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Nutrient balances under different coffee cropping systems and soil input practices in the Mt. Elgon Region

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Abstract

The study aimed to establish the effect of coffee cropping systems and soil management on the nutrient balances at different elevations in the Mt. Elgon Region (MER) in Uganda to inform sustainable management efforts in the area. Treatments included altitude at 3 levels (1000 - 1310, 1311 - 1800, 1801 - 2300 meters above sea level); five coffee cropping system (coffee pure stand, coffee + annual crop, coffee + banana, coffee + banana + shade trees, and coffee + shade trees), and three soil input practices (organic, inorganic, and no input). The study revealed that soil fertility inputs were rarely used in coffee fields across the MER. Where the fertiliser were applied, very modest amounts (< 300 kg yr^{-1} for organic fertiliser) were typically applied and at irregular intervals. Elevations and soil input use interacted to influence N balances with farms under inorganic input management posting the highest positive N balances. The coffee monocrop system had outstanding positive N balances. Where inorganic fertilisers were utilised, there were positive P balances across elevations and cropping systems. Conversely, there were negative K balances across elevations, cropping systems, or soil input practices. Integrating usage of inorganic and organic fertilisers can effectively sustain nutrient balances in the various coffee cropping systems and at the various elevations in the MER in Uganda.

Key words: Annual crops, banana, coffee, elevation, fertilisers, shade trees, Uganda

Introduction

Maintenance of stable but positive nutrient balances is critical for a sustainable agricultural system (Bahr *et al.*, 2015). Nutrients are lost in arable soil through crop removal, erosion, leaching and gaseous emissions and quite often, in sub-Saharan Africa, these are not replaced because of the inefficient soil nutrient management strategies (Bekunda and Manzi, 2003). The situation is exacerbated by inadequate usage of fertiliser inputs due to limiting knowledge and resources (Vitousek *et al.*, 2009). All these trends translate into negative nutrient balances in different cropping systems. Nutrient balances refer to the net difference in nutrient input and outputs of farming system. Nutrient balances and organic matter levels are critical for assessing the sustainability of soil fertility management practices and agroecosystems of cropping systems (Oliveira *et al.*, 2022). Soil nutrient balances reflect the net change in soil fertility trends in time, but do not necessarily determine the current state of soil fertility (Van Beek *et al.*, 2016).

The Mt. Elgon region (MER) of Uganda is one of the main producers of the lucrative Arabica coffee in eastern Africa (Cherukut *et al.*, 2016). Nonetheless, productivity in the region has been variable due to suboptimal management of soil fertility across different coffee cropping systems (Wang *et al.*, 2015). Coffee cropping systems in the MER is characterised by mosaics of farmlands comprising of coffee and/or banana, annual crops such as maize, beans, and shade trees whose intensity varies from farm to farm (Sebatta *et al.*, 2019). The choice of the coffee cropping system is critical in the management decision, as they greatly impact the soil health and quality (Apanovich and Lenssen, 2018). In addition to cropping system, elevation and soil input practices may influence sustainable productivity of coffee plantations.

Elevation reportedly has a relevance on soil physico-chemical properties, as it defines water and material movement in hill slopes, thus contributing to the spatial differences in soil properties in general, and fertility in particular (Liu *et al.*, 2020). Elevation has a substantial effect on the rate of soil erosion, which results in loss of finer soil particles containing high levels of soil organic carbon and total nitrogen (Wubie and Assen, 2020). The higher altitudes with steep slopes are characterised by heavy soil losses; while the lower altitudes become sinks for the eroded soil particles (Wubie and Assen, 2020). The high human population pressure in the highlands of eastern Uganda has forced farmers to extend coffee farmlands into the steep slope areas (Mugagga and Buyinza, 2013), which are highly vulnerable to degradation. Knowledge of site-specific variations in soil fertility and soil properties is relevant for development of site-specific soil management interventions along the altitude gradient of the MER.

In addition to biophysical drivers, agricultural intensification combined with minimal use of soil conservation methods may have serious negative effects on soil productivity, leading to negative nutrient balances (Karamage *et al.*, 2017). Agricultural intensification can be technically defined as an increase in agricultural production per unit of inputs. Studies have shown that the intensification of the coffee-banana cropping system is more feasible and sustainable through the integration of different trees and crops to enhance soil fertility, biodiversity, reduce erosion and improve water quality (Bellamy, 2013); and diversification of ecosystems services (Rahn *et al.*, 2018). Farmers employ different management practices, which may not match the cropping system incumbent at different elevations; inadvertently compromising sustainable soil management and crop production. Moreover, the use of unsustainable soil fertility management practices such as frequent tillage practices in coffee plantations may result in physical breakdown of soil aggregates, and depletion of soil organic carbon, which may also expose soils to a high risk of erosion and organic matter loss.

Thus, anthropogenic and biophysical pressures may lead to progressive loss of nutrients with direct impact on nutrient balances and carbon stocks. Therefore, this study aimed to establish the nutrient balances at different elevations under different coffee cropping systems and soil input practices in the Arabica coffee producing highlands of the MER of Uganda. This information is critical for achieving and maintaining sustainable coffee productivity and ecosystems services in the montane agroecosystem.

Material and methods

Study area

The study was conducted in Kapchorwa Sub regions of MER in eastern Uganda. Kapchorwa district (Latitude 1°7'N, 1°36'N and Longitude 34°18'E, 34°48'E) was purposively selected because of the heavy production and harvests of Arabica coffee, distinct hierarchical elevation (escarpments) and farm management classes. The study site covered altitudes ranging between 1000m - 2300m above sea level. This area was divided into three elevation zones separated by two escarpments, namely the lower altitude zone (1000 and 1300 m.a.s.l), mid-altitude zone (1310 and 1800 m.a.s.l.) and a higher altitude zone (1810 and 2300 m.a.s.l.) (De Bauw *et al.*, 2016; Sarmiento-Soler *et al.*, 2020).

Kapchorwa receives bimodal rainfall pattern with the peaks during March-May and September-November (De Bauw *et al.*, 2016), with a pronounced dry period from December to February (Rahn *et al.*, 2018). Mean annual rainfall averages at 1200 mm and 1800 mm for the low to high altitudes, respectively (Rahn *et al.*, 2018). The mean annual temperature for Kapchorwa is 18 °C (Rahn *et al.*, 2018).

The soils on these slopes are predominantly Nitisols, originating from finely textured weathering products of intermediate to basic parent rock, possibly rejuvenated by recent admixtures of volcanic ash parent materials (De Bauw *et al.*, 2016). The area has a comparable adherence to nutrient management with the use of organic and inorganic fertilisers given a strong economic attachment to the coffee crop. Arabica coffee is the major cash crop grown in this area, in sole and mixed crop cultures, mainly with banana, annual crops, and shade trees (Sebatta *et al.*, 2019).

Study design

Three factors were considered in this study, namely (i) elevation, (ii) cropping systems and soil inputs. Elevation was considered at three levels, low altitude (1000-1310 m.a.s.l), mid (1311- 1800 m.a.s.l), and high (1801-2300 m.a.s.l.). Cropping system was categorised at five levels, (i) coffee pure stand (C), (ii) coffee and annual crops (CA), (iii) coffee and banana (CB), (iv) coffee, banana and shade trees (CBT), and (v) coffee and shade trees (CT). Soil inputs had three levels, (i) No input (INP), Organic-Intensive (ORG) - (where organic fertilisers were predominantly used), and Inorganic-Intensive (ING) - (where inorganic fertilisers were predominantly used). The factors were laid out in a nested arrangement. The blocking factor was elevation, the main factor was the cropping system, and soil input was nested in the cropping systems. The treatment combinations were replicated four times at each of the three elevations. The coffee plots selected were of minimum area of 20 m × 20 m and with mature coffee trees at least five years old. Information on soil management practices and soil inputs was obtained from semi-structured interviews with the farmers.

Data collection

Field survey

Information on the cropping system and soil management practices in the March-June 2019, and September-December 2019 seasons was obtained using a semi-structured questionnaire administered to a sample of 180 households of selected coffee fields. The questionnaire emphasized information related to coffee cropping systems in the areas, namely cropping systems, soil fertility inputs, quantities of crop harvests and residues for the respective seasons, as they contribute to the nutrient flows. In addition, samples of crop residues, crop harvests, manure, and plant tissue were collected for further laboratory tests.

Collection of soil samples for laboratory analysis

Three sub soil samples were collected from each field at 0 – 30 cm (top soil) using the zig zag soil sampling method to obtain a representative sample as outlined by Habumugisha *et al.* (2019). The choice of the sampling depth was based on the fact that about 90% of the roots develop in the upper 30 cm layer (Kufa and Burkhardt, 2013). A total of 540 composite soil samples were collected. Samples of manure, harvested products, plant leaves were concurrently collected. A total of 3 samples were randomly picked per treatment group for lab analysis. The contents were then averaged for computation of the mineral balances.

Laboratory soil and material analysis

Soil samples were air-dried, grinded and sieved using a 2 mm sieve before laboratory analysis. The other samples (manure, crop harvest, plant leaves and crop residues) were also air dried (in an enclosed room at approximately room temperature) in the MER to prevent rotting. The samples were further oven dried at 60 °C for 24 hours and ground to obtain fine samples. The fine powder samples were labelled and used for subsequent analyses using Okalebo *et al.* (2002), unless otherwise specified. Soil pH was measured in water using a pH meter. Soil texture was determined using the hydrometer method. Bulk density was determined using the core sampling method. Available phosphorus (P) and exchangeable K were extracted by Mehlich-1 solution (Mehlich, 1953). The concentrations of available P and exchangeable K were then determined using a spectrophotometer and flame photometer, respectively, as described by Mehlich (1953). Total N was determined using the Kjeldahl procedure. Similar methods were used to determine the total N P and exchangeable potassium (K) for manure, crop harvest, crop residues, and leaf samples.

Quantification of nutrient balances

Partial N, P and K were used to represent nutrient balances. Nutrient balances were computed using the substance flow analysis (SFA) from the inflow (IN1 – Inflows due to Mineral fertiliser, IN2 – Inflows due to organic fertilisers) and outflow (OUT1 – Outflow due to harvested products, OUT2 – Outflow due to crop residues) data at plot level. Substance flow analysis (SFA) provides a systematic assessment of flows and stocks within a defined system in space and time. This was done following the method described by Brunner and Rechberger (2004). The assessment of flows and stocks of nutrients were based on the principle of mass balance founded on the first law of thermodynamics (Golubiewski, 2012).

Quantification of process inflows

IN1 and IN2 refer to N, P and K that is supplied through application of mineral fertilisers and organic fertilisers (manure), respectively as described by Kiros *et al.* (2014). The data about N, P and K including the type and the quantity of mineral fertilisers applied, type and quantity of organic fertilisers were obtained through administering a questionnaire to interviewee farmers. Cow manure given consideration for organic fertiliser analysis as it is the main organic input for most African countries and is related to the number of livestock (Lesschen *et al.*, 2007). Inflow due to mineral and organic fertiliser were determined using Equation 1 and Equation 2, respectively.

$$IN1 = FA \text{x} NCM \quad (1)$$

$$IN2 = 0FA \text{x} NC \quad (2)$$

Where: IN1 = the inflow due to mineral fertiliser (kg/ha/year), FA = mineral fertiliser applied (kg/ha/year), NCM = nutrient content (N, P, K) in mineral fertiliser, IN2 = the inflow due to organic fertiliser (kg/ha/year), OFA = organic fertiliser applied (kg/ha/year), NC = nutrient content (N, P and K) in organic fertiliser.

Quantification of process outflows

Nutrient removal by crop production is normally the most important factor for nutrient export from agricultural lands. OUT 1 and OUT2 refers to N, P and K that is lost through harvested produce and crop residues, respectively. The data about N, P and K was obtained using the amount of harvested product and crop residues generated through administering a questionnaire to farmers and nutrient composition of the harvested product through laboratory analysis as described by Kiros *et al.* (2014). The quantity of crop residues generated at harvest was attained using the residues-to-product ratio (Kiros *et al.*, 2014) on assumption that 85% of the total crop residues are used for generation of energy or for animal feeds. OUT 1 and OUT2 were calculated using Equation 3 and Equation 4, respectively.

$$OUT1_A = Y \text{x} NC_A \quad (3)$$

$$OUT2_A = R \text{x} NC_A \text{x} F \quad (4)$$

Where: Y = crop yield (kg/ha), R = amount of crop residue (kg/ha), NC = nutrient content of crop residue (kg/kg harvested product), A = nutrient such as N, P and K, F = removal factor of crop residues.

Data analysis

Field survey data were tabulated and analysed using the Statistical Package for Social Scientists (SPSS), version 26 for frequencies and graphs. Inflow and outflow data (N, P and K) were used to compute the nutrient balances using STAN software version 2.6.801, a material flow analysis tool following procedures described in

Cencic and Rechberger (2008). Nutrient balances were calculated for all sampled field plots within the research area. Additionally, nutrient balances were then grouped according to elevation, cropping system, and soil input. The obtained nutrient balances were analysed statistically using three-way Analysis of Variance (ANOVA) to evaluate the influence of elevation, soil management, and cropping system (fixed factors) on nutrient balances (dependent variables) in coffee production cropping systems in MER of Uganda. Significantly different means were separated using Tukey HSD (Honest Significant Difference) at 5 % significance level.

Results

Soil input use amongst the coffee farmers

Most coffee farmers (52-59%) regardless of the elevation did not apply any soil input to their gardens (Fig. 1). Organic fertiliser usage ranged between 20-30% across the cropping systems in the different elevations, and inorganic fertilisers' usage was at 10-20% (Fig. 1). When inorganic fertiliser use was mapped against cropping system, results showed that the CA systems received the highest inorganic fertiliser usage; whereas the CBT system had the lowest. The most used inorganic fertilisers were NPK and DAP. Animal manure was the most used organic fertiliser. Cow dung emerged as the most used form of animal manure followed by goat manure and isolated cases used poultry manure. Organic fertilisers were usually applied once a season; though some farmers applied more than once, and in relatively small quantities of < 300 kg yr^{-1}.

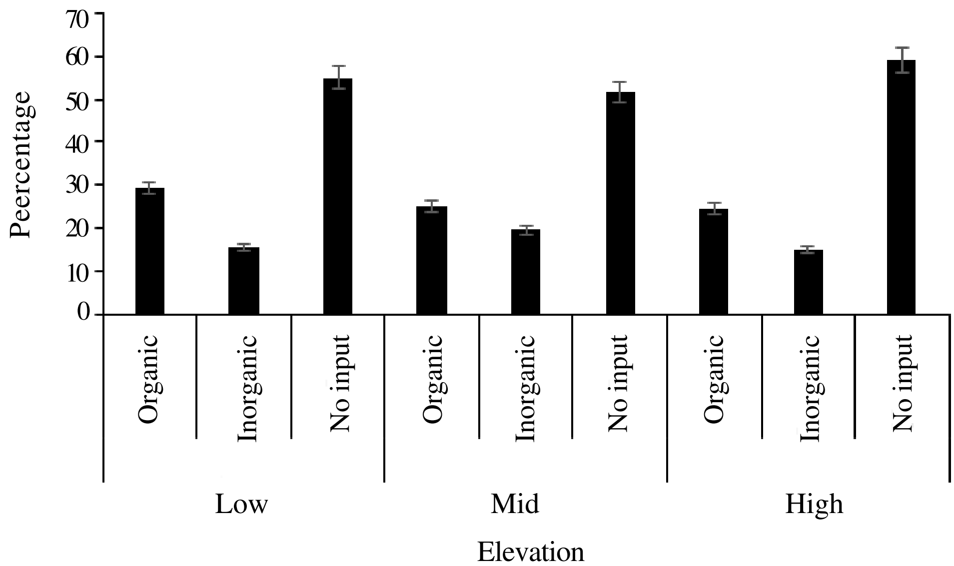

Figure 1. Soil management practices used amongst coffee farmers.

Nitrogen balances

All interactions except for elevation and soil input usage, did not significantly influence N balances (P < 0.05). Solely, elevation, and cropping systems did not have significant influence on the N balances (P < 0.05) whereas soil input usage had a significant effect on N balances (P < 0.05). The mean N balances for coffee fields at low, mid, and high elevations was -4.52, 1.35, and -11.05 kg/ha/yr, respectively. The mean N balances for coffee fields of different cropping systems was 3.64, -5.13, -8.77, -10.10, and -2.87 kg/ha/yr, for C, CB, CA, CBT, and CT, respectively. The mean N balances for coffee fields under ORG, ING and NIP was -14.34, 17.77, and -17.37 kg/ha/yr, respectively. Post hoc analysis showed that N balances were significantly different for soils under ING and NIP management, and ING and ORG management (P<0.001). The N balances for coffee fields under ING usage was positive for low and mid elevation, and negative (>-30 kg N/ha/yr) at high elevation. All coffee fields under NIP and ORG had negative N balances (Fig. 2). Figure 3 gives a graphical representation of N balances of a case study of Coffee only farms under ING at mid elevation, where N inflow through application of urea fertiliser in September-December season made the greatest contribution to the observed annual positive N balance of 109.28 ± 3.3 kg/annum (Fig. 3).

Phosphorus balances

None of the interactions of elevation, cropping system and soil input usage significantly affected P balances (P < 0.05). Also, solely, elevation levels, and cropping systems did not influence P balances (p < 0.05). On the other hand, soil input usage significantly affected P balances (P < 0.05). A post hoc test showed that P balances were significantly different for fields under ING and NIP management, and ING and ORG management (P < 0.01). The P balances for coffee fields under ORG, ING and NIP were -1.21, 12.01, and -2.6 kg/ha/yr, respectively. The mean P balances for coffee fields at low, mid, and high elevations were 2.69, 3.95, and 0.78 kg/ha/yr, respectively. The mean P balances for coffee fields with the C, CB, CA, CBT, and CT cropping systems were 4.66, 1.64, 7.16, 1.91, and -1.7 kg/ha/yr, respectively. The P balances for coffee fields under ING usage was positive for low, mid and high elevations. Coffee systems under NIP and ORG had negative P balances in all elevations, more so at low and high elevation, with the exception of the CA fields that consistently posted positive P balances (Fig. 2). The material flow for P balances for the case study of CB farms under ING management at mid elevation are graphically presented in Figure 4, and show that application of NPK and DAP in the March-June season made the greatest contribution to the positive P balances.

Potassium balances

There was no significant difference in K balances noted at elevation levels, cropping systems, and soil input (P < 0.05). Similarly, all the interaction effects were not significant

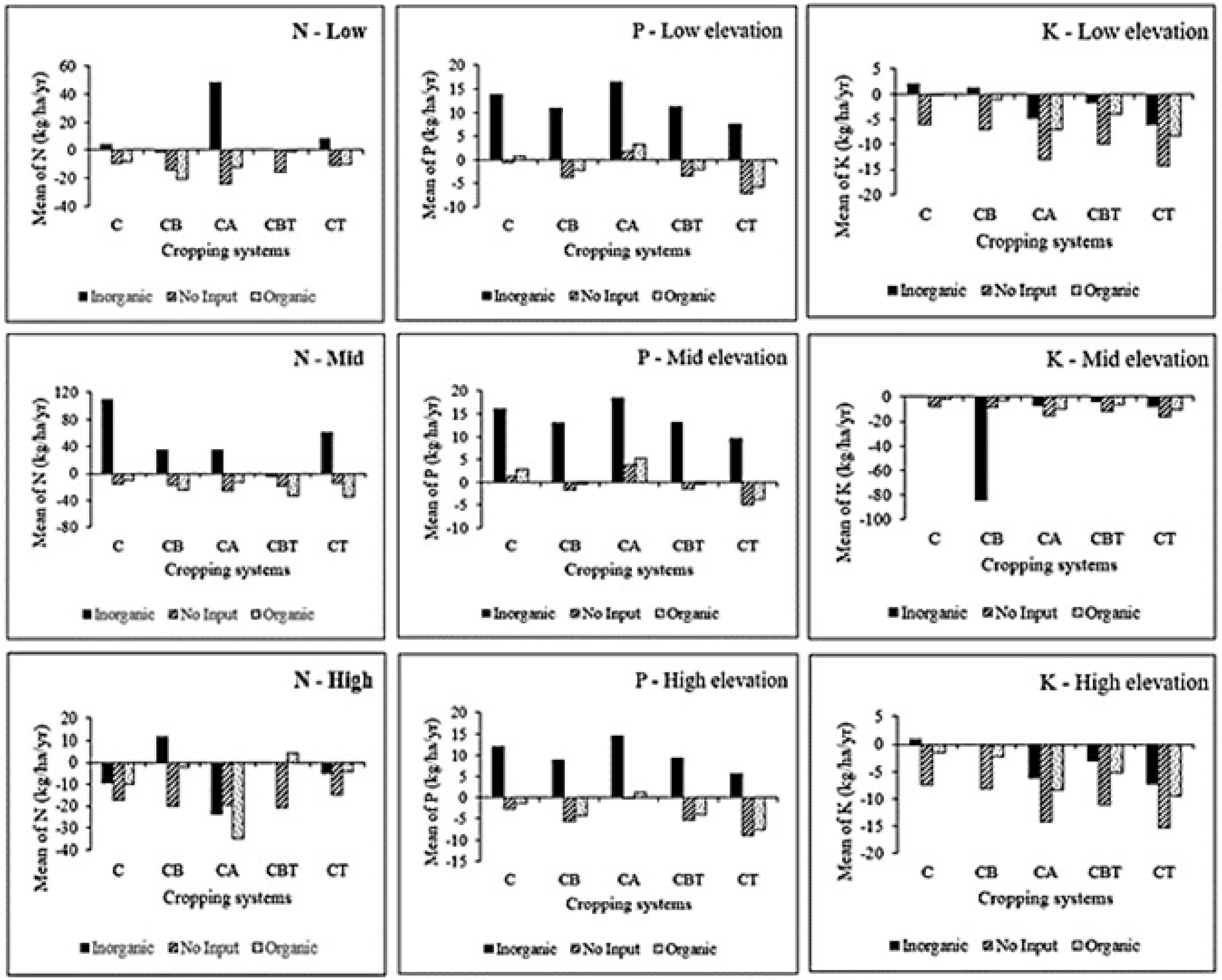

Figure 2. Nutrient balances for Nitrogen, Phosphorus, and Potassium at low, mid, and high elevations for the various soil input usage and cropping system.

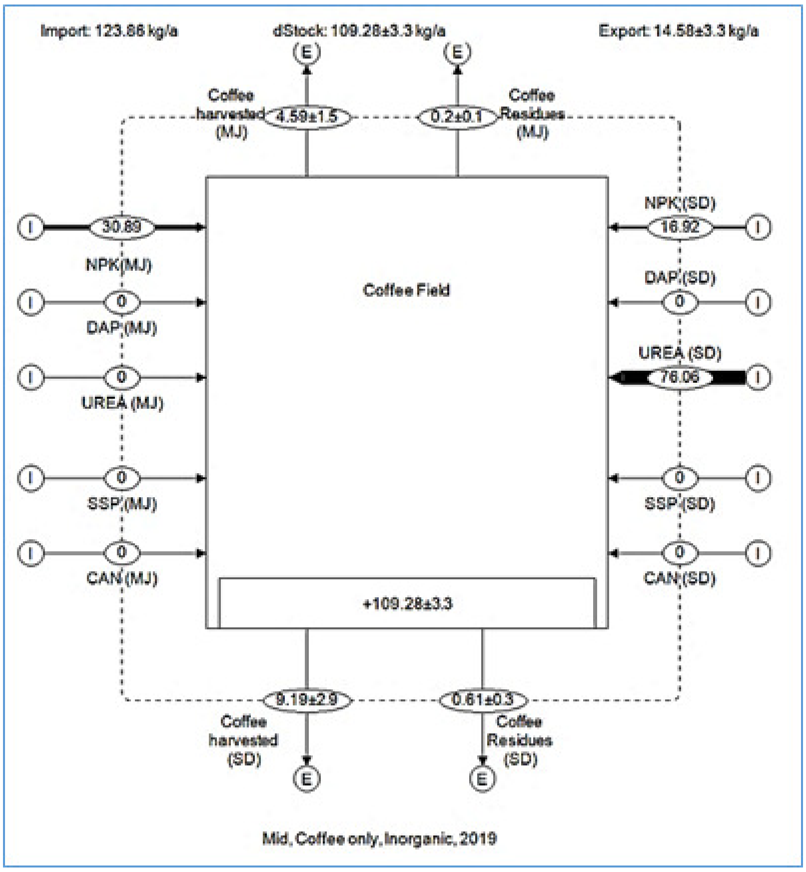

Figure 3. Material flow of N balances for C farms ING at mid elevation (MJ and SD refer to the March-June and September-December Seasons, respectively).

($P < 0.05$). The mean K balances for coffee fields at low, mid, and high elevations was - 5.34, -6.21, and -6.64 kg/ha/yr, respectively. The K balances among soil inputs were -5.27, -2.97, and -11.19 kg/ha/yr for ORG, ING, and NIP usage, respectively. The mean K balances for C, CB, CA, CBT, CT were - 2.54, -3.38, -9.47, -6.37, and -10.62 kg/ha/yr, respectively. Individually, K balances were as prior stated generally negative, with isolated cases of C farms under ING management at low and high elevation presenting positive values (Fig. 2). A case study of CB farms under ORG at high elevation showed that nutrient extraction through coffee harvests made the greatest contribution to the negative K balances (Fig. 5).

Discussion

Soil input use among the coffee farmers

The low fertiliser application in terms of quantity and frequency among coffee farmers shown in this study may be due to the high cost of inorganic fertiliser, a lack of

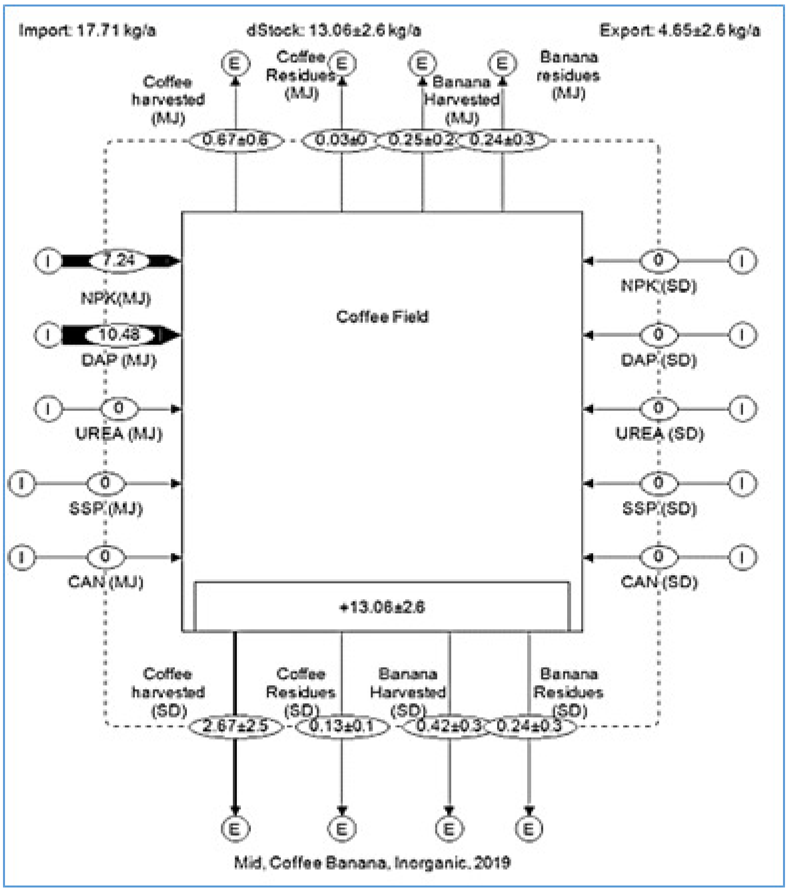

Figure 4. Material flow of P balances for CB under ING at mid elevation (MJ and SD refer to the March-June and September-December Seasons, respectively).

knowledge about effective fertiliser application, and/or limited access to fertiliser-specific extension services (Okoboi and Barungi, 2012; Veljanoska, 2022). This echoes the national status as inorganic fertiliser use in Uganda is estimated at about 3 kg NPK per hectare per year (FAOSTAT, 2020). In the interactions with farmers in this study, coffee farmers under inorganic intensive management considered lack of knowledge as one of the most pressing issues for not using organic fertilisers whereas farmers under organic intensive farming considered the cost of inorganic fertilisers as key to their limited use. Also, the lack of access to organic fertilisers was the most pronounced limitation for organic manure application on the farms. According to a study by Babasola *et al.* (2018), availability of organic fertilisers is the third most important factor influencing their use, after transportation and high labour costs. Lack of knowledge and skills to understand and process available information could be driving the low adoption of both organic and inorganic soil inputs. Education is a driving force behind technology adoption because more educated farmers are better

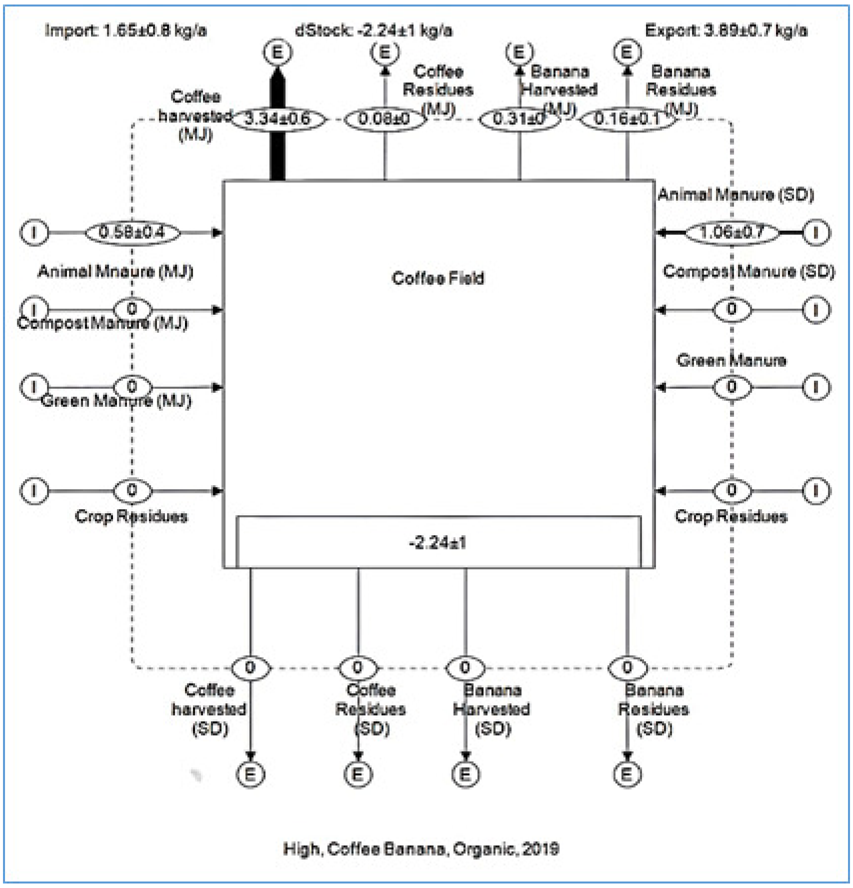

Figure 5. Material flow of K balances for CB under ORG at high elevation (MJ and SD refer to the March-June and September-December Seasons, respectively).

able to process often-abstract information and put it into practice. Education enables farmers to follow written instructions regarding the application of adequate and recommended doses of chemical and other inputs. Epeju (2016) identified poor farmer education as a critical factor responsible for low agricultural productivity in the Teso sub-region of Uganda. As such, responsible government institutions should put effort in customising the coffee production manuals to fit the needs of the farming communities.

Animal manure was the most common organic fertiliser used, this was somewhat expected given that cattle are one of the most common types of livestock in eastern Uganda (Nsubuga *et al.*, 2019). Also Nsubuga *et al.* (2019) and Muhereza *et al.* (2014) asserted that cow dung is a valuable on-farm source of plant nutrients for meeting N, P, and K needs. The use of animal manure could also be linked to its ease of transportation and application; predominantly applied in solid form (Muhereza *et al.*, 2014). In Kapchorwa, farmers use donkeys for transportation. The increased use of animal manure could also be attributed to intercropping of coffee with banana as many banana farmers regard animal manure to be essential for banana productivity (Braber *et al.*, 2022). Intercropping and agroforestry were recommended by Shanka (2020) as technologies for low external input systems that improve environmental protection and soil fertility, improve ecological stability, and affect soil biodiversity.

Effect of coffee cropping systems and soil management on soil nutrient balances

Nitrogen balances

To obtain healthy coffee plants, especially during critical growth stages such as flowering, necessitates adequate levels of macronutrients such as N, P and K to reduce crop failure due to nutrient stress (Byrareddy *et al.*, 2019). The results of this study on balances of the macronutrients in the soil varied with elevation, cropping system and especially with respect to soil input usage. Results showed relatively higher N negative balances at high elevation. Nitrogen is known to be a mobile element in the ecosystem, susceptible to leaching; and gaseous losses, and uptake by plants (crops and weeds). The high negatives at high altitude could be attributed to increased erosion at those elevations (He *et al.*, 2016) and across the topo-sequences. The continuous accumulation of eroded material at mid elevations could have contributed the changes in N balances at these levels.

On average, it was the coffee monocrop that had positive nitrogen balances. The relatively higher negative N balances for coffee fields under CBT, CT, CB, and CA can be attributable to the net crop harvest and increased soil N uptake due to competition by annual crops and banana, feeding in the same root zone with coffee. The system of CT has the next level of N balances after C, even though still negative. Whereas N is highly leachable, the recovery of leached N by the tree deep root system from below the coffee root system could explain the less negative N balances for CT (Carvalho and Foulkes, 2018). The tree tap root system therefore plays a nutrient recovery complementary role. The relatively higher negative N balance under CBT compared to CT, however, is attributable to the increased competition for N by the banana, which feeds in the same root zone as coffee.

Application of inorganic fertilisers significantly increased N balances averaging 17.77 kg/ha/yr, showing that well planned applications can indeed replenish and provide the requirements for this essential element. The organic fertilisers levels used in this study, on the other hand, were rather ineffectual and may not have had significant nutrient quantities to effect N accumulation because of irregular and low application and use. Though the organic fertilisers did not bring the N levels above zero, they brought a slight improvement from the no-input management, averaging -14.34, compared to -17.37 kg/ha/yr. The slight improvement in N balances for organic compared to no-input management could be due to N immobilisation and reduced N losses to the environment under organic management (Ren *et al.*, 2014). Elevation-soil input combinations could also explain some of the exhibited positive N balances especially at mid altitudes.

Phosphorus balances

This study showed positive P balances at plot level especially in the inorganic input cases. This could be because P is the least mobile and accessible macro nutrient in soils, causing its accumulation (Balemi and Negisho, 2012). The variations in P balances in the context of soil input usage especially in the case of coffee systems under inorganic management could be due to the fact that coffee being a cash crop, mineral fertilisers are highly sought after as a strategy for increased yields. For instance, the Agricultural Cluster Development Project (ACDP) of the Ministry of Agriculture, Animal Industry, and Fisheries (MAAIF) reported a 9% increase in household yield (MT/acre) for project beneficiaries who utilised the project's subsidised fertiliser inputs (MAAIF, 2021). It is expected for soils under organic management to have negative P balances (Friedel et al., 2014), as the organic P is mineralised and is available for plant uptake and growth (Ferreira *et al.*, 2022). Organically managed soils also prevent the formation of insoluble iron phosphates that make P unavailable for plant uptake.

Potassium balances

The predominantly negative K balances in the study area could be attributed to the region's high soil moisture content due to heavy rains. This facilitates K movement to plant roots and increases availability, facilitating vegetative plant growth. This eventually leads to a reduction in K reservoirs. The fact that perennial crops like coffee and banana accumulate and export a large amount of K at harvest may also contribute to the region's negative K balances across different cropping system. Coffee plantations can live for about 30 years on average, even up to 50 years in some cases (Bunn *et al.*, 2015). This could also explain the very high negative K balances under CT systems. While it is widely assumed that intercropping coffee increases soil nutrient competition, this study demonstrated no significant variations in K balances under different cropping systems. The higher deposition of banana pseudo stem and leaves under CB and CBT cropping systems, which have been shown to have high potassium concentrations (Mithamo *et al.*, 2017), may be responsible for the less negative K balances when compared to C cropping system. A similar argument might be given for CBT's lesser negative K balances when compared to CT. The relatively high negative K balance for CA could be attributed to the continuous nutrient mining through annual crop harvest. For instance, maize, the most popular annual crop intercropped with coffee, has the capacity to remove up to 16 kg K/acre (Peterson, 1999). The negative K balances suggest an increase in K deficiencies over time, especially for coffee farmers that do not apply K fertiliser such as the no input soil management. The application of organic manure increases potassium release and decreases potassium fixation in soils, even though the availability of potassium in the soil increases with various amendments (Bader *et al.*, 2021; Taiwo *et al.*, 2018). This accounts for the relatively more negative K balances for coffee fields under organic management compared to those under inorganic management. In general, as elevation decreased, negative K balances decreased. This could be attributable to significant K nutrient losses in runoff water due to erosion with particulate material at higher altitudes (Goulding *et al.*, 2021).

The collective findings of N, P, and K suggest that individual use of organic fertilisers cannot effectively sustain nutrient balances, and thus, inorganic and organic fertiliser integration should be encouraged to benefit from their individual soil amendment abilities. Since the findings indicate a scarcity of organic fertiliser, coffee farmers should aim to include more trees in their coffee systems to take advantage of the free ground cover provided by leaf litter and "tree mulch," which acts as organic soil amendments.

Conclusion

Most coffee farmers in the study area did not apply any soil amendments in their fields; and where organic and inorganic fertilisers were applied, very modest amounts were applied and at irregular intervals. Elevation interacted with soil input use to influence N balances with positive balances under inorganic input management, especially at low and mid elevations. On average, the coffee monocrop was the only cropping system with positive N balances. There were positive P balances for all elevations and cropping systems when inorganic fertilisers were used. Uniquely, K balances were predominantly negative regardless of elevation, cropping system, and soil input. Blended use of inorganic and organic inputs is a recommended strategy to build up positive balances and ensure sustainability in the coffee farmlands of the Mount Elgon region.

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