH was affected by the concentration of sulphur. Furthermore, we found that cation exchange capacity was significantly inversely related to sand ($R^2 = -0.48$), clay ($R^2 = -0.48$), and silt ($R^2 = -0.33$) concentrations among the study sites.

4. Discussion

Declining soil fertility and productivity is a major challenge among smallholder farmers in Malawi (Kumssa et al., 2022). Poor soil fertility is recognised as a key obstacle to macadamia production globally. In Malawi, studies and recommendations on soil fertility improvement on macadamia farms have been tailored for the commercial macadamia subsector as opposed to the smallholder subsector (World Bank, 1994). For this reason, it is challenging for smallholders to address nutrient deficiencies on their farms. Therefore, this study sought to address this knowledge gap and to determine soil fertility improvement recommendations for the smallholder macadamia producers.

4.1. Current soil fertility status and macadamia needs

Soil texture and structure are important soil properties that define the general inherent capacity of soil and have profound implications on the soil's water holding capacity, drainage, nutrient retention and supply, and nutrient leaching (Nalivata et al., 2017; Huang & Hartemink, 2020; FAO, 2022). Our study reveals that the majority (67%) of the soils among smallholder macadamia farms in the study sites are sandy, i.e., sandy loam (52%) or sandy clay loams (15%), while only 16% are classified as clays, i.e., clay loam (13%) and clay (3%). These findings concur with descriptions of Malawi soils as generally sandy in texture (Li et al., 2017; Eze et al., 2020).

However, we observed variations in soil textural classes at the individual farm levels. We noted that some macadamia farms, especially those in hilly areas of Nachisaka, Neno, and Tithandizane cooperatives, had a greater sand content (≥ 70%) than the other cooperatives. One possible reason is soil erosion which was evident during the field survey. This was possibly enhanced by the previous sifting, as ridges were made for annual crops. Contrarily, the proximity of some areas in Malomo, Nachisaka, and Mwanza cooperatives to Lake Malawi and Shire valley explain why some of the farms in these areas have a higher sand content. However, some soils, as can be seen in Fig. 2b and Fig. 2c, have higher clay content (≥ 40%). This is because the farms are located in flood alluvial plains (locally known as dambos).

The high sand content in the study sites negatively impacted the availability of essential soil nutrients and contributed to the lower levels of CEC and SOM content (Fig. 7). Because of these characteristics, sandy soils have poor soil fertility status, necessitating regular and increasing levels of fertiliser applications to ensure the healthy growth of crops annually. However, this is becoming increasingly difficult for Malawi's smallholders to achieve and afford. Additionally, this has been made worse by the rapid increase in fertiliser costs (more than 130–160% higher than in 2020) and limited availability attributed to Russia's invasion of Ukraine, both of which are major global suppliers of fertilisers.

Soil pH is a crucial indicator of soil fertility since it influences the availability of all nutrients in the soil. This study has shown that only 11.1% of the sampled macadamia farms have soil pH levels within the optimum range for the crop. This translates to about 4.76% of macadamia farms belonging to Tithandizane cooperative and 1.59% of macadamia farms belonging to each of the four cooperatives (Chikwatula, Mwanza, Mphaza, and Neno). We learned from HIMACUL staff that some of the wealthy macadamia smallholders, especially those whose soils had a near-neutral pH, use agricultural lime to manage the pH of their soils. In contrast, 87.3% of the soil samples were strongly acidic (≤ 5.5), rendering them unsuitable for growing macadamia production.

Principal contributors to the soil's strong acidity were agronomic practices, loss of major cations (leaching and soil erosion), and higher nutrient uptake accompanied by lower nutrient replenishment. Some examples of agronomic practices include low input of organic materials, previous continuous monoculture of annual crops, and use of higher rates of compound inorganic fertilisers, especially NPK, in an effort to achieve higher growth and productivity of crops. Our results complement and, more importantly, extend the findings of Mutegi et al. (2015), who found that continuous monoculture and blanket inorganic fertiliser applications are responsible for soil acidification in Malawi. Moreover, soil acidification may have been exacerbated through the inorganic fertiliser only nutrition strategy among the smallholders (Dougill et al., 2002; Steward et al., 2018).

The strong soil acidity in some of the upland areas (≥ 1400 m.a.s.l) of Chikwatula and Tithandizane cooperatives can be partially attributed to the heavy precipitation amounts received in these areas (Table S2). According to Munthali et al. (2021), the intense precipitation received in the higher altitude areas (1200–1700 m.a.s.l) of Dedza district makes the soil vulnerable to acidification and nutrient losses due to soil erosion, confirming our study results. Thus, for areas that receive intense precipitation, water management technologies that promote infiltration are recommended. These may include constructing box, contour, and tier ridges, mulching, intercropping, and using live plants such as vetiver grass.

CEC is an important soil property that influences soil structure stability, nutrient availability, pH, and the soil's response to fertilisers and other ameliorants (Hazelton & Murphy, 2016). We have observed that soils from all study sites barely exceed the lower threshold for CEC, which for sandy soils falls between 5 and 10 cmol (+) kg^{-1} (Van Ranst et al., 1999). This reflects the soil's high sand content, strong acidity, low organic matter content, and possibly the clay type (kaolinite). In Malawi, Mloza-banda et al. (2016) found that acidity lowered the CEC of soil, thus verifying our results. Furthermore, the lower CEC may be attributed to the rapid mineralisation rate resulting from previous conventional tillage practices by smallholder farmers.

The present study has also revealed a negative correlation ($R^2 = -0.48$) between cation exchange capacity and clay content. This suggests that the SOM fractions, rather than clay particles, are the source of CEC across our study sites. As kaolinite clays are predominant in Malawi, including our study areas, the finding by Tudela et al. (2010) that kaolinite clays do not contribute much to the CEC provides additional context for our results. Moreover, Bortoluzzi et al. (2006) found that organic matter fractions contribute more than 50% of the negative charges in the soil compared to clay particles (31%). This demonstrates that organic matter fractions have a greater impact on the CEC of the soil than clay particles.

Soil organic matter, is crucial for crop productivity and maintaining soil health (Belachew & Abera, 2010; Omuto & Vargas, 2018). Majority of the sampled macadamia farms in this study have very low levels of SOM (≤ 1%), below the recommended threshold (≥ 2%) for macadamia. This is partially attributed to previous conventional tillage practices, continuous cultivation, the inherent nature of sandy soils and the smallholders' low incorporation of organic residues. However, while most of the sampled macadamia farms had very low SOM levels, 3.2% and 4.7% of the sampled farms in Chikwatula and Malomo had optimal soil organic matter levels. Field observations and farmer conversations revealed that the incorporation of farmyard manure and crop residues were responsible for the observed higher SOM content. These farmers reported having easy access to farmyard manure due to their ownership of considerable herds of cattle and goats (made possible by livestock pass on programmes in the areas) and crop residues because of the cultivation of legumes. Thus, encouraging the incorporation of livestock manure and crop residues is also a viable option for increasing the content of SOM among smallholder macadamia producers in Malawi.

The results of this study have shown variability in terms of essential nutrient concentrations in smallholder macadamia farms. We found that the total N concentrations among the study sites were below the average values recommended for macadamia soils. However, our results have also revealed that the average potassium concentrations of the examined soils were adequate for macadamia production. Nevertheless, at the individual farm level, only 44.4% of the sampled soils had adequate levels of available K^+. These results suggest that soil potassium reserves on some macadamia farms within the cooperatives are becoming inadequate for macadamia's needs.

Soil available phosphorus among the study sites was generally deficient. About 83% of the soils were below the critical value of 30 mg kg^{-1} recommended for macadamia. The average concentration of available P was only sufficient for macadamia production in Mphaza cooperative. This is because five of the sampled macadamia farms were markedly high in soil available P ($\geq$ 50 mg kg^{-1}), which can be attributed to previous monoculture tobacco production and the ongoing intercropping of tobacco in the rows of macadamia trees. With regard to available calcium and magnesium, we have established that nearly all of the study sites were deficient in both elements. We recommend the application of lime in order to increase the levels of calcium and the application of dolomite to increase the levels of magnesium in smallholder macadamia producing areas.

Boron and zinc are essential micronutrients required in small but critical amounts for macadamia's normal growth and development (Stephenson et al., 1986). In general, we found that the B and Zn levels on smallholder macadamia farms were below the minimum reference levels for macadamia production. This is due to the course texture of sandy soils, and the lack of organic matter in the soils. Our findings are consistent with Jiménez et al. (2022), who reported that low soil clay content stimulate rapid SOM decomposition in tropical ecosystems and thus reduce soil micronutrient concentrations. In addition, boron and zinc are naturally deficient in Malawian soils (Evans, 2020).

The absent utilisation of boron and zinc fertilisers may also be the reason for the low levels of B and Zn in the study areas, as the nutrients are taken up and not replenished. Evans (2021) found that commercial estate producers in the country have increased their B and Zn levels through routine foliar applications. In light of this, boron and zinc fertilisers should be made available to smallholder farmers, which are currently scarce within Malawi. Furthermore, mulching, intercropping, and cover crops should be encouraged as these systems reduce the direct exposure of soil to sunlight, thus maintaining cool temperatures in the soil and, subsequently, biological activities.

4.2. Implications of the study and recommendations for management

Nutrient management is one of the most important aspects of a successful macadamia crop. Based on our study findings, it is possible to conclude that nutritional imbalances and deficiencies are one of the factors affecting the productivity of macadamia among smallholder farmers in Malawi. According to the "Law of Minimum," a limited supply of one of the essential nutrients can limit crop yield (Austin, 2007). As such, the identified deficiencies and imbalances in the study areas will need to be addressed simultaneously to improve their soil fertility status in a reasonable amount of time.

Contrasted with what was reported in the 1990s, our findings show that the current soil fertility status of smallholder macadamia growing areas in Malawi is very different and in a poor state. Early recommendations for macadamia production were that farmers maintain and replenish soil fertility with the addition of only manure, as opposed to inorganic fertilisers. A key message from our findings is that "no one size fits all" or "silver bullet" solutions can be applied to maintain and replenish soil fertility loss in macadamia farms. Thus, soil organic matter and inorganic fertiliser application management are essential for sustainable macadamia productivity.

However, for the precise application of inorganic fertilisers, providing smallholders with local-scale information about their soil fertility status is beneficial. This can be achieved through the annual low-cost testing of soil nutrients by trained agricultural officers or lead farmers (LUANAR is already trialling this technology in some parts of Malawi). Nevertheless, this necessitates additional research to develop recommended application rates of proposed blended (mixture of micro and micronutrients) inorganic fertilisers and to understand the response of trees to fertilisers as well as the long-term effects on soil health.

With respect to crop productivity and speed in supplying soil nutrients, there is evidence that inorganic fertilisers produce higher crop yields at a point in time and readily supply nutrients to the soil for plant use. However, organic fertilisers such as manure and crop residues have longer-term benefits than inorganic fertilisers. This means that an integrated soil fertility management system is viable for cost-effective soil fertility management. For sustainable productivity, mixed use of organic (crop residues, farmyard, and green manure) and inorganic fertilisers has proved to be highly beneficial in terms of balanced nutrient supply (Li et al., 2007; Rutkowska et al., 2014; Wani et al., 2017) and significantly increased yields of various crops (Phiri et al., 2010; Mungai et al., 2016; Ghimire et al., 2017; Abbas et al., 2012; Roba, 2018). To improve the soil fertility status of smallholder macadamia farms in Malawi, we recommended that farmers utilise a combination of organic and inorganic fertilisers and practices to increase soil pH.

Soil acidity amelioration is a prerequisite for sustainable soil fertility management. When soil pH is maintained at the proper level, plant nutrient availability is optimised, the solubility of toxic elements is minimised, and beneficial soil organisms are most active (Malla et al., 2020). Therefore, raising the soil pH to near neutral (5.5–6.5) among the smallholder macadamia production areas will enable the availability of essential nutrients, particularly boron and zinc. It is therefore recommended that smallholders effectively manage the soil acidity through the application of agricultural lime or gypsum in conjunction with organic matter management.

Cover crops provide numerous benefits to agroecosystems. Specifically, they protect the soil from erosion, improve water infiltration, help to control weeds, help to reduce soil temperature and build soil organic matter (Suci et al., 2021). We thus recommend growing annual crops, especially legumes (groundnuts, pigeon peas, and soybeans), between the rows of macadamia trees. This will assist in increasing the amount of high-quality organic residues and N resulting from biological nitrogen fixation, provided that residues are retained or spread under the tree canopy. Maize-legume associations (cowpeas and pigeon peas) have been reported to enhance the status of SOM and improve soil hydraulic properties, including soil water storage pores, water transmission, and retention within the root zone in Malawi (Eze et al., 2020; Hermans et al., 2021). In addition, interplanting annual crops will ensure that farmers harvest an additional crop annually for food security, income generation, and resilience in case of crop failure. Figure 8 provides a summary of recommendations that smallholders can utilise to improve the soil fertility of their farms

5. Conclusions

The results of our study reflect that the soil fertility status of the study areas is very low for macadamia production. The study revealed that soils on smallholder macadamia farms in Malawi are predominantly sandy loams, highly acidic, and deficient in essential macro and micronutrients. In addition, the soil's cation exchange capacity and soil organic matter content are low. Poor agronomic practices among the smallholders' macadamia farming communities have been identified as the primary drivers of the observed soil fertility decline. As there are no "one size fits all" solutions, a combination of management practices is recommended to assist in the restoration of soil fertility. We advise farmers to implement agricultural practices that encourage the build-up of organic matter (such as crop residue incorporation, application of manure, cover cropping, and intercropping) and protect the soil from erosion. This should be coupled with the application of blended foliar inorganic fertilisers containing important macro and micronutrients but should consider the nutrient limitations of each growing area.

Declarations

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could be perceived as having influenced the work presented in this paper.

Funding

The research was supported by The Open University and the UK Research and Innovation via Global Challenges Research Fund (GCRF).

Data and code availability

The data, compiled code, and files used in this study are freely available on GitHub: https://github.com/EJEYZiE01/Soil-analysis.

Acknowledgements

We thank Prof. Clare Warren and Richard Holliman of The Open University, Prof. Andy Dougill of York University, Dr. Michael G. Chipeta of Oxford University, and Dr. Thirze D.G. Hermans of Wageningen University for their insightful assistance during the research and writing of this paper. We should also thank HIMACUL smallholder farmers for allowing us to collect soil samples from their macadamia farms and for welcoming us. In addition, we would like to thank Mr. Ken Mkangala for his assistance during the fieldwork. However, mistakes and omissions are our responsibility.

Appendix A. Supporting information

Supplementary materials associated with this article can be found in the online version at https://figshare.com/account/home.

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Tables

Table 1 and Supplementary Tables S1-S2 are not available with this version.

Figures

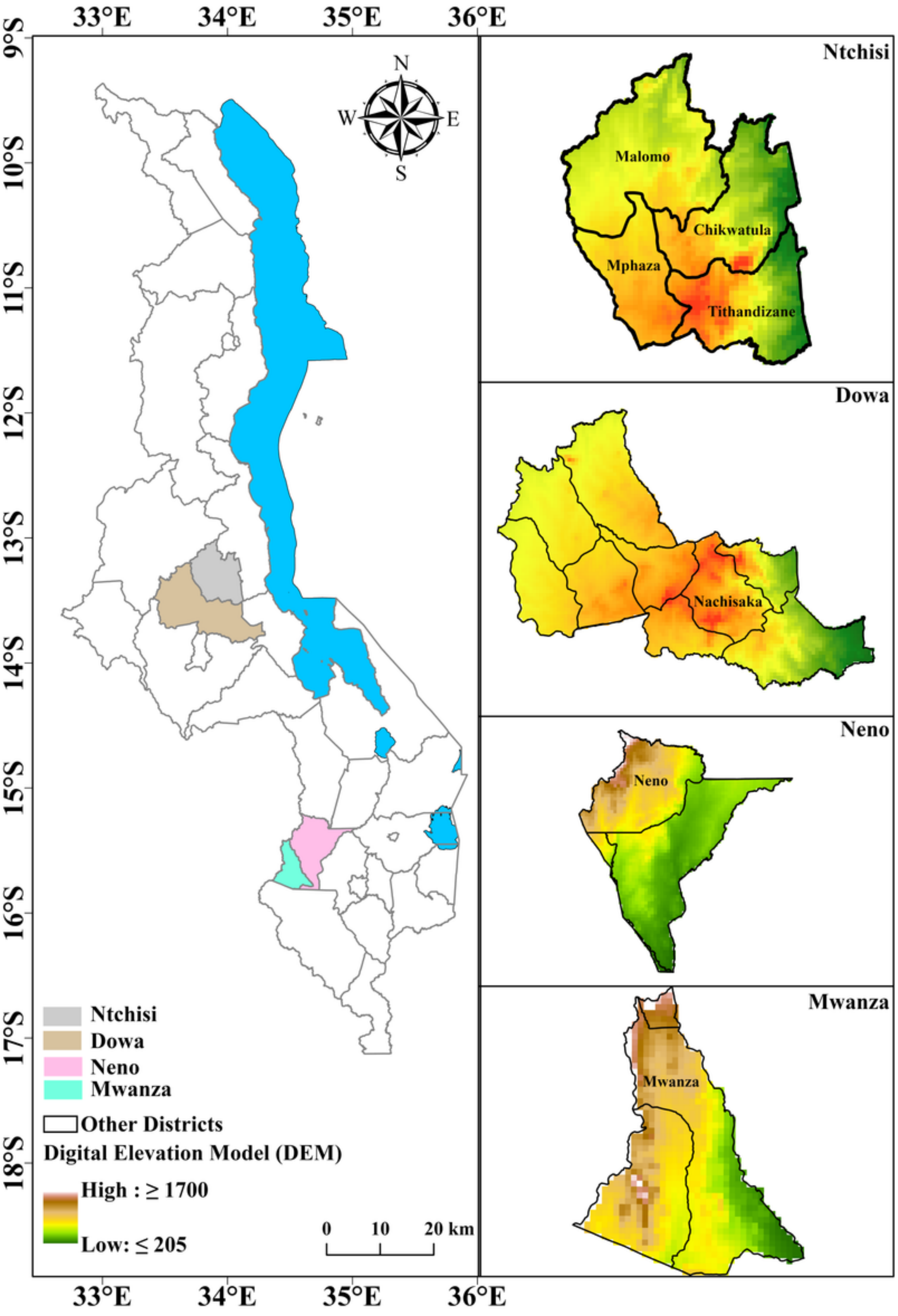


Figure 1

Map of Malawi showing study sites.

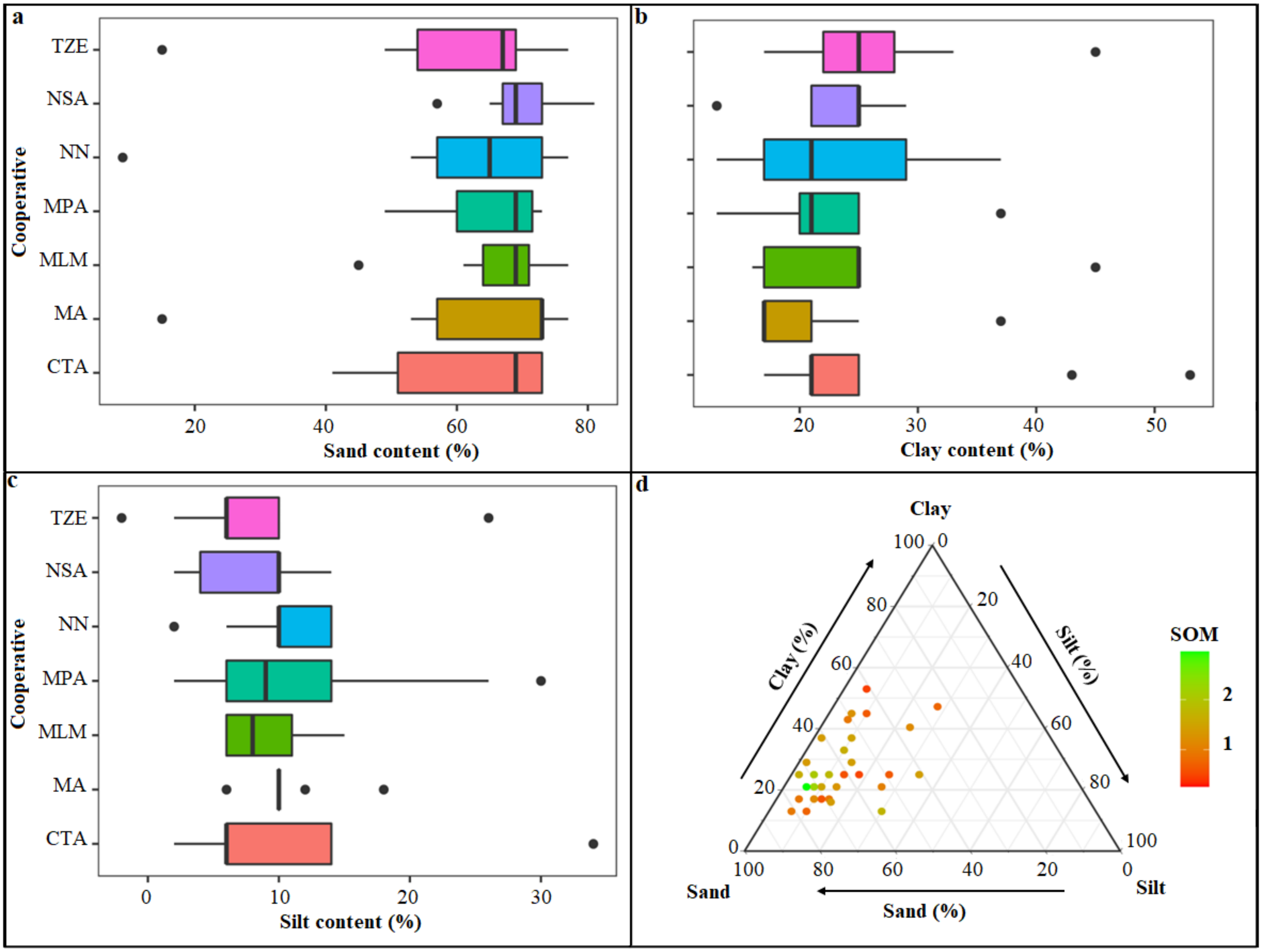


Figure 2

Percentages of a) sand, b) clay, c) silt (Dots represent outliers and the boxes represent medians ± IQRs), and d) soil triangle for each sampled site (each of the dots represents the proportion of sand, clay and silt and corresponding SOM content in %).

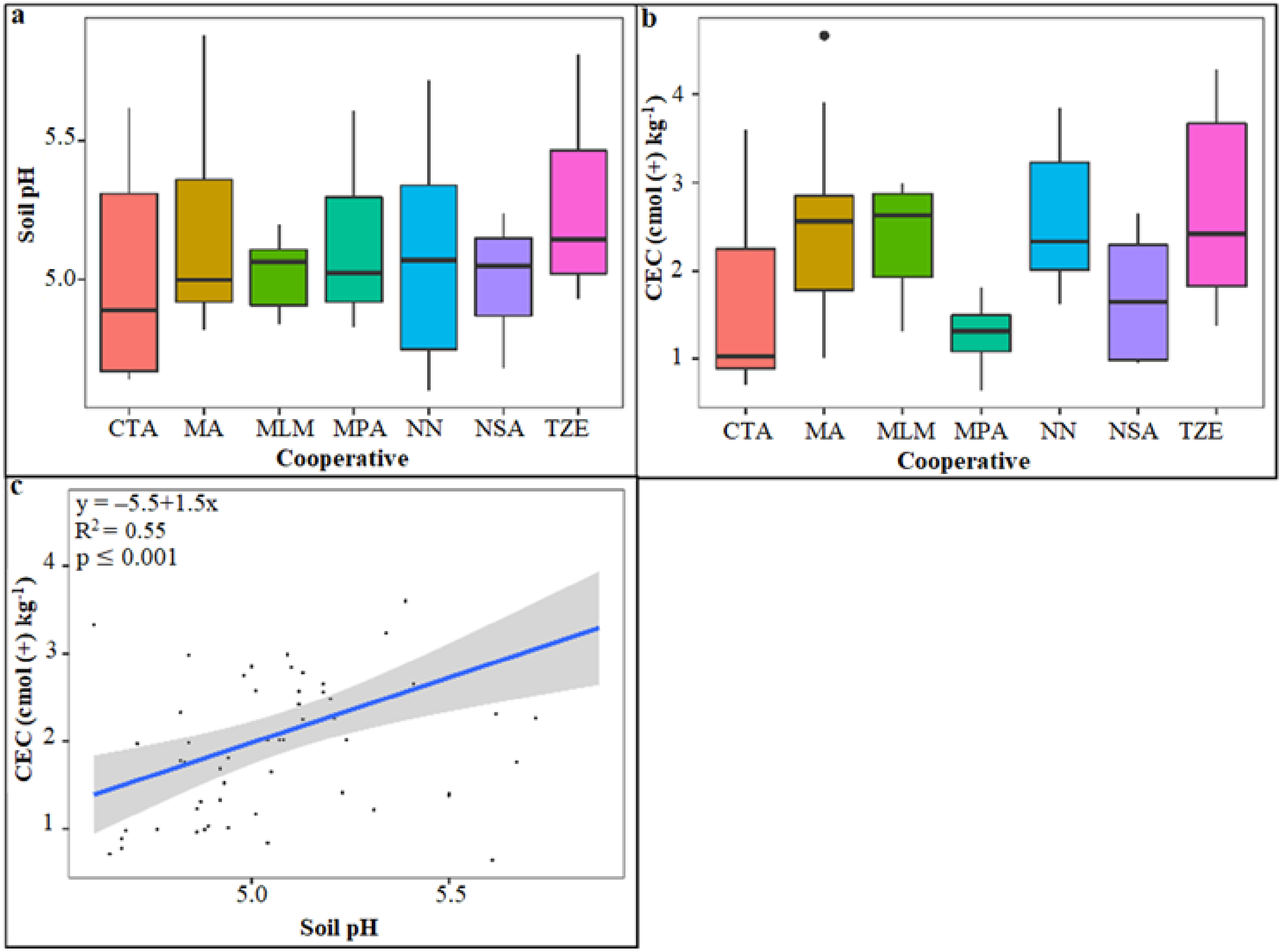


Figure 3

Distribution and variation of a) Soil pH (box plots represent median ± IQRs), b) CEC, and c) Relationship between soil pH and CEC among smallholder macadamia farms in Malawi.

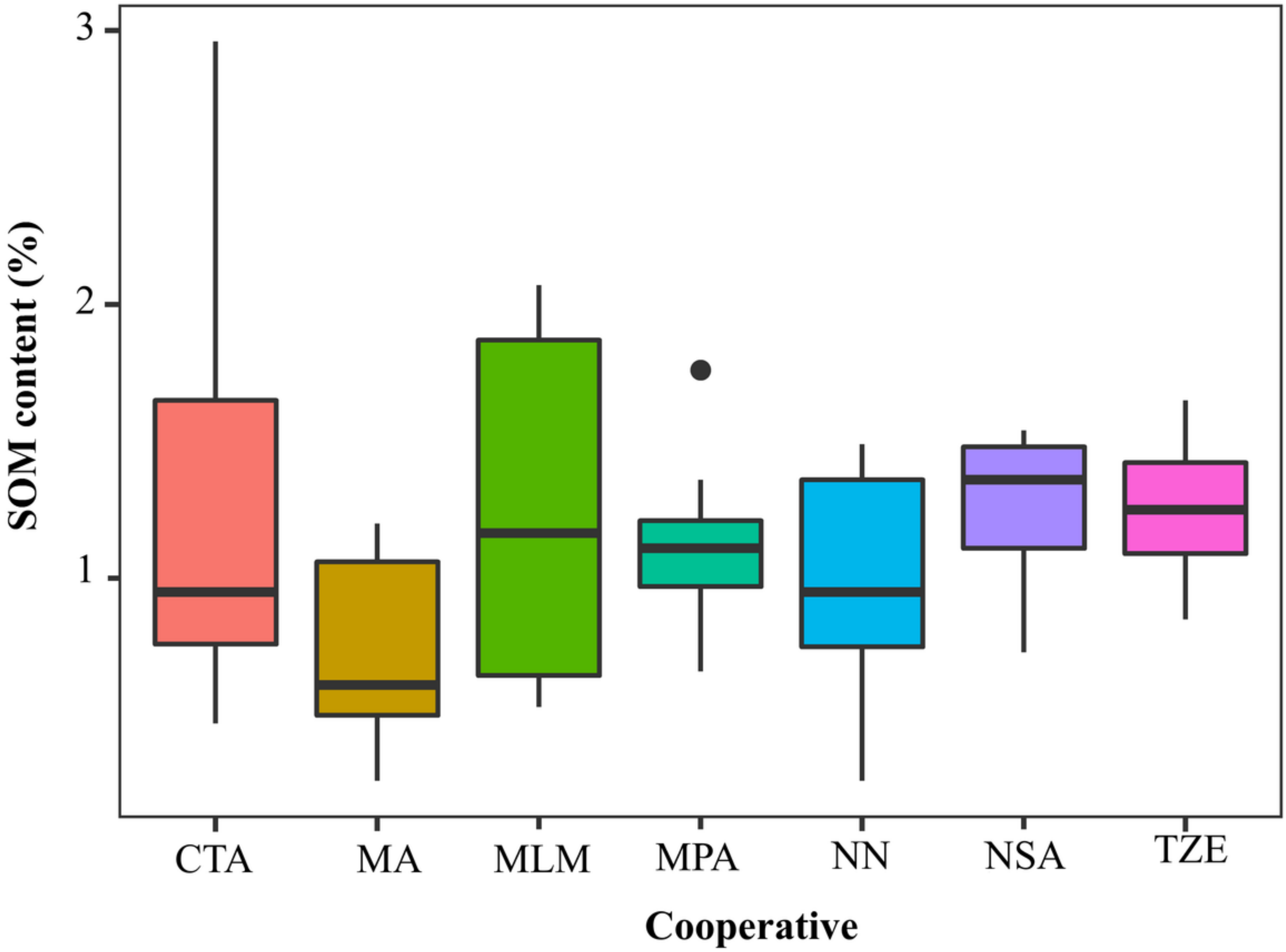


Figure 4

Soil organic matter content among smallholder farms in macadamia cooperatives in Malawi.

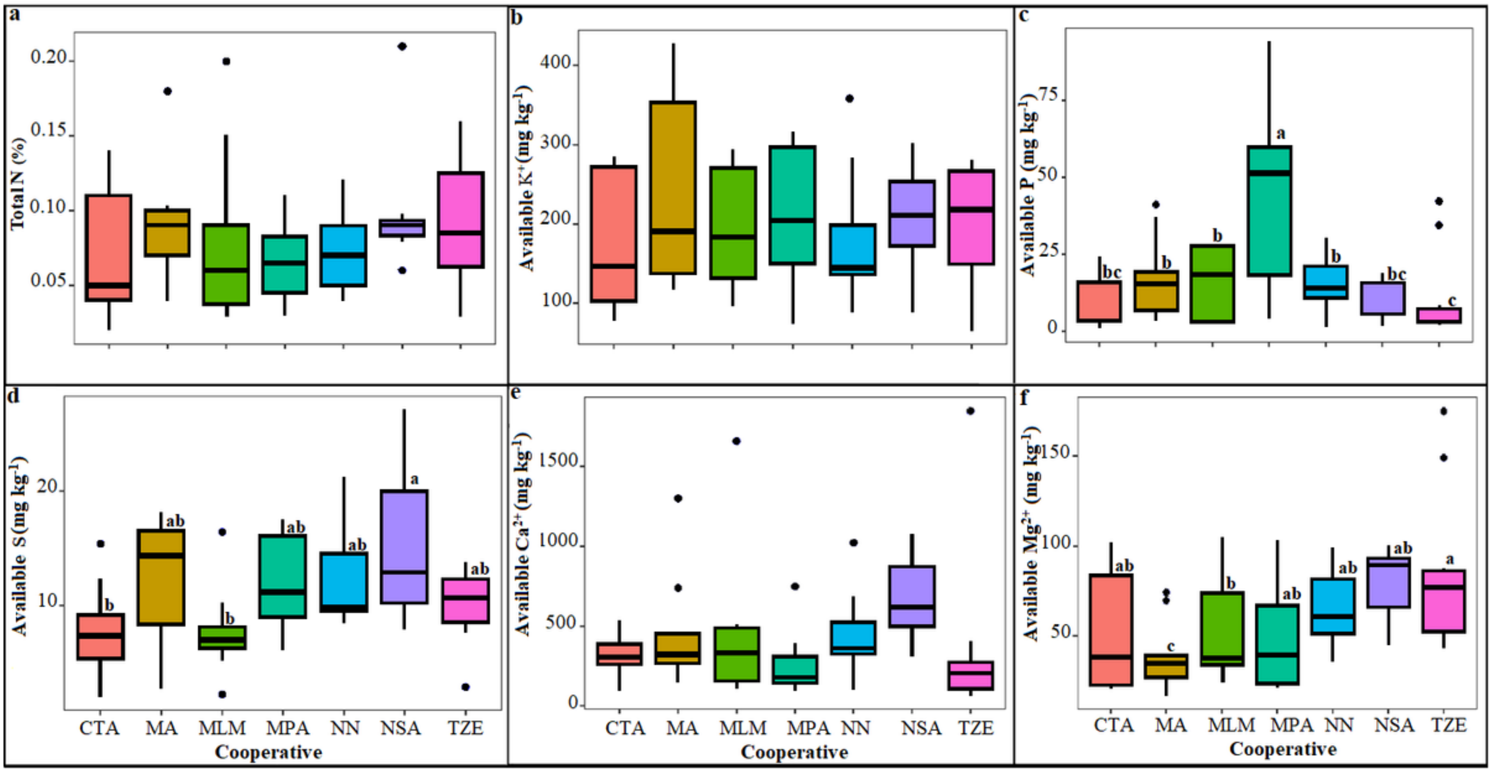


Figure 5

Status of soil macronutrients among smallholder macadamia farms in Malawi (medians followed by the same letters are statistically the same at $p \leq 0.05$).

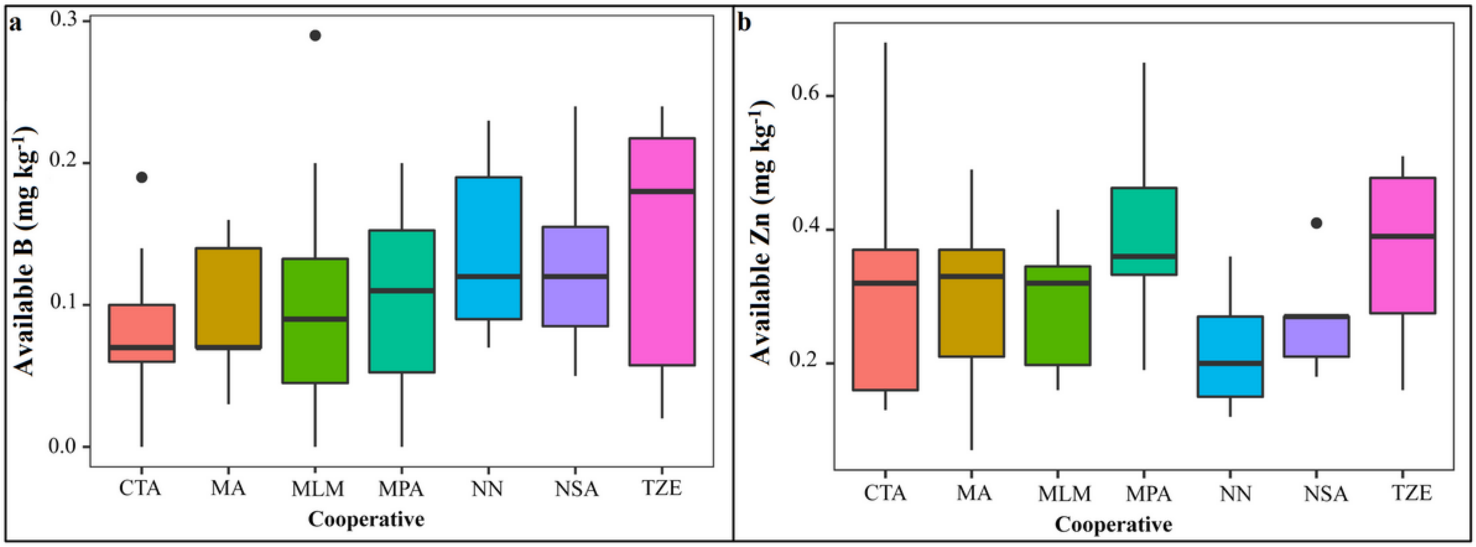
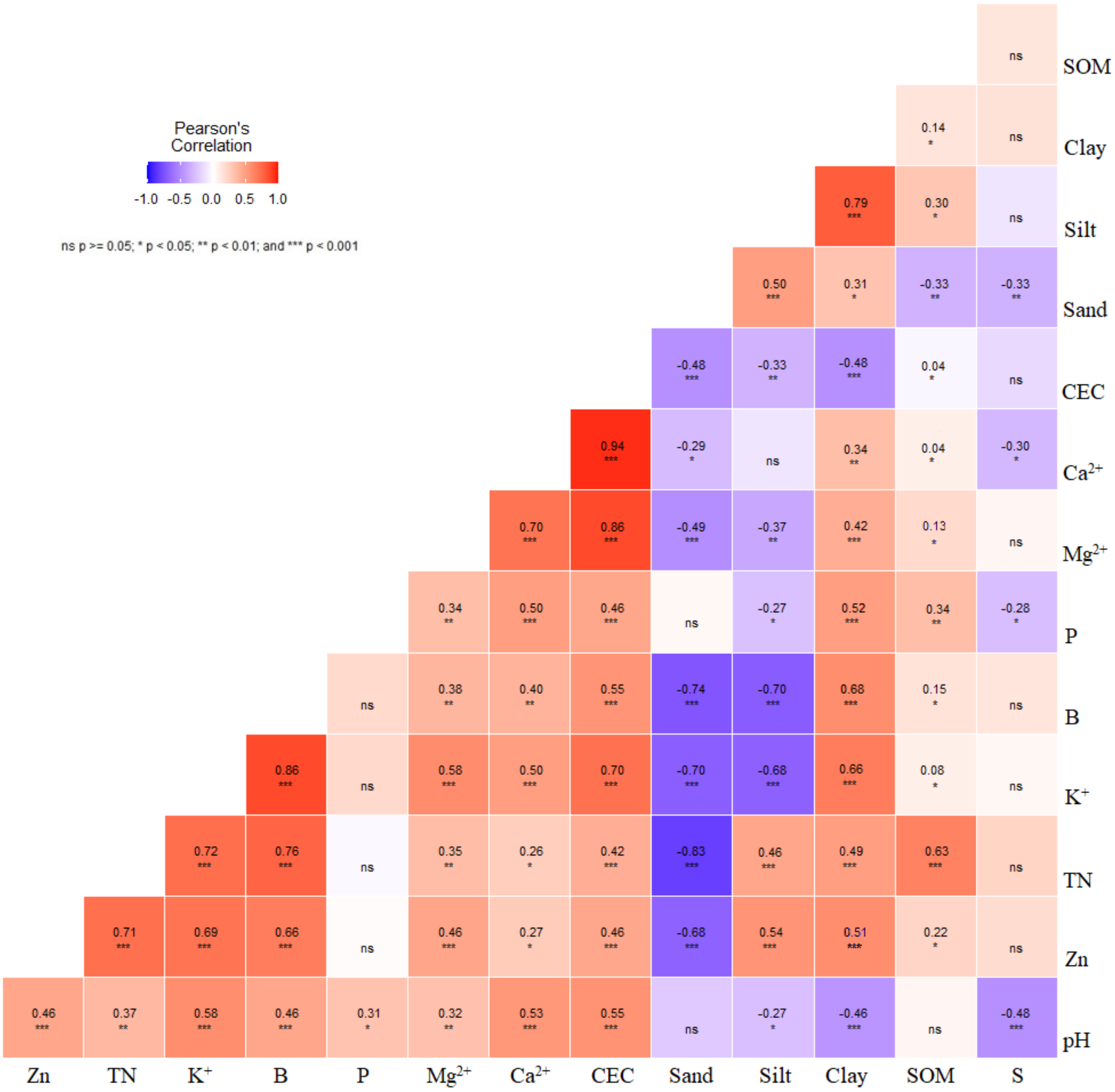


Figure 6

Distribution of boron and zinc among smallholder macadamia farms.



	Zn	TN	K⁺	B	P	Mg^{2+}	Ca^{2+}	CEC	Sand	Silt	Clay	SOM	S
SOM													ns
Clay												0.14 *	ns
Silt											0.79 ***	0.30 *	ns
Sand										0.50 ***	0.31 *	-0.33 **	-0.33 **
CEC									-0.48 ***	-0.33 **	-0.48 ***	0.04 *	ns
Ca^{2+}								0.94 ***	-0.29 *	ns	0.34 **	0.04 *	-0.30 *
Mg^{2+}							0.70 ***	0.86 ***	-0.49 ***	-0.37 **	0.42 ***	0.13 *	ns
P						0.34 **	0.50 ***	0.46 ***	ns	-0.27 *	0.52 ***	0.34 **	-0.28 *
B					ns	0.38 **	0.40 **	0.55 ***	-0.74 ***	-0.70 ***	0.68 ***	0.15 *	ns
K⁺				0.86 ***	ns	0.58 ***	0.50 ***	0.70 ***	-0.70 ***	-0.68 ***	0.66 ***	0.08 *	ns
TN			0.72 ***	0.76 ***	ns	0.35 **	0.26 *	0.42 ***	-0.83 ***	0.46 ***	0.49 ***	0.63 ***	ns
Zn		0.71 ***	0.69 ***	0.66 ***	ns	0.46 ***	0.27 *	0.46 ***	-0.68 ***	0.54 ***	0.51 ***	0.22 *	ns
pH	0.46 ***	0.37 **	0.58 ***	0.46 ***	0.31 *	0.32 **	0.53 ***	0.55 ***	ns	-0.27 *	-0.46 ***	ns	-0.48 ***

Figure 7

Correlations among soil parameters in smallholder macadamia farms in Malawi.

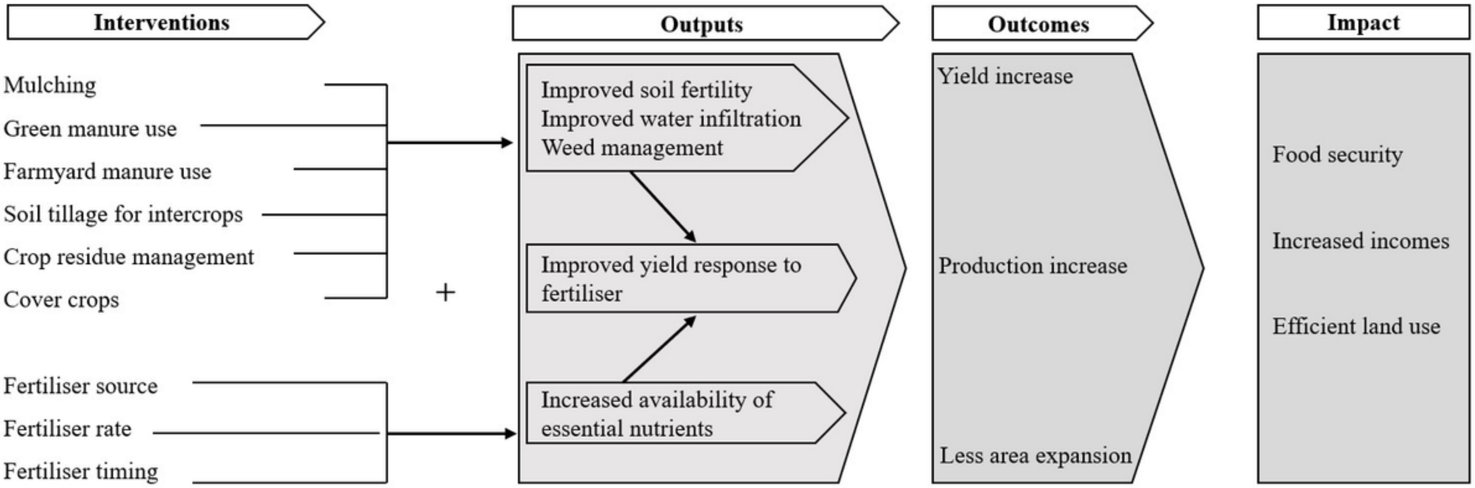


Figure 8

Recommended best-fit solutions for improving soil fertility for smallholder macadamia farmers in Malawi.