

Article

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 m³ yr^{−1} CaSa-compost (human excreta and biochar) and its application on 600 m² 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 $\text{ha}^{-1} \text{yr}^{-1}$ (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%).

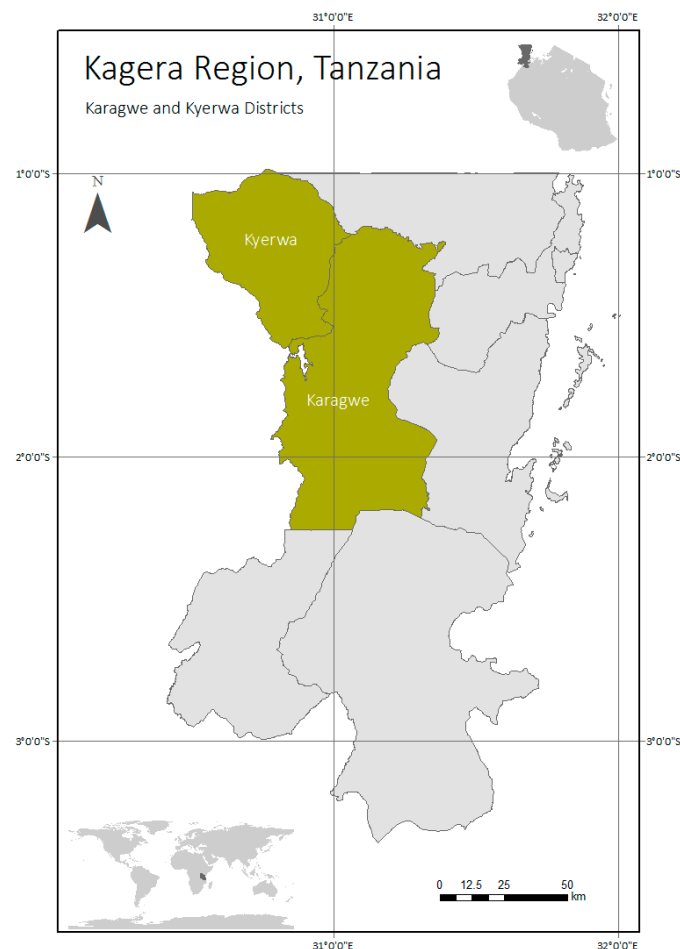


Figure 1. Map of the study area showing the Karagwe and Kyerwa districts of the Kagera region in NW Tanzania [24].

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.

Household Characteristics		Untrained Households ^I					Trained Farm Households ^{II}		
		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 (<i>Musa spp.</i>)	t homegarden ⁻¹ yr ⁻¹	4.2	1.8	0.2	2.1	11–57	2.8–18	0.7–1.2	
Coffee (<i>Coffea canephora</i>)	t homegarden ⁻¹ yr ⁻¹	0.5	0.1	0.1	0.2	≤0.7	≤0.1	≤0.1	
Beans (<i>Phaseolus vulgaris spp.</i>)	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 (<i>Zea mays spp.</i>)	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 (<i>Manihot esculenta spp.</i>)	t homegarden ⁻¹ yr ⁻¹	0.4	0.4	0.2	0.3	0.8	0.5	0.2	
Banana (<i>Musa spp.</i>)	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 (<i>Coffea canephora</i>)	t ha ⁻¹ yr ⁻¹ ^{IV}	0.2	0.1	0.1	0.1	≤0.5	≤0.2	≤0.1	
Beans (<i>Phaseolus vulgaris spp.</i>)	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 (<i>Zea mays spp.</i>)	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 (<i>Manihot esculenta spp.</i>)	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	OUTPUT	STOCK
Atmospheric deposition (IN1)	Harvested crops (OUT1)	Human body (STOCK1)
Inputs by plants and trees (IN2)	<ul style="list-style-type: none"> Perennial crops (OUT1a) Annual crops (OUT1b) 	Animal body (STOCK2)
<ul style="list-style-type: none"> Litterfall (IN2a) Deep capture (IN2b) Biological fixation (IN2c) 	Fodder (OUT2)	Pit latrine (STOCK3)
Organic fertiliser (IN3)	Wood (OUT3)	Soil (STOCK4)
<ul style="list-style-type: none"> Crop residues (IN3a) Kitchen and food waste (IN3b) Cooking ash (IN3c) Livestock manure and urine (IN3d) Human excreta (IN3e) 	Market (OUT4)	
	Sold crop residues (OUT5)	
	Leaching from soil (OUT6)	
	Leaching from pit latrines (OUT7)	
	River discharge (OUT8)	
	Gaseous losses (OUT9)	

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.

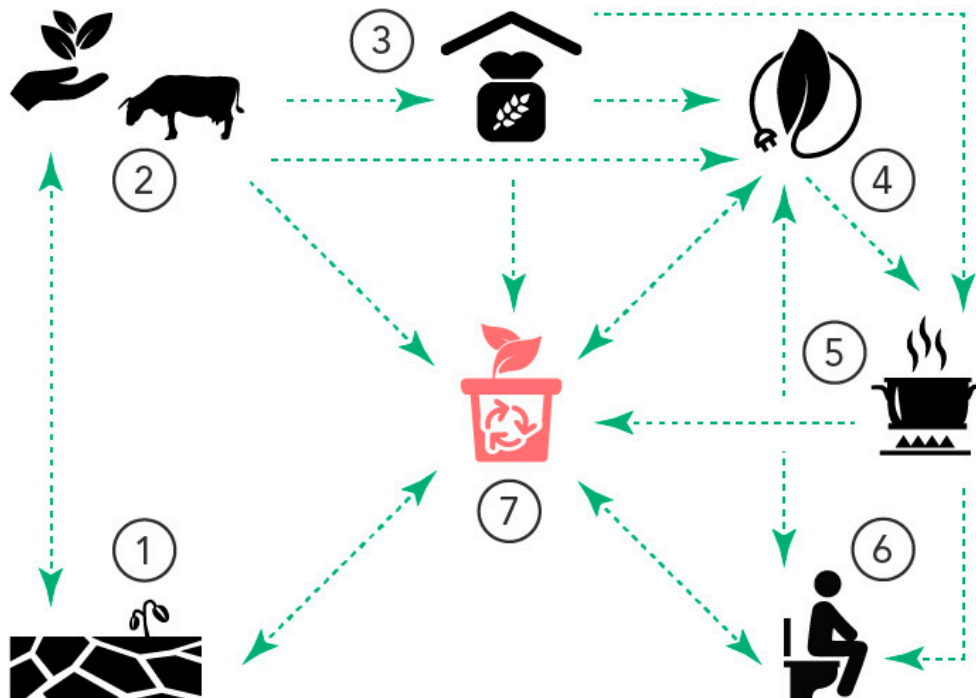


Figure 2. Biomass and waste dynamics and the mass fluxes of nutrients and energy in multifunctional land-use systems in smallholder farming systems in the tropical highlands of East Africa. Labelling as follows: 1: the soil sub-system, 2: plant and animal production as a sub-system, 3: harvest and storage 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 $21.2 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ on *Ferralsol* and *Acrisol* in the Congo basin, comprising NH_4^+ , NO_3^- , and dissolved organic nitrogen (DON) of 9.6, 5.8, and $5.8 \text{ kg N ha}^{-1} \text{ yr}^{-1}$, respectively [48]. These values are considered the maximum values for IN1a, whereas the estimated wet deposition from the rain samples was about $1.8 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ 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 N₂ [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:

$$P_{ban} = H_{ban} \times 1.2 \quad (4)$$

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.

Collection and Storage System	Average Nutrient Losses in %				Practised by Household Groups
	Dung N	Dung P	Urine N	Urine K	
Open kraal/boma ¹	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

¹ 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			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 $27.7 \pm 17.7 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ with 2.0 ± 1.1 , 19.2 ± 12.6 , and $6.5 \pm 4.2 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ for NH_4^+ , NO_3^- , and DON, respectively. In [49], leaching of $21.0 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ and $11 \text{ kg K ha}^{-1} \text{ yr}^{-1}$ 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% \pm 13% sand, 44% \pm 11% silt, and 7% \pm 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 $7.2 \text{ kg N ha}^{-1} \text{ yr}^{-1}$, with 1.4, 3.8, and $2.0 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ for NH_4^+ , NO_3^- , and DON, respectively [48]. These values are comparable to the $6 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ result in [49].

Gaseous Losses (OUT9)

Gaseous losses through the denitrification of soil are about $20 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ [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, ρ_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	ρ_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	<i>maximum</i>	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	<i>high</i>	80	A _T
Well managed but with lower density and traditional farming; soils are often covered with crop residues (in situ composting)	<i>moderate</i>	60	A _U
Moderately well managed, soils covered for some months of the year, lower yields, partial food insecurity	<i>low</i>	40	B _T , B _U
Poorly managed with very few crops and trees, frequent labour shortages, very low yields, food insecurity	<i>very low</i>	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 $300 \times 270 \text{ cm}$ with a variety of vegetables was provided, to which $8.3 \text{ dm}^3 \text{ m}^{-2}$ 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 m² 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.

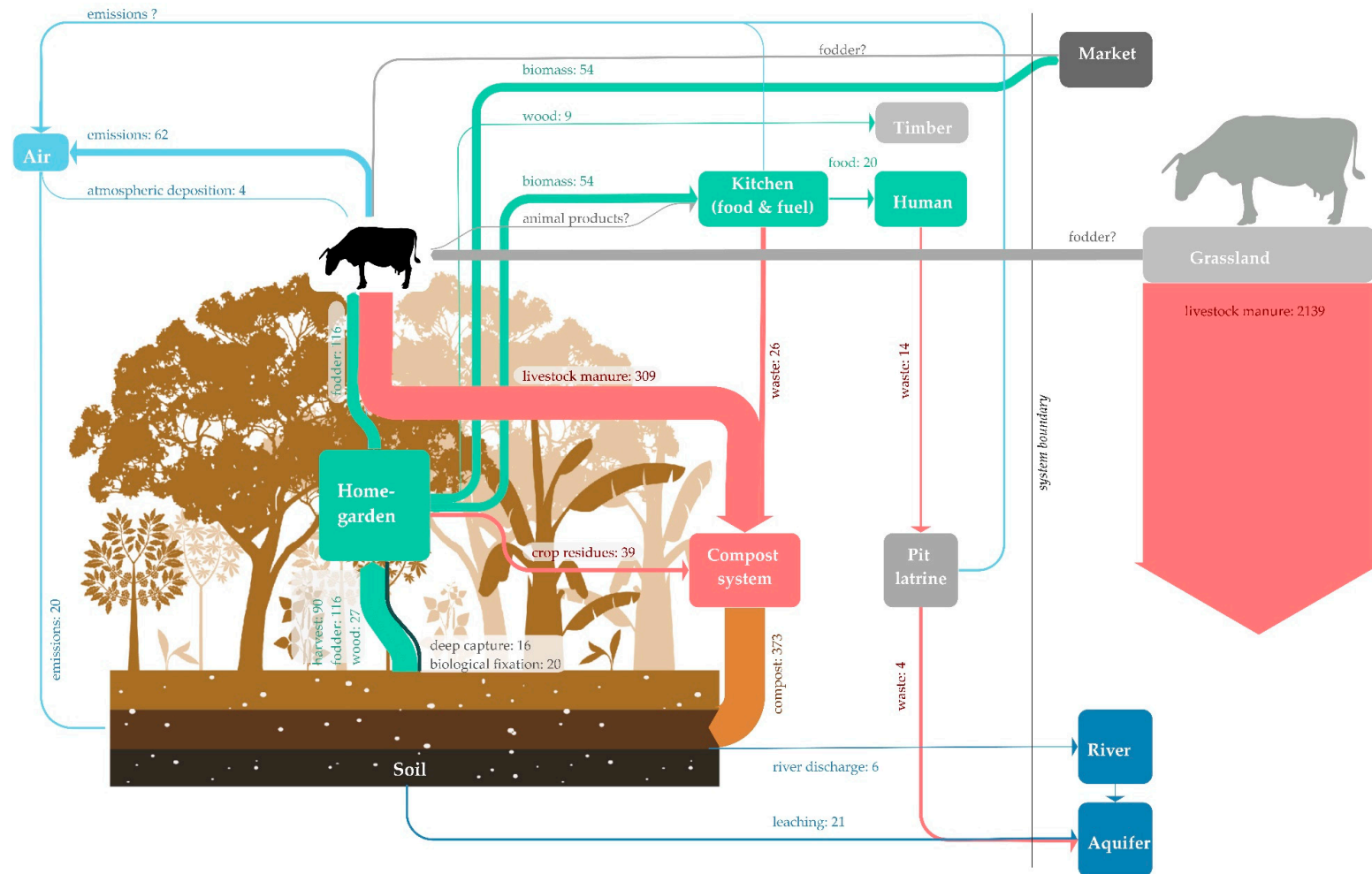


Figure 3. Main nitrogen flows in household group A_T (non-vulnerable to food insecurity, trained farm households). All values in kg N ha⁻¹ hh⁻¹ yr⁻¹. (Design of background picture: Claudia Matthias, modified by Atiqah Fairuz Salleh.)

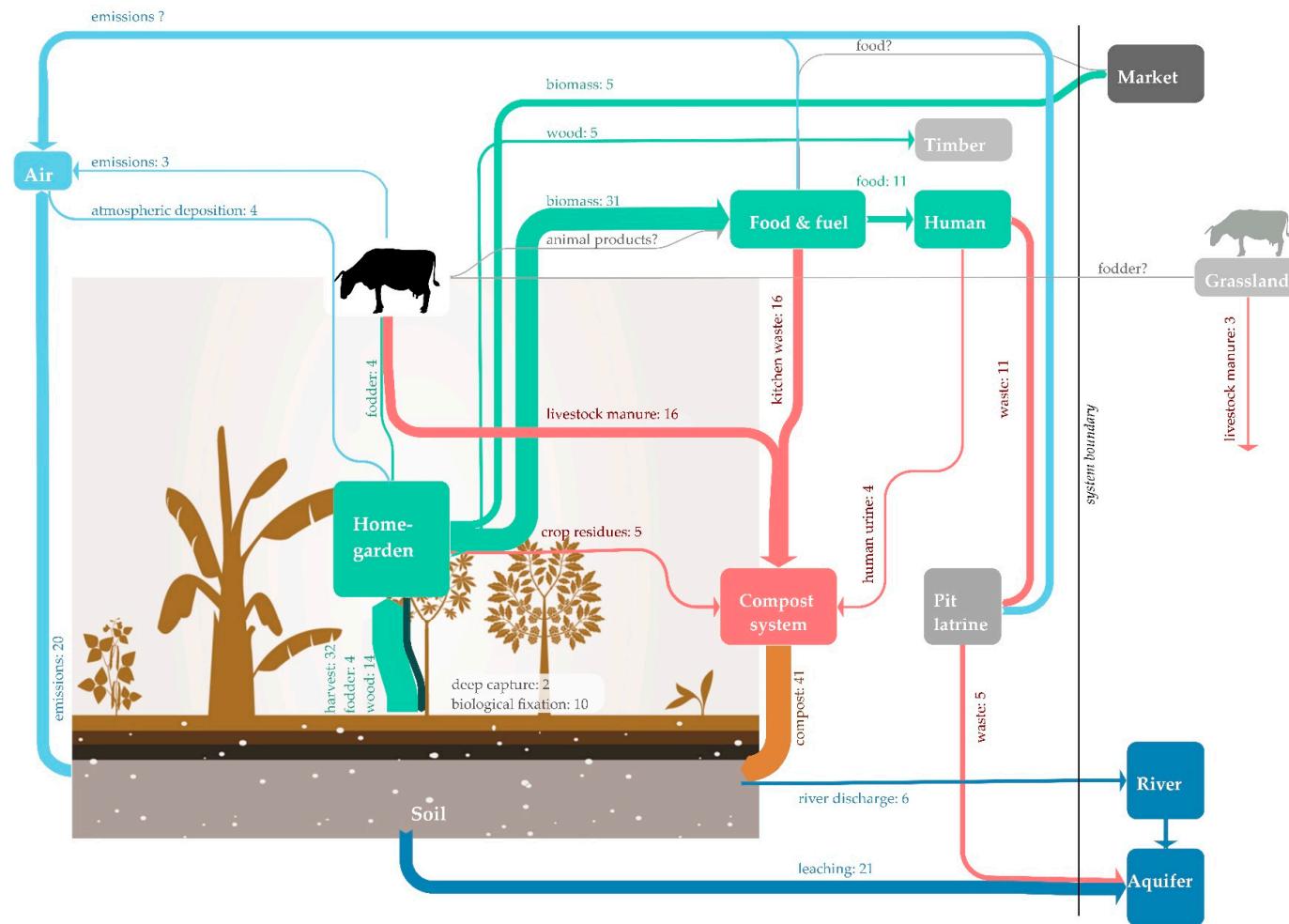


Figure 4. Main nitrogen flows in household group C_U (most vulnerable to food insecurity, untrained farm households). All values in kg N ha⁻¹ hh⁻¹ yr⁻¹. (Design of background picture: Claudia Matthias, modified by Atiqah Fairuz Salleh.)

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 homestead 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 homesteads 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]
IN1b	In montane tropical mixed forest, Congo	K	3.1	kg ha ⁻¹ yr ⁻¹	[68]
	Throughfall in montane tropical mixed forest	TDN	21.2	kg ha ⁻¹ yr ⁻¹	[44]
IN2a	Litterfall and deep capture	TDN	42.1 ± 0.8	kg ha ⁻¹ yr ⁻¹	[44]
IN2b	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]
	Deep capture from below the root zone	N	16.6	kg ha ⁻¹ yr ⁻¹	[49]
IN2c	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]
	Biological fixation				
	Beans (<i>Phaseolus vulgaris</i>)	N	19.0	kg ha ⁻¹ yr ⁻¹	[48]
	Beans (<i>Phaseolus vulgaris</i>)	N	17–57	kg ha ⁻¹ yr ⁻¹	[88]
	Beans (<i>Phaseolus vulgaris</i>)	N	8–58	kg ha ⁻¹ yr ⁻¹	[51]
	Groundnut (<i>Arachis hypogaea</i>)	N	6.93	kg ha ⁻¹ yr ⁻¹	[49]
	Permanent crops, cereals and oil crops	N	4.0	kg ha ⁻¹ yr ⁻¹	[68]
IN4a	Pulses	N	18.0	kg ha ⁻¹ yr ⁻¹	[68]
	Vegetables	N	8.0	kg ha ⁻¹ yr ⁻¹	[68]
	Crop residues of perennial crops after harvest				
	Banana leaves (<i>Musa AAA, Cavendish, cv. Robusta</i>)	N	1.3	g plant ⁻¹	[89]
	Banana leaves (<i>Musa AAA, Cavendish, cv. Robusta</i>)	P	0.2	g plant ⁻¹	[89]
	Banana leaves (<i>Musa AAA, Cavendish, cv. Robusta</i>)	K	2.8	g plant ⁻¹	[89]
	Banana leaves (<i>Musa spp.</i>)	N	2.0–2.5	%	[89]
	Banana leaves (<i>Musa spp.</i>)	N	4.4	% DM	[55]
	Banana leaves (<i>Musa spp.</i>)	P	0.15	% DM	[55]
	Banana leaves (<i>Musa spp.</i>)	K	1.0	% DM	[55]
	Banana leaves (<i>Musa spp.</i>)	N	2.75	% DM	[23]

Table A1. Cont.

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

Table A1. Cont.

Flow	Variable	Nutr.	Value	Unit	Source
IN4b	Maize stover, dry (<i>Zea mays</i> L.)	K	14.0	g kg DM ⁻¹	[80]
	Cassava foliage, fresh (<i>Manihot esculenta</i> C.)	P	3.7	g kg DM ⁻¹	[80]
	Cassava foliage, fresh (<i>Manihot esculenta</i> C.)	K	12.5	g kg DM ⁻¹	[80]
	Cassava foliage, wilted (<i>Manihot esculenta</i> C.)	P	3.0	g kg DM ⁻¹	[80]
	Kitchen and food waste				
	Banana peel (<i>Musa</i> , AAA-EAH)	N	1.14	% DM	[48]
	Banana peel (<i>Musa</i> , AAA-EAH)	P	0.12	% DM	[48]
	Banana peel (<i>Musa</i> , AAA-EAH)	K	4.99	% DM	[48]
	Banana peel (<i>Musa</i> spp.)	N	1.16	% DM	[23]
	Banana peel (<i>Musa</i> spp.)	P	0.64	% DM	[23]
	Banana peel (<i>Musa</i> spp.)	K	4.63	% DM	[23]
	Banana stalk (<i>Musa</i> , AAA-EAH)	N	0.92	% DM	[48]
	Banana stalk (<i>Musa</i> , AAA-EAH)	P	0.17	% DM	[48]
	Banana stalk (<i>Musa</i> , AAA-EAH)	K	8.33	% DM	[48]
	Banana stalk (<i>Musa</i> spp.)	P	2.9	g kg ⁻¹ DM ⁻¹	[80]
	Banana stalk (<i>Musa</i> spp.)	K	53.5	g kg ⁻¹ DM ⁻¹	[80]
	Cassava, peels, fresh (<i>Manihot esculenta</i> C.)	P	2.1	g kg DM ⁻¹	[80]
	Cassava, peels, fresh (<i>Manihot esculenta</i> C.)	K	6.4	g kg DM ⁻¹	[80]
	Cassava, peels, dry (<i>Manihot esculenta</i> C.)	P	0.8	g kg DM ⁻¹	[80]
	Cassava, peels, dry (<i>Manihot esculenta</i> C.)	K	7.1	g kg DM ⁻¹	[80]
	Maize cobs, without grain (<i>Zea mays</i> L.)	P	0.7	g kg DM ⁻¹	[80]
	Maize cobs, without grain (<i>Zea mays</i> 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 (<i>Musa</i> , AAA-EAH)	N	0.71	% DW	[48]
	Banana pulp (<i>Musa</i> , AAA-EAH)	P	0.11	% DW	[48]
	Banana pulp (<i>Musa</i> , AAA-EAH)	K	0.49	% DW	[48]
	Coffee beans (<i>Coffea robusta</i>)	N	2.28	% FW	[48]
	Coffee beans (<i>Coffea robusta</i>)	P	0.23	% FW	[48]
	Coffee beans (<i>Coffea robusta</i>)	K	2.26	% FW	[48]
	Coffee (<i>Coffea arabica</i> L.), pulp, without seeds	P	1.3	g kg DM ⁻¹	[80]
	Mango (<i>Mangifera indica</i> L.) fruits, fresh	P	1.0	g kg DM ⁻¹	[80]
	Mango (<i>Mangifera indica</i> L.) fruits, fresh	K	7.7	g kg DM ⁻¹	[80]
	Mango (<i>Mangifera indica</i> L.), pulp, fresh	P	1.1	g kg DM ⁻¹	[80]
	Mango (<i>Mangifera indica</i> L.), pulp, fresh	K	13.3	g kg DM ⁻¹	[80]
OUT1b	Harvest of annual crops				
	Beans (<i>Phaseolus vulgaris</i>)	N	4.24	% DW	[48]
	Beans (<i>Phaseolus vulgaris</i>)	P	0.58	% DW	[48]
	Beans (<i>Phaseolus vulgaris</i>)	K	1.71	% DW	[48]
	Maize grain (<i>Zea mays</i> L.)	N	3.0	g kg DM ⁻¹	
	Maize grain (<i>Zea mays</i> L.)	P	2.9	g kg DM ⁻¹	[80]
	Maize grain (<i>Zea mays</i> L.)	K	3.6	g kg DM ⁻¹	[80]
	Cassava tubers, fresh (<i>Manihot esculenta</i> C.)	P	1.2	g kg DM ⁻¹	[80]
	Cassava tubers, fresh (<i>Manihot esculenta</i> C.)	K	7.7	g kg DM ⁻¹	[80]
	Cassava tubers, fresh, peeled (<i>Manihot esculenta</i> C.)	P	0.4	g kg DM ⁻¹	[80]
	Cassava tubers, dehydrated (<i>Manihot esculenta</i> C.)	P	1.1	g kg DM ⁻¹	[80]
	Cassava tubers, dehydrated (<i>Manihot esculenta</i> 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 ₂ O	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 ₂ O, N ₂ , cereals	N	5.6	kg ha ⁻¹ yr ⁻¹	[68]
	Release of NH ₃ , NO, N ₂ O, N ₂ , pulses	N	3.3	kg ha ⁻¹ yr ⁻¹	[68]
	Release of NH ₃ , NO, N ₂ O, N ₂ , banana, coffee	N	15.2	kg ha ⁻¹ yr ⁻¹	[68]
	Release of NH ₃ , NO, N ₂ O, 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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