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# Optimising Nutrient Cycles to Improve Food Security in Smallholder Farming Families—A Case Study from Banana-Coffee-Based Farming in the Kagera Region, NW Tanzania

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**Abstract:** In East Africa, soil nutrient depletion and low yields jeopardise the food security of smallholder farming families and exacerbate poverty. The main reasons for the depletion of soil nutrients are overuse due to population growth, limited land, and increasing uncertainty in agricultural production caused by climate change. This study aims to analyse and optimise nutrient flows and stocks in the homegardens of smallholder banana-coffee-based farming systems in the Kagera region in NW Tanzania. The plant nutrients nitrogen (N), phosphorus (P), and potassium (K) in plant-based biomass and organic farm waste are under investigation. We used data from a farm household survey (150 households) and from focus group discussions with 22 trainers who had been training about 750 farm households in sustainable land management (SLM) at a local farmer field school. In total, we identified six farm household types and calculated a nutrient balance (NB) for the homegardens of each household type. The NB was calculated for the following five management scenarios: S0: business as usual; S1: the use of 80% of the available human urine; S2: the incorporation of 0.5 t $yr^{-1}$ of the herbaceous legume species *Crotalaria grahamiana* into the soil; S3: the production of 5 $m^3$ $yr^{-1}$ CaSa-compost (human excreta and biochar) and its application on 600 $m^2$ land; and S4: a combination of S1, S2, and S3. The results show that the NB varies considerably depending on whether farmers have implemented the SLM training, apply nutrient-preserving manure collection and storage methods, and purchase fodder (imported nutrients), or whether they do not collect manure or do not purchase fodder. Trained farm households are more likely to have a positive NB than untrained households because they have already improved the nutrient management of their farms through the successful implementation of SLM practices. Untrained households would improve the NB in their homegardens under all management scenarios. However, the NB depends on labour-intensive manure collection and compost production, labour shortages, prolonged dry seasons, and socio-economic imbalances. As long as these constraints remain, nutrient deficiencies will not be overcome with mineral fertilisers alone, because soils have to be further enriched with organic matter first. In this paper, we also emphasise the importance of the system boundary, because only a complete NB can give an estimate of actual nutrient removal and the resulting nutrient demand (including removals by fodder and trees). Further improvements in the SLM training may be achieved by (i) measuring the current nutrient status of soils, (ii) analysing the need for the coexistence of free-range livestock on the grassland and zero-grazing in trained households, and (iii) conducting an in-depth analysis of the socio-economic differences between successful and unsuccessful households. In conclusion, if smallholder farmers were to integrate further improved SLM training and optimised nutrient management (S1 to S4), we assume that the NB would turn positive. Last but not least, the SLM training by the farmer field school may serve as a best-practice example for training and policy recommendations made by government institutions.

**Keywords:** sustainable land management; soil fertility management; farm waste management; agroforestry; nutrient balances; human urine; legume; biochar; CaSa-compost; food security

## 1. Introduction

In Sub-Saharan Africa (SSA), rapid population growth has increased demand for food, water, and energy, while limited land, water scarcity, environmental and soil degradation, and growing regional vulnerability to climate change hamper agricultural intensification [1–4]. Yield gaps and food imports remain high in many African agricultural systems. Although total cereal production has increased over the last four decades, production per hectare remains highly variable, and food production is not keeping pace with population growth [5,6]. Since most farmers in SSA are subsistence smallholder farmers, poor yields directly drive such farmers into poverty [7–9].

Yields are stagnating or collapsing due to poor soil fertility, poor nutrient and water management, low organic and mineral inputs, labour shortages, and progressive climate change (unpredictable rainy seasons, intermittent rain, and prolonged droughts) [10–14]. As a result of these constraints, the soil nutrient balance (NB) in small-scale farming systems is often negative because nutrient removals are often higher than nutrient inputs [15–18]. In previous studies, the NB in sub-humid mountainous regions in East Africa varied between −77 and 17 kg N, −8 and 7 kg P, −57 and 12 kg K $ha^{-1}$ $yr^{-1}$ (on *Andosols*, *Ferralsols*, and *Plinthosols*), with positive values on farms with access to cattle manure and biomass imports from the surrounding grass- and woodland [19–22].

Soil nutrient analyses and nutrient management were based on the principles of the circular economy (CE) long before the conceptual framework of the CE was named and written down by Pearce and Turner in 1990 [19] (e.g., in 1946 and 1961, in the studies on the relationship between crop yield and soil nutrient status [20,21], and in 1977, in the study on nutrient intensity (concentration) [22]): "The central theme of the CE concept is the valuation of materials within a closed-loop system with the aim to allow for natural resource use while reducing pollution or avoiding resource constraints and sustaining economic growth" [19]. In recent years, the concept of the CE has become much more attractive, as overconsuming throwaway societies in industrialised countries have increasingly developed the desire or the need to transform into zero-waste societies. However, smallholder farming families in East Africa are hardly affected by overconsumption, and seek to use and reuse materials they produce on their farms, which they rarely call "waste". Using organic farm waste as fertiliser is still the most prominent example of the applied CE in East African agriculture. Another example of the reuse of waste in agriculture is the use of old plastic water bottles for drip irrigation. Farmers have become informal experts in composting and the production of organic fertiliser. As the authors in [23] note, "farmers possess intuitive knowledge of the decomposition and nutrient mineralisation of the readily available organic resources".

In this context, we investigated in previous studies how 150 smallholder farming families used organic farm waste and how another 750 farm households were trained in sustainable land management (SLM) by a self-organised farmer field school [24,25]. Both groups of farmers practise small-scale, organic agriculture to produce plantain (*Musa* spp.) as their main staple crop, coffee (*Coffea canephora var. robusta*) as their principal cash crop, and common beans (*Phaseolus vulgaris* L.)

and maize (*Zea mays* L.) as additional food crops in rainfed banana-coffee-based farming systems in the mountainous Kagera region in NW Tanzania [24,26,27]. They rarely have access to synthetic fertiliser (under 2% of the households in the area). In the past, the composting of organic farm waste, such as livestock manure, crop residues, litter, kitchen and food waste, and human urine, was of crucial importance for maintaining the soil fertility of homegardens and is still an important practice today [24,28–30]. Since the 1950s, the region has experienced rapid population growth, partially due to refugee immigration. Previously fertile soils and densely grown, multi-layered homegardens have been degraded into single-layered vegetation with just a few crops, such as bananas and beans, on poor soils [24,25,31–33].

This previous research led us to the question of whether nutrient cycles could be closed to increase soil fertility and crop productivity and, if so, under what conditions. Thus, here we ask the following research questions: (A) Are the nutrient balances of trained households more positive than those of untrained households? (B) Can nutrient cycles be closed through composting? (C) Under what scenarios could soil nutrient balances be optimised? (D) What other ecological and socio-economic conditions need to be met to close nutrient cycles at the farm level? To answer these questions, we used material flow analysis (MFA) to calculate the NB of nitrogen (N), phosphorus (P), and potassium (K) for each household group in five scenarios. In this paper, we give background information on the study area and the data sets used, describe the variables applied in the MFA in detail, and introduce the scenarios (Section 2). Values for the variables can be found in the Appendix A. We have illustrated the main results in a Sankey diagram (Section 3) and discuss the methodology and the results in Section 4. Our conclusions also involve recommendations for science and policy development.

## 2. Materials and Methods

### *2.1. Study Area*

The study area covers the Kyerwa and Karagwe districts in the Kagera region in NW Tanzania between 1.0° S, 30.4° E, 1200 m a.s.l and 2.1° S, 31.4° E, 1650 m a.s.l. (Figure 1). The region is characterised by a bimodal rain pattern, with annual precipitation of 716 to 1286 mm (mean 982 ± 127 mm) in Kayanga, and moderate temperatures, with minimum mean temperatures between 11.6 °C and 16.2 °C and maximum between 24.6 °C and 28.3 °C [25,34,35]. Most of the rain falls in two rainy seasons: the Masika rainy season from March to May, and the Vuli rainy season from October to January. Soils in the study area are variously classified as *Andosols* [34], *Ferralsols*, *Leptosols*, *Acrisols*, *Cambisols*, and *Phaeozems*; in river terraces as *Fluvisols*, *Gleysols*, and *Planosols*; and in swamps as *Histosols* [25], with *Andosols* and *Ferralsols* being the most important soil types for agricultural production (up to 90%).

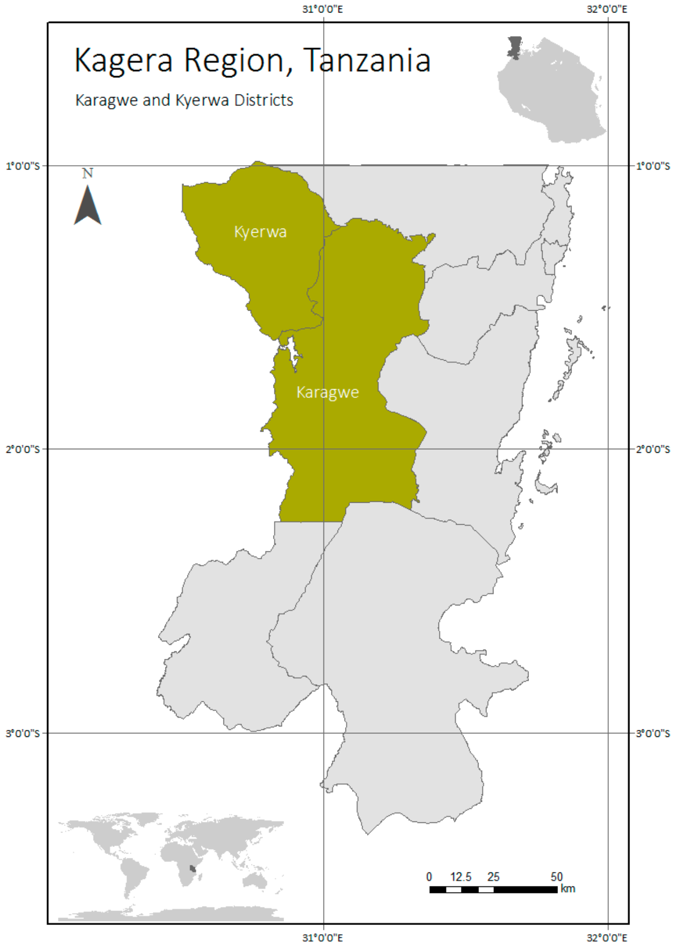


**Figure 1.** Map of the study area showing the Karagwe and Kyerwa districts of the Kagera region in NW Tanzania [24].

### *2.2. Data*

In this paper, we combine two data sets from our previous research. The first data set is quantitative and is taken from a survey of 150 smallholder farm households [24]. The second data set is qualitative and is taken from five focus group discussions with 22 trainers from the local farmer field school: the MAVUNO Project [25].

#### Background Information on the Data

In our previous research, we built farm household typologies for each of the two data sets. Each data set resulted in three household groups as follows: ($A_U$) non-vulnerable to food insecurity, untrained; ($B_U$) vulnerable, untrained; ($C_U$) most vulnerable, untrained; ($A_T$) non-vulnerable, trained; ($B_T$) vulnerable, trained; and ($C_T$) most vulnerable, trained. Groups $A_U$ to $C_U$ emerged from the survey data [24], and groups $A_T$ to $C_T$ from the focus group discussions [25]. The main household and production data of all groups are presented in Table 1.

**Table 1.** Characteristics of smallholder farm household groups. Untrained households (groups $A_U$, $B_U$, $C_U$) were surveyed in 2017 and grouped within a multivariate statistical analysis [24]. Mean values of the quantitative survey data are presented here. Trained households (groups $A_T$, $B_T$, $C_T$) were trained in sustainable land management (SLM) [25]. Qualitative data from focus group discussions with the trainers who trained the households are also presented here.

| | | **Untrained Households** [I] | | | | **Trained Farm Households** [II] | | |
|---|---|---|---|---|---|---|---|---|
| **Household Characteristics** | **Unit** | **$A_U$** | **$B_U$** | **$C_U$** | **Mean** | **$A_T$** | **$B_T$** | **$C_T$** |
| | **Households Group$^{-1}$** | **58** | **52** | **44** | | **296** | **262** | **198** |
| Homegarden size | | | | | | | | |
| Homegarden | ha (average) | 2.8 | 1.8 | 0.6 | 1.8 | 0.6–2.8 (1.4) | 0.4–1.0 (0.7) | 0.2–0.8 (0.5) |
| Transformed homegarden | ha (average) | 0.0 | 0.0 | 0.0 | 0.0 | 0.4–0.8 (0.6) | 0.1–0.4 (0.2) | ≤ 0.1 |
| Household characteristics | | | | | | | | |
| Household size | p household$^{-1}$ | 10.2 | 9.7 | 5.7 | 8.5 | 5.3 | 5.1 | 5.1 |
| Female-headed | % of households | 16 | 35 | 43 | 31 | 30 | 29 | 33 |
| Labour | hours adult$^{-1}$ day$^{-1}$ | 5.6 | 5.0 | 3.6 | n.a. | 7.6 | 6.7 | 5.1 |
| Available food [III] | months yr$^{-1}$ | 6.6 | 3.2 | 1.7 | 4.2 | n.a. | n.a. | n.a. |
| Meals | meals day$^{-1}$ | n.a. | n.a. | n.a. | n.a. | 3.0 | 2.2 | 1.7 |
| Crop yields | | | | | | | | |
| Banana *(Musa spp.)* | t homegarden$^{-1}$ yr$^{-1}$ | 4.2 | 1.8 | 0.2 | 2.1 | 11–57 | 2.8–18 | 0.7–1.2 |
| Coffee *(Coffea canephora)* | t homegarden$^{-1}$ yr$^{-1}$ | 0.5 | 0.1 | 0.1 | 0.2 | ≤0.7 | ≤0.1 | ≤0.1 |
| Beans *(Phaseolus vulgaris spp.)* | t homegarden$^{-1}$ yr$^{-1}$ | 1.5 | 0.7 | 0.2 | 0.8 | 0.4–0.8 | 0.1–0.4 | 0.1–0.2 |
| Maize *(Zea mays spp.)* | t homegarden$^{-1}$ yr$^{-1}$ | 0.6 | 0.7 | 0.1 | 0.5 | 0.3–1.0 | 0.1–0.5 | 0.1–0.2 |
| Cassava *(Manihot esculenta spp.)* | t homegarden$^{-1}$ yr$^{-1}$ | 0.4 | 0.4 | 0.2 | 0.3 | 0.8 | 0.5 | 0.2 |
| Banana *(Musa spp.)* | t ha$^{-1}$ yr$^{-1}$ [IV] | 1.5 | 1.0 | 0.3 | 1.2 | 7.9–36 | 4.0–25.7 | 1.4–2.4 |
| Coffee *(Coffea canephora)* | t ha$^{-1}$ yr$^{-1}$ [IV] | 0.2 | 0.1 | 0.1 | 0.1 | ≤0.5 | ≤0.2 | ≤0.1 |
| Beans *(Phaseolus vulgaris spp.)* | t ha$^{-1}$ yr$^{-1}$ [IV] | 0.5 | 0.4 | 0.3 | 0.4 | 0.3–0.6 | 0.1–0.6 | 0.2–0.4 |
| Maize *(Zea mays spp.)* | t ha$^{-1}$ yr$^{-1}$ [IV] | 0.2 | 0.4 | 0.2 | 0.3 | 0.2–0.7 | 0.1–0.7 | 0.2–0.4 |
| Cassava *(Manihot esculenta spp.)* | t ha$^{-1}$ yr$^{-1}$ [IV] | 0.1 | 0.2 | 0.3 | 0.2 | 0.6 | 0.4 | 0.1 |
| Livestock | | | | | | | | |
| Improved cattle (Friesian) (homegarden) | TLU [V] | 0.2 [VI] | 0.3 [VI] | 0.0 [VI] | 0.1 [VI] | 2.0 | 0.6 | 0.0 |
| Indigenous cattle (grassland) | TLU | 6.6 [VI] | 3.1 [VI] | 0.0 [VI] | 3.4 [VI] | ≤26 | <10 | 0.0 |
| Goats, sheep, pigs (homegarden) | TLU | 1.1 [VI] | 0.9 [VI] | 0.4 [VI] | 0.8 [VI] | ≤2.0 | <1.2 | ≤0.3 |
| Chickens, rabbits (homegarden) | TLU | 0.1 [VI] | 0.0 [VI] | 0.0 [VI] | 0.0 [VI] | ≤1.0 | ≤0.4 | ≤0.2 |
| Bees (homegarden) | beehives | 0.0 [VI] | 0.0 [VI] | 0.0 [VI] | 0.0 [VI] | ≤3 | ≤1 | 0.0 |

A, B and C = household group identity, U = untrained, T = trained, and n.a. = not analysed. [I] Untrained farm household groups analysed in [24] from household data [36,37], with the averaged values of each group and mean values of all groups. [II] Trained farm households analysed in [25] from focus group discussions and interviews with SLM trainers. [III] Number of months in one year in which the household has enough food and is not starving or hungry as self-assessed by the households. [IV] All crops grow in the same homegarden. The unit refers to multi-cropped land and not to monocultures. [V] Tropical livestock units (1 TLU = 257 kg) referring to the smallholder farmers in Tanzania; 1 cow = 1.3 TLU; 1 goat, sheep, or pig = 0.2 TLU; 1 chicken or rabbit = 0.01 TLU [38]. [VI] The data were not published in [24], but taken from the same data set [36,37].

The findings in [24] revealed that (a) farm nutrient management in untrained households (groups $A_U$, $B_U$, and $C_U$) is based on the traditional practices of in situ, pit, and ring-hole composting of crop residues, and (if available) kitchen and food waste and livestock manure; however, (b) half of the livestock manure is not collected and thus remains unused; (c) the nutrients in coffee hulls are exported in their entirety; (d) 30% of the untrained households use human urine as an organic fertiliser and pesticide; (e) none use human faeces; and (f) the remaining inorganic ash from cooking above three-stone fires is rarely used in farm waste management due to negative spiritual beliefs.

In comparison, trained households (groups $A_T$, $B_T$, and $C_T$) also apply in situ, pit, and ring-hole composting to produce organic fertiliser and additionally employ: (a) trench composting along contour lines to minimise soil erosion from runoff and to increase water infiltration along the trenches; (b) zero-grazing in homegardens to facilitate manure collection and livestock monitoring; (c) the mulching of bare soils with grass throughout the year; (d) the cultivation of drought-tolerant crop species to meet changing rain patterns; (e) the frequent planting of indigenous tree species to increase biodiversity, provide shade for underlying crops, and compensate for the deforestation of nearby woodlands and forests; and (f) gender-inclusive communication and decision-making, and gender-balanced labour division [25].

However, in both cases, the crop yields remained below the potentially attainable yields. Not all farm households have been equally successful in implementing their training, and some families remain trapped in a weak socio-economic position [24,25]. As a comparison, under optimal soil fertility management, yields of the East African highland banana (*Musa* AAA-EA), red coffee cherries (*Coffea canephora var. robusta*), maize (*Zea mays* L.), and common beans (*Phaseolus vulgaris* L.) in East African smallholder agriculture can reach up to 67 t, 1.7 t, 7.9 t, and 0.9 t $ha^{-1}$ $yr^{-1}$, respectively [2,39–44].

### 2.3. Analysis

For both data sets, a material flow analysis was applied after [45] to calculate the yearly nutrient balance (NB) of N, P, and K per hectare of farmland (homegarden). NB is defined as the difference between the sum of nutrient inputs entering the system and the sum of the nutrients leaving the system at a specific scale, such as at the farm level or within a farming system [17,18,46]. In this analysis, the following input, output, and stock variables were considered:

INPUT
Atmospheric deposition (IN1)
Inputs by plants and trees (IN2)
- Litterfall (IN2a)
- Deep capture (IN2b)
- Biological fixation (IN2c)

Organic fertiliser (IN3)
- Crop residues (IN3a)
- Kitchen and food waste (IN3b)
- Cooking ash (IN3c)
- Livestock manure and urine (IN3d)
- Human excreta (IN3e)

OUTPUT
Harvested crops (OUT1)
- Perennial crops (OUT1a)
- Annual crops (OUT1b)

Fodder (OUT2)
Wood (OUT3)
Market (OUT4)
Sold crop residues (OUT5)
Leaching from soil (OUT6)
Leaching from pit latrines (OUT7)
River discharge (OUT8)
Gaseous losses (OUT9)

STOCK
Human body (STOCK1)
Animal body (STOCK2)
Pit latrine (STOCK3)
Soil (STOCK4)

Input variables lead to an inflow of N, P, and K into the farm system, and output variables to an outflow out of the farm system. Stocks are elements of the farm system where N, P, K are saved for a certain time, e.g., human excreta in pit latrines. The boundaries of farming systems are key in calculating and interpreting the NB. Depending on the system boundaries that are defined and the flows and stocks considered, the NB may vary between positive, neutral, and negative on the same piece of land [17,18].

The analysis followed a scheme of biomass and waste dynamics (Figure 2) incorporating seven sub-systems: soil, farm, food production, energy, food processing, sanitation, and composting. The system boundaries are set around these sub-systems.

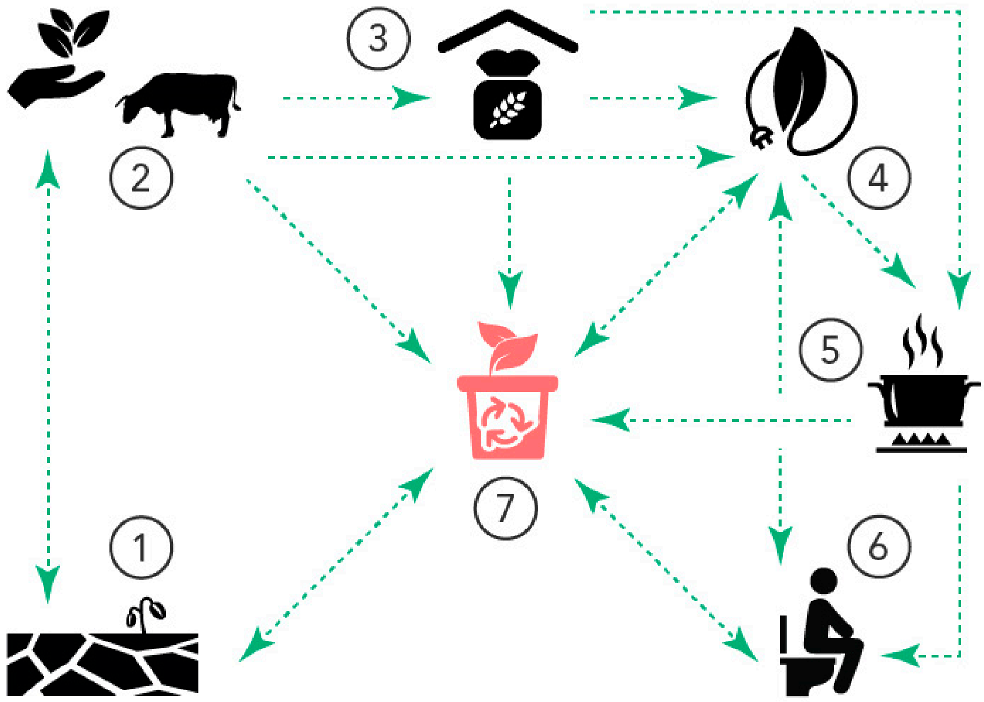


**Figure 2.** Biomass and waste dynamics and the mass fluxes of nutrients and energy in multifunctional land-use systems in smallholder farming systems in the tropical highlands of East Africa. Labelling as follows: 1: the soil sub-system, 2: plant and animal production as a sub-system, 3: harvest and storage of food, 4: bioenergy production, 5: food processing, 6: sanitation, and 7: the compost sub-system. (Design: Claudia Matthias)

2.3.1. Variables

We collected values for the variables from a systematic literature review after [47] on the Web of Science by using the search string "TITLE: (nutrient balance) AND TOPIC: (Africa)". The variables are described and calculated as follows.

Deposition (IN1)

In dense montane tropical forest systems, the wet deposition of total dissolved nitrogen (TDN) is about 21.2 kg N ha$^{-1}$ yr$^{-1}$ on *Ferralsol* and *Acrisol* in the Congo basin, comprising $NH_4^+$, $NO_3^-$, and dissolved organic nitrogen (DON) of 9.6, 5.8, and 5.8 kg N ha$^{-1}$ yr$^{-1}$, respectively [48]. These values are considered the maximum values for IN1a, whereas the estimated wet deposition from the rain samples was about 1.8 kg N ha$^{-1}$ yr$^{-1}$ in the same study area (Karagwe-Ankolean) 20 years ago [25,49]. In [50], atmospheric deposition (wet and dry) was estimated according to [46] by using the following equations (with p for annual rainfall in mm yr$^{-1}$):

$$IN1_{a_N} = 0.14 \times p^{\frac{1}{2}} \quad (1)$$

$$IN1_{a_P} = 0.023 \times p^{\frac{1}{2}} \quad (2)$$

$$IN1_{a_K} = 0.092 \times p^{\frac{1}{2}} \quad (3)$$

We applied these equations in this paper, and found that atmospheric deposition reaches 4.4 kg N, 0.7 kg P, and 2.9 kg K $ha^{-1}$ $yr^{-1}$, with a mean annual rainfall of 982 mm.

Above-Ground and Below-Ground Inputs by Plants and Trees (IN2)

To determine the above-ground and below-ground inputs by plants, we have summarised the litterfall (IN2a), deep capture (IN2b), and biological fixation (IN2c).

Litterfall (IN2a) and Deep Capture (IN2b)

We found litterfall data for a mixed crop–livestock–forest system in Cameroon with a bimodal tropical rainfall regime and a multitude of crops, such as cacao and plantain, as well as trees with food and medicinal value and timber tree species [50]. The annual litterfall was measured to be 5 t $ha^{-1}$ $yr^{-1}$, with nutrient inputs of 66 kg N, 5.2 kg P, and 26 kg K $ha^{-1}$ $year^{-1}$, and a corresponding deep capture of 16 kg N, 1.4 kg P, and 6.6 kg K $ha^{-1}$ $yr^{-1}$ [50]. The authors in [50] assumed that 75% of the nutrients in the litter were recycled in the root zone and that 25% were deep-captured from below the root zone, as most trees on acidic soils ($pH_{KCl}$ 4 to 4.5) have 70% to 80% of their roots in the top 57 cm, as shown in [51]. The soils in the study area have a $pH_{KCl}$ of 3.8 [30]. We assume that the farm household group $A_T$ reaches similar values (100%). We estimated 80% of this value for $A_U$, 60% for $B_T$, 40% for $B_U$, 30% for $C_T$, and 10% for $C_U$.

Biological Fixation (IN2c)

In [49], the inputs through biological fixation from common beans (*Phaseolus vulgaris*) were estimated to be half of the total plant uptake in the above-ground biomass at 19.0 kg N $ha^{-1}$ $yr^{-1}$, with an asymbiotic N fixation rate of 3 kg N $ha^{-1}$ $yr^{-1}$, corresponding to a yield of 557 kg beans $ha^{-1}$. The fixed amount of N in the cultivation of common beans in Africa ranges from 8 to 58 kg N $ha^{-1}$, with 10% to 55% of the crop N derived from atmospheric $N_2$ [52]. We adopted the biological fixation rate from [49] because it was analysed for smallholder banana-coffee-based farming systems in the same study area, and applied it to the yields reached in each household group.

Organic Fertiliser (IN3)

Organic fertiliser is usually a mixture of organic crop residues (IN3a), kitchen and food waste (IN3b), cooking ash (IN3c), livestock manure (IN3d), and (rarely) human excreta (IN3e). Farmers mix organic farm waste to produce in situ, pit, ring-hole, and trench compost, as described in detail in [24,25,53].

Crop Residues (IN3a)

We estimated the amount of crop residues from the harvest, as presented in Table 2. Banana plants were estimated from the harvest of banana bunches. The formula was validated in the field with $P_{ban}$ for banana plants and $H_{ban}$ for harvested bunches of bananas:

$$P_{ban} = H_{ban} \times 1.2 \tag{4}$$

**Table 2.** Amounts of crop residues and kitchen and food waste of perennial and annual crops per household group and year. Dry weights are taken according to [54]. The amounts of crop residues depend on the crop yield. The crop yield varied among the trained households. T = trained, U = untrained, av. = mean value, min. = minimum value, max. = maximum value in this group of households, DM = dry matter, n.a. = not analysed.

| **Annual Crop Residues** | **Household Groups** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Unit** | **$A_U$** | **$B_U$** | **$C_U$** | **$A_T$** | | | **$B_T$** | | | **$C_T$** | | |
| | | | | | **av.** | **min.** | **max.** | **av.** | **min.** | **max.** | **av.** | **min.** | **max.** |
| Banana | | | | | | | | | | | | | |
| Plants | $ha^{-1}$ | 60 | 60 | 52 | 585 | 377 | 1200 | 446 | 168 | 617 | 57 | 56 | 72 |
| Leaves | kg $ha^{-1}$ | 494 | 300 | 90 | 6585 | 3300 | 15,000 | 4495 | 840 | 5400 | 285 | 210 | 360 |
| Leaves, dry | kg DM $ha^{-1}$ | 68 | 49 | 14 | 988 | 535 | 2257 | 468 | 126 | 810 | 43 | 32 | 57 |
| Pseudostems | kg $ha^{-1}$ | 225 | 157 | 49 | 3293 | 1657 | 7570 | 2228 | 400 | 2700 | 143 | 105 | 180 |
| Peel, fresh | kg $ha^{-1}$ | 357 | 233 | 70 | 5114 | 2563 | 11,657 | 2403 | 652 | 4194 | 221 | 163 | 280 |
| Peel, dry | kg DM $ha^{-1}$ | 57 | 36 | 11 | 788 | 395 | 1794 | 373 | 100 | 646 | 34 | 25 | 43 |
| Stalk | kg $ha^{-1}$ | 35 | 23 | 6.9 | 579 | 253 | 1157 | 239 | 64 | 414 | 22 | 16 | 28 |
| Coffee | | | | | | | | | | | | | |
| Husks | kg $ha^{-1}$ | 90 | 49 | 49 | 135 | 49 | 225 | 68 | 49 | 90 | 23 | 14 | 49 |
| Leaves | kg $ha^{-1}$ | 20 | 10 | 10 | 30 | 10 | 57 | 15 | 10 | 20 | 5 | 3 | 10 |
| Leaves, dry | kg DM $ha^{-1}$ | 19 | 9.2 | 9.2 | 28 | 9.2 | 46 | 14 | 9.2 | 19 | 4.6 | 2.8 | 9.2 |
| Beans | | | | | | | | | | | | | |
| Foliage | kg $ha^{-1}$ | 1071 | 861 | 655 | 949 | 630 | 1260 | 735 | 210 | 1260 | 630 | 400 | 840 |
| Straw | kg DM $ha^{-1}$ | 940 | 758 | 573 | 832 | 557 | 1109 | 647 | 185 | 1109 | 557 | 370 | 739 |
| Maize | | | | | | | | | | | | | |
| Foliage | kg $ha^{-1}$ | 280 | 560 | 280 | 630 | 280 | 980 | 560 | 140 | 980 | 400 | 280 | 560 |
| Stover | kg DM $ha^{-1}$ | 83 | 166 | 83 | 186 | 83 | 290 | 166 | 41 | 290 | 124 | 83 | 166 |
| Cobs | kg $ha^{-1}$ | 36 | 72 | 36 | 81 | 36 | 126 | 72 | 18 | 126 | 57 | 36 | 72 |
| Cobs, dry | kg DM $ha^{-1}$ | 33 | 66 | 33 | 74 | 33 | 115 | 66 | 16 | 115 | 53 | 33 | 66 |
| Cassava | | | | | | | | | | | | | |
| Foliage | kg $ha^{-1}$ | 120 | 240 | 360 | 720 | n.a. | n.a. | 520 | n.a. | n.a. | 120 | n.a. | n.a. |
| Foliage, dry | kg DM $ha^{-1}$ | 27 | 57 | 81 | 162 | n.a. | n.a. | 108 | n.a. | n.a. | 27 | n.a. | n.a. |
| Peel, fresh | kg $ha^{-1}$ | 12 | 23 | 35 | 69 | n.a. | n.a. | 46 | n.a. | n.a. | 12 | n.a. | n.a. |
| Peel, dry | kg DM $ha^{-1}$ | 10 | 20 | 30 | 60 | n.a. | n.a. | 40 | n.a. | n.a. | 10 | n.a. | n.a. |

A banana plant should be replaced by another species every 10 to 15 years to minimise nutrient depletion, the incidence of pests, and diseases; this minimises dependency on synthetic fertilisers and pesticides [53]. Banana leaves and pseudostems are greater than twice the bunch weight [51], with 50% of the weight from leaves and 50% from pseudostems [53]. Assuming that a banana plant is cut down every 10 years [53] and one-third of the leaves fall as crop residues every year [55], the annual crop-residue factor is 0.15 for the pseudostem and 0.3 for banana leaves. For the leaves of evergreen coffee shrubs, we assume a crop-residue factor of 0.1. For maize, the crop-residue factor is 1:1.4 [55]. For cassava, we assume a factor of 1:1.2, and for beans and soybeans, we assume a factor of 1:2.1 according to [55].

Kitchen and Food Waste (IN3b)

About 16% of the dry weight of harvested banana bunches is pulp, 5% peel, and 0.5% stalk [49]. Peels and stalks are considered kitchen waste. About 45% of harvested coffee cherries consist of husks [49], which are exported and thereby not counted as kitchen waste. Bean husks, maize cobs, and cassava peel are also kitchen waste. Each ton of maize consists of approximately 180 kg cobs [54]. The peel of the cassava tuber accounts for 8% to 15% of the tuber [54]. Kitchen and food waste is the second-largest plant-based farm waste fraction. Generally, food waste remains low in the area as most households are food insecure. Most food waste occurs when harvested crops are not properly stored and spoil. The amounts of crop residues, along with kitchen and food waste, are multiplied by the nutrient values taken from Table A1 and summarised in Table 2.

Cooking Ash (IN4c)

Cooking ash remains after burning firewood and charcoal in either three-stone fires or improved cooking stoves. Cooking ash contains mineral nutrients such as P, K, calcium (Ca), and magnesium (Mg), but hardly any C, N, or sulphur (S) due to volatilisation during the oxidation process [56]. Cooking ash may improve the compost's properties. According to [57], one smallholder household produces 23 kg ash $yr^{-1}$ if they cook over three-stone fires, which contain a total of 1.0 kg P and no nitrogen.

Livestock Manure and Urine (IN3d)

We estimated the daily livestock manure production and multiplied the yearly amounts of manure with nutrient contents according to [50,58–61] and presented in Table 3. Manure is defined as a mixture of dung, possibly with urine and bedding [58]. In [61], the nutrient content in cattle manure in East Africa varied between 0.9% and 1.6% N, 0.3% and 0.6% P, and 1.3% and 2.4% K. Usually, the amount of chicken urine is too small to be relevant. Urine can only be collected under zero-grazing conditions on a bedding floor, with daily collection of fresh manure and composting of urine-soaked bedding [58].

**Table 3.** Daily livestock manure and urine production and nutrient concentration in manure and urine.

| | Manure | | | | | Urine | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Solid dung [I] | Fresh dung [I] | N | P | K | Amount [III] | N | P | K |
| | kg $animal^{-1}$ $d^{-1}$ | | in solid dung | | | L $animal^{-1}$ $d^{-1}$ | g $L^{-1}$ | g $L^{-1}$ | g $L^{-1}$ |
| Cattle | 16.3 | 15–20 | 1.2 [II] | 0.3 [II] | 2.1 [II] | 13.0–16.0 | 6.8 [IV] | n.d. | n.d. |
| Goat, sheep | 1.5 | 0.9–3.0 | 1.5 [II] | 0.2 [II] | 3.0 [II] | 0.5–2.0 | 3.0 | n.d. | n.d. |
| Pig | 1.0 | 1.2–4.0 | 2.5 [III] | 0.5 [III] | 0.7 [III] | 2.0–6.0 | n.d. | n.d. | n.d. |
| Chicken | 0.1 | 0.02–0.2 | 1.4 [II] | 0.3 [II] | 1.8 [II] | n.r. | n.d. | n.d. | n.d. |

n.r. = not relevant, n.d. = no data found. [I] [58]. [II] In %, in kraals [59]. [III] In g $kg^{-1}$ [50]. [IV] [60].

Livestock urine cannot be collected from bare soil, and dung is exposed to higher nitrogen losses (ibid.). The authors in [61] describe the nutrient losses between excretion and application. The nutrient losses during manure and urine collection and storage under different management systems are listed in Table 4. N losses vary from 20% to 100% for urine and 5% to 50% for dung, P losses vary between 3% and 30% in dung, and K losses vary between 5% and 80% in urine [61]. Farmers who practise zero-grazing usually keep their animals in a simple shelter with a fence and a roof for shade, but without a sealed floor—such as the kraal used in [61]. About 10% of the farmers in group $A_U$ and 40% in $A_T$ have bedding for their livestock. In group $A_U$, 59% of the households use livestock manure in composting, 63% in $B_U$, and 28% in $C_U$ [24], which is comparable to the management of the "manure in compost pit" presented in [61]. Trained households use a higher proportion of their livestock manure than untrained households because they collect and store it. Farmers in group $A_T$ use between 90% and 100% of the livestock manure collected in the homegarden, group $B_T$ uses 50% to 90%, and group $C_T$ uses less than 50% [25].

**Table 4.** Nutrient losses during manure and urine collection and storage under different management systems summarised by [61]; K in dung and P in urine were not mentioned. T = trained, U = untrained.

| | Average Nutrient Losses in % | | | | |
|---|---|---|---|---|---|
| **Collection and Storage System** | **Dung N** | **Dung P** | **Urine N** | **Urine K** | **Practised by Household Groups** |
| Open kraal/boma [I] | 30 | 15 | 70 | 49 | $A_U$, $A_T$, $B_U$, $B_T$ |
| Manure in compost heap | 20 | 10 | 60 | 40 | not practised |
| Manure in compost pit | 15 | 10 | 57 | 20 | $A_U$, $A_T$, $B_U$, $B_T$ |
| Deep litter compost (in situ compost) | 15 | 10 | 55 | 25 | all groups |
| Compact manure pit/heap and urine pit | 10 | 5 | 40 | 10 | $A_U$, $A_T$ |
| Slurry pit (watertight, covered) | 7 | 5 | 30 | 10 | not practised |

[I] A kraal or boma is a shelter with fences made of wood or bush branches. It stands on unsealed ground and usually has no bedding. It may have a roof for shade.

Human Excreta (IN3e)

Human excreta are rarely used in composting, although they contain relatively high amounts of major nutrients, especially N in urine and P in faeces. We consider human excreta as the inflow (IN3e) if they are used to produce organic fertiliser, as outflow (OUT5) if they leach from the pit latrine, or as stock (STOCK3) if they stay in the pit latrines. The amount of human excreta depends on the residents' dietary intake of food and fluids, activities, sex, social status, anal cleansing methods, diarrhoea prevalence, and environmental conditions [62,63]. In [62], the median faecal wet mass production was 128 g $pers^{-1}$ $d^{-1}$ with a mean dry mass of 29 g $pers^{-1}$ $d^{-1}$ and 1.2 defecations per 24 h in healthy individuals.

We assume that the amount and composition of nutrients in human faeces differ among the household groups due to their different diets and varying availability of food (Table 5). In the trained households, those in $A_T$ eat 3.0 meals $d^{-1}$, those in $B_T$ eat 2.2 meals $d^{-1}$, and those in $C_T$ eat 1.7 meals $d^{-1}$ [25]. Thus, households in $A_T$ are the reference group, and are assigned the value of 100%. In comparison, untrained households only have full access to food for 6.6 ± 3.1 months $yr^{-1}$ in group $A_U$, 3.2 in group $B_U$, and 1.8 months $yr^{-1}$ in group $C_U$ [24]. Accordingly, households produce 100% of the nutrients (taken from [25]) in group $A_T$, 79% in $A_U$, 66% in $B_T$, 55% in $C_T$, 38% in $B_U$, and 22% in $C_U$. The authors in [64] measured 18 g N, 3.0 g P, and 44 g K $kg^{-1}$ human faeces in South Africa.

**Table 5.** Amounts and nutrient concentrations of human faeces and urine per household group. T = trained, U = untrained, hh = household, p = person, d = day, yr = year.

| Amounts and Nutrients in Human Excreta | | Household Groups | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Unit | $A_U$ | $B_U$ | $C_U$ | $A_T$ | $B_T$ | $C_T$ |
| Households | | hh group$^{-1}$ | 58 | 52 | 44 | 296 | 262 | 198 |
| Household size | | p hh$^{-1}$ | 10.2 | 9.7 | 5.7 | 5.3 | 5.1 | 5.1 |
| Human faeces | | | | | | | | |
| | Percentage of food intake [I] | % of $A_T$ | 79 | 38 | 22 | 100 | 66 | 55 |
| | Amount [II] | g p$^{-1}$ d$^{-1}$ | 101 | 53 | 28 | 128 | 85 | 65 |
| | Amount [II] | kg p$^{-1}$ yr$^{-1}$ | 37 | 18 | 10 | 47 | 31 | 24 |
| | N [II] | kg hh$^{-1}$ yr$^{-1}$ | 6.8 | 3.1 | 1.1 | 4.5 | 2.8 | 2.2 |
| | P [II] | kg hh$^{-1}$ yr$^{-1}$ | 1.1 | 0.5 | 0.2 | 0.7 | 0.5 | 0.4 |
| | K [II] | kg hh$^{-1}$ yr$^{-1}$ | 16 | 7.6 | 2.6 | 11 | 6.9 | 5.3 |
| Human urine | | | | | | | | |
| | Amount [II] | L p$^{-1}$ d$^{-1}$ | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 |
| | N [II] | kg hh$^{-1}$ yr$^{-1}$ | 62 | 59 | 35 | 32 | 31 | 31 |
| | P [II] | kg hh$^{-1}$ yr$^{-1}$ | 3.5 | 3.3 | 1.9 | 1.8 | 1.7 | 1.7 |
| | K [II] | kg hh$^{-1}$ yr$^{-1}$ | 11 | 10 | 6.2 | 5.7 | 5.5 | 5.5 |

[I] Group $A_T$ being the reference group at 100%. [II] According to [65].

The average amounts of human urine vary between 1.4 and 1.5 L d$^{-1}$ according to [62,65]. Human urine contains the largest fractions of N and K released from the body [62]. About 86% of N excreted is included in urine and only 14% in faeces [62]. The authors in [66] found the mean nutrient concentrations in human urine to be 4.3 g N, 0.24 g P, and 0.76 g K L$^{-1}$ human urine pers$^{-1}$ d$^{-1}$, and we have used these values in this paper. In contrast to the variations in human faeces, we assume that human urine does not vary between household groups, since fluid intake (drinking water) does not fluctuate much.

Harvested Crops (OUT1)

The yields of perennial crops and annual crops for all household groups are presented in Table 6. Nutrient contents were taken from Table A1. About 20% of the nutrients in consumed food are taken up by the human body (STOCK1) [50].

**Table 6.** Annually harvested food crops after first processing them (peeling) before cooking for each household group. Dry weights are taken from [54]. T = trained, U = untrained, DM = dry mass, av. = mean value, min. = minimum value, max. = maximum value in this group of households.

| Annual Harvest | Household Groups | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $A_U$ | $B_U$ | $C_U$ | $A_T$ | | | $B_T$ | | | $C_T$ | | |
| | Unit | | | | av. | min. | max. | av. | min. | max. | av. | min. | max. |
| Banana | | | | | | | | | | | | | |
| Bunches | ha$^{-1}$ | 57 | 57 | 40 | 528 | 314 | 1000 | 260 | 140 | 557 | 52 | 47 | 60 |
| Bunch weight | kg | 35 | 20 | 5.0 | 49 | 35 | 57 | 40 | 20 | 35 | 20 | 15 | 20 |
| Pulp | kg ha$^{-1}$ | 1116 | 744 | 223 | 16,331 | 8184 | 37,200 | 7738 | 2083 | 13,392 | 707 | 521 | 893 |
| Pulp, dry | kg DM ha$^{-1}$ | 240 | 160 | 52 | 3552 | 1760 | 8000 | 1664 | 492 | 2880 | 152 | 112 | 192 |
| Coffee, green | kg ha$^{-1}$ | 110 | 55 | 55 | 165 | 55 | 275 | 83 | 55 | 110 | 28 | 17 | 55 |
| Beans (seeds) | kg DM ha$^{-1}$ | 494 | 365 | 276 | 401 | 267 | 535 | 312 | 89 | 535 | 267 | 178 | 356 |
| Maize | | | | | | | | | | | | | |
| Grains | kg ha$^{-1}$ | 164 | 328 | 164 | 369 | 164 | 574 | 328 | 82 | 574 | 246 | 164 | 328 |
| Grains, dry | kg DM ha$^{-1}$ | 152 | 26 | 3.9 | 17 | 120 | 10 | 14 | 15 | 2.3 | 7.1 | 5.9 | 1.6 |
| Cassava | | | | | | | | | | | | | |
| Tuber, peeled | kg ha$^{-1}$ | 89 | 177 | 266 | 531 | NA | NA | 357 | NA | NA | 89 | NA | NA |
| Tuber, peeled, dry | kg DM ha$^{-1}$ | 25 | 57 | 76 | 155 | NA | NA | 101 | NA | NA | 25 | NA | NA |

Fodder (OUT2)

We estimate the amount of fodder from the amount of livestock manure, assuming that 20% of the nutrients contained in the fodder are absorbed by animals (STOCK2) and that 80% are excreted [50].

Wood (OUT3)

According to [57], one smallholder household consumes 1775 kg $yr^{-1}$ firewood cooking on three-stone fires. This amount of firewood contains a total of 5.1 kg N and 1.0 kg P according to [57]. We estimated the K content in ashes to be 3.0 kg K according to [67,68]. We assume that the household groups $A_U$, $B_U$, $A_T$, and $B_T$ consume the same amount of timber every year; groups $C_U$ and $C_T$ use half of that amount of timber. Additionally, we assume that households in groups $A_T$ and $A_U$ sell the same amount of wood on the market (OUT4), and $B_T$ and $B_U$ sell half of this amount; whereas groups $C_U$ and $C_T$ do not sell home-produced wood on the market.

Market (OUT4)

In all groups of households, the entire coffee harvest is sold to nearby coffee factories. Group $A_T$ sells about 70% of its banana harvest, $A_U$ and $B_T$ sell about 50%, and $B_U$, $C_T$, and $C_U$ sell about 30%. Of the bean harvest, 50% is sold in groups $A_T$, $A_U$, $B_T$, and $B_U$, and 20% in $C_U$ and $C_T$. Of the maize and cassava harvest, 30% is sold in groups $A_T$, $A_U$, $B_T$, and $B_U$, and 10% in $C_U$ and $C_T$.

Sold Crop Residues (OUT5)

If the farmers sell crop residues or give them as a present to other farmers, an outflow of the farming system emerges in the nutrient balance.

Leaching (OUT6)

In [44], leaching of total dissolved nitrogen (TDN) at a 20 cm soil depth was found to be 27.7 ± 17.7 kg N $ha^{-1}$ $yr^{-1}$ with 2.0 ± 1.1, 19.2 ± 12.6, and 6.5 ± 4.2 kg N $ha^{-1}$ $yr^{-1}$ for $NH_4^+$, $NO_3^-$, and DON, respectively. In [49], leaching of 21.0 kg N $ha^{-1}$ $yr^{-1}$ and 11 kg K $ha^{-1}$ $yr^{-1}$ was observed in Karagwe. The soils studied in [49] had (slightly) higher sand and clay content and less silt (60% sand, 14% silt, and 26% clay) than that in [48] (52% ± 13% sand, 44% ± 11% silt, and 7% ± 2% clay). These leaching values do not include leaching of human excreta from pit latrines.

Leaching from Pit Latrines (OUT7)

We estimate that 30% of the human excreta in unsealed pit latrines leaches into the aquifer.

River Discharge (OUT8)

The stream losses of TDN through river discharge are about 7.2 kg N $ha^{-1}$ $yr^{-1}$, with 1.4, 3.8, and 2.0 kg N $ha^{-1}$ $yr^{-1}$ for $NH_4^+$, $NO_3^-$, and DON, respectively [48]. These values are comparable to the 6 kg N $ha^{-1}$ $yr^{-1}$ result in [49].

Gaseous Losses (OUT9)

Gaseous losses through the denitrification of soil are about 20 kg N $ha^{-1}$ $yr^{-1}$ [49]. They are higher if mineral fertiliser is applied to the soil [69].

Human Body (STOCK1)

We assume that the human body assimilates 20% of the nutrients contained in food [50].

Animal Body (STOCK2)

We assume that animals assimilate 20% of the nutrients contained in the fodder [50].

Pit Latrine (STOCK3)

We assume that 70% of human excreta remain in the pit latrine and are converted to sludge.

Soil (STOCK4)

The soil stores important amounts of nutrients. Soil data were taken from a recent field trial study on the ground at the farmer field school known as the MAVUNO Project [30]. Table 7 presents the soil data.

**Table 7.** Soil properties of a *vitric Andosol* in the Karagwe district study area from field trials at the farmer field school MAVUNO Project during 2014–2015; water depth in cm, $\rho_B$: bulk density in kg $dm^{-3}$, $CEC_{eff}$: effective cation exchange capacity in cmol $kg^{-1}$, BS: base saturation in %, TOC: total organic carbon in %, $N_{tot}$: total nitrogen in %, and C/N: carbon-nitrogen ratio [30]. n.a. = not analysed.

| Soil Horizon | Depth | Munsell Colour Code | Clay % | Silt % | Sand % | pH KCl | *TOC* | $N_{tot}$ | *C/N* | $\rho_B$ | $CEC_{eff}$ | BS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ap | 20 | 2.5 YR 3/2 | 3.2 | 16 | 81 | 3.8 | 3.5 | 0.3 | 13 | 0.9 | 17 | 100 |
| Ah | 37 | 2.5 YR 3/2 | 3.6 | 13 | 83 | 3.8 | 2.7 | 0.2 | 13 | 0.9 | 11 | 97 |
| B1 | 53 | 2.5 YR 2.5/3 | 2.2 | 16 | 82 | n.a. | 2.0 | 0.2 | 13 | 1.1 | 8.0 | 95 |
| B2 | 74 | 2.5 YR 3/3 | 2.2 | 20 | 78 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| C | 100+ | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |

Vegetation Density

As several variables depend on the crop, tree, and livestock density, we estimated the vegetation densities for each farm household group as presented in Table 8. The lower the density of vegetation, the smaller the harvest and amount of litterfall, crop residues, and leaching. The lower the harvest, the lower the food security, products sold, and amount of nutrients in human excreta. The throughfall is presumed to be higher in less densely grown vegetation. The fewer the beans that are planted, the lower the biological nitrogen fixation rate. The more frequently and continuously the soil is covered with mulch or grass, the fewer the gaseous emissions that emerge from the soil. The less livestock there is, the smaller the amount of livestock manure. When livestock manure is quickly collected and composted, the gas losses from open manure storage are the lowest.

**Table 8.** Crop and tree density variation among the farm household groups. T = trained, U = untrained.

| Agroforestry System Stage | Density | % | Household Group |
|---|---|---|---|
| Biodiverse, dense, well-managed farming system grown over several years/decades with old trees and sufficient nutrient input, soils covered with mulch throughout the year | *maximum* | 100 | Not reached by any group |
| Biodiverse, well-managed farming system with few older trees, integrated sustainable land use management, soils covered with grass throughout the year | *high* | 80 | $A_T$ |
| Well managed but with lower density and traditional farming; soils are often covered with crop residues (in situ composting) | *moderate* | 60 | $A_U$ |
| Moderately well managed, soils covered for some months of the year, lower yields, partial food insecurity | *low* | 40 | $B_T$, $B_U$ |
| Poorly managed with very few crops and trees, frequent labour shortages, very low yields, food insecurity | *very low* | 20 | $C_T$, $C_U$ |

### 2.3.2. Scenarios

Afterwards, five scenarios were calculated. In the "business as usual" scenarios (S0), we applied the following principles based on the principles of "system dynamics": the more of A, the more of B (+); the more of A, the less of B (−). The following management scenarios were investigated and compared with S0:

S1. Human Urine,
S2. Legumes,
S3. CaSa-compost, and
S4. Combination of S1, S2, and S3.

S1 is called "Human Urine" because sustainable agricultural intensification can be supported by the application of human urine as suggested in [70]. In this scenario, 80% of human urine is separately collected, applied close to the ground in furrows along the plant rows, and immediately covered with soil.

S2 is called "Legumes" because in this scenario 0.5 t $ha^{-1}$ *Crotalaria grahamiana* is incorporated into the soil. This should result in 17 kg N $ha^{-1}$ being biologically fixed in the soil, as research revealed in [27].

S3 is called "CaSa-compost". In this scenario, we predict that farm households will introduce the production of CaSa-compost as recommended in [30,56,57]. The term "CaSa" originates from a project called "Carbonisation and Sanitation" (ibid.). The CaSa-compost contains human faeces and urine, biochar from sawdust, crop residues, kitchen waste, and ash (ibid.). In the field trial in [30], a field sized 300 × 270 cm with a variety of vegetables was provided, to which 8.3 $dm^3$ $m^{-2}$ CaSa-compost was applied. In S3, we adjusted this application rate to a field size of 600 $m^2$, to which the farmers applied 6.4 kg $m^{-2}$ compost. In S4, we combined the impacts of S1, S2, and S3.

## 3. Results

The nutrient inflows, outflows, and the resulting nutrient balances (NB) in the homegardens of all household groups are presented in Table 9. The atmospheric deposition (IN1), litterfall (IN2b), and deep capture (IN2b) per hectare are equal for all household groups. Biological nitrogen fixation (IN2c) depends on the yield of common beans. Organic materials that emerge in the homegarden are summarised as organic fertiliser (IN3). Organic fertiliser is the main input (IN3) of nutrients into homegardens, whereas the crop harvest (OUT1) is the main outflow, followed by woodcutting and the harvest of fodder. All residues of coffee cherries are exported by all households.

Huge amounts of N and K in group $A_T$ originate from large amounts of livestock manure (IN4d), which are collected in the homegardens (Table 10). Nutrient inflows from livestock manure from the grassland is not considered in the NB because the manure is not collected and thus does not return to the homegardens. The high nutrient charges in the total inputs in the groups $A_T$, $B_T$, $A_U$, and $B_U$ can be explained by the relatively high numbers of livestock kept in their homegardens, and by fodder imports from the surrounding grassland and forests. The annual production of nutrients in human excreta per household is presented in Table 11. The amount depends on the household size. The amount of N and K included in IN3 follows the order $A_T > B_T > A_U > B_U > C_T > C_U$. For phosphorus (P), the order is similar, except for $A_U = B_U$ and $C_U > C_T$.

**Table 9.** The "business as usual" scenario for each trained and untrained farm household group, along with scenario S1 (using 80% of the human urine in accordance with [70,71]), S2 (incorporating 0.5 t of *Crotalaria grahamiana* into the soil in accordance with [72]), S3 (applying 6.4 kg $m^{-2}$ of CaSa-compost to 600 $m^2$ as per [30,73]), and S4, combining S1, S2, and S3. All values are given in kg $ha^{-1}$ $hh^{-1}$ $yr^{-1}$. U = untrained, T = trained, n.d. = no data, NB = nutrient balance.

| | Inflows, Outflows, and Nutrient Budgets in Farm Household Groups | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Flow** | $A_U$ | | | $B_U$ | | | $C_U$ | | | $A_T$ | | | $B_T$ | | | $C_T$ | | |
| **Nutrient (kg $ha^{-1}$ $yr^{-1}$)** | **N** | **P** | **K** | **N** | **P** | **K** | **N** | **P** | **K** | **N** | **P** | **K** | **N** | **P** | **K** | **N** | **P** | **K** |
| IN1 Atmospheric deposition | 4.4 | 0.7 | 2.9 | 4.4 | 0.7 | 2.9 | 4.4 | 0.7 | 2.9 | 4.4 | 0.7 | 2.9 | 4.4 | 0.7 | 2.9 | 4.4 | 0.7 | 2.9 |
| IN2 Input by plants and trees | 30 | 1.1 | 5.3 | 20 | 0.6 | 2.6 | 12 | 0.1 | 0.7 | 36 | 1.4 | 6.6 | 30 | 0.8 | 4.0 | 18 | 0.4 | 2.0 |
| IN3 Organic fertiliser | 102 | 15 | 153 | 86 | 15 | 142 | 41 | 9.6 | 64 | 373 | 64 | 565 | 169 | 29 | 267 | 54 | 8.1 | 65 |
| Crop residues | 4.4 | 1.1 | 10 | 4.9 | 2.1 | 14 | 4.6 | 3.1 | 13 | 39 | 7.3 | 94 | 20 | 4.7 | 50 | 3.3 | 1.1 | 9.7 |
| Banana leaves | 1.9 | 0.1 | 3.3 | 1.2 | 0 | 2.2 | 0.4 | 0 | 0.7 | 27.2 | 1.0 | 48 | 12.9 | 0.5 | 23 | 1.2 | 0 | 2.1 |
| Banana pseudostems | 0.2 | 0 | 1.4 | 0.1 | 0 | 0.9 | 0.0 | 0 | 0.3 | 2.7 | 0.3 | 20 | 1.3 | 0.1 | 9.6 | 0.1 | 0 | 0.9 |
| Coffee leaves | 0.7 | 0 | 0.0 | 0.4 | 0 | 0.0 | 0.4 | 0 | 0.0 | 1.1 | 0 | 0.1 | 0.6 | 0 | 0.1 | 0.2 | 0 | 0.0 |
| Maize stover | 0.5 | 0 | 2.2 | 1.0 | 0 | 4.4 | 0.5 | 0 | 2.2 | 1.1 | 0.1 | 5.0 | 1.0 | 0 | 4.4 | 0.7 | 0 | 3.3 |
| Cassava foliage | 1.1 | 1.0 | 3.4 | 2.2 | 2.0 | 6.8 | 3.3 | 3.0 | 10 | 6.7 | 6.0 | 20 | 4.5 | 4.0 | 14 | 1.1 | 1.0 | 3.4 |
| Kitchen waste | 25 | 1.8 | 20 | 20 | 1.9 | 18 | 16 | 1.7 | 14 | 26 | 2.9 | 35 | 20 | 2.5 | 29 | 15 | 1.4 | 14 |
| Cooking ash [I] | 0 | 1.0 | n.d. | 0 | 1.0 | n.d. | 0 | 1.0 | n.d. | 0 | 1.0 | n.d. | 0 | 1.0 | n.d. | 0 | 1 | n.d. |
| Livestock manure | 68 | 10 | 118 | 53 | 9.0 | 103 | 16 | 2.2 | 33 | 309 | 53 | 437 | 129 | 21 | 188 | 36 | 4.6 | 41 |
| Livestock manure, grassland [II] | 540 | 91 | 634 | 262 | 43 | 298 | 3.3 | 0 | 0 | 2139 | 357 | 2499 | 822 | 137 | 961 | 2.5 | 0 | 0 |
| Human urine | 4.8 | 0.9 | 5.2 | 7.4 | 1.4 | 6.4 | 4.3 | 1.7 | 3.2 | 0 [III] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Total nutrient inflow** | 144 | 17 | 161 | 125 | 17 | 147 | 66 | 10 | 67 | 414 | 66 | 575 | 204 | 30 | 274 | 77 | 8 | 71 |
| OUT1 Harvest | 52 | 6.0 | 36 | 42 | 5.9 | 32 | 32 | 4.6 | 25 | 90 | 14 | 115 | 56 | 9.0 | 65 | 30 | 4.2 | 23 |
| Banana pulp | 2.0 | 0.4 | 1.6 | 1.3 | 0.2 | 1.1 | 0.4 | 0.1 | 0.3 | 29 | 5.3 | 24 | 14 | 2.5 | 11 | 1.3 | 0.2 | 1.0 |
| Banana peel | 0.6 | 0.1 | 2.7 | 0.4 | 0.0 | 1.8 | 0.1 | 0.0 | 0.5 | 9.0 | 0.9 | 39.3 | 4.3 | 0.4 | 18.6 | 0.4 | 0.0 | 1.7 |
| Banana stalk | 0.1 | 0.0 | 0.6 | 0.0 | 0.0 | 0.4 | 0.0 | 0.0 | 0.1 | 1.0 | 0.2 | 9.1 | 0.5 | 0.1 | 4.3 | 0.0 | 0.0 | 0.4 |
| Coffee beans | 2.5 | 0.3 | 2.5 | 1.3 | 0.1 | 1.2 | 1.3 | 0.1 | 1.2 | 3.8 | 0.4 | 3.7 | 1.9 | 0.2 | 1.9 | 0.6 | 0.1 | 0.6 |
| Coffee husks | 1.8 | 0.2 | 2.5 | 0.9 | 0.1 | 1.2 | 0.9 | 0.1 | 1.2 | 2.7 | 0.3 | 3.7 | 1.4 | 0.1 | 1.9 | 0.5 | 0.0 | 0.6 |
| Common beans | 19 | 2.6 | 5.3 | 15 | 2.1 | 4.3 | 12 | 1.6 | 3.2 | 17 | 2.3 | 4.7 | 13 | 1.8 | 3.6 | 11 | 1.6 | 3.1 |
| Bean waste | 24 | 1.5 | 17 | 19 | 1.2 | 14 | 14 | 0.9 | 11 | 21 | 1.3 | 15 | 16 | 1.0 | 12 | 14 | 0.9 | 10 |
| Maize grains | 0.4 | 0.4 | 0.5 | 0.9 | 0.9 | 1.1 | 0.4 | 0.4 | 0.5 | 1.0 | 1.0 | 1.2 | 0.9 | 0.9 | 1.1 | 0.7 | 0.6 | 0.8 |
| Maize cobs | 0.5 | 0.2 | 1.6 | 1.0 | 0.5 | 3.2 | 0.5 | 0.2 | 1.6 | 1.2 | 0.5 | 3.6 | 1.0 | 0.5 | 3.2 | 0.8 | 0.3 | 2.4 |
| Cassava tubers | 0.5 | 0.2 | 1.1 | 1.0 | 0.3 | 2.2 | 1.5 | 0.5 | 3.2 | 3.0 | 1.0 | 6.5 | 2.0 | 0.6 | 4.3 | 0.5 | 0.2 | 1.1 |
| Cassava peel | 0.2 | 0.2 | 0.6 | 0.4 | 0.4 | 1.3 | 0.6 | 0.6 | 1.9 | 1.3 | 1.3 | 3.9 | 0.8 | 0.8 | 2.6 | 0.2 | 0.2 | 0.6 |

**Table 9.** *Cont.*

| | Inflows, Outflows, and Nutrient Budgets in Farm Household Groups | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Flow** | $A_U$ | | | $B_U$ | | | $C_U$ | | | $A_T$ | | | $B_T$ | | | $C_T$ | | |
| **Nutrient (kg ha$^{-1}$ yr$^{-1}$)** | **N** | **P** | **K** | **N** | **P** | **K** | **N** | **P** | **K** | **N** | **P** | **K** | **N** | **P** | **K** | **N** | **P** | **K** |
| Food (part of OUT1) | 11 | 1.9 | 4.6 | 10 | 2.1 | 5.1 | 11 | 2.1 | 6.2 | 20 | 4.1 | 15 | 16 | 3.2 | 11 | 11 | 2.1 | 4.9 |
| Banana pulp | 1.0 | 0.2 | 0.8 | 0.9 | 0.2 | 0.8 | 0.3 | 0.1 | 0.2 | 8.8 | 1.6 | 7.1 | 7.0 | 1.3 | 5.6 | 0.9 | 0.2 | 0.7 |
| Common beans | 9.6 | 1.3 | 2.7 | 7.7 | 1.1 | 2.1 | 9.4 | 1.3 | 2.6 | 8.5 | 1.2 | 2.3 | 6.6 | 0.9 | 1.8 | 9.1 | 1.2 | 2.5 |
| Maize grains | 0.3 | 0.3 | 0.4 | 0.6 | 0.6 | 0.7 | 0.4 | 0.4 | 0.5 | 0.7 | 0.7 | 0.8 | 0.6 | 0.6 | 0.7 | 0.6 | 0.6 | 0.7 |
| Cassava tubers | 0.3 | 0.1 | 0.8 | 0.7 | 0.2 | 1.5 | 1.3 | 0.4 | 2.9 | 2.1 | 0.7 | 4.5 | 1.4 | 0.4 | 3.0 | 0.4 | 0.1 | 1.0 |
| OUT2 Fodder | 17 | 2.6 | 29 | 13 | 2.3 | 26 | 4.1 | 0.5 | 8.2 | 116 | 20 | 164 | 32 | 5.2 | 47 | 8.9 | 1.1 | 10 |
| OUT3 Wood | 27 | 5.3 | 9.0 | 23 | 4.4 | 7.5 | 14 | 2.7 | 4.5 | 27 | 5.3 | 9.0 | 23 | 4.4 | 7.5 | 14 | 2.7 | 4.5 |
| Firewood | 9.1 | 1.8 | 3.0 | 9.1 | 1.8 | 3.0 | 9.1 | 1.8 | 3.0 | 9.1 | 1.8 | 3.0 | 9.1 | 1.8 | 3.0 | 9.1 | 1.8 | 3.0 |
| Timber | 9.1 | 1.8 | 3.0 | 9.1 | 1.8 | 3.0 | 4.5 | 0.9 | 1.5 | 9.1 | 1.8 | 3.0 | 9.1 | 1.8 | 3.0 | 4.5 | 0.9 | 1.5 |
| For sale | 9.1 | 1.8 | 3.0 | 4.5 | 0.9 | 1.5 | 0.0 | 0.0 | 0.0 | 9.1 | 1.8 | 3.0 | 4.5 | 0.9 | 1.5 | 0.0 | 0.0 | 0.0 |
| **Nutrients withdrawn by plants** | 105 | 16 | 78 | 82 | 13 | 66 | 50 | 7.8 | 37 | 242 | 41 | 291 | 116 | 20 | 121 | 53 | 8.0 | 37 |
| OUT4 Sold on the market | 25 | 4.1 | 14 | 11 | 1.8 | 6.6 | 5.0 | 0.7 | 4.2 | 54 | 9.2 | 68 | 25 | 4.5 | 27 | 4.1 | 0.6 | 3.3 |
| Banana | 1.3 | 0.2 | 2.5 | 0.5 | 0.1 | 1.0 | 0.2 | 0.0 | 0.3 | 28 | 4.5 | 50 | 9.3 | 1.5 | 17 | 0.5 | 0.1 | 0.9 |
| Coffee | 4.3 | 0.4 | 5.0 | 2.2 | 0.2 | 2.5 | 2.2 | 0.2 | 2.5 | 6.5 | 0.6 | 7.5 | 3.2 | 0.3 | 3.7 | 1.1 | 0.1 | 1.2 |
| Beans | 9.6 | 1.3 | 2.7 | 3.1 | 0.4 | 0.9 | 2.3 | 0.3 | 0.6 | 8.5 | 1.2 | 2.3 | 6.6 | 0.9 | 1.8 | 2.3 | 0.3 | 0.6 |
| Maize | 0.3 | 0.2 | 0.6 | 0.2 | 0.1 | 0.4 | 0.1 | 0.1 | 0.2 | 0.7 | 0.4 | 1.4 | 0.6 | 0.4 | 1.3 | 0.1 | 0.1 | 0.3 |
| Cassava | 0.2 | 0.1 | 0.5 | 0.1 | 0.1 | 0.3 | 0.2 | 0.1 | 0.5 | 1.3 | 0.7 | 3.1 | 0.8 | 0.4 | 2.1 | 0 | 0 | 0.2 |
| Wood | 9.1 | 1.8 | 3.0 | 4.5 | 0.9 | 1.5 | 0.0 | 0.0 | 0.0 | 9.1 | 1.8 | 3.0 | 4.5 | 0.9 | 1.5 | 0 | 0 | 0 |
| OUT5 Residues given away | 0 | 0 | 0 | 0 | 0 | 0 | 1.4 | 0.9 | 4.0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.0 | 0.3 | 2.9 |
| OUT6 Leaching from soil/runoff | 21 | n.d. | 11 | 21 | n.d. | 11 | 21 | n.d. | 11 | 21 | n.d. | 11 | 21 | n.d. | 11.0 | 21 | n.d. | 11 |
| OUT7 Human excreta | 24 | 4.6 | 28 | 20 | 3.8 | 18 | 11.2 | 2.1 | 8.7 | 13 | 2.5 | 17 | 11.6 | 2.2 | 12 | 11 | 2.1 | 11 |
| Faeces | 5.4 | 1.1 | 17 | 2.5 | 0.5 | 7.6 | 0.8 | 0.2 | 2.6 | 3.6 | 0.7 | 11 | 2.3 | 0.5 | 6.9 | 1.7 | 0.4 | 5.3 |
| Urine | 19 | 3.5 | 11 | 18 | 3.3 | 11 | 10 | 1.9 | 6.2 | 9.7 | 1.8 | 5.7 | 9.3 | 1.7 | 5.5 | 9.3 | 1.7 | 5.5 |
| OUT8 Discharge | 6.0 | n.d. | n.d. | 6.0 | n.d. | n.d. | 6.0 | n.d. | n.d. | 6.0 | n.d. | n.d. | 6.0 | n.d. | n.d. | 6.0 | n.d. | n.d. |
| OUT9 Gaseous losses, soil | 20 | 0 | 0 | 20 | 0 | 0 | 20 | 0 | 0 | 20 | 0 | 0 | 20 | 0 | 0 | 20 | 0 | 0 |
| OUT10 Leaching from pit latrine | 7.2 | 1.4 | 8.3 | 6.0 | 1.1 | 5.4 | 3.4 | 0.6 | 2.6 | 4.0 | 0.8 | 5.0 | 3.5 | 0.7 | 3.7 | 3.3 | 0.6 | 3.3 |
| STOCK1 Human | 2.3 | 0.4 | 0.9 | 2.0 | 0.4 | 1.0 | 2.3 | 0.4 | 1.2 | 4.0 | 0.8 | 3.0 | 3.1 | 0.6 | 2.2 | 2.2 | 0.4 | 1.0 |
| STOCK2 Animal | 3.4 | 0.5 | 5.9 | 2.7 | 0.5 | 5.1 | 0.8 | 0.1 | 1.6 | 23 | 4.0 | 33 | 6.4 | 1.0 | 9.4 | 1.8 | 0.2 | 2.0 |
| STOCK3 Pit latrine | 90 | 12 | 102 | 72 | 10 | 80 | 45 | 7.3 | 43.7 | 9.3 | 1.8 | 11.6 | 110 | 17 | 146 | 85 | 11 | 77 |

**Table 9.** *Cont.*

| | Inflows, Outflows, and Nutrient Budgets in Farm Household Groups | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Flow** | $A_U$ | | | $B_U$ | | | $C_U$ | | | $A_T$ | | | $B_T$ | | | $C_T$ | | |
| **Nutrient (kg ha$^{-1}$ yr$^{-1}$)** | **N** | **P** | **K** | **N** | **P** | **K** | **N** | **P** | **K** | **N** | **P** | **K** | **N** | **P** | **K** | **N** | **P** | **K** |
| **S0. Business as usual** | | | | | | | | | | | | | | | | | | |
| Inflow | 137 | 17 | 161 | 111 | 17 | 147 | 57 | 10.4 | 67 | 414 | 66 | 575 | 204 | 30 | 274 | 77 | 9.2 | 70 |
| Total, outflow | −213 | −19 | −119 | −191 | −17 | −100 | −139 | −15 | −62 | −317 | −42 | −315 | −192 | −21 | −143 | −133 | −10.1 | −59 |
| **Nutrient balance** | **−76** | **−2** | **43** | **−81** | **−1** | **47** | **−82** | **−5** | **5** | **97** | **24** | **260** | **12** | **9** | **131** | **−56** | **−1** | **11** |
| **S1. Human urine used** | | | | | | | | | | | | | | | | | | |
| Inflow | 152 | 17 | 161 | 125 | 17 | 147 | 66 | 10 | 67 | 422 | 66 | 575 | 211 | 30 | 274 | 84 | 9 | 70 |
| Outflow | −197 | −15 | −102 | −173 | −13 | −84 | −125 | −9 | −55 | −309 | −40 | −309 | −185 | −19 | −137 | −127 | −9 | −57 |
| **Nutrient balance** | **−44** | **2** | **59** | **−48** | **4** | **64** | **−60** | **2** | **12** | **112** | **26** | **265** | **27** | **11** | **137** | **−42** | **1** | **13** |
| **S2. Legumes planted** | | | | | | | | | | | | | | | | | | |
| Inflow | 169 | 17 | 161 | 142 | 17 | 147 | 83 | 10 | 67 | 439 | 66 | 575 | 228 | 30 | 274 | 101 | 9 | 70 |
| Outflow | −213 | −19 | −119 | −191 | −17 | −100 | −139 | −15 | −62 | −317 | −42 | −315 | −192 | −21 | −143 | −133 | −10 | −59 |
| **Nutrient balance** | **−44** | **−2** | **43** | **−49** | **−1** | **47** | **−57** | **−5** | **5** | **122** | **24** | **260** | **36** | **9** | **131** | **−31** | **−1** | **11** |
| **S3. CaSa-compost used** [IV] | | | | | | | | | | | | | | | | | | |
| Inflow | 144 | 21 | 178 | 117 | 20 | 164 | 64 | 14 | 84 | 421 | 70 | 592 | 211 | 34 | 291 | 84 | 13 | 86 |
| Outflow | −195 | −14 | −94 | −172 | −13 | −80 | −125 | −9 | −54 | −308 | −40 | −304 | −184 | −19 | −134 | −126 | −8 | −54 |
| **Nutrient balance** | **−50** | **6** | **84** | **−54** | **7** | **84** | **−61** | **5** | **30** | **113** | **30** | **288** | **27** | **15** | **157** | **−42** | **4** | **33** |
| **S4. Combination of S1 + S2 + S3** | | | | | | | | | | | | | | | | | | |
| Inflow | 176 | 21 | 178 | 149 | 20 | 164 | 89 | 14 | 84 | 446 | 70 | 592 | 235 | 34 | 291 | 108 | 13 | 86 |
| Outflow | −195 | −14 | −94 | −172 | −13 | −80 | −125 | −9 | −54 | −308 | −40 | −304 | −184 | −19 | −134 | −126 | −8 | −54 |
| **Nutrient balance** | **−19** | **6** | **84** | **−23** | **7** | **84** | **−36** | **5** | **30** | **138** | **30** | **288** | **51** | **15** | **157** | **−17** | **4** | **33** |

[I] Cooking ash is not used as compost by all household groups. $A_U$ uses 49% of the ash, $B_U$ 54%, $C_U$ 44%, $A_T$ 100%, $B_T$ 50%, and $C_T$ 0%. Unused ash is included in STOCK3. [II] Not included in the nutrient balance of the homegarden. Trained households do not collect livestock manure from the grassland. [III] Trained households do not apply human urine as organic fertiliser to the fields. [IV] Includes eco-sanitation with urine-diverted toilets and avoids pit latrines, thus avoiding leaching from pit latrines. Additionally, only half of the human excreta are considered as OUT7.

**Table 10.** Annual manure production and nutrient concentrations of all household groups. U = untrained, T = trained.

| Annual Manure Production and Nutrient Concentrations | | Household Groups | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Unit | $A_U$ | $A_T$ | $B_U$ | $B_T$ | $C_U$ | $C_T$ |
| Cattle, homegarden | | | | | | | | |
| | Dung | kg yr$^{-1}$ | 915 | 9153 | 1373 | 2746 | 0 | 0 |
| | N | kg yr$^{-1}$ | 11 | 110 | 16 | 33 | 0 | 0 |
| | P | kg yr$^{-1}$ | 2.7 | 27 | 4.1 | 8.2 | 0 | 0 |
| | K | kg yr$^{-1}$ | 19 | 192 | 29 | 58 | 0 | 0 |
| | Urine | m$^3$ yr$^{-1}$ | 0.7 | 7.3 | 1.1 | 2.2 | 0 | 0 |
| | N | kg yr$^{-1}$ | 5.0 | 57 | 7.4 | 15 | 0 | 0 |
| Cattle, grassland | | | | | | | | |
| | Dung | kg yr$^{-1}$ | 30,205 | 118,990 | 14,187 | 45,765 | 0 | 0 |
| | N | kg yr$^{-1}$ | 362 | 1408 | 170 | 553 | 0 | 0 |
| | P | kg yr$^{-1}$ | 91 | 357 | 43 | 137 | 0 | 0 |
| | K | kg yr$^{-1}$ | 634 | 2539 | 298 | 961 | 0 | 0 |
| | Urine | m$^3$ yr$^{-1}$ | 24 | 95 | 11 | 37 | 0 | 0 |
| | N | kg yr$^{-1}$ | 164 | 649 | 77 | 252 | 0 | 0 |
| Goats, sheep, pigs | | | | | | | | |
| | Dung | kg yr$^{-1}$ | 3011 | 5475 | 2464 | 3285 | 1095 | 821 |
| | N | kg yr$^{-1}$ | 49 | 82 | 37 | 53 | 16 | 12 |
| | P | kg yr$^{-1}$ | 6.0 | 11 | 4.9 | 6.6 | 2.2 | 1.6 |
| | K | kg yr$^{-1}$ | 90 | 164 | 74 | 99 | 33 | 25 |
| | Urine | m$^3$ yr$^{-1}$ | 3.0 | 5.5 | 2.5 | 3.3 | 1.1 | 0.8 |
| | N | kg yr$^{-1}$ | 9.0 | 16 | 7.4 | 10 | 3.3 | 2.5 |
| Chickens | | | | | | | | |
| | Dung | kg yr$^{-1}$ | 365 | 3650 | 0 | 1460 | 0 | 730 |
| | N | kg yr$^{-1}$ | 12 | 117 | 0 | 47 | 0 | 23 |
| | P | kg yr$^{-1}$ | 1.5 | 15 | 0 | 5.8 | 0 | 2.9 |
| | K | kg yr$^{-1}$ | 8.0 | 80 | 0 | 32 | 0 | 16 |

In the "business as usual" scenario (S0), the trained household groups $A_T$ and $B_T$ have an entirely positive nutrient budget, with 97 kg N, 24 kg P, and 260 kg K ha$^{-1}$ hh$^{-1}$ yr$^{-1}$, and 12 kg N, 9 kg P, and 131 kg K ha$^{-1}$ hh$^{-1}$ yr$^{-1}$, respectively. The household groups $A_U$, $B_U$, $C_U$, and $C_T$ have a negative balance for N and P. The flows of N in the groups $A_T$ and $C_U$ are visualised in Figures 3 and 4. This is where the differences are the highest between these two groups. The differences in the N flows of biomass and waste are illustrated by the thickness of the arrows. The thicker the arrows, the higher the N charge. The amount of unused manure remains high in households where most livestock are kept on grassland. The nutrient losses from manure storage are already considered in these NBs.

**Table 11.** Annual production of human excreta and nutrients in human excreta per household group. U = untrained, T = trained, p = person, hh = household.

| Human Excreta | | Household Groups | | | | | |
|---|---|---|---|---|---|---|---|
| | Unit | $A_U$ | $B_U$ | $C_U$ | $A_T$ | $B_T$ | $C_T$ |
| Number of farm households | hh group$^{-1}$ | 58 | 52 | 44 | 296 | 262 | 198 |
| Homegarden size (average) | ha | 2.8 | 1.8 | 0.6 | 1.4 | 0.7 | 0.5 |
| Household size | p hh$^{-1}$ | 10.2 | 9.7 | 5.7 | 5.3 | 5.1 | 5.1 |
| Amount of faeces | kg hh$^{-1}$ yr$^{-1}$ | 376 | 172 | 59 | 248 | 157 | 122 |
| N | kg hh$^{-1}$ yr$^{-1}$ | 6.8 | 3.1 | 1.1 | 4.5 | 2.8 | 2.2 |
| P | kg hh$^{-1}$ yr$^{-1}$ | 1.1 | 0.5 | 0.2 | 0.7 | 0.5 | 0.4 |
| K | kg hh$^{-1}$ yr$^{-1}$ | 17 | 7.6 | 2.6 | 11 | 6.9 | 5.3 |
| Amount of urine | L hh$^{-1}$ yr$^{-1}$ | 5212 | 4957 | 2913 | 2708 | 2606 | 2606 |
| N | kg hh$^{-1}$ yr$^{-1}$ | 69 | 62 | 36 | 37 | 34 | 33 |
| P | kg hh$^{-1}$ yr$^{-1}$ | 4.6 | 3.8 | 2.1 | 2.5 | 2.2 | 2.1 |
| K | kg hh$^{-1}$ yr$^{-1}$ | 28 | 18 | 9 | 17 | 12 | 11 |
| Total amounts of nutrients in human excreta … | | | | | | | |
| … after 70% ammonia losses in urine | | | | | | | |
| N | kg hh$^{-1}$ yr$^{-1}$ | 25 | 21 | 11 | 14 | 12 | 11 |
| … used in composting | | | | | | | |
| N | kg hh$^{-1}$ yr$^{-1}$ | 4.8 | 7.4 | 4.3 | 0.0 | 0.0 | 0.0 |
| P | kg hh$^{-1}$ yr$^{-1}$ | 0.9 | 1.4 | 1.7 | 0.0 | 0.0 | 0.0 |
| K | kg hh$^{-1}$ yr$^{-1}$ | 5.2 | 6.4 | 3.2 | 0.0 | 0.0 | 0.0 |
| N | kg hh$^{-1}$ ha$^{-1}$ yr$^{-1}$ | 1.7 | 4.1 | 7.1 | 0.0 | 0.0 | 0.0 |
| P | kg hh$^{-1}$ ha$^{-1}$ yr$^{-1}$ | 0.3 | 0.8 | 2.8 | 0.0 | 0.0 | 0.0 |
| K | kg hh$^{-1}$ ha$^{-1}$ yr$^{-1}$ | 1.9 | 3.6 | 5.4 | 0.0 | 0.0 | 0.0 |
| … not used (pit latrine) | | | | | | | |
| N | kg hh$^{-1}$ yr$^{-1}$ | 21 | 13 | 7.2 | 21 | 13 | 10 |
| P | kg hh$^{-1}$ yr$^{-1}$ | 3.7 | 2.5 | 1.4 | 3.1 | 2.0 | 1.5 |
| K | kg hh$^{-1}$ yr$^{-1}$ | 22 | 12 | 5.5 | 8 | 5 | 4 |

The NB of the trained group of households $A_T$ and $B_T$ that implemented the measures taught in the SLM training is considerably more positive than that of the best-performing untrained group ($A_U$). A similar trend can be found by comparing the moderately performing untrained group of households ($B_U$) with the corresponding trained group ($B_T$). The NB of the $A_U$ group, however, is not nearly as positive as that of the $B_T$ group. The NB for group $C_T$ is also more positive than the NB in group $C_U$, although the NB of the group $C_T$ is also in the negative range for N and P.

Compared to the baseline scenario (S0), the NB would improve in all groups of households under all management scenarios. Untrained households improve their nutrient balances under all management scenarios, but the N budget remains negative. The differences in the NB under all scenarios for the households in groups $C_U$ and $C_T$ are relatively small due to the low crop yields and resulting crop residues, and low amounts of livestock manure. In summary, the NBs are most positive under S4.

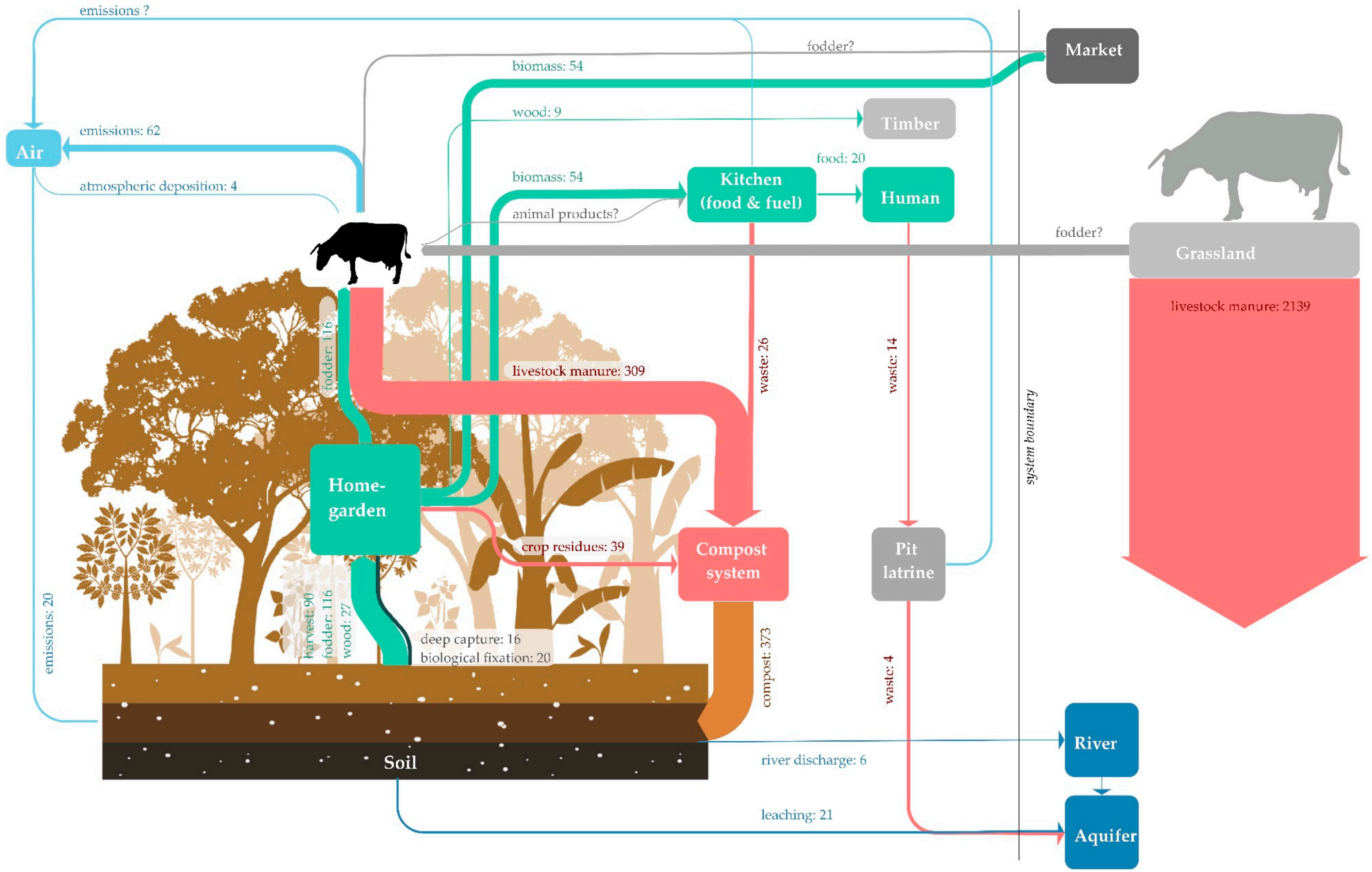


**Figure 3.** Main nitrogen flows in household group $A_T$ (non-vulnerable to food insecurity, trained farm households). All values in kg N $ha^{-1}$ $hh^{-1}$ $yr^{-1}$. (Design of background picture: Claudia Matthias, modified by Atiqah Fairuz Salleh.)

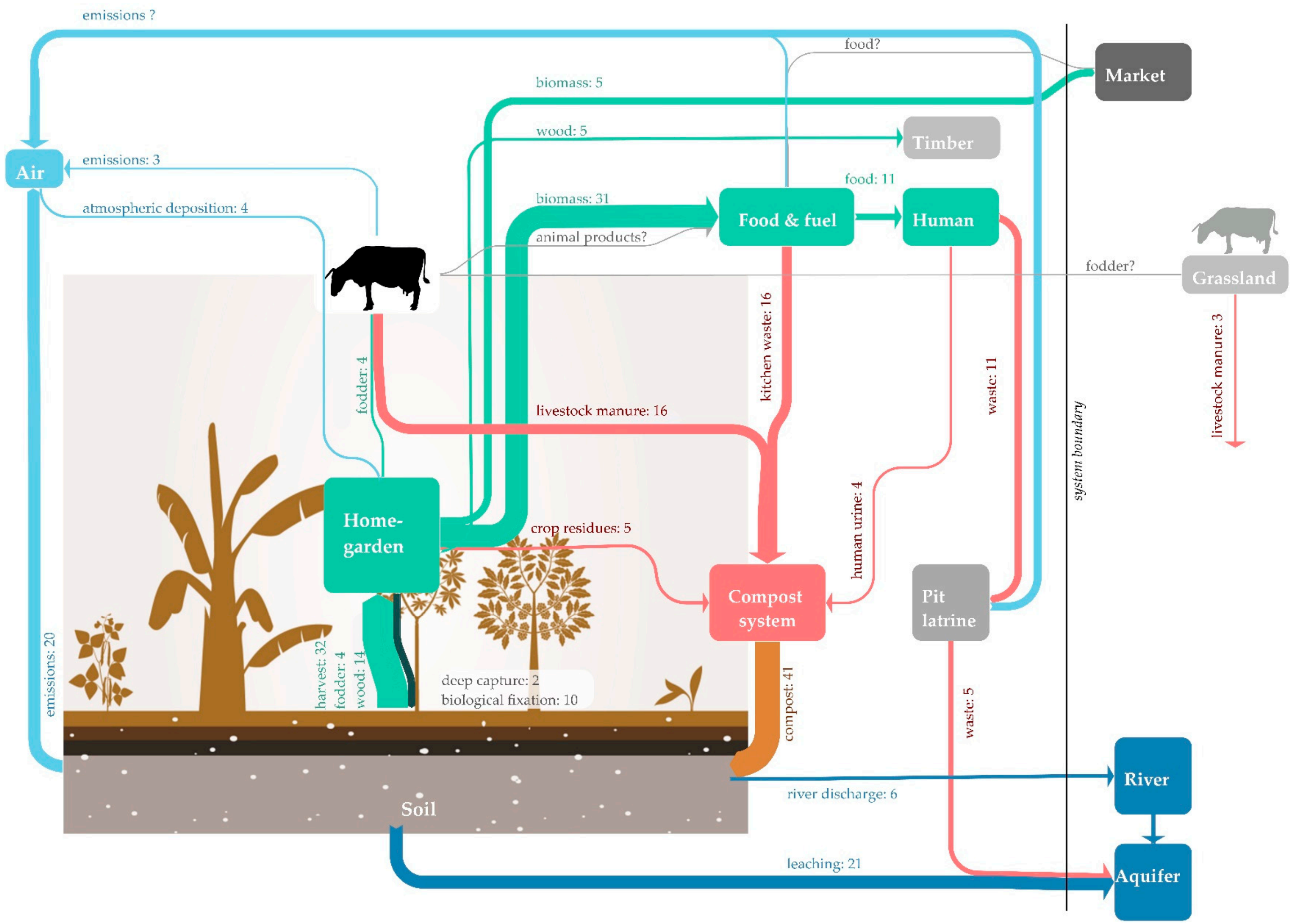


**Figure 4.** Main nitrogen flows in household group $C_U$ (most vulnerable to food insecurity, untrained farm households). All values in kg N $ha^{-1}$ $hh^{-1}$ $yr^{-1}$. (Design of background picture: Claudia Matthias, modified by Atiqah Fairuz Salleh.)

## 4. Discussion

### 4.1. Methodology

We calculated the nutrient balances (NBs) according to the best of our knowledge and systematic literature research, e.g., [46,49,50,54,57,58,62,66,67,71,73]. Nevertheless, these values are primarily estimates based on derivations from the values found in the literature, which were then transferred to the study area investigated in this paper. We did not carry out any field measurements, and the nutrient balances in the field may deviate considerably from the values estimated here. However, this is an initial assessment of nutrient depletion due to agricultural production and the possible nutrient inputs that could compensate for this depletion. Our research also identifies opportunities to help smallholder farmers improve their nutrient management and thus increase their yields, and also highlights the positive achievements of the farmer field school MAVUNO Project, which are presented here as a best-practice example for organisations with similar goals (e.g., increasing soil fertility, biodiversity, and food security).

### 4.2. Results

As hypothesised, the NBs of the trained farm households are more balanced than those of the untrained households due to the implementation of sustainable land management (SLM) practices. The consistently positive N, P, and K contents in groups $A_T$ and $B_T$ are mainly achieved by the recycling of livestock manure and the relatively high production of plant-based biomass and the resulting amount of organic fertiliser. These values are comparable to those of the farm households studied in the same area in [22], in which the livestock manure from zero-grazing in the homegardens resulted in the highest nutrient inflow. In our analysis, the nutrient concentrations of livestock manure were taken from the kraals in [59], where nutrient losses through volatilisation were already considered according to [61]. Nutrient losses can be minimised by improving the shelter and storage of collected manure; e.g., some of the livestock urine can be collected in bedding, which is then immediately covered with soil in compost pits [58,61]. However, the NBs vary greatly depending on how much fodder a household cultivates in its own homegarden and how much it imports from outside. The household group $A_T$ produces only 30% of the fodder required for the animals kept in the homegarden, and all other groups produce less than 20%. If the farmers were to grow the entire fodder demand for their cattle themselves, the NBs would be clearly negative in the baseline scenario (S0), even under the management scenario S4, e.g., for group $A_T$ under S4 the NB would be −142 kg N, −19 kg P, and −106 kg K $ha^{-1}$ $hh^{-1}$ $yr^{-1}$.

Figures 3 and 4 clearly show the differences in nutrient flows between the most successful trained group of farmers $A_T$ and the most unsuccessful untrained group $C_U$. Although the illustrations only show the nitrogen cycles, the differences in the quantities for the phosphorus and potassium cycles are comparable as shown in Table 9. Considerably higher amounts of nutrients circulate in the homegardens of the $A_T$ group than in the $C_U$ group. Less successful farmers remove fewer nutrients from their soil in absolute numbers. However, they also add fewer nutrients and implement fewer measures that have a positive effect on nutrient balance and availability. For example, they enrich the soil less with humus, which is essential to store nutrients in a plant-available way, and mulch their soil less often, which leads to faster drying out of the soil and less plant-available water. We suspect that the households in the $C_U$ and $C_T$ groups are also among those that had worse farming conditions from the beginning. We observed during our survey that refugees from neighbouring countries often settled on land that was characterised by little or no vegetation, and probably by high soil degradation and low nutrient levels in the soil.

Besides, the potential for the additional use of livestock manure from grassland seems to be enormous at first glance (cf. Figure 3). However, this applies only if the cattle graze solely on the grassland (outside the system boundary of the NB) and do not eat fodder grown in the homegarden (inside the system boundary). In contrast, manure collection from grassland would have a negative impact on the NB of the grassland, where overgrazing can lead to long-term environmental damage, such as a reduction in vegetation, less humus formation, nutrient depletion, an exposed soil surface, and soil erosion by runoff (cf. [74]).

We assume that the implementation of the management scenarios investigated in this paper would improve the NB of untrained households. Thus, untrained households can considerably improve the overall NB of their homegarden via the incorporation of herbaceous legumes (according to [75]), the use of urine (according to [76]), and the additional production of CaSa-compost (human faeces, biochar from sawdust, crop residues, kitchen waste, and ash) (according to [21,51,56]). However, all untrained farm households remain in a negative range for N, P, and K. Successful implementation of the management scenarios would depend on various conditions, such as farm and soil management, soil nutrient status, water balance, and the timing and duration of rainfall.

In general, balance deficits can be eliminated or enhanced by various effects. Untrained farmers would additionally improve the NB in their homegardens if they were to implement training on SLM as recommended by the farmer field school MAVUNO Project. Effects on the NB are achieved via the following measures: minimising erosion due to runoff, nutrient-efficient compost production, (rain)water supply, and mulching. Nutrient losses from erosion due to runoff on slopes can be minimised by terracing and trench composting [24,75,76]. Additionally, improper compost production (e.g., no cover or shade over the compost trench) may lead to a higher volatilisation of nitrogen [25]. Further, the amount of rainfall determines the rate of leaching of nutrients [50]. Leaching might decrease over time if the rainfall decreases due to climate change (cf. [13]). On the other hand, changes in rainfall patterns exacerbate crop cultivation and livestock keeping in Tanzania and require small-scale water harvesting technology to overcome water scarcity through irrigation [13,77–79]. Banana plants depend on high soil water availability; thus, the mulching of soil surfaces to reduce unproductive water loss from the soil becomes unavoidable. It should be noted that in order to promote the deep root growth of banana plants, the ground around the banana plant should be left free up to a radius of several centimetres [80].

Not all household groups will be able to engage in composting, due to the extra work required and their inability to hire extra labour, especially not $C_U$ and $C_T$. The household groups $C_U$ and $C_T$ are vulnerable to food insecurity and have a weak socio-economic position. The households in group $C_T$ show some improvements in their socio-economic status compared to $C_U$, but are still socio-economically weak and vulnerable to food insecurity (cf. [24,25]). Poor soil and nutrient management are two reasons for these problems.

Moreover, treatment with urine and human faeces offered higher water productivity in [79]. Trained households do not apply human urine to their fields by the same methods employed by untrained households, although this may change in the future (increasing tendency) if human urine is safely used to enrich soils with N and P (e.g., [56,70]). In groups $B_U$, $C_U$, and $C_T$, the nutrient content in human excreta might have been overestimated because the nutrient contents are based on healthy and food secure persons. These groups of households are not food secure throughout the year, as shown in [24,25]. Data on human excreta under food shortage conditions is not available in this study area. In addition, biochar from sawdust and human faeces has the positive effects of long-term humus accumulation, nutrient storage in humus, and carbon sequestration [81–83]. Farmers may have no problem with the origin of organic amendments if they have a positive effect on the soil, but caution should be taken in the case of any rejection of products derived from human excreta [83] and if the soil health is affected [84].

In addition, as long as the nutrient status of the soil is not analysed on every farm and the nutrient flows between household groups remain unclear, we cannot be sure whether the additional application of synthetic fertiliser is necessary [85]. However, due to its high cost, detailed soil sampling is not feasible. We assume that nutrient depletion is high in these small-scale systems, as has been shown for banana-coffee-based farming systems in Uganda [86] and in annual cropping systems in NW Tanzania [56]. We also assume that households in the groups $A_T$, $B_T$, and $A_U$ operate based on the same "nutrient costs" of the other groups ($B_U$, $C_T$, and $C_U$). This hypothesis can only be confirmed or disproven if the nutrient flows between the groups are examined in detail by additional interviews with the farmers concerned. Nevertheless, trained farm households have transformed a part of their homegardens into densely grown and biodiverse agroforestry systems with almost closed nutrient cycles. Thus, not only were the NBs in these homegardens improved, but also the food security and prosperity of their families (cf. [25]).

As a final remark, NBs are highly dependent on many variables. Farm management improves under SLM and different management scenarios, especially with respect to the use of waste, fodder production, treatment of the soil, mulching, available mineral nitrogen and non-available nitrogen in the soil and soil water, amendments to organic fertiliser, plant density, harvest time, exposure to sunlight, length of the dry season, irrigation in the driest months, the decomposition rate of organic materials, gaseous losses, the weather, and the climate [30,56,70,71,79,87–89].

## 5. Conclusions and Recommendations

We first conclude that nutrient balances (NBs) in banana-coffee-based smallholder farming systems can be improved through the successful implementation of sustainable land use management practices. In successful households, the NBs are thoroughly positive. In less successful households, the NBs can be improved by utilising human urine, through the incorporation of herbaceous legumes, and via the production and application of biochar and sanitised human faeces in so-called CaSa-compost. However, under all scenarios, the same dependencies and constraints remain (labour-intensive manure collection and compost production, labour shortages, prolonged dry seasons, and socio-economic imbalances). As long as these constraints remain, nutrient deficiencies will not be overcome with mineral fertilisers alone.

As a second conclusion, we stress the importance of the system boundary. Only complete nutrient balances can give an estimation of the actual nutrient depletion and the resulting nutrient demand. Nutrient balances, however, must always take into account all removals, including those of fodder plants and trees or wood, and must not exclusively consider the nutrient gains from livestock manure as input; otherwise, this will always lead to an underestimation of nutrient removals. Thus, smallholder farmers in banana-coffee-based farming systems will always have to import fodder and wood to keep the nutrient balance neutral. The alternative is to reduce the number of livestock. Synthetic fertilisers could make up part of the nutrient deficit, but they must be used wisely, i.e., only on humus-rich soils, otherwise they would be too much of an economic burden on households and lead to further environmental damage.

Third, the observations made from this study raise the need to (i) study the current nutrient status of soil in depth (at least at a practical soil testing level), (ii) analyse the necessity of the coexistence of free-range livestock on grassland, and (iii) conduct an in-depth analysis of the socio-economic differences between successful and unsuccessful households. These further measures should be the next step in training at the farmer field school. Farmer field schools also play a crucial role as multipliers of farm management knowledge and can serve as a best-practice example to be used in training and policy recommendations by government institutions to achieve the following SDGs in rural areas of East Africa: SDG 1 (no poverty), SDG 2 (zero hunger), SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), and SDG 15 (life on land).

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## Appendix A

**Table A1.** Literature data of the input (IN) and output (OUT) flows of nutrients, including nitrogen (N), phosphorus (P), and potassium (K) in different ecosystems or farming systems with a focus on African countries and tropical montane regions, except for coffee leaves. TDN refers to the total dissolved nitrogen. DM = dry matter, Nutr. = nutrient content.

| Flow | Variable | Nutr. | Value | Unit | Source |
|---|---|---|---|---|---|
| IN1a | Atmospheric deposition in smallholder mixed farming in Africa | | | | |
| | | N | 1.8 | kg ha$^{-1}$ yr$^{-1}$ | [48] |
| | | N | 4.3 | kg ha$^{-1}$ yr$^{-1}$ | [49] |
| | | N | 4.7 | kg ha$^{-1}$ yr$^{-1}$ | [68] |
| | | P | 0.2 | kg ha$^{-1}$ yr$^{-1}$ | [48] |
| | | P | 1.0 | kg ha$^{-1}$ yr$^{-1}$ | [49] |
| | | P | 0.8 | kg ha$^{-1}$ yr$^{-1}$ | [68] |
| | | K | 3.4 | kg ha$^{-1}$ yr$^{-1}$ | [48] |
| | | K | 3.9 | kg ha$^{-1}$ yr$^{-1}$ | [49] |
| | | K | 3.1 | kg ha$^{-1}$ yr$^{-1}$ | [68] |
| | In montane tropical mixed forest, Congo | TDN | 21.2 | kg ha$^{-1}$ yr$^{-1}$ | [44] |
| IN1b | Throughfall in montane tropical mixed forest | TDN | 42.1 ± 0.8 | kg ha$^{-1}$ yr$^{-1}$ | [44] |
| IN2a | Litterfall and deep capture | | | | |
| | In smallholder agroforestry with plantain and cacao | N | 66.4 | kg ha$^{-1}$ yr$^{-1}$ | [49] |
| | In smallholder agroforestry with plantain and cacao | P | 5.15 | kg ha$^{-1}$ yr$^{-1}$ | [49] |
| | In smallholder agroforestry with plantain and cacao | K | 26.2 | kg ha$^{-1}$ yr$^{-1}$ | [49] |
| | In montane tropical mixed forest | N | 250 ± 20 | kg ha$^{-1}$ yr$^{-1}$ | [44] |
| IN2b | Deep capture from below the root zone | N | 16.6 | kg ha$^{-1}$ yr$^{-1}$ | [49] |
| | Deep capture from below the root zone | P | 1.38 | kg ha$^{-1}$ yr$^{-1}$ | [49] |
| | Deep capture from below the root zone | K | 6.55 | kg ha$^{-1}$ yr$^{-1}$ | [49] |
| IN2c | Biological fixation | | | | |
| | Beans *(Phaseolus vulgaris)* | N | 19.0 | kg ha$^{-1}$ yr$^{-1}$ | [48] |
| | Beans *(Phaseolus vulgaris)* | N | 17–57 | kg ha$^{-1}$ yr$^{-1}$ | [88] |
| | Beans *(Phaseolus vulgaris)* | N | 8–58 | kg ha$^{-1}$ yr$^{-1}$ | [51] |
| | Groundnut *(Arachis hypogeae)* | N | 6.93 | kg ha$^{-1}$ yr$^{-1}$ | [49] |
| | Permanent crops, cereals and oil crops | N | 4.0 | kg ha$^{-1}$ yr$^{-1}$ | [68] |
| | Pulses | N | 18.0 | kg ha$^{-1}$ yr$^{-1}$ | [68] |
| | Vegetables | N | 8.0 | kg ha$^{-1}$ yr$^{-1}$ | [68] |
| IN4a | Crop residues of perennial crops after harvest | | | | |
| | Banana leaves *(Musa AAA, Cavendish, cv. Robusta)* | N | 1.3 | g plant$^{-1}$ | [89] |
| | Banana leaves *(Musa AAA, Cavendish, cv. Robusta)* | P | 0.2 | g plant$^{-1}$ | [89] |
| | Banana leaves *(Musa AAA, Cavendish, cv. Robusta)* | K | 2.8 | g plant$^{-1}$ | [89] |
| | Banana leaves *(Musa spp.)* | N | 2.0–2.5 | % | [89] |
| | Banana leaves *(Musa spp.)* | N | 4.4 | % DM | [55] |
| | Banana leaves *(Musa spp.)* | P | 0.15 | % DM | [55] |
| | Banana leaves *(Musa spp.)* | K | 1.0 | % DM | [55] |
| | Banana leaves *(Musa spp.)* | N | 2.75 | % DM | [23] |

**Table A1.** *Cont.*

| Flow | Variable | Nutr. | Value | Unit | Source |
|---|---|---|---|---|---|
| | Banana leaves *(Musa spp.)* | P | 0.1 | % DM | [23] |
| | Banana leaves *(Musa spp.)* | K | 4.85 | % DM | [23] |
| | Banana leaves *(Musa spp.)* | N | 25 | kg $ha^{-1}$ $yr^{-1}$ | [23] |
| | Banana leaves *(Musa spp.)* | K | 43 | kg $ha^{-1}$ $yr^{-1}$ | [23] |
| | Banana leaves and stem *(Musa spp.)* | P | 2.6 | g $kg^{-1}$ DM | [80] |
| | Plantain trunk *(Musa spp.)* | P | 0.9 | % DM | [80] |
| | Plantain trunk *(Musa spp.)* | K | 40.8 | % DM | [80] |
| | Banana pseudostems *(Musa spp.)* | N | 3.0 | kg $ha^{-1}$ $yr^{-1}$ | [23] |
| | Banana pseudostems *(Musa spp.)* | K | 26 | kg $ha^{-1}$ $yr^{-1}$ | [23] |
| | Banana pst. *(Musa AAA, Cavendish, cv. Robusta)* | N | 0.7 | g $plant^{-1}$ | [89] |
| | Banana pst. *(Musa AAA, Cavendish, cv. Robusta)* | P | 0.07 | g $plant^{-1}$ | [89] |
| | Banana pst. *(Musa AAA, Cavendish, cv. Robusta)* | K | 4.2 | g $plant^{-1}$ | [89] |
| | Banana pseudostems *(Musa spp.)* | N | 1.01 | % DM | [23] |
| | Banana pseudostems *(Musa spp.)* | P | 0.07 | % DM | [23] |
| | Banana pseudostems *(Musa spp.)* | K | 7.70 | % DM | [23] |
| | Banana rhizome *(Musa AAA, Cavendish cv. Rob.)* | N | 0.8 | g $plant^{-1}$ | [89] |
| | Banana rhizome *(Musa AAA, Cavendish cv. Rob.)* | P | 0.07 | g $plant^{-1}$ | [89] |
| | Banana rhizome *(Musa AAA, Cavendish cv. Rob.)* | K | 3.6 | g $plant^{-1}$ | [89] |
| | Coffee *(Coffea arabica L.), leaves* | P | 1.2 | g kg $DM^{-1}$ | [80] |
| | Coffee *(Coffea arabica L.), leaves* | K | 4.6 | g kg $DM^{-1}$ | [80] |
| | Coffee *(Coffea arabica L.), hulls* | N | 2.01 | % | [48] |
| | Coffee *(Coffea arabica L.), hulls* | P | 0.20 | % | [48] |
| | Coffee *(Coffea arabica L.), hulls* | K | 2.77 | % | [48] |
| | Coffee *(Coffea arabica L.), hulls* | P | 1.4 | g kg $DM^{-1}$ | [80] |
| | Coffee *(Coffea arabica L.), hulls* | K | 22.6 | g kg $DM^{-1}$ | [80] |
| | Mango *(Mangifera indica L.), peels, dried* | P | 2.8 | g kg $DM^{-1}$ | [80] |
| | Mango *(Mangifera indica L.), kernels, dried* | P | 2.8 | g kg $DM^{-1}$ | [80] |
| | Mango *(Mangifera indica L.), kernels, dried* | K | 0.6 | g kg $DM^{-1}$ | [80] |
| IN4b | Crop residues of annual crops | | | | |
| | Beans *(Phaseolus vulgaris)* | N | 4.24 | % DM | [48] |
| | Beans *(Phaseolus vulgaris)* | P | 0.58 | % DM | [48] |
| | Beans *(Phaseolus vulgaris)* | K | 1.71 | % DM | [48] |
| | Bean trash *(Phaseolus vulgaris)* | N | 2.53 | % DM | [23] |
| | Bean trash *(Phaseolus vulgaris)* | P | 0.16 | % DM | [23] |
| | Bean trash *(Phaseolus vulgaris)* | K | 1.85 | % DM | [23] |
| | Beans *(Phaseolus vulgaris)* | N | 29 | kg $ha^{-1}$ $yr^{-1}$ | [23] |
| | Beans *(Phaseolus vulgaris)* | K | 21 | kg $ha^{-1}$ $yr^{-1}$ | [23] |
| | Maize leaves, fresh *(Zea mays L.)* | P | 1.5 | g kg $DM^{-1}$ | [80] |
| | Maize leaves, fresh *(Zea mays L.)* | K | 16.6 | g kg $DM^{-1}$ | [80] |
| | Maize stover, fresh *(Zea mays L.)* | P | 1.6 | g kg $DM^{-1}$ | [80] |
| | Maize stover, fresh *(Zea mays L.)* | K | 16.8 | g kg $DM^{-1}$ | [80] |
| | Maize stover, dry *(Zea mays L.)* | N | 0.58 | % DM | [23] |
| | Maize stover, dry *(Zea mays L.)* | P | 0.03 | % DM | [23] |
| | Maize stover, dry *(Zea mays L.)* | K | 2.67 | % DM | [23] |
| | Maize stover, dry *(Zea mays L.)* | N | 12 | kg $ha^{-1}$ $yr^{-1}$ | [23] |
| | Maize stover, dry *(Zea mays L.)* | K | 57 | kg $ha^{-1}$ $yr^{-1}$ | [23] |
| | Maize stover, dry *(Zea mays L.)* | P | 0.8 | g kg $DM^{-1}$ | [59] |

**Table A1.** *Cont.*

| Flow | Variable | Nutr. | Value | Unit | Source |
|---|---|---|---|---|---|
| | Maize stover, dry *(Zea mays L.)* | K | 14.0 | g kg DM$^{-1}$ | [80] |
| | Cassava foliage, fresh *(Manihot esculenta C.)* | P | 3.7 | g kg DM$^{-1}$ | [80] |
| | Cassava foliage, fresh *(Manihot esculenta C.)* | K | 12.5 | g kg DM$^{-1}$ | [80] |
| | Cassava foliage, wilted *(Manihot esculenta C.)* | P | 3.0 | g kg DM$^{-1}$ | [80] |
| IN4b | Kitchen and food waste | | | | |
| | Banana peel *(Musa, AAA-EAH)* | N | 1.14 | % DM | [48] |
| | Banana peel *(Musa, AAA-EAH)* | P | 0.12 | % DM | [48] |
| | Banana peel *(Musa, AAA-EAH)* | K | 4.99 | % DM | [48] |
| | Banana peel *(Musa spp.)* | N | 1.16 | % DM | [23] |
| | Banana peel *(Musa spp.)* | P | 0.64 | % DM | [23] |
| | Banana peel *(Musa spp.)* | K | 4.63 | % DM | [23] |
| | Banana stalk *(Musa, AAA-EAH)* | N | 0.92 | % DM | [48] |
| | Banana stalk *(Musa, AAA-EAH)* | P | 0.17 | % DM | [48] |
| | Banana stalk *(Musa, AAA-EAH)* | K | 8.33 | % DM | [48] |
| | Banana stalk *(Musa spp.)* | P | 2.9 | g kg$^{-1}$ DM$^{-1}$ | [80] |
| | Banana stalk *(Musa spp.)* | K | 53.5 | g kg$^{-1}$ DM$^{-1}$ | [80] |
| | Cassava, peels, fresh *(Manihot esculenta C.)* | P | 2.1 | g kg DM$^{-1}$ | [80] |
| | Cassava, peels, fresh *(Manihot esculenta C.)* | K | 6.4 | g kg DM$^{-1}$ | [80] |
| | Cassava, peels, dry *(Manihot esculenta C.)* | P | 0.8 | g kg DM$^{-1}$ | [80] |
| | Cassava, peels, dry *(Manihot esculenta C.)* | K | 7.1 | g kg DM$^{-1}$ | [80] |
| | Maize cobs, without grain *(Zea mays L.)* | P | 0.7 | g kg DM$^{-1}$ | [80] |
| | Maize cobs, without grain *(Zea mays L.)* | K | 4.8 | g kg DM$^{-1}$ | [80] |
| IN4c | Livestock manure | | | | |
| | Indigenous cattle, manure | N | 14.9 | g kg$^{-1}$ | [48] |
| | Indigenous cattle, manure | P | 3.45 | g kg$^{-1}$ | [48] |
| | Indigenous cattle, manure | K | 12.39 | g kg$^{-1}$ | [48] |
| | Indigenous cattle, manure | N | 1.49 | % | [48] |
| | Indigenous cattle, manure | P | 0.35 | % | [48] |
| | Indigenous cattle, manure | K | 1.24 | % | [48] |
| | Improved cattle, manure | N | 16.69 | g kg$^{-1}$ | [48] |
| | Improved cattle, manure | P | 5.07 | g kg$^{-1}$ | [48] |
| | Improved cattle, manure | K | 26.35 | g kg$^{-1}$ | [48] |
| | Improved cattle, manure | N | 1.67 | % | [48] |
| | Improved cattle, manure | P | 0.51 | % | [48] |
| | Improved cattle, manure | K | 2.64 | % | [48] |
| | Cattle manure | N | 1.2 | % | [58] |
| | Cattle manure | P | 0.3 | % | [58] |
| | Cattle manure | K | 2.1 | % | [58] |
| | Goat and sheep manure | N | 1.5 | % | [58] |
| | Goat and sheep manure | P | 0.2 | % | [58] |
| | Goat and sheep manure | K | 3.0 | % | [58] |
| | Goat manure | N | 3.8 | g kg$^{-1}$ | [49] |
| | Goat manure | P | 0.67 | g kg$^{-1}$ | [49] |
| | Goat manure | K | 0.50 | g kg$^{-1}$ | [49] |
| | Sheep manure | N | 3.2 | g kg$^{-1}$ | [49] |
| | Sheep manure | P | 0.32 | g kg$^{-1}$ | [49] |
| | Sheep manure | K | 0.40 | g kg$^{-1}$ | [49] |
| | Pig manure | N | 2.5 | g kg$^{-1}$ | [49] |
| | Pig manure | P | 0.48 | g kg$^{-1}$ | [49] |
| | Pig manure | K | 0.65 | g kg$^{-1}$ | [49] |
| | Chicken manure | N | 3.2 | % | [58] |
| | Chicken manure | P | 0.4 | % | [58] |
| | Chicken manure | K | 2.2 | % | [58] |

**Table A1.** *Cont.*

| Flow | Variable | Nutr. | Value | Unit | Source |
|---|---|---|---|---|---|
| | Chicken manure | N | 2.2 | g kg$^{-1}$ | [49] |
| | Chicken manure | P | 0.37 | g kg$^{-1}$ | [49] |
| | Chicken manure | K | 0.65 | g kg$^{-1}$ | [49] |
| | Bedding | N | 6.14 | g kg$^{-1}$ | [48] |
| | Bedding | P | 0.89 | g kg$^{-1}$ | [48] |
| | Bedding | K | 7.03 | g kg$^{-1}$ | [48] |
| | Bedding | N | 0.61 | % | [48] |
| | Bedding | P | 09 | % | [48] |
| | Bedding | K | 0.70 | % | [48] |
| OUT1a | Harvest of perennial crops | | | | |
| | Banana pulp *(Musa, AAA-EAH)* | N | 0.71 | % DW | [48] |
| | Banana pulp *(Musa, AAA-EAH)* | P | 0.11 | % DW | [48] |
| | Banana pulp *(Musa, AAA-EAH)* | K | 0.49 | % DW | [48] |
| | Coffee beans *(Coffea robusta)* | N | 2.28 | % FW | [48] |
| | Coffee beans *(Coffea robusta)* | P | 0.23 | % FW | [48] |
| | Coffee beans *(Coffea robusta)* | K | 2.26 | % FW | [48] |
| | Coffee *(Coffea arabica L.)*, pulp, without seeds | P | 1.3 | g kg DM$^{-1}$ | [80] |
| | Mango *(Mangifera indica L.)* fruits, fresh | P | 1.0 | g kg DM$^{-1}$ | [80] |
| | Mango *(Mangifera indica L.)* fruits, fresh | K | 7.7 | g kg DM$^{-1}$ | [80] |
| | Mango *(Mangifera indica L.)*, pulp, fresh | P | 1.1 | g kg DM$^{-1}$ | [80] |
| | Mango *(Mangifera indica L.)*, pulp, fresh | K | 13.3 | g kg DM$^{-1}$ | [80] |
| OUT1b | Harvest of annual crops | | | | |
| | Beans *(Phaseolus vulgaris)* | N | 4.24 | % DW | [48] |
| | Beans *(Phaseolus vulgaris)* | P | 0.58 | % DW | [48] |
| | Beans *(Phaseolus vulgaris)* | K | 1.71 | % DW | [48] |
| | Maize grain *(Zea mays L.)* | N | 3.0 | g kg DM$^{-1}$ | |
| | Maize grain *(Zea mays L.)* | P | 2.9 | g kg DM$^{-1}$ | [80] |
| | Maize grain *(Zea mays L.)* | K | 3.6 | g kg DM$^{-1}$ | [80] |
| | Cassava tubers, fresh *(Manihot esculenta C.)* | P | 1.2 | g kg DM$^{-1}$ | [80] |
| | Cassava tubers, fresh *(Manihot esculenta C.)* | K | 7.7 | g kg DM$^{-1}$ | [80] |
| | Cassava tubers, fresh, peeled *(Manihot esculenta C.)* | P | 0.4 | g kg DM$^{-1}$ | [80] |
| | Cassava tubers, dehydrated *(Manihot esculenta C.)* | P | 1.1 | g kg DM$^{-}$ | [80] |
| | Cassava tubers, dehydrated *(Manihot esculenta C.)* | K | 9.9 | g kg DM$^{-1}$ | [80] |
| | Tubers (cassava) | N | 0.56 | % FW | [48] |
| | Tubers (cassava) | P | 0.18 | % FW | [48] |
| | Tubers (cassava) | K | 1.22 | % FW | [48] |
| OUT6 | Leaching | | | | |
| | Leaching below the root zone | N | 6.0 | kg ha$^{-1}$ yr$^{-1}$ | [48] |
| | Leaching below the root zone | P | 0 | kg ha$^{-1}$ yr$^{-1}$ | [48] |
| | Leaching below the root zone | K | 11.0 | kg ha$^{-1}$ yr$^{-1}$ | [48] |
| | Leaching below the root zone | N | 26.4 | kg ha$^{-1}$ yr$^{-1}$ | [49] |
| | Leaching below the root zone | K | 0.88 | kg ha$^{-1}$ yr$^{-1}$ | [49] |
| | Leaching at 20 cm depth | TDN | 27.7 ± 17.7 | kg ha$^{-1}$ yr$^{-1}$ | [44] |
| | Leaching at 40 cm depth | TDN | 17.3 ± 16.6 | kg ha$^{-1}$ yr$^{-1}$ | [44] |
| | Leaching at 80 cm depth | TDN | 15.5 ± 9.7 | kg ha$^{-1}$ yr$^{-1}$ | [44] |
| OUT9 | Gaseous loss | | | | |
| | Emission from soil | N | 6.34 | kg ha$^{-1}$ yr$^{-1}$ | [49] |
| | Emission from soil | $N_2O$ | 3.45 | kg ha$^{-1}$ yr$^{-1}$ | [44] |
| | Emission from burning natural vegetation | N | 47.8 | kg ha$^{-1}$ yr$^{-1}$ | [49] |

**Table A1.** *Cont.*

| Flow | Variable | Nutr. | Value | Unit | Source |
|---|---|---|---|---|---|
| | Emission from burning natural vegetation | P | 1.8 | kg $ha^{-1}$ $yr^{-1}$ | [49] |
| | Emission from burning natural vegetation | K | 14.2 | kg $ha^{-1}$ $yr^{-1}$ | [49] |
| | Emission from denitrification | N | 20 | kg $ha^{-1}$ $yr^{-1}$ | [48] |
| | Release of $NH_3$, NO, $N_2O$, $N_2$, cereals | N | 5.6 | kg $ha^{-1}$ $yr^{-1}$ | [68] |
| | Release of $NH_3$, NO, $N_2O$, $N_2$, pulses | N | 3.3 | kg $ha^{-1}$ $yr^{-1}$ | [68] |
| | Release of $NH_3$, NO, $N_2O$, $N_2$, banana, coffee | N | 15.2 | kg $ha^{-1}$ $yr^{-1}$ | [68] |
| | Release of $NH_3$, NO, $N_2O$, $N_2$, vegetables | N | 21.3 | kg $ha^{-1}$ $yr^{-1}$ | [68] |

DW = dry weight. DM = dry matter. cv. = cultivar. pst. = pseudostem. Rob. = Robusta [23]. Smallholder banana-based farming systems in Uganda [44]. Tropical montane mixed forest in Congo basin [48]. Banana-coffee-based farming, Karagwe, Kagera region, Tanzania [49]. Smallholder mixed farming, Cameroon [51]. Worldwide study on nitrogen-fixing crop legumes [80]. Data collection of feeding recommendations in tropical and Mediterranean regions [55]. Laboratory experiments in basic research [58]. Review of manure samples from kraals and animal sheds in eastern and southern Africa [68]. Smallholder mixed farming, Ethiopia [90]. Field trial in horticulture research in Bangalore [90]. Banana production in Hawaii.

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