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Influence of farmers' socio-economic characteristics on nutrient flow and implications for system sustainability in smallholdings: a review

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The rise in global human population, coupled with the effects of climate change, has increased the demand for arable land. Soil fertility has been the most affected, among other things. Many approaches to soil fertility management have been proposed by studies in Sub-Saharan Africa (SSA); however, the question of sustainability remains. Nutrient monitoring (NUTMON), which combines biophysical and socio-economic features for soil fertility management, gives an *in-situ* soil fertility status of a given land use system, which ultimately provides guidance in proposing appropriate soil management techniques in a given land use system. In this review, the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) approach was deployed for a systematic search of the literature materials. The review evaluated various studies on nutrient monitoring in SSA soils in order to understand the socioeconomic attributes and their influence on farming systems, as well as nutrient flow and balances. The review identified two dominant smallholder farming systems in SSA: mixed crop-livestock and mixed crop farming systems. Also, this review revealed that most nutrient balance studies in SSA have been done in mixed crop and livestock farming systems. However, regardless of the farming systems, the overall mean nutrient balances in all studies, particularly those of nitrogen (N) and potassium (K), were negative, indicating significant nutrient mining. The review further revealed a vast range of biophysical soil fertility management technologies; however, their adoption has been limited by socio-economic aspects including land ownership, gender, financial position, literacy level, and access to inputs. Therefore, in view of this situation, integrating biophysical and socioeconomic disciplines could address the problem of soil nutrient depletion holistically, thus decreasing the existing negative nutrient balances in the SSA region.

KEYWORDS

agro-ecosystems, nutrient balances, farming systems, smallholders, manure

1 Introduction

1.1 Background information

The variety of natural resources and climate conditions found in smallholding systems has resulted in a wide range of land use systems (1). Consequently, farming systems vary greatly depending on socioeconomic and agro-ecological environments, which ultimately affect system management practices in a given community (2–4). Various farming systems exist in smallholder settings in sub-Saharan Africa (SSA) based on cropping systems. Perennial crops, crop-livestock mixed farming, maize-mixed farming, root and tuber farming, and cereal-root crops are among the major farming systems in SSA (1, 4). However, crop-livestock mixed farming is the most common farming system for smallholders who produce for subsistence, accounting for roughly two-thirds of smallholder farmers' livelihoods in Sub-Saharan Africa (SSA) (5). Crop-livestock mixed farming is preferred due to the interdependence of livestock and crops, which results in nutrient recycling within the system (6).

The challenge of nutrient cycling in mixed crop-livestock farming is that, quantities of animal manure produced within farmsteads in SSA are smaller due to the small number of livestock kept per household, unlike in developed countries where manure is considered a problematic waste (7). As a result, smallholder farmers are forced to use little manure, which does not meet nutrition crop requirements; thus, crop production in this region relies heavily on natural soil fertility (8, 9). It is estimated that 60–80% of household income is generated at the expense of natural soil fertility (10). Reports show that over the last three decades, nutrient mining from arable lands in SSA has been estimated to be 660, 75, and 450 kg ha^{-1} yr^{-1} of N, P, and K, respectively (11). Consequently, these practices contribute to land degradation through nutrient mining, threatening the sustainability of existing farming systems (12). Understanding the interaction between farmers' socioeconomic attributes of soil fertility management and soil nutrient depletion is critical in developing appropriate approaches to address soil fertility problems (13–15). Designing biophysical nutrient management without consideration of socioeconomic factors is likely to yield low adoption, despite being technically sound (14). In the past, soil management interventions were derived from less participatory, top-down policies and thus did not work because they appeared to interfere with farmers' decision-making (16). Adoption of nutrient management is determined by accessibility and affordability of the technology and the respective requirements for input, materials (17) and labor. To that end, smallholder farmers in SSA often respond to these challenges in various alternative ways by using easily available resources within their environment, such as animal manure, mulching, or intercropping (18). However, due to the insufficient quantity and often low quality of animal manure produced within farmsteads, their contribution to improving soil fertility is negligible (19, 20).

The majority of smallholder farmers are still struggling to increase crop production in order to feed more people, a result of the high population growth rate (21, 22). However, reaching potential yields has remained a challenge due to smallholder farmers' reliance on rain-fed agriculture, insufficient soil nutrient supply, use of low-yielding varieties, and a lack of mechanization (3, 14). According to Aschonitis et al. (23), the introduction of the "green revolution" in the 1960s greatly improved crop yields ranging from 3 to 5 MT ha^{-1} in Asia and China, respectively, to 10 MT in North America, Europe, and Japan through the use of improved crop varieties, fertilizers, pesticides, and advanced farm machinery. The green revolution was not realized in developing countries, leaving Africa with the lowest yield at around 1.5 MT ha^{-1} (24), due to the inaccessibility and high cost of the agricultural technologies. Nonetheless, previous research findings, such as those by Omuto and Vargas (25) and Takele et al. (14), revealed that agricultural technological change, such as the use of advanced machinery, high yielding varieties, fertilizers, and pesticides, has been linked to land degradation in many arable lands, including erosion, salinity, and soil nutrient depletion.

1.2 Rationale of the review

Global population growth is expected to reach 9.7 billion people by 2050, with African population growth expected to reach 2.5 billion in 2050, up from 1.3 billion in 2020, and the SSA population expected to reach 3.1 billion by 2100, up from around 1.24 billion today (3). With these population projections, the governments, including those in the SSA region, have to take critical actions to be able to feed the growing population by addressing the rapid decline in soil fertility and increased food constraints (3). It is, therefore, important that global and/or regional food production be increased through holistic strategies to meet the demand of the growing population. While research centers have developed many promising systems of soil amendment techniques for nutrient enrichment, the majority of them rely on mono-disciplinary approaches with a focus on the biophysical aspects (26–29), with little consideration of the socio-economic aspects. Integrating biophysical and socio-economic disciplines could address the problem of soil nutrient depletion more holistically (29). It all starts, nevertheless, with estimating nutrient budgets, and this has been gaining popularity among the researchers (30). A nutrient budget can be viewed as a reliable indicator for nutrient mining and related land degradation, allowing for improved soil nutrient management. The nutrient budget was defined by Bindraban et al. (31) as the difference between the system's nutrient inputs and outputs within predefined spatial-temporal boundaries. The difference is calculated based on the nutrient stocks present within the top 30 cm of the soil profile (32) and the depth where most of the crop roots are active (33).

There are several modes available for better evaluation of nutrient flow and budgets and the limitations of soil nutrient content in SSA. A system for quantitative evaluation of the fertility in tropical soil (QUEFS), for example, was designed to assess the efficacy of N, P, and K ratios during fertilizer application (34). Other models, like NuMass, were developed to diagnose soil fertility in terms of N, P, and soil acidity (35). However, the NUTMON methodology, introduced in 1990 by Stoorvogel and Smallings, mainly focused on nutrient flow and balance by indicating the nutrient inputs and outputs of a certain land use and farming system (36–38). Because it combines biophysical and socioeconomic approaches to soil fertility management, the NUTMON concept has been opened to a wide range of studies related to nutrient budget and flow (30). NUTMON is essentially a decision support model that has been modified from the Nutrient Balance Model (NUTBAL), which was previously developed to generate quantitative nutrient balances for the major macronutrients (N, P and K) for African land use systems (33). NUTMON, goes beyond NUTBAL by including, in addition to nutrient balance, changes in land use, farm activities, and economic analysis to generate qualitative and quantitative nutrient stock and flows data within and outside the farm (29, 39–41). The economic analysis tool was included in order to estimate the farm's economic performance (33, 42). As a result of the integration of biophysical and economic performance, farmers and researchers can make recommendations for alternative methods of implementing Integrated Nutrient Management (INM) while keeping the underlying constraints in mind.

The NUTMON methodology can be used by researchers and farmers to assess the environmental and financial sustainability of tropical farming systems (11, 29). Other research has shown that NUTMON can be used to assess the degree of nutrient mining in an agro-ecosystem and the effects of the various nutrient management strategies on soil nutrient stocks (32, 33). NUTMON categorizes inputs into five groups (N1 to N5): incoming nutrients from fertilizers (mineral and organic), wet and dry deposition, nitrogen fixation, and sedimentation. Harvested products (grain, tubers, or animal products), crop residues, leaching beyond the rooting zone, gaseous N and S losses (denitrification, valorization, and burning), and erosion are the five output categories (OUT1–OUT5) (16, 40, 43). As shown in Figure 1, a farm-level NUTMON consists of a structured questionnaire, a data base, and two statistical models: one for calculating nutrient flows (NUTCAL-model) and the other for calculating economic performance (ECCAL-model) (33).

Because there have been numerous studies on NUTMON in SSA and elsewhere, this review intends to investigate the sustainability of smallholder farming systems in terms of nutrient flow and balance by utilizing previous studies on nutrient monitoring (NUTMON) in smallholder farming system soils. However, due to inconclusive results from diverse settings of smallholder farmers worldwide, this review will only focus on Sub-Saharan Africa (SSA) as a representative of other areas with extensive nutrient mining and low-resource farming systems. As a result, this paper intends to; (i) examine biophysical attributes that influence soil fertility management in SSA smallholder farming systems, (ii) provide narrations on how socio-economic categories affect farming systems and nutrient flow and balance., (iii) Identifying existing smallholder farming systems and their soil nutrient balance status (iv) Identifying the nutrient monitoring (NUTMON) research gap in SSA.

2 Methodology used in gathering information

The goal of this review was to look at the characteristics of smallholder farming systems in terms of nutrient flow and balance in NUTMON studies in SSA soils. During the systematic search of the materials, a PRISMA approach was used, with ScienceDirect and Google Scholar serving as search engines. The keywords were "NUTMON" AND "sub-Saharan Africa" AND "Farming systems" with the link of "nutrient balance" AND "Socio-economic". Numerous articles were drawn from the internet, as shown in Figure 2. The search was limited to the last three decades, i.e., from 1990 to 2022 (Table 1). Details on literature relevance using quality assessment, exclusion, and inclusion criteria are shown in Figure 2. At the end, 43 articles were considered for this review based on the selection criteria. Numerous theories and knowledge on the socioeconomics of smallholder farmers, farming systems, and soil nutrient budgets were discussed in these sources. Therefore, the results of soil fertility management strategies and the NUTMON

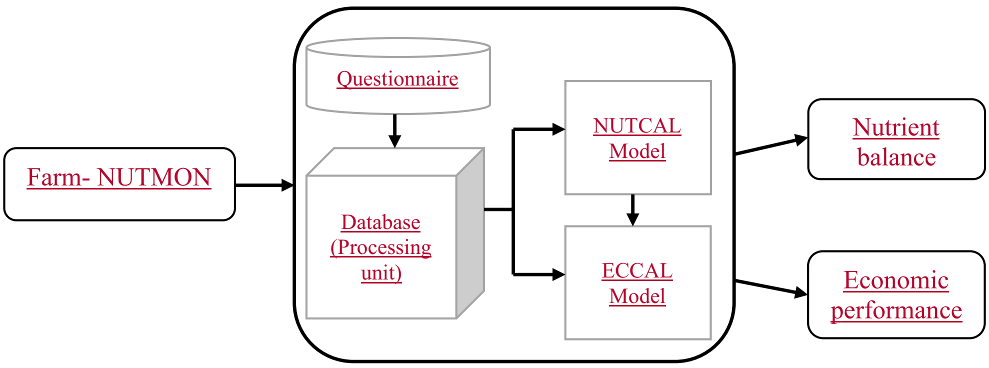

FIGURE 1
A schematic representation of a farm NUTMON (Source: 33).

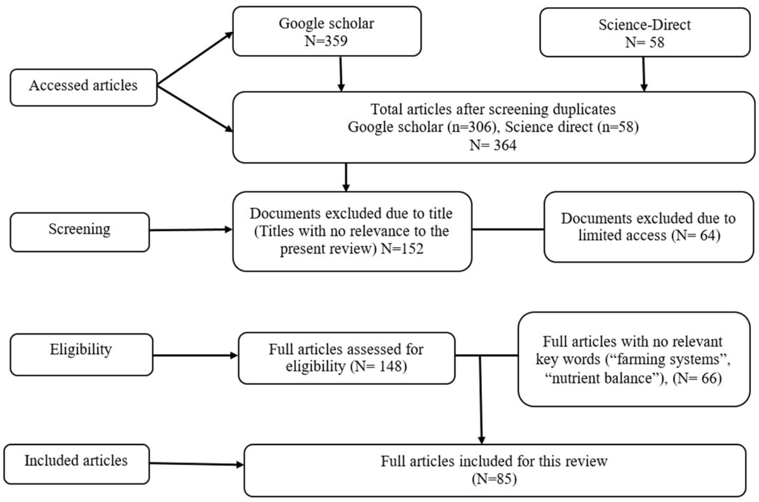

FIGURE 2
A schematic literature search based on PRISMA in acquisition of appropriate articles for this review.

concept were reviewed to gain an understanding of the successes and challenges of soil fertility management.

3 Findings from the explored literature

The review consisted eight five (85) documents which met the inclusion criteria. However, of the 85 documents 72 were peer reviewed journal articles, 4 were proceedings, 4 Master thesis, and 5 PhD thesis. Kenya and Ethiopia are the most studied countries on nutrient flow and balances by, 28 and 22 documents, respectively (Table 1). Other countries including Mali, Tanzania, Burkina Faso, Nigeria, Uganda, Rwanda, Madagascar, Ivory Coast, Benin, and Mozambique which consisted 1 to 5 articles (Table 1). This results is in line with the report by (30) that more than one-third of research in nutrient balances documented in SSA are done in Kenya. Furthermore, results show that the majority of studies were conducted in the 2000s and 2010s (Table 1).

3.1 Focus of this review article

The emphasis of this review is on smallholders’ characteristics and soil nutrient management in SSA. Soil fertility, being the most

TABLE 1 Chronological trend of nutrient flow and budgets studies in SSA farming systems.

Year	Number of studies	Country studied	Reference
1990’s	20	Mali (5), Kenya (6), Tanzania (2) Ethiopia (3), Nigeria (1), and Burkina Faso (1), Mozambique (1), Uganda (1)	Stoorvogel and Smaling, (41); Stoorvogel and Smaling, (39); Smaling & Fresco (40); van der Pol & Traore, (44); Van den Bosch et al. (33); De Jager et al. (27, 29); Elias et al. (45); Harris (46); Ramisch (47); Krogh, (48); Defoer et al., (49); Shepherd & Soule (50); Budelman et al. (51); Folmer et at, (52); Saleem (53); Wortmann & Kaizzi (54)
2000’s	33	Kenya (12), Ethiopia (8), Zimbabwe (3) and Uganda (3), South Africa (1), Tanzaniza (2), Burkina Faso (2), Mali (1), Mozambique (1), Benin (1)	Haileslassie et al. (55); Kathuku et al. (56); Ncube et al. (57); Nkonya et al. (58); Onduru et al. (59); De Jager et al. (60); De Jager et al. (61); Zingore et al. (62); Van Beek et al. (10); Utiger et al. (63); Assefa and van Keulen (64); Gachimbi et al. (32); Gachimbi et al. (65); Elias (66); Bekunda and Manzi (67); Abegaz (18); Haileslassie et al. (55); Haileslassie et al, (68); Dougill et al. (69); Tittonell et al. (70); Leonardo (71); Baijukya et al. (19); Lesschen et al., (72); Ramisch et al. (73); Elias (74); De Jager et al. (60); De Jager et al. (61); Saidou et al. (75); Zougmore et al. (76); Mwijage et al. (77); Kaliiss (78).
2010’s	30	Kenya (11), Uganda (2), Ethiopia (8), Rwanda (2), Nigeria (2), Cameroon (2), Ivory Cost (1) & Burkina Faso (2)	Adamtey et al. (79); 12; Tully et al. (80); 81; Ebanyat et al. (82); Esilaba et al. (83); Kabirigi et al. (84); Tankou et al. (85); Bucagu et al. (86); Tadesse et al, (87); Lelei & Tunya (88); Vaittinen (89); Ehabe et al, (90); Sitienei et al. (91); Abdulrahaman et al. (22) Muendo et al. (92); Namoi et al. (93); Huluka et al. (11); Meylan (94); Onwonga et al. (95); Achola (96); Rufino et al. (97); Tunya (98); Kiros et al. (99); Enyew, (100); Melese et al. (101); Onduru (102); Diarisso et al. (103).
2020’s	9	Madagascar (1) Tanzania (1), Uganda (1), Kenya (1) and Ethiopia (5)	Fanjaniaina et al. (5); Amann et al. (21); Reetsch et al. (104); Mesfin et al. (105); Gebresamuel et al. (106); Esubalew et al. (107); Lewoyehu et al. (108); Mamuye et al. (109).

important indicator that determines the capacity of the soil to produce crops, is controlled by many factors ranging from biophysical (110) to socio-economic (14, 106). In the past, smallholder farmers in SSA used to cultivate land by moving from one place to another (the practice is known as shifting cultivation); thus, farms were left fallow to rejuvenate their fertility (9, 111). Clearly, the aforementioned practice is no longer appropriate due to increased population, which has resulted in pressure on agricultural lands (112, 113). The current smallholder farming systems in SSA are comprised of homestead farms (home gardens), which are typically small pieces of land (1 acre), and distant farms, which are relatively large (> 1 acre but less than 5 acres) (3, 114). We discussed soil fertility management by smallholder farmers in terms of biophysical and socioeconomic attributes in this section.

3.1.1 Attributes related to biophysical aspects on soil fertility management

Historically, the SSA experienced moderate growth in agricultural production between the 1960s and 1970s, but the trend later began to decline, making it the least developed region in comparison to the developed world (115). Factors attributed to the decline in crop production are not other than pests and diseases, climate change (too much or too little rainfall), and most importantly, land degradation, which ultimately affects the quality of soils (104). Soil fertility management, from a biophysical standpoint, includes managing soil nutrients at the farm level as well as improving soil condition (physicochemical and biological attributes) for improved plant production (116, 117). Since the introduction of the green revolution in the 1960s, agricultural scientists have been coming up with a vast range of soil fertility management technologies for the purpose of combating world hunger (118, 119). Ofori and Amoakohene (116) highlighted varieties of technologies, including the use of (i) inorganic fertilizers alone, (ii) organic inputs together with inorganic fertilizers, (iii) organic inputs alone (organic farming), and (iv) Integrated Soil Fertility Management (ISFM) practices (currently highly promoted).

In SSA, smallholder farmers engage in a variety of farming systems with different management practices, yet the sustainability of these systems is at stake (3, 79). The current review found that, with the exception of plot-level experimental studies, almost all (90%) studies in smallholder farming systems rely on organic inputs, specifically farm yard manure and crop residues, with little or no inorganic fertilizers (5, 85, 105). A similar observation is reported by Masso et al. (120), who find that more than 65% of smallholder farmers in developing countries do not use inorganic fertilizers in their farming systems. Although animal manure has been reported as the main source of nutrient inputs in most smallholder fields, these sources are constrained by limited access and poor quality (24, 105). Studies demonstrate that the amount and quality of manure have been affected by various factors, but most importantly poor animal nutrition, a poor livestock keeping system, and poor manure handling (121). For example, a study by Tittonel (2015) on diversity in soil fertility management on smallholder farms in western Kenya found that only 38% of N, 38% of P, and 34% of K remained in the manure after storage.

In SSA, fertilizer use is definitely very low compared to the developed world (122). Reports have shown that the average fertilizer use on crop land is 135 $kgha^{-1}$ $year^{-1}$ in developed countries, whereas SSA exhibits the lowest rate of less than 15 kg ha^{-1} $year^{-1}$ (123, 124). The 2006 Abuja Fertilizer Declaration estimated that by 2015 the fertilizer use in SSA could be 50 kg ha^{-1} of N, P, and K (123). Generally, there are some efforts to increase fertilizer use in SSA countries, yet the pace is too slow to meet the target, with an average of 5 kg in 1990 and 10 kg in 2008 (122). Some limitations on the use of inorganic fertilizers have been associated with limited access, high prices, poor extension services, and inappropriate fertilizer recommendations due to little research on fertilizer use (14, 124–126).

In view of the above information, livestock plays a vital role in nutrient cycling in crop-livestock-based farming systems (5). However, there is an ongoing debate by environmentalists that livestock contribute about 14.5% of all emitted anthropogenic greenhouse gasses (nitrous oxide and methane), threatening global climatic conditions (5). The question remains: "Should we abandon the systems?" Based on these varying situations of soil nutrient management among smallholder farmers' fields, integrated soil fertility management (ISFM) could serve the purpose of improving soil fertility in smallholder farming systems in SSA. The biophysical soil fertility management approach is well discussed in almost all the reviewed articles. However, the generic nature of scientific approaches when it comes to soil fertility management failed to incorporate indigenous knowledge, resulting in poor adoption of the recommended soil fertility management technologies (118).

3.1.2 Socio-economic attributes on soil fertility management

Agriculture is the primary source of income for the majority of people in most developing countries, SSA in particular, accounting for more than 70% of smallholder farmers' livelihoods, with 60% concentrated in rural areas (127–130). Low crop yields, which lead to food insecurity, are the most significant constraint for smallholder farmers in SSA (131, 132), negatively affecting their economic status. Among other things, socioeconomic factors that influence farmers' ability to adopt soil fertility management technologies threaten existing smallholder farming systems (78, 85, 105, 113). This review found significant evidence that socioeconomic factors influence farmers' decisions to adopt proposed soil management technologies (133). Inorganic fertilizers, for example, appear to be the most widely adopted among the various introduced soil fertility management technologies by many farmers in developed countries due to their immediate effect. However, this is not the case in developing countries, including SSA, due to the prohibitively high cost of inorganic fertilizers, which the majority of smallholder farmers cannot afford (17). Previous research, for example, by Zingore et al. (62) and Kathuku et al. (56), shows that soil nutrient management varies significantly across socioeconomic classes, ranging from insufficient inputs (typically poor resource farmers) to adequate and excessive inputs (rich farmers). The direct socio-economic factors that influence soil nutrient flow are management practices and levels of crop-livestock interaction, and the level of importation and exportation of soil nutrients through crop and livestock product sales and purchases (58, 101). However, Stewart et al. (24) and Giller et al. (3) reported that land ownership or tenure, access to labor, household income and endowments, gender equity, and access to market services were other socioeconomic factors that constrained most smallholder farmers' soil fertility management decisions.

Socioeconomic factors impede the adoption of biophysical soil management technologies among farmers in SSA (29, 129). For instance, the deteriorating relative price relations between farm inputs and outputs have disappointed farmers' efforts to invest in soil nutrient management techniques (27, 32), as it makes agriculture a non-profitable venture. As a result, crop production is being performed by elders, women, and children since many youths migrate from rural to urban centers seeking job opportunities (32, 83, 96). Studies demonstrate that women can manage the soils around their homes and gardens because manure and other organic residues are concentrated at home and less attention is paid to distant fields (19, 114). Nevertheless, in SSA countries, women are constrained by poor agricultural extension services, access to financial resources, and access to improved agricultural inputs such as seeds, herbicides, pesticides, fertilizers, and mechanization (106, 129). This scenario has aggravated the problem of soil fertility decline and thus low crop production in most smallholder farming systems in Africa, threatening the livelihood of most rural communities.

Furthermore, this study discovered that smallholder farmers prioritize soil fertility management for crops with high monetary value (84). According to our findings, the staple and monetary value of crops for smallholders varied by country and region within the same country based on agro-ecological characteristics. For example, in Kenya, Mairura et al. (129) found that more fertilizer was applied to crops that generate more income and have staple value for farmers, such as coffee, banana, napier, tobacco, and maize, while less fertilizer was applied to sorghum, green gram, and millet. Similarly, Haileslassie et al. (68) found that in Ethiopia, crops with high monetary value, such as teff and wheat, receive more attention than crops with low profitability. Positive nutrient balances (particularly N, P, and K) were observed in Rwandan fields with high-value crops such as rice, banana, and tomato, whereas negative nutrient balances were observed in fields with maize, sorghum, cassava, onions, and ground nuts (84).

Another socioeconomic issue that most smallholder farmers face is a lack of information on the status of soil fertilitySome of the issues that smallholder farmers are unaware of are soil analysis, fertilizer recommendation rates, and new soil fertility technologies (22). This has resulted in fertilizer over application (high resource farmers) or under application (low resource farmers) resulting in nutrient imbalances in the majority of smallholder farming systems in SSA (22). In general, socioeconomic factors influence the adoption, efficacy, and sustainability of soil management technologies; thus, farmer participation in modifying existing or developing new soil management technologies is critical because they are the primary actors in farming activities (14, 134, 135).

3.2 Status of soil nutrient balance in smallholders' farming systems

According to the findings of this review, the majority of studies on nutrient flow and balances have been conducted on mixed crop-livestock systems. The most researched farming systems in Kenya are highland perennials (dominated by coffee, bananas, and tea, with annual crops such as maize and legumes) and lowland cereals such as maize, sorghum, millet, and root crops like cassava. All of these systems are linked to livestock like cattle, goats, sheep, and poultry (Table 2). Similarly, the dominant farming systems in Ethiopia are crop-livestock farming systems, mostly enset-based with banana and cereals like barley, wheat, and teff and vegetables in

TABLE 2 Average full nutrient balances in the different farming systems.

Country	Farming systems	Nutrient balance ($kgha^{-1}yr^{-1}$)			Reference
		N	P	K	
Kenya	- Highland perennials (mixed crop-livestock dominated by coffee, tea, banana, and other crops like napier grass, maize, and vegetables)	-57.24 (38.79)	15.85 (26.57)	-34 (40.09)	Smaling & Fresco (40); Van den Bosch et al. (33); De Jager et al. (27); Utiger et al. (63); Kathuku et al. (56); Onduru et al. (59); Van Beek et al. (10);
	- Lowland mixed crop-livestock (mainly maize, sorghum, cassava, legumes, millet, and vegetables)	-30.06 (25.26)	-8.95 (9.75)	-13 (15.31)	De Jager et al. (60); Gachimbi et al. (65); Gachimbi et al. (32); Lelei & Tunya (88); Onwonga et al. (95)
Ethiopia	- High-land farming (mixed crop-livestock, predominantly enset-based, bananas, cereals like wheat, barley, and maize, and vegetables)	-21 (9.09)	7.26 (3.25)	-25.71 (27.23)	Haileslassie et al. (55); Haileslassie et al, (136); Elias et al. (45); Gebresamuel et al, (106);
	- Lowland farming (mixed crop-livestock, predominantly teff-based, and cereals like wheat, barley, maize, millet, sorghum, and legumes)	-44.41 (31.46)	-1.2 (9.78)	-51.11 (45.47)	Haileslassie et al, (68); Haileslassie et al. (55); Haileslassie et al. (55); Elias et al. (45); Abegaz (18); Huluka et al. (11); Kiros et al. (99); Gebresamuel et al, (106); Lewoyehu et al. (108); Esubalew et al. (107)

The numbers in parentheses are the standard deviations.

the highlands, and teff-based with barley, wheat, maize, sorghum, and legumes in the lowlands (Table 2). Other farming systems investigated include agro pastoral in Nigeria, Mali, Tanzania, Uganda, and Burkina Faso (46, 47, 49, 72, 73, 81, 82, 137, 138), and maize-mixed with crops such as legumes, cassava (57, 62, 71, 75). Based on the current review, Table 2 shows the average nutrient balance in the most studied countries over the last three decades. Regardless of the farming systems, the overall mean nutrient balances (particularly for N and K) reported in all studies were negative, with P being relatively small positive. Nitrogen, unlike other soil nutrients that are most likely derived from parent materials, must be supplemented externally. Nonetheless, N is the most required nutrient by plants and the most mobile nutrient, making it easily lost from the soil through harvested products, leaching, volatilization, erosion, and denitrification if not managed properly (88, 139). Potassium, on the other hand, is the third most important nutrient for crops after phosphorus (140). Despite the fact that potassium is abundant in soils, the readily available pool is so small, and the fate of K in soil is almost similar to that of N (141). This has been attributed to the high negative nitrogen and potassium balances found in most studies, particularly when the same field is cultivated for an extended period of time with little or no nutrient replenishment. The degree of nutrient depletion between N and K varied from study to study, depending on the cropping system in a given area. For example, Wortmann and Kaizzi (54) found a high negative balance of K in banana, bean, and sweet potato cropping systems, while maize and soybean cropping systems had a high negative balance of N in the same agro-ecological zone. Similarly, studies by Amann et al. (21); Diarisso et al. (103); and Abegaz (18), to name a few, found a high negative balance in K compared to N, whereas De Jager et al. (27); Bekunda and Manzi (67); and Tunya (98) found a high negative balance in N compared to K. The positive P balance observed in some studies could be attributed to the residue effect of applied P fertilizers or manure in those farming systems (98, 142). It is estimated that 70-90% of applied P fertilizer in soil becomes sorbed to soil particles and transforms into less available forms very quickly (143).

Crop harvesting and soil erosion are reported to be the major nutrient outputs in smallholder farming systems. According to Smaling and Fresco (40), harvested crop products and crop residues exported up to 61, 11, and 46 kg ha^{-1} year^{-1} of N, P, and K, respectively, accounting for 50–70% of total losses, while soil erosion contributed roughly one-third of total losses. Other nutrient outputs, such as leaching and gaseous losses, varied depending on soil type, climatic conditions, and management practices, but their contributions to nutrient loss were significantly low (40, 68).

The current review discovered significant differences in nutrient balances among farmers with similar agro-ecological conditions (i.e., soils, climate, and infrastructure). It demonstrates the importance of management practices in nutrient flow and balance. Given the diverse settings of smallholder farming systems across all studies, we found it difficult to make comparisons on nutrient balance in various farming systems for the current review due to variation between studies in terms of type of balance (partial or full), scale of study (farm, plot, village, district), and wealthy categories (rich, medium, poor). However, studies comparing wealthy farmers found that farm nutrient flow and balances were more positive in richly endowed resource farmers (i.e., those with high resource access) than in poor resource farmers [Shepherd & Soule (5, 50, 56, 62, 81, 87, 114, 144)]. It follows that richer farmers use large amounts of inorganic fertilizers and organic inputs on their fields (5). Moreover, richer farmers own more livestock which accounts for large amounts of manure produced on their farms and are likely to outsource additional manure/and or crop residues as fodder (145). This contrasts with poor farmers, whereby most of them are faced with multiple constraints including shortage of family labour and low purchasing power to inorganic fertilizers and/or additional source of manure (28, 62, 114). However, this is not always the case; for example, Elias (74) found high nutrient depletion, particularly N (-85 and -102 kg ha^{-1} yr^{-1}) in some rich farmer fields, whereas poor farmers had a low negative N balance (-50 and -56 kg ha^{-1} yr^{-1}). This explains that not how much input is put into the soil but how to manage those inputs matters.

Similar observations are reported in studies that compared homestead farms with distant fields (Figure 3) (62, 84). As smallholder farmers have limited access to inputs and focus on surviving, a considerable soil fertility gradient usually develops from the homestead to the so-called “far” fields. (68). The limited attention to soil fertility management on fields that are located away from home derives directly from the low farmers’ income (62, 114). Hence, the cost of transporting inputs such as fertilizers (both inorganic and organic fertilizers) and the labour requirement preclude optimal nutrient management in these fields. Gender differences also contributes to differences in adoption of soil fertility management, hence nutrient balance. A study by Gebresamuel et al. (106), found that female-headed households had more positive N, P, and K balances in their fields than male-headed households. Among other things, it appears that female-headed households have fewer animals or no livestock, resulting in low crop residue removal from their fields (106). Although women seem to be good soil fertility managers, due to multiple tasks obliged by women such as handling children their effort in soil fertility management is negligible thus crop production remains below potential yields. There are conflicting findings regarding the relationship between farming systems and nutrient balance; however, most studies concluded that farms with high levels of inputs (both organic and inorganic) performed well in terms of productivity and nutrient balance and stocks.

3.3 Studies on nutrient budgets in smallholders’ farming systems in SSA

The decline in soil fertility in SSA soils is threatening soil productivity in most arable lands. Most nutrient balance studies have found more negative nutrient balances, particularly for macronutrients (N, P, and K), and the trend continued to rise year after year. In central Kenya, for example, the N, P and K balances were -55, 9 and -15 kgha^{-1} yr^{-1}, respectively, in 1998, but had more than doubled to -116.2, -22.1, and -31.7 kgha^{-1} yr^{-1} five years later (56). Studies indicate that understanding the dynamics of farm nutrient flow is fundamental for

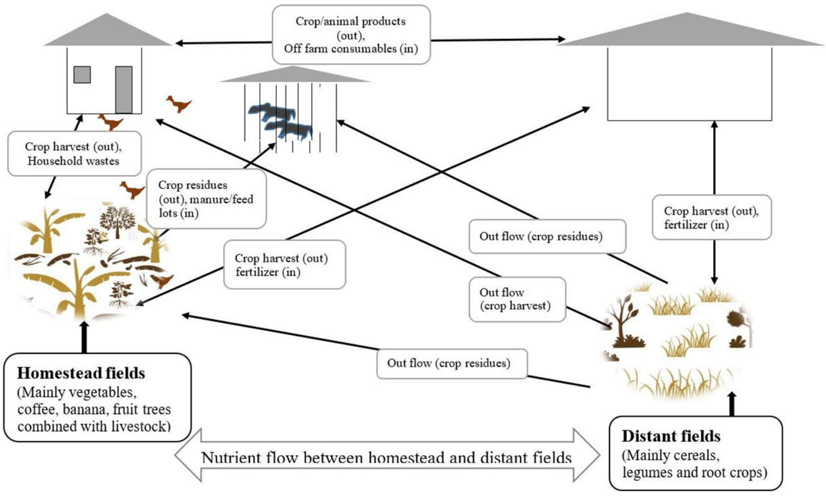

FIGURE 3
A schematic representation of nutrient flow between, within, and outside homesteads and distance farms.

proper implementation of appropriate soil nutrient management techniques (38, 146–148). Over the last three decades, numerous researchers have developed nutrient balance and budget models, including the system for quantitative evaluation of fertility in tropical soils (QUEFS), universal soil loss equation (USLE), nutrient monitoring (NUTMON), and material flow analysis (MFA), to name a few (21). NUTMON, however, is the most popular model for evaluating nutrient flow and budget in several SSA countries, particularly in East Africa, due to its ability to integrate both biophysical and socioeconomic approaches (29, 33, 38). When used properly, NUTMON provides an insight indicator for soil nutrient depletion and/or surplus, aiding in the planning of proper soil management practices (37). A better understanding of the nutrient budget may also raise awareness among agricultural stakeholders and policymakers. Nutrient budgets at the farm level can provide a comprehensive picture of nutrient flow from the village to the national level, informing stakeholders' interventions (149).

In this review, we discovered that almost all NUTMON studies focused on the major three nutrients, namely N, P, and/or K, rather than other essential nutrients such as magnesium, calcium, sulfur, and micronutrients. Reports have shown that micronutrients such as zinc, iron, boron, and copper have been gradually decreasing in SSA soils, leading to malnutrition, particularly in children under the age of five (148, 150, 151). Iron and zinc deficiencies, for example, have been reported in many African countries, particularly among children under the age of five (151, 152). Despite this, little to no effort has been made to monitor these plant nutrients. Thus, researchers should investigate the balances of other essential plant nutrients. Furthermore, in most SSA countries, a lack of research capacity, particularly for long-term trials, has made it difficult to draw valid conclusions from NUTMON research (120, 153). Despite the success stories of NUTMON reported in SSA and elsewhere, the validity of the remains in doubt (30, 154). Transfer functions, which rely heavily on regression models, are too general and may not be applicable everywhere, contradicting the actual losses (36). Simply put, extensive use of NUTMON tools may result in an overestimation or underestimation of actual nutrient losses (30, 64). This suggests that there is still much work to be done on NUTMON, particularly in smallholder farming systems.

4 Conclusion

The goal of this review was to draw attention to problems involving the characteristics of smallholder farmers in soil nutrient management in SSA as a factor impacting soil nutrient balance. A phrase by Goulding et al. (86) stated that '*You do not get something for nothing*'; '*you get out what you put in*'. Agriculture must literally return to its roots by rediscovering the value of healthy soil, relying on natural sources of plant nutrition, and employing mineral fertilizers wisely. This review demonstrates that farming systems have a significant impact on soil nutrient flow and balance. However, socioeconomic factors play an important role in the management and sustainability of a specific farming system. While smallholder farmers recognize the importance of various technologies in soil fertility restoration, most SSA farmers have found it difficult to adopt these technologies.

Based on the findings of this review, it is clear that the majority of smallholder farmers in SSA rely entirely on organic inputs such as animal manure and crop residues, both of which are insufficient in quantity and quality. The reliance on organic inputs has been attributed to either smallholder farmers' low purchasing power, poor agricultural policy and government support, or the research methods used, i.e., the “top-down” approach (without engaging the targeted community). Farmers in good financial standing, for example, have access to inputs, labor, off-farm income, and livestock possessions that poor farmers do not. As a result, it is past time for research efforts in developing countries to focus on site-specific nutrient management in the context of socioeconomic aspects, with close engagement of smallholder farmers (the primary stakeholders), so that the introduced technologies are well suited to the intended farming systems. NUTMON, the most widely used model in assessing soil nutrient balance, should take into account other limiting nutrients, such as micronutrients, and be validated based on the farming system of a given area.

Author contributions

LM: Conceptualization, writing original draft and editing. Other authors: Reviewing, editing and approved the final manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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