Agriculture, Ecosystems and Environment 207 (2015) 26–39

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

The potential of wastes to improve nutrient levels in agricultural soils: A material flow analysis case study from Busia District, Uganda

Jakob Lederer [a,*], Jeninah Karungi [b,1], Francis Ogwang [b,2]

[a] Institute for Water Quality, Resource and Waste Management, Vienna University of Technology, Karlsplatz 13/226.2, A-1040 Vienna, Austria
[b] School of Agricultural Sciences, College of Agricultural and Environmental Sciences, Makerere University, P.O. Box 7062, Kampala, Uganda

ARTICLE INFO

Article history:
Received 30 October 2014
Received in revised form 10 March 2015
Accepted 22 March 2015
Available online xxx

Keywords:
Material flow analysis
Soil nutrient balance
Uganda
Organic waste
Human excrement
Recycling

ABSTRACT

Like many other countries in Sub-Saharan Africa (SSA), Uganda faces a remarkable soil nutrient deficit in farmland soils. In order to cope with this deficit, many authors suggest increasing the recycling of hitherto unused nutrient sources from human excrement and urban municipal solid waste (MSW). However, a quantification of the potential of these nutrient sources to overcome soil nutrient deficits in Uganda has not been carried out so far. This research paper presents a case study calculating the soil nutrient balance for nitrogen (N), phosphorus (P), and potassium (K), as well as the potential of hitherto unused human excrement and urban MSW to decrease soil nutrient deficits in agricultural land by applying the method of material flow analysis (MFA) in Busia District (Uganda). Results show a high soil nutrient deficit of agricultural soils in the district, with values of $-33\,\mathrm{kg\,N\,ha^{-1}}$, $-6\,\mathrm{kg\,P\,ha^{-1}}$, and $-41\,\mathrm{kg\,K\,ha^{-1}}$. The potential to reduce these negative balances is negligible for hitherto unused urban MSW (1–3%), but higher for human excrement (17–60%). The low potential of urban MSW as well as the hygienic problems associated with human excrement (particularly feces) means that other measures such as soil conservation and mineral fertilizer application should not be ignored in the effort to increase agricultural productivity. This is not only valid for Busia District, but also for other regions in SSA.

1. Introduction

Contemporary societies in Sub-Saharan Africa (SSA) have the highest population growth rates in the world (World Bank, 2013). At the same time, agricultural soil nutrient deficits of nitrogen (N), phosphorus (P), and potassium (K) in many countries of the region impair their ability to feed their growing population (Sheldrick and Lingard, 2004). Among the countries in SSA, Uganda occupies a special position, having the third highest population growth (3.3% per year) together with high nutrient depletion in agricultural soils (Stoorvogel and Smaling, 1990; Sheldrick and Lingard, 2004; World Bank, 2013). This is also highlighted by local studies carried out in Uganda (Wortmann and Kaizzi, 1998; Bekunda and Manzi, 2003; Nkonya et al., 2005). However, Uganda is also one of the countries where a number of initiatives aim to reduce the soil nutrient deficit and thereby increase the crop yield by hitherto widely unused nutrient sources from organic municipal solid wastes (MSW) from urban areas or human excreta. For instance, the long-term ambitions on recycling human excrement by means of so-called ecological sanitation systems are internationally recognized (Tumwebaze et al., 2011; Dagerskog et al., 2013). Another activity that is seen to be a role model for other countries in SSA is the first country-wide small-scale composting program under the clean development mechanism (CDM) scheme, which not only aims to reduce greenhouse gas emissions through composting of organic MSW from 17 urban areas in Uganda, but also to increase the agricultural productivity through applying this compost on crop land (World Bank, 2008). Even though all these activities exist, in none of the soil nutrient balance studies from Uganda reviewed have researchers attempted to estimate the quantitative potential of recycling organic MSW from urban areas as well as human excrement. Thus, the general aim of this article is to determine the potential of these two nutrient sources in the case of Uganda.

To do so, not only must the soil nutrient balance be determined, but other nutrient containing materials flows, particularly solid wastes and human excrement, must be as well. However, the

---

[*] Corresponding author. Tel.: +43 1 58801 22653.
E-mail addresses: jakob.lederer@tuwien.ac.at (J. Lederer), jkarungi@caes.mak.ac.ug (J. Karungi), ogwafa@caes.mak.ac.ug (F. Ogwang).
[1] Tel.: +256 712 804 179.
[2] Tel.: +256 752 658 273.

http://dx.doi.org/10.1016/j.agee.2015.03.024
0167-8809/© 2015 Elsevier B.V. All rights reserved.

question arises for which area the nutrient balance, nutrient flows and stocks should be determined. One option is to consider an area that hosts (1) one of the 17 locations from the CDM composting program, and (2) human excreta recycling initiatives. Among the few areas that fulfill these criteria is Busia District in Eastern Uganda (Obernosterer, 2006; Lederer et al., 2012). Therefore, the detailed research questions in this article are:

1. What is the soil nutrient balance for the soils of agricultural land in the case study area of Busia District?
2. What is the quantitative potential of human excrement and hitherto unused MSW, particularly from urban areas as nutrient sources for agricultural soils in Busia District?

In order to answer these research questions, data from a research project carried out by the authors (Lederer et al., 2012) and from literature was used.

2. Methods and materials

After briefly describing the study area in Section 2.1, material flow analysis (MFA), which is a method that goes beyond soil nutrient balancing on a farm level and is thus suitable for answering the research question, is presented in Section 2.2. The data to carry out the MFA is shown in Sections 2.1 and 2.3. Some information is presented in the Supplementary materials, and the related tables and figures are indicated by an S (e.g., Table S1).

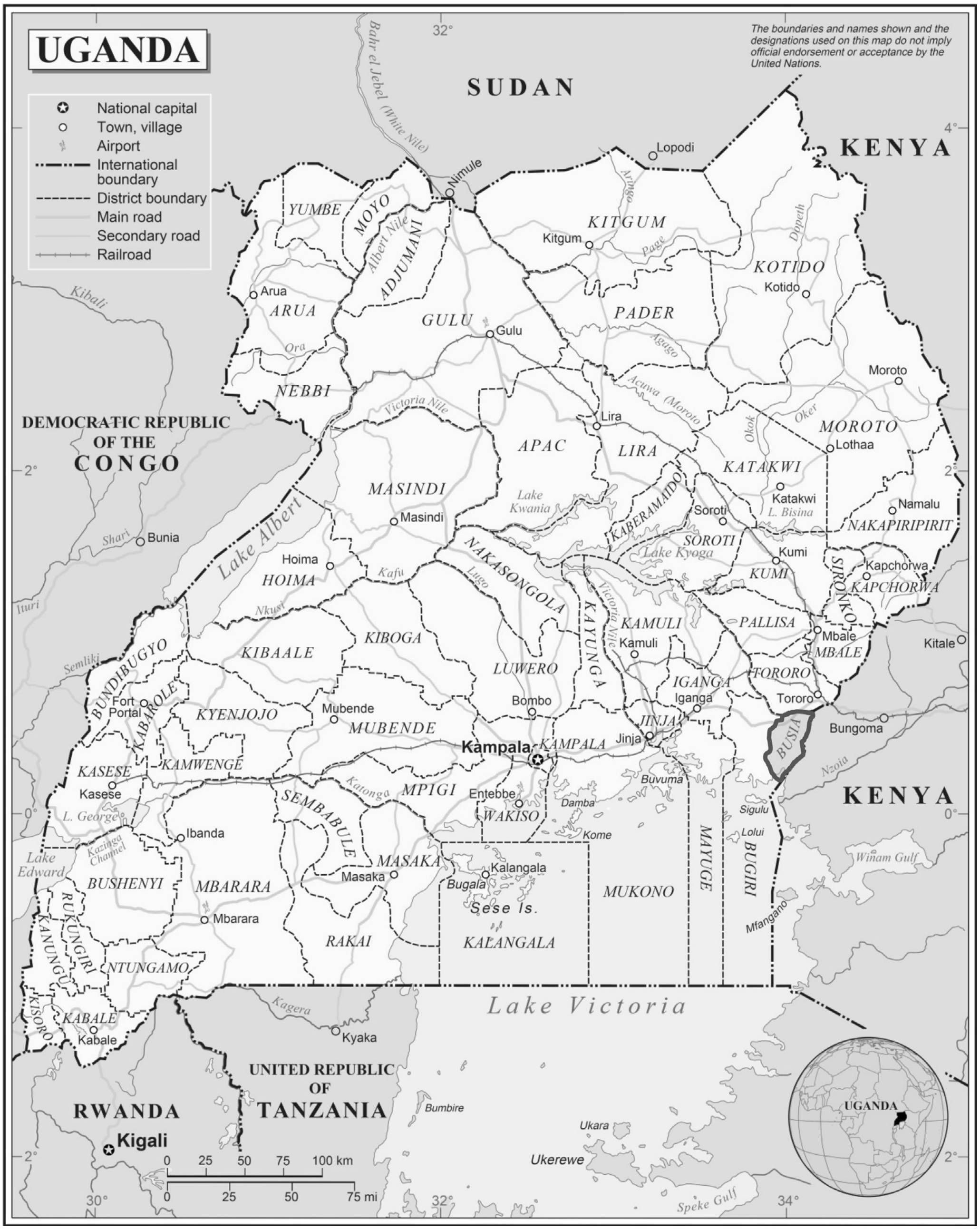

Fig. 1. Map of Uganda and situation of Busia District.

2.1. Background of the study area

Busia District in Eastern Uganda (see Fig. 1) (00°23′N 34°00′E) has a population of 281,200 inhabitants, of which 17% live in the only urban area, Busia Municipality, and 83% live in rural areas. The district land has slopes of generally less than 5% (Roussel, 2012), and the dominating soil types are medium fertile *lixic ferrasols* and *petric plinthosols* (Ssali, 2001; Obernosterer, 2006) (see Table S1 for soil properties). Rainfall is bimodal, with 1450 mm per year (Otim, 2008).

75% of households in the district are agricultural house holds, and the number of farms in the district is 39,000 (UBoS, 2011). The main crops grown are maize, cassava, beans, sorghum and sweet potatoes, often in mixed cropped systems, and the average number of animals per farm is 0.7 cattle, 2.0 goats/sheep, 0.4 pigs, and 11 poultry (UBoS, 2010c,b,b). Poultry usually scavenges for food, while cows, goats and sheep are fed using on- and off-farm grazing as well as by crop residues (NEMA, 2004). Application of manure and crop residues to crop land is widely practiced, while feeding of crop residues to animals, and their removal and burning is less frequently reported (UBoS, 2010a; Lederer et al., 2012).

2.2. Material flow analysis (MFA)

2.2.1. Theoretical background

MFA is a method that has been widely applied for questions of nutrient management beyond the farm level (Brunner and Rechberger, 2004). Having a clearly defined methodology and terminology (highlighted in italics), MFA aims to calculate and illustrate the mass flows of *materials* such as tradable *goods G* (e.g., fertilizer) and chemical *substances S* (e.g., N, P, K), through a defined and usually open system. *Material* in MFA is the umbrella term used for *goods* and *substances*. MFA systems under investigation can be private production units (e.g., farms), natural-geographic units (e.g., water sheds), or administrative-political units (e.g., districts, countries), and the unit under investigation constitutes the *spatial boundary* of the system. The *temporal boundary* of the system is the time period in which the unit is investigated, usually one year. Within the system, the *material flows* ($\dot{m}$) given in mass per time unit (e.g., kg yr^{-1}) run through *processes* of transport, transformation, and stock change. Flows into the system and from the system are termed as *import* and *export flows*, and flows into a process and from a process are termed *input* and *output flows*. For both, *processes* and *systems*, the law of conservation of mass is

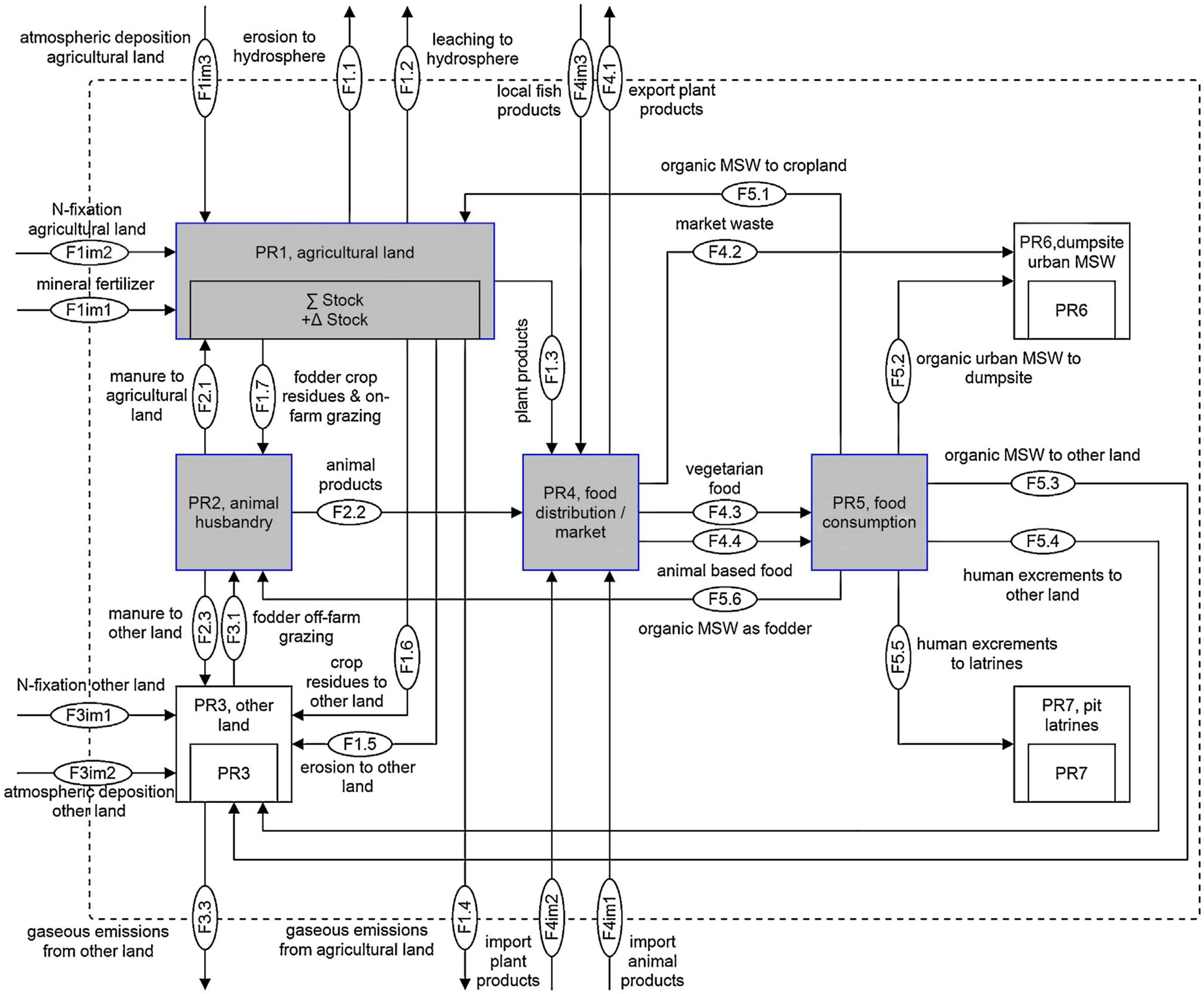

Fig. 2. MFA model for nutrient flows in Busia District in 2010.

applied. Two formulae are usually used in MFA, exemplified for a single process having a number of *input flows*, *output flows*, as well as a *stock change* (Δ stock). The first is the mass balance formula, which is defined as

$$\Sigma_{i=1}^{k} \dot{m}_{input,i} = \Sigma_{j=1}^{l} \dot{m}_{output,j} \pm \dot{m}_{storage} \tag{1}$$

where $\Sigma_{i=1}^{k} \dot{m}_{input,i}$ is the total mass of k *input material flows* $\dot{m}_{input}$, $\Sigma_{j=1}^{l} \dot{m}_{output,j}$ is the total mass of l *output material flows* $\dot{m}_{output}$, and $\dot{m}_{storage}$ is the mass of the *material flow* per time unit from or to a *stock* located in a *process* per time unit. Examples for stocks are materials stored in landfills or soils, and stock changes in a process are positive if the input is higher than the output (e.g., landfills) or negative if outputs are higher than the inputs (e.g., erosion from soils). The second formula used is the transfer formula, defined as

$$\mathrm{TC}_j = \frac{m_{output,j}}{\Sigma_{i=1}^{k} \mathrm{m}_{input,i}} \tag{2}$$

where TC_j is the mass *transfer coefficient* for an output flow j, $\dot{m}_{output,j}$ is the mass of the output flow j, and $\Sigma_{i=1}^{k} \dot{m}_{input,i}$ is the total mass of k input flows $\dot{m}_{input}$. The same formulae are applied for entire systems, except that the terminology changes (*import* and *export* instead of *input* and *output* flow).

In the usual procedure of MFA for a *substance* under investigation, (1) the *material flows* of *goods* containing the *substance*, (2) the concentration of the *substance* in each of these *material flows* of *goods*, and (3) by multiplying both, the *material flows* of the *substance* are determined. In some cases, it is sufficient to merely calculate the *material flow* of the *substance* (e.g., N volatilized).

Beside primary data, data usually used for MFA are statistics from private and public organizations (e.g., production statistics), secondary data from literature (e.g., substance concentration in products), as well as estimations by experts. All of these data are usually subject to uncertainty. In MFA, various approaches have been used to consider data uncertainty (Laner et al., 2014). In this article, the traditional approach of Gauss error propagation for independent variables is applied (Cencic et al., 2012). Given an arithmetic mean value (MW) $\bar{x}$ and a standard deviation (SD) σ calculated from the data set available, the relative standard uncertainty (RSU) $u_{r,i}$ for a value i is defined as the SD in percent of the mean value (see Eq. (3))

$$u_{r,i} = \frac{\sigma_i}{x_i} \times 100\% \tag{3}$$

Under the assumption that the variables are independent from each other, the total RSU u_r for a mass flow is calculated as follows:

$$u_r = u_{r_{i=1}^{k}} = \sqrt{{u_{r,1}}^2 + {u_{r,2}}^2 + \cdots + {u_{r,k}}^2} \tag{4}$$

The result is then expressed as

$$\bar{x} \pm u_r \tag{5}$$

where $\bar{x}$ is the mean value of the flow, and $\pm u_r$ is the RSU in percent of the mean value. To give an example for the calculation procedure: if the amount of N in annual crop production of an area is desired, the mean value of the yield is multiplied by the concentration of N in the crop. The residual u_r is calculated by the $u_{r,i}$ of yield ($u_{r,1}$), and concentration ($u_{r,2}$) according to Eq. (4).

2.2.2. Examples of MFA in nutrient management

Numerous MFA studies on nutrient management of N and P in political-administrative areas (cities, districts, countries) have been carried out, particularly in Europe, the US, and Asia. However, only a few studies have been undertaken in SSA. Moreover, no MFA for K has been published for an international readership (Chen and Graedel, 2012). Belevi (2002) and Meinzinger and Otterpohl (2009) presented studies for N and P for urban areas in Ghana (Kumasi) and Ethiopia (Arba Minch). Other examples investigated the N and P flows on a national level, for instance in Finland and Austria (Antikainen et al., 2005; Egle et al., 2014), or even on a worldwide scale (Liu et al., 2008).

2.2.3. MFA as used in this work

The spatial boundary of the system investigated in this article was defined by the political-administrative boundary of Busia District, and the temporal boundary is the year 2010. Water bodies were excluded in the calculation. The MFA model for the calculation is shown in Fig. 2.

This model contains all processes (PR), nutrient-containing material flows (F), as well as stock changes in processes (Δ stock) to perform the calculation. For some more complex processes, installing so-called subsystems containing subprocesses was necessary in order to perform the calculation, highlighted in light grey in Fig. 2 (PR1, PR2, PR4, and PR5). The calculation of mean values and uncertainties (SD) of material flows and transfer coefficients was first carried out on excel sheets based on the literature and our own data (Lederer et al., 2012), and the intermediate results were inserted into the MFA model created with the software STAN (Cencic and Rechberger, 2008; Cencic et al., 2012). The uncertainties were first calculated in numerical values for the flow of goods and concentrations, and then converted into percent of the mean value as shown in Eq. 3 in order to calculate the total RSU of the flow of substances (see Eq. 4). Afterwards, they were again converted into numerical values, which was required to insert them into the STAN model. In the text, uncertainties are generally given as numerical values, while in the MFA figures, they are shown in percent of the mean value. STAN (1) calculated the material flows, stock sizes and stock changes not known, and (2) recalculated the figures inserted (data reconciliation), which was necessary due to the uncertainties. The algorithm for the data reconciliation is described in detail in Appendix A in Fellner et al. (2011).

2.3. Data for MFA calculation

2.3.1. Land use data

Busia has a crop land area of major crops of 24,608 ha (UBoS, 2010b). As this data only considered selected major crops, a survey among 50 farmers was carried out, leading to a total crop land area of 37,700 ha (see Table S2). Data on the size of total agricultural land, pasture, forest, bush, and grass land, as well as built-up area, was taken from UBoS (2010c; UBoS, 2010c. By subtracting pasture and crop land from the total agricultural land, the size of the fallow land was calculated, shown in Table 1. In the subsequent sections, the term *agricultural land* subsumes cropland, pasture, and fallow, and the term *other land* subsumes bush and grassland, forests, and built-up areas.

2.3.2. Process PR1: agricultural land

Fig. 3 shows the model for the process *agricultural land* (PR1), which has a subsystem that contains the subprocesses of *cropland*,

Table 1
Land use in Busia District after UBoS (2010b,c; 2011).

Land use		Area in (ha)		Area in (ha farm^{-1})	
Agricultural land	Cropland	53,300	37,666	1.40	1.00
	Pasture		6,500		0.17
	Fallow		9,134		0.23
Bush and grassland			6,210		
Forest			7,370		
Built-up areas			3,300		
Wetlands and water bodies			5,760		
Total			75,940		

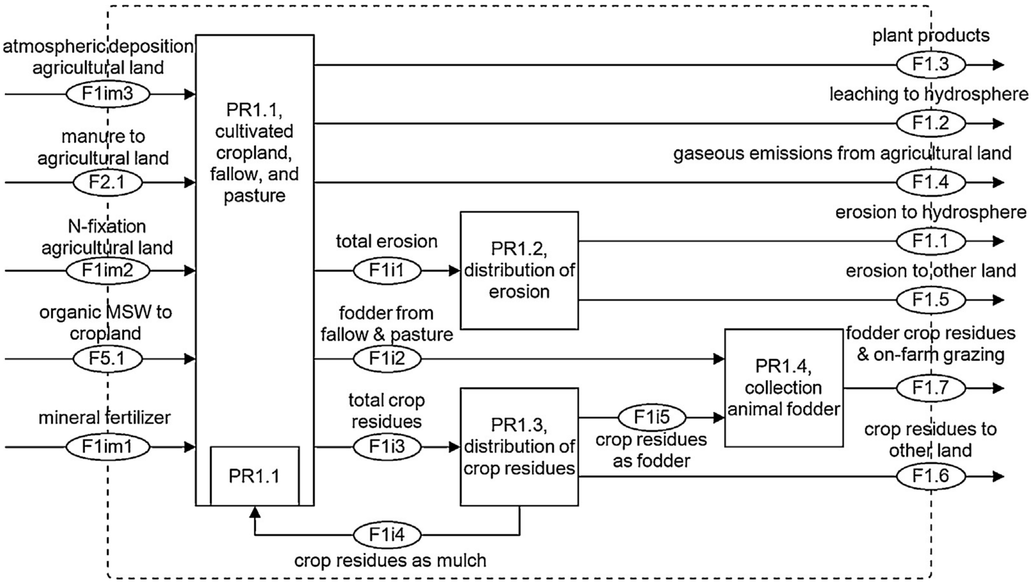

Fig. 3. MFA model for the subsystem in the process PR1 agricultural land.

fallow and pasture (PR1.1), *distribution of eroded soils* (PR1.2) and *distribution of crop residues* (PR1.3), as well as *collection of animal fodder* (PR1.4) from crop residues, but also from pasture and fallow.

Major input flows into the process are *mineral fertilizer* (F1im1), *N-fixation* (F1im2), *atmospheric deposition* (F1im3), *organic MSW to cropland* (F5.1), and *manure* (F2.1). Major output flows are *erosion and leaching to hydrosphere* (F1.1 and F1.2), *plant products harvested* (F1.3), *gaseous emissions* of N (F1.4), *erosion* sediment *to other land* (F1.5), *crop residues* disposed of *to other land* (F1.6), and animal *fodder* from *crop residues & on-farm grazing* (F1.7). In the subsystem, there is a stock of nutrients in the subprocess, *cultivated cropland*, as well some internal flows (*total erosion* F1i1; *fodder from fallow & pasture* F1i2; *total crop residues* F1i3; *crop residues as mulch* F1i4; *crop residues as fodder* F1i5). The calculation of the process *agricultural land* is comparable to soil nutrient balancing as described, for instance, by Van den Bosch et al. (1998) (see Table S3).

Mineral fertilizer (F1im1) was calculated based on average consumption for Uganda according to FAO (2013) and a survey carried out among fertilizer dealers in Busia. The resulting values were inserted in the STAN model (see Table S4).

Biological N-fixation (F1im2) per hectare of crop (beans, peas, soybeans, groundnuts, rice, and pasture and fallow) was calculated based on data from Stoorvogel and Smaling (1990), Wortmann and Kaizzi (1998), Brady and Weil (1999) and Lesschen et al. (2007) and multiplied by the area per crop (see Table S5).

Atmospheric deposition (F1im3) was calculated based on per hectare deposition values according to Stoorvogel and Smaling (1990), Wortmann and Kaizzi (1998), Scheren et al. (2000), Nkonya et al. (2005) and Tamatamah et al. (2005) multiplied by the total agricultural land in Busia (see Table S6).

The calculation of inputs *organic MSW to cropland* (F5.1) and *animal manure* (F2.1) is shown in the appropriate Sections (Animal husbandry, 2.3.3; Food consumption, 2.3.6).

Usually, the most relevant output flow are *plant products* (F1.3). UBoS (2010b) presents data on crop production area and yields for selected crops in Busia District. For other crops not considered by UBoS, primary data was collected in a survey (Lederer et al., 2012) (see Table S2). The result (total yield per crop in Busia District) was multiplied by the average concentration for each plant product, based on USDA (2011), Stadlmayer et al. (2012), Stoorvogel and Smaling (1990), Smaling et al. (1993), Lentner et al. (1981), and Wortmann and Kaizzi (1998) (see Table S7).

The *total erosion* from agricultural land (F1i1) was calculated by using the Universal Soil Loss Equation (USLE), which is, according to Wischmeier (1978), defined as

$$A = K_E \times R \times S \times L \times C \times P_E \tag{6}$$

The soil erodability factor K_E was calculated based on values from Wortmann and Kaizzi (1998), Henao and Baanante (1999), Smaling et al. (1993), and Jiang (2013), the rainfall factor R based on Wortmann and Kaizzi (1998), UNEP (1987), and a rainfall of 1450 mm yr^{-1} (Otim, 2008). The slope gradient S was calculated based on GIS data, resulting in 15% of area with a slope gradient of 0%, 70% of area with a slope gradient of 5%, and 15% of area with a slope gradient of 10% (Jarvis et al., 2008). The slope length L was estimated to be 100 ± 50 m as plots are usually smaller than 1 ha and fenced with natural barriers. In calculating the cropped factor C, three land use types within the agricultural land were distinguished: mixed cropping (9040 ha), sole cropping (28,626 ha), and pasture and fallow (15,634 ha). The distribution of mixed and sole cropping was estimated based on a questionnaire survey with 50 farmers Lederer et al. (2012) and UBoS (2003). The C factor for these land use types was calculated according to Smaling et al. (1993), Wortmann and Kaizzi (1998), and Henao and Baanante (1999). P_E (erosion management factor) was determined at 1.0 ± 0 for no erosion management (30% of crop land), 0.15 ± 0.07 for mulching (70% of crop land), and 0.25 ± 0.21 for fallow and pasture (Wortmann and Kaizzi, 1998; Henao and Baanante, 1999; Lederer et al., 2012). The USLE calculation yields the total soil loss, which was multiplied by the nutrient content in the upper 20 cm of soils (Lederer et al., 2012; Wortmann and Kaizzi, 1998), and an enrichment factor (based on Lesschen et al., 2007; Stoorvogel and Smaling, 1990; Wortmann and Kaizzi, 1998) (see Tables S8 and S9). The soil loss through erosion was assumed to divert to wetlands, rivers, and lakes (80%; F1.1), and other land (20%; F1.5), an assumption derived from Ruecker et al. (2008).

Leaching losses of N and K from agricultural land to the hydrosphere (F1.2) were calculated by applying the empirical formulae of Stoorvogel and Smaling (1990):

$$
\begin{aligned}
N &: \mathrm{F1.2} \\
&= 2.3 + (0.0021 + 0.007 \times F) \times R + 0.3 \times (\mathrm{Flim1} + \mathrm{F2.1}) \\
&\quad - 0.1 \times (\mathrm{F1.3} + \mathrm{Fli2} + \mathrm{Fli3})
\end{aligned}
\tag{7}
$$

$$
\begin{aligned}
K &: \mathrm{F1.2} \\
&= 0.5 + (0.0011 + 0.002 \times F) \times R + 0.5 \times (\mathrm{Flim1} + \mathrm{F2.1}) \\
&\quad - 0.1 \times (\mathrm{F1.3} + \mathrm{Fli2} + \mathrm{Fli3})
\end{aligned}
\tag{8}
$$

where F is the soil fertility class (moderate, 2.0 ± 0.5), R is the annual average rainfall (1450 mm), F1im1 is the application of *mineral fertilizer*, F2.1 is *manure to agricultural land*, and F1.3, F1i3, F1i2 is the total uptake of N and K by *plant products* ($24 \pm 18\,\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$ and $14 \pm 7\,\mathrm{kg\,K\,ha^{-1}\,yr^{-1}}$), *total crop residues* ($13 \pm 3\,\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$ and $19 \pm 11\,\mathrm{kg\,K\,ha^{-1}\,yr^{-1}}$), and *fallow and pasture plants* ($40 \pm 18\,\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$ and $46 \pm 27\,\mathrm{kg\,K\,ha^{-1}\,yr^{-1}}$) (determined according to Stoorvogel and Smaling (1990), Wortmann and Kaizzi (1998), Mubiru and Coyne (2009) and Johansson (2013) (see Tables S10 and S11).

Similarly, *gaseous emissions* of N *from agricultural land* (F1.4) were calculated according to Stoorvogel and Smaling (1990) (Eq. (9)):

$$
\begin{aligned}
\mathrm{F1.4} &= \mathrm{Base} + 2.5 \times F + 0.3 \times (\mathrm{Flim1} + \mathrm{F2.1}) - 0.1 \\
&\quad \times (\mathrm{F1.3} + \mathrm{Fli2} + \mathrm{Fli3})
\end{aligned}
\tag{9}
$$

Base is the base denitrification ($5.0 \pm 2.0\,\mathrm{kg\,ha^{-1}\,yr^{-1}}$). For all other factor descriptions, see Eq. (7) (see Table S12 for calculation details).

2.3.3. Process PR2: animal husbandry

The process *animal husbandry* contains a subsystem with two subprocesses (*animal feeding* PR2.1, *manure diversion* PR 2.2) and has three input and output flows (see Fig. 4).

First, the total amount of nutrients excreted by the major animal types in Busia district (cattle, goats/sheep, pigs, and poultry – flow *excretion*, F2i1) was determined by multiplying nutrient generation according to Powell et al. (1994), Wortmann and Kaizzi (1998), Sheldrick et al., (2003) Lesschen et al. (2007), Ogejo et al. (2010) and Snijders et al. (2013) by the total animal number in Busia (26,787 cattle, 76,473 goats and sheep, 14,203 pigs, and 408,490 poultry; UBoS, 2010c) (see Table S14). Subsequently, several assumptions on the manure diversion were made: (1) animals are kept in an open stall (*boma*) in the night (12 h), and taken out for grazing in the day (12 h). The manure excretion is distributed proportionally to the time the animals spend at a particular location. (2) Initial calculations showed that on-farm nutrient sources cannot sustain the number of farm animals in Busia, thus pasturing was assumed to occur at *other land* (grass land) as well (off-farm grazing). According to the land distribution in the district, 72% of pasturing is on farm *pasture and fallow land*, and 28% on *other land*. (3) Manure excreted during pasturing remains on the farm *pasture and fallow land* (36% of manure), as well as on *other land* (PR3; 14% of manure). (4) 100% of urine excreted at *bomas* was assumed to be lost to *other land* (PR3) (Snijders et al., 2009). The share of nutrients in urine was calculated according to Snijders et al. (2013) for cattle and Ogejo et al. (2010) for goats/sheep. (5) 90% Of farmers collect animal manure (feces) of cattle, goats, sheep, and poultry from the *boma* for fertilizing crop land. The residual share was assumed to be lost to *other land* (PR3). (6) Of the manure (feces) collected, liquid storage losses to *other land* (PR3) from storage at *bomas* of 30% for N and 15% for P and K was used (Snijders et al., 2009). (7) Gaseous losses of N were assumed to occur from *other land* (PR3) and *agricultural land* (PR1) (see Sections 2.3.2 and 2.3.4).

Table 2
Transfer coefficients (TC) for the process manure diversion (PR 2.2).

		N	P	K
1	TC cultivated crop land	0.17	0.18	0.07
2	TC fallow and pasture	0.36	0.36	0.36
3	TC agricultural land (=row 1 + row 2)	0.53	0.54	0.43
4	TC other land	0.47	0.46	0.57
5	Total (=row 3 + row 4)	1.00	1.00	1.00

The residual transfer coefficients of animal manure excreted (F2i1) are shown in Table 2.

By inserting total excretion figures and the transfer coefficients into the STAN model, nutrients in *manure to agricultural land* (F1.2) and *other land* (F2.3) are calculated.

The calculation of other flows to and from *animal husbandry* were *fodder crop residues and on-farm grazing* (F1.7), *animal products* (F2.2), and *organic MSW as fodder* (F5.6), shown in Sections 2.3.2, 2.3.5, and 2.3.6. The residual flow of *fodder from off-farm grazing* (F3.1) at *other land* (PR 3) was calculated by balancing input and output flows in STAN (F3.1 = F1.7 + F5.6 – F2.2 – F2i1).

2.3.4. Process PR3: other land

The process *other land* subsumes different land use types, as shown in Table 1. Input and output flows connected to this process and already considered in other sections are *manure to other land* (F2.3), *crop residues* (F1.6), *erosion to other land* (F1.5), *human excrements to other land* (F5.4), *dumping of organic MSW to other land* (F5.3), and *fodder from off-farm grazing* (F3.1).

N-fixation (F3im1) is calculated according to Wortmann and Kaizzi (1998), Giller et al. (1997), and Lesschen et al. (2007)

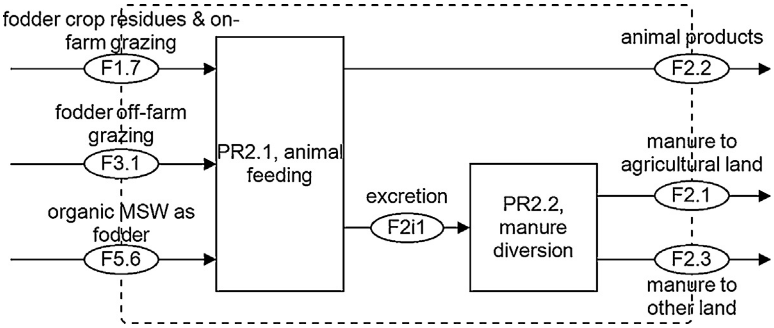

Fig. 4. MFA model for the subsystem in process PR2 animal husbandry.

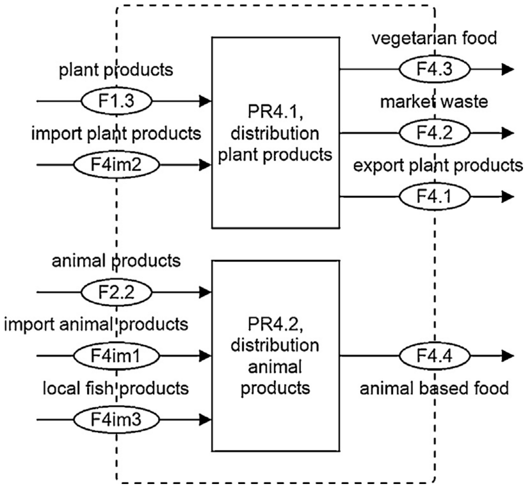

Fig. 5. MFA model for the subsystem in process PR4 food distribution/market.

(Table S5). N-fixation in forests was not considered. *Atmospheric deposition* was calculated as for agricultural land (Section 2.3.2 and Table S6). *Gaseous emissions* of N from excretion of farm animals during off-farm grazing were calculated by applying Eq. (10) according to Stoorvogel and Smaling (1990):

$$F1.4 = \text{Base} + 2.5 \times F + 0.3 \times F2.3 - 0.1 \times U_N \qquad (10)$$

The N-uptake by plants (U_N) was assumed to be 40 ± 18 kg N ha^{-1} yr^{-1}. All other factors are described in Eq. (9), and calculation details are shown in Table S13.

2.3.5. Process PR4: food distribution/market

The process *food distribution/market* (PR4) contains a subsystem for calculation. Food distribution means food distributed by agricultural households for domestic consumption and sales. Market means purchasing and selling food to and from both sources from within and outside the district (see Fig. 5).

The first input into this subsystem (*plant products* F1.3) has already been calculated (Section 2.3.2).

Vegetarian food (F4.3) supplied to consumers in Uganda is 471 kg capita^{-1} yr^{-1} (FAO, 2013). To adjust this value to local food consumption patterns, survey data from the World Food Program (WFP) on food intake in different regions in Uganda was used (McKinney, 2009). By determining the deviation of food consumption in the survey region that contains Busia District (East-Central) from the national mean value, food consumption adjustment factors for all foods have been determined (Table S15). These factors were multiplied by the food supply data provided by the FAO (2013), leading to a total food supply of 510 kg capita^{-1} yr^{-1}. The uncertainty range is the difference between average national and adjusted regional data (Table S16). The *export of plant products* (F4.1) from Busia was calculated by the subtraction of *vegetarian food* supply (F4.3) from *plant products* produced (F1.3) for each crop *i* ($F4.1_i = F1.3_i - F4.3_i$). A negative result means that no export but an *import of plant products* (F4im2) exists. For these crops, the calculation was the other way round than for the export calculation ($F4im2_i = F4.3_i - F1.3_i$, Table S17). Finally, the values calculated were multiplied by the concentration of nutrients in food products (Table S7).

For animal products and animal based food, a similar procedure was applied. Nutrients in *animal based food* (F4.4) supplied to consumers in Busia District is calculated based on FAO (2013) and McKinney (2009) (Table S20) and multiplied by average nutrient concentrations (Table S7). This food was either produced locally in Busia or imported from other parts of Uganda. The ratio between *import of animal products* from other parts of Uganda (F4im1) and locally produced *animal products* (F2.2) was calculated by comparing the per capita animal stock in Busia to the average value of Uganda (0.10 vs. 0.35 cattle capita^{-1}, 0.27 vs. 0.48 goats/sheep capita^{-1}, 0.05 vs. 0.10 pigs capita^{-1}, 1.45 vs. 1.19 poultry capita^{-1}; see Table S19; after UBoS, 2010c). Based on this, the import ratio of *animal based food* consumed in Busia was determined to be 73% for cattle and milk products, 57% for goats/sheep, and 52% for pork. Though the poultry production is 20% above the average value in Uganda, no export of poultry products was considered as nutrient flows have been found to be negligible. All *local fish products* (F4im3) consumed are produced in the district. By multiplying the *animal based food* (F4.4) by the import ratio for each animal type, the *import* through *animal products* (F4im1) was calculated (Table S19). Balancing both flows in STAN yields the *animal products* (F2.2) produced in local animal husbandry (F2.2 = F4.4 – F4im1 – F4im3) (Table S20).

During the distribution of food products at markets, 1334 ± 334 t yr^{-1} of *market waste* is generated (F4.2) (Lederer et al., 2012), multiplied by the concentrations of nutrients in fresh waste (5.09 ± 1.25 g N kg^{-1}; 1.03 ± 0.48 g P kg^{-1}; 9.48 ± 1.36 g K kg^{-1}) according to Amoding (2007), Tumuhairwe (2011), and Komakech et al. (2014). The market waste is collected and dumped at the local *dumpsite* (PR6).

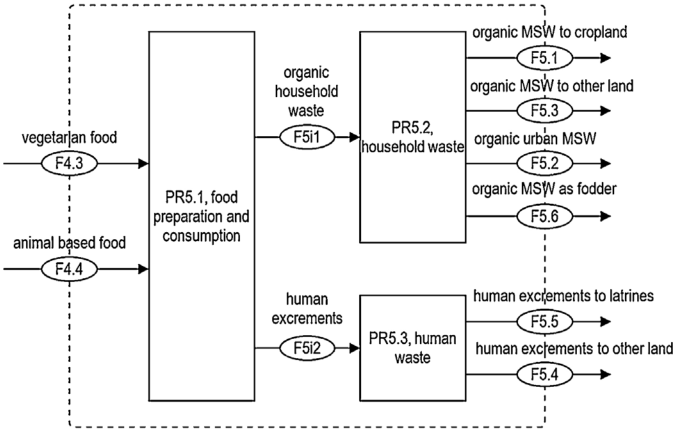

Fig. 6. MFA model for the subsystem in process PR5 food consumption.

Table 3
Comparison of major nutrient flows for determination of the soil nutrient balance with selected studies from Uganda in kg ha^{-1} yr^{-1}. The values from Wortmann and Kaizzi refer to three locations in Iganga, Kamuli, and Mpigi District, values from Nkonya to four locations in Sironko, Soroti, Kumi, and Kapchorwa District, and values from Sheldrick and Lingard to the whole country of Uganda. "–" means that the value was given as zero, while no figure in the cell means that no specific value has was given at all.

		This study			Wortmann and Kaizzi (1998)			Sheldrick and Lingard (2004)			Nkonya et al. (2005)		
		N	P	K	N	P	K	N	P	K	N	P	K
Inputs													
F1i4	Crop residues as mulch	6.4	1.4	9.5				3.6	0.6	4.6			
F1im1	Mineral fertilizer	0.4	0.1	0.1	–	–	–	0.1	–	–	7.8	3.9	0.9
F1im2	N-fixation	9.3	–	–	9.6	–	–	2.6	–	–	16.9	–	–
F1im3	Atmospheric deposition	11.2	1.5	3.7	11.0	–	–	5	–	–	16.1	0.8	3.2
F2.1	Manure to agricultural land	8.7	1.1	7.3	7.6	2.5	8.6	4.9	1.5	3.5			
F5.1	Organic MSW to cropland	2.7	0.6	5.1	0.5	–	0.5	1.5	0.7	0.1			
	Organic inputs (imported)										1.5	–	–
	Sedimentation										18.2	0.4	1.3
Input total		39	5	26	29	3	9	18	3	8	61	5	5
Outputs													
F1.1	Erosion to hydrosphere	14.3	4.2	19.6	5.4	1.4	5.4				10.0	9.9	3.2
F1.5	Erosion to other land	3.6	1	4.9									
F1.2	Leaching to hydrosphere	5.9	–	7.6	16.0	–	–				21.3	–	0.9
F1.4	Gaseous emissions	9.4	–	–	7.5	–	–				9.0	–	–
F1.3	Plant products	17	2.3	10.0	18.1	1.5	29	28.6	4.4	26.5	54	6.8	60.3
F1.6	Crop residues to other land	1.8	0.4	2.7	4.6	0.7	9.9				1.2	0.1	1.0
F1.7	Crop residues and on-farm grazing	13.3	1.7	12.0									
F1i4	Crop residues as mulch	6.4	1.4	9.5									
Output total		72	11	66	52	4	44	29	4	27	96	21	65
	Balance calculated based on data given	−33	−6	−41	−23	−1	−35	−11	−2	−18	−35	−16	−60
	Balance as stated in reviewed studies				−31	−4	−39	−19	−3	−20	−48	−11	−100

2.3.6. Process PR 5: food consumption

The inputs into this process have already been determined in the previous section (F4.3 and F4.4; Section 2.3.5), and the outputs are organic solid waste from food preparation and human excreta (see Fig. 6).

The amount of *organic household waste* generated (F5i1) is 0.4 ± 0.1 kg capita^{-1} day^{-1} wet weight (Lederer et al., 2012; Ojok et al., 2013), resulting in 41,055 ± 10,264 t yr^{-1}. 83% of this is generated in rural and 17% in urban areas. Rural households divert 80% of *organic MSW to cropland* (F5.1) and 20% *of organic MSW as fodder* for animals (F5.6), while urban households divert 15% of *organic MSW to cropland* (F5.1), 35% *of organic MSW other land* (F5.3, PR3), and 50% to waste collection, from where organic urban MSW is dumped at the local dumpsite (F5.2, PR6) (Lederer et al., 2012). The nutrient concentration is the same as for market wastes.

The total amount of nutrients in *human excrement* (F5i2) was calculated by subtracting the outputs (F5i1) from the inputs into the process (F4.3 and F4.4). Due to latrine coverage in Busia District (UBoS, 2011), this total amounts diverts to 73% to pit latrines (F5.5), and to 27% to *other land* by open defecation and urination (F5.4).

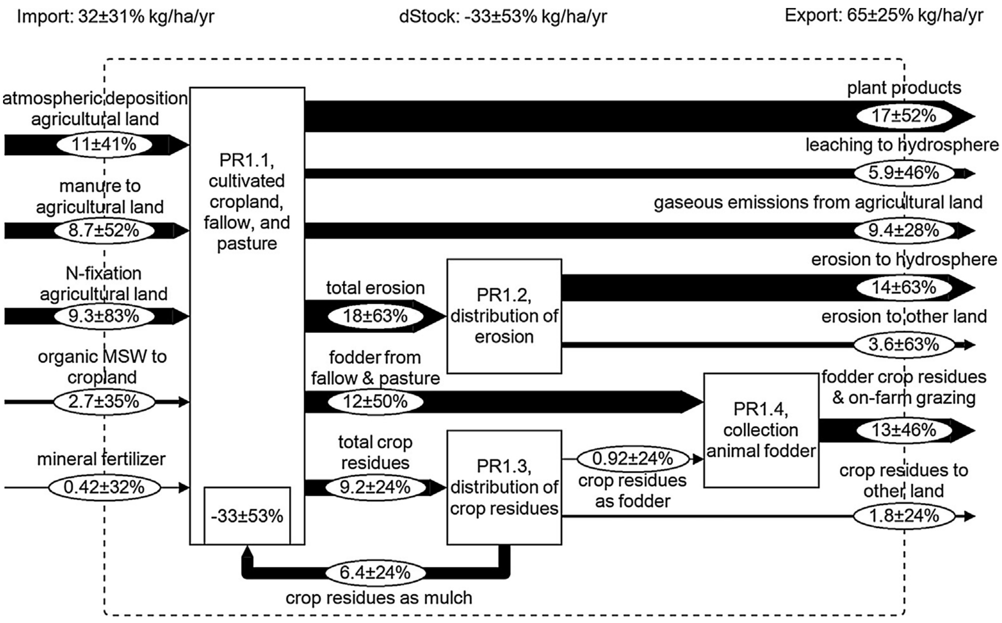

Fig. 7. MFA for N in Busia District's agricultural land in the year 2010 in kg ha^{-1} yr^{-1}.

2.3.7. Processes PR6 and PR7: dumpsite urban MSW (PR6) and pit latrines (PR7)

Both processes receive nutrient containing material flows as inputs, in both processes a stock is built-up, and both have outputs, mainly leaching of nutrients to the hydrosphere and gaseous N emissions. As these outputs are not required to answer the research questions postulated, they are not quantified.

2.3.8. Functional unit and expression of results

To compare the results to existing soil nutrient balance studies, the calculated flow and Δ stock values for the process *agricultural land* are divided by the agricultural land (53,310 ha), and shown in kg ha^{-1} yr^{-1}. For the overall system, the results for flows and Δ stocks are shown in t yr^{-1}. An overview of all input values into the STAN model is shown in Table S21.

3. Results

3.1. Agricultural soil nutrient balance in Busia District in 2010

The soil nutrient balance in Busia District's agricultural soils has been determined to be negative for all three nutrients investigated (see Table 3, Section 4.1.1). Fig. 7 shows the flows for N.

The soil nutrient deficit is −33 kg ha^{-1} yr^{-1}. The largest inputs into the process are *atmospheric deposition* (Fim3) and *manure to agricultural land* (F2.1), followed by *N-fixation* (F1im2) and *crop residues* applied (F1i4). *Organic MSW to cropland* (F5.1) and *mineral fertilizer* (F1im1) do not contribute much to the result. The largest output flows are *total erosion* (F1i1), *plant products* (F1.3) and *fodder* from *crop residues and on-farm grazing* (F1.7). Other relevant outputs are environmental flows of *leaching* (F1.4) and *gaseous emissions* (F1.2). *Crop residues to other land* (F1.6) are of lower relevance.

Flows of P are smaller than N, and so is the soil nutrient deficit (see Fig. 8). The most relevant input flows are *manure to agricultural land* and *atmospheric deposition* (F2.1 and F1im3), while other inputs (*organic MSW to cropland*, F5.1, and *mineral fertilizer*, F1im1) are smaller. *Total erosion* (F1i1) is by far the most important output, followed by *fodder* from *crop residues and on-farm grazing* (F1.7), while removal of *crop residues to other land* is not that relevant (F1.6).

The deficit is higher for K than for N (see Fig. 9). Small inputs are challenged by much bigger outputs, particularly through *total erosion* (F1i1) and harvesting of *plant products* (F1.3), as well as *fodder* from *crop residues and on-farm grazing* (F1.7). Removal of *crop residues to other land* (F1.6) is not that relevant.

3.2. Nutrient flows in Busia District in 2010

Busia annually imports 2,000 t N, 190 t P, and 640 t K, and exports 2,200 t N, 280 t P, and 1,600 t K, meaning that the total stock of these substances in the soils of the district decreases every year. The results are exemplified for N in Fig. 10.

The largest imports of N into the system are *atmospheric deposition* and *N-fixation*, while the *import* of *plant products* is somewhat smaller. The by far largest export occurs through *erosion from agricultural land* to the hydrosphere, followed by *gaseous emissions*, *export* of *plant products*, and *leaching to hydrosphere*. The large stock decrease in *agricultural land* is in contrast a significant stock build-up in *pit latrines* and *other land*. The stock build-up in the *dumpsite* is negligible.

For P, as well as for K, the system is dominated by *erosion to hydrosphere*, which counts for 220 t P yr^{-1} (80% of P-export) and 1,000 t K yr^{-1} (60% of K-export). *Leaching to hydrosphere* is the second largest export flow of K (400 t yr^{-1}), but not relevant for P. *Export* of *plant products* is of a much smaller size (56 t yr^{-1} for P; 180 t yr^{-1} for K). For inputs, the P-system primarily depends on atmospheric deposition (82 t yr^{-1} on *agricultural land* and 21 t yr^{-1} on *other land*), followed by the *import* of *plant products* (61 t yr^{-1}). It is the other way round for K. The largest stock-build up for K and P occurs in other land (+870 t yr^{-1} for K; +150 t yr^{-1} for P) followed by pit latrines (+260 t yr^{-1} for K; +88 t yr^{-1} for P). As is the case for N, the stock build-up in the dumpsite is negligible (+44 t yr^{-1} for K; +5 t yr^{-1} for P) (see Figs. S1 and S2 for the MFA system, and Table S22 for a summary of all flows).

3.3. Nutrient flows of MSW and human excreta

Market waste (F4.2) contains 7 t yr^{-1} of N, 1.4 t yr^{-1} of P, and 13 t yr^{-1} of K, while *organic MSW total* (F5i1) contains 214 t yr^{-1} of N, 43 t yr^{-1} of P, and 389 t yr^{-1} of K. Altogether, solid wastes contain 221 t yr^{-1} of N, 45 t yr^{-1} of P, and 402 t yr^{-1} of K. 17% of these are not

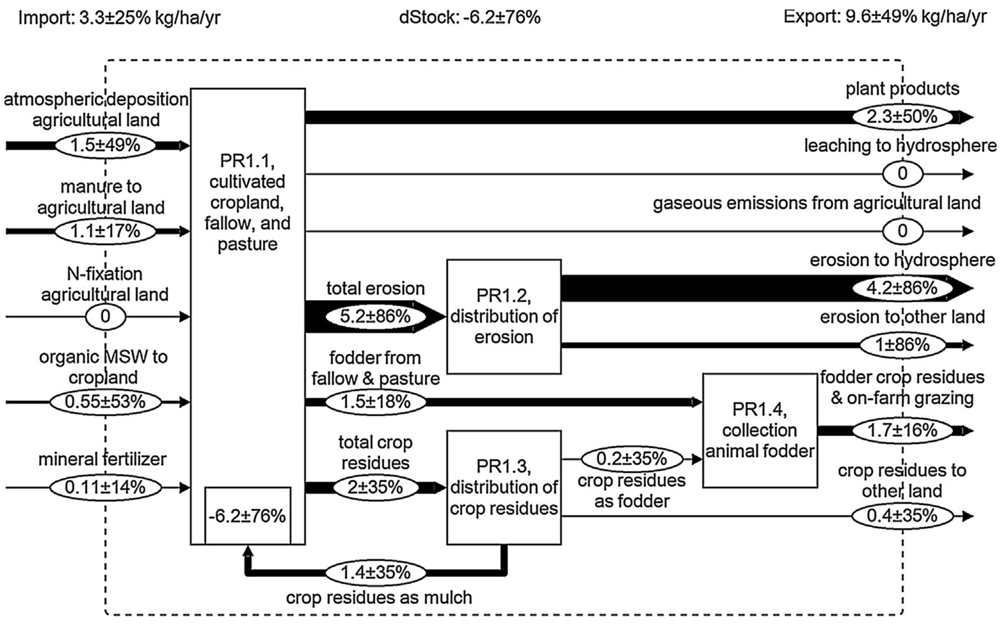

Fig. 8. MFA for P in Busia District's agricultural land in the year 2010 in kg ha^{-1} yr^{-1}.

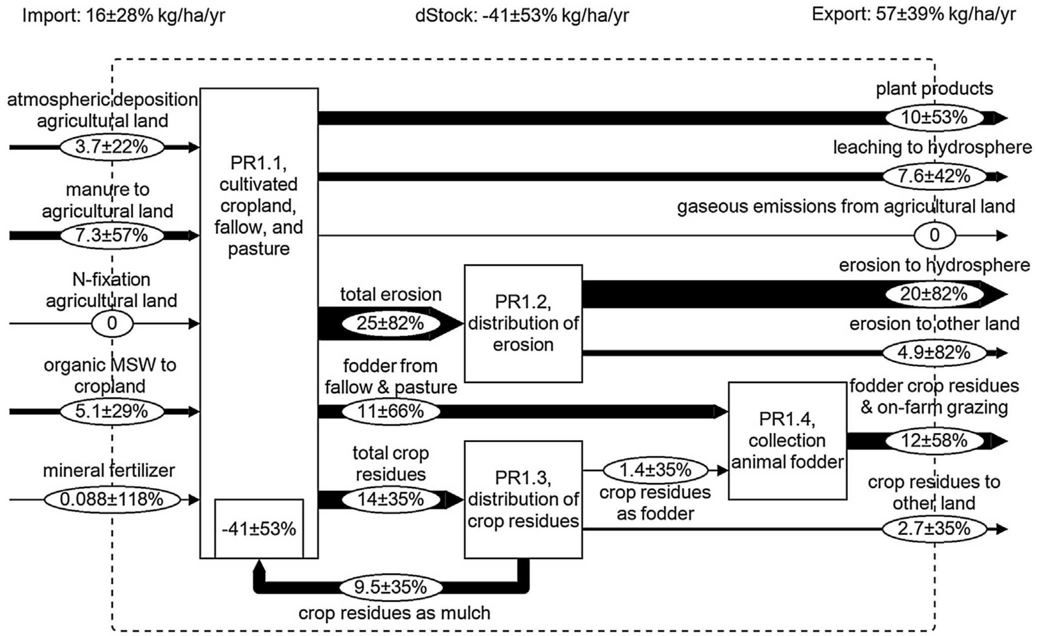

Fig. 9. MFA for K in Busia District's agricultural land in the year 2010 in kg ha^{-1} yr^{-1}.

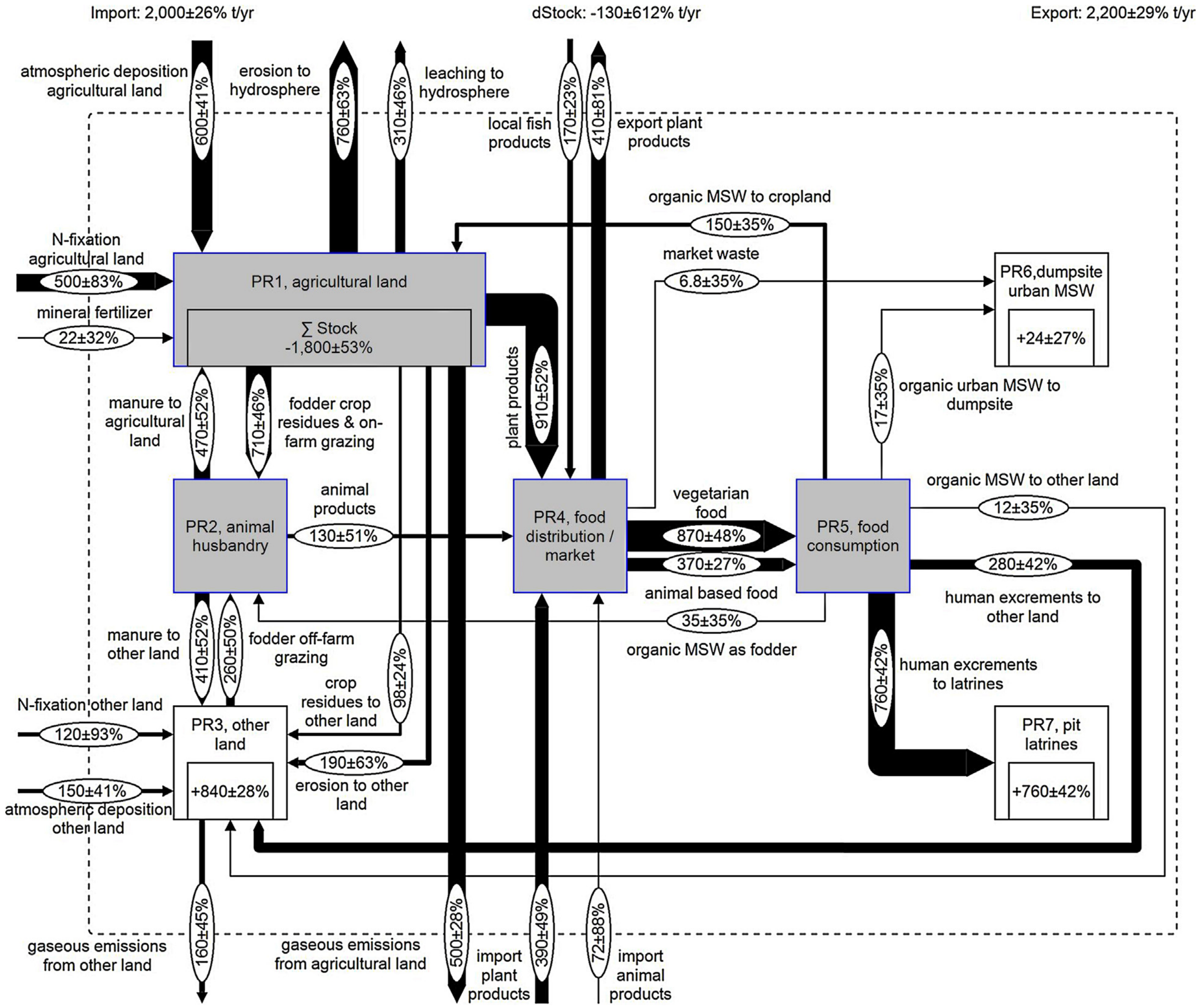

Fig. 10. MFA for N in Busia District (total system) in the year 2010 in t yr^{-1}.

utilized in agriculture and disposed of at the *dumpsite* (PR6) and *other land* (PR3). 70% are utilized on crop land (F5.1) and 13% as fodder for animals (F5.6), indicating a relatively high recycling rate of 83%. The 17% of waste actually dumped is generated in urban areas, and parts of this will be directed to crop land through the CDM composting program of the World Bank (2008). However, the quantitative potential of these to reduce the annual soil nutrient deficit in agricultural land is only 1–3%.

Nutrients generated from human excrement were calculated at rates of 1040 t yr^{-1} of N, 121 t yr^{-1} of P, and 360 t yr^{-1} of K. No utilization in agriculture has been found, and the theoretical potential of human excrement to overcome the soil nutrient deficit is much higher (60% for N, 37% for P, and 17% for K).

4. Discussion

Like other studies in Uganda, the soil nutrient balance has been determined to be negative in this work. As the comparability to these studies is limited due to different approaches and system boundaries used, the discussion focuses first on the single flows in the system.

4.1. Soil nutrient balance

4.1.1. Selected material flows of soil nutrient balance studies in Uganda

This study unveiled lower levels of mineral fertilizer application than Nkonya et al. (2005), but similar ones as Wortmann and Kaizzi (1998) and Sheldrick and Lingard (2004). Due to the use of two data sources, the values determined in this study are relatively certain. N-fixation was lower in this study than in Nkonya et al. (2005), which might be due to different assumptions on acreages and fixation rates of N-fixing legumes. N-fixation by Wortmann and Kaizzi is similar to this study, which is likely due to similar fixation rates and acreage of pulses.

Atmospheric deposition in this study is about the mean value of other studies for N, but higher for P and K. Wortmann and Kaizzi did not assume any P and K deposition, while Nkonya et al. values are similar for K and half as much for P. This is particularly relevant for P as atmospheric deposition was determined to be the second biggest input flow. Though large uncertainties exist, a review of studies from SSA suggest that a value of zero would be too low (Scheren et al., 2000).

Deviations from other studies exist for animal manure, but different degrees in detail of illustration and system boundaries make a comparison difficult. Nkonya et al., for instance, draw their system boundary along the farm and don't visualize internal flows. For Wortmann and Kaizzi, it was possible to follow the determination of the amount of nutrients supplied to cropland and fallow. Results are similar for P and K, but a little bit lower for N, which can be explained by a different system boundary, as Wortmann and Kaizzi assume that gaseous losses of N happen in the *boma*, and not at the field, as in this study. The animal manure nutrient supply as determined by Sheldrick and Lingard is much lower, which is mainly due to their assumptions that excretion during pasturing is counted as loss. Considering this, the share of manure nutrients applied to crops is similar in this (7–18%) and their study (15–20%).

Results given by Nkonya et al. further suggest that sedimentation is a large input flow, particularly in valley plains. This flow has not been considered in this study as eroded soil was assumed to be transported to other land or to water bodies and wetlands. Therefore, future research should focus more on soil erosion and redistribution as soil erosion is one of the largest outputs in soil nutrient balance studies. Cobo et al. (2010) also suggest using other approaches than the frequently used USLE equation.

The low output of crop residues removed in this study highly agrees with Nkonya et al., while the high input of crop residues to agricultural land is in contradiction to Sheldrick and Lingard. No explanation can be given therefore, except the different spatial and temporal system boundaries and, subsequently, a different crop residues management. Therefore, it would be worthy to further investigate whether farmers in Uganda have increasingly adopted mulching and other crop residue management measures in order to maintain their soil's fertility. This is of particular relevance for NGOs and Government Initiatives to assess the success of their soil conservation programs.

In all studies, the largest output flow from agricultural land was plant products. Values in this study are comparable to Wortmann and Kaizzi, higher than those of Sheldrick and Lingard, but much lower than those by Nkonya et al. As more details are not given by the latter, it is difficult to explain the differences although the comparatively low yields in Busia District are a reasonable explanation (UBoS, 2010b). Erosion values determined in this study are generally higher than for Wortmann and Kaizzi due to the higher soil loss rates determined (7.0 vs. 2.3–4.4 t ha^{-1} yr^{-1}) and the higher nutrient enrichment factor used (1.9–2.2 vs. 1.5). For a comparison to other studies we lack the detailed information, but it must be mentioned that some erosion studies in Uganda found much higher soil loss rates than in this study (Ssali, 2001; Jiang, 2013).

Leaching, which is another major output flow of N and K in this study, is only relevant for N in the other studies. Therefore, gaseous emissions of N are in the same range for all studies. The transfer of crop residues is assumed to be a relatively small flow in both this and Nkonya's study, but larger in Wortmann and Kaizzi. Again, this could be the sign of a change in crop management, but more information is needed to support this suspicion.

By comparing the size of flows of this to other studies, it becomes clear that all of them deal with uncertain data. However, these uncertainties are rarely discussed even though in studies by other authors like Lesschen et al. (2007) or Oenema et al. (2003) these amount to up to 200% RSU (see Section 4.3.3).

4.1.2. District wide soil nutrient balance studies

The spatial system boundary used in this study allows a comparison to the studies of Smaling et al. (1993) of Kisii District (Western Kenya) and Bekunda and Manzi (2003) of Kabale District (Uganda).

The aggregated nutrient losses in Kisii were much higher than in this study for N (112 vs. 33 kg ha^{-1} yr^{-1}) and K (70 vs. 41 kg ha^{-1} yr^{-1}), but half the size for P (3 vs. 6 kg ha^{-1} yr^{-1}). The reasons are the higher average yields and higher erosion rates through steeper slopes in Kisii. The result of K was furthermore influenced by a higher share of crops removed from crop land in Kisii than in Busia, while the relatively low deficit for P is explained by relatively high mineral fertilizer application rates.

To compare the results from this study to the partial nutrient balance of Kabale by Bekunda and Manzi (2003), environmental flows were left unconsidered. The resulting deficits in this study were much higher than in Kabale (−20 vs. −1.5 kg N ha^{-1} yr^{-1}; −3 vs. +1.2 kg P ha^{-1} yr^{-1}; −10 vs. −6.3 kg K ha^{-1} yr^{-1}), which is due to the higher application of mineral fertilizer in Kabale. What the comparison of both results also show is that Kabale is a net exporter of food and thus nutrients (944 t N yr^{-1}; 167 t P yr^{-1}; 822 t K yr^{-1}), while Busia is a net importer (200 t N yr^{-1}; 50 t P yr^{-1}; 180 t K yr^{-1}; fish is not counted in this comparison). In other words, districts with a low agricultural productivity like Busia depend on areas with higher productivity such as Kabale.

4.2. MFA and the potential of wastes to overcome soil nutrient deficits

4.2.1. MFA to support nutrient management in SSA

Great hopes have been raised to close nutrient cycles by recycling nutrients from human excrement and MSW to agricultural land. This study showed that these hopes have to be put into perspective under the given system boundaries, even though MFA examples from other areas in SSA reach different conclusions (Belevi, 2002; Meinzinger and Otterpohl, 2009). The main reason therefore is the spatial MFA system boundary. Both Belevi (2002) and Meinzinger and Otterpohl (2009) draw their boundary along the borders of cities (Kumasi in Ghana; Arba Minch in Ethiopia), which are primarily consumers of food imported from outside the city. With this system boundary selected and the consequential net-import of food and nutrients, it is clear that the wastes from the city are sufficient to serve as a relevant nutrient source for urban agriculture in the cities. Meinzinger and Otterpohl, for instance, state that only 33% of human urine collected would replace all mineral fertilizer consumed in the city of Arba Minch. However, if the *hinterland* that produces most of the food consumed by the urban populations in Kumasi and Arba Minch had been considered, the conclusions of the authors might have been different.

Even though this study considered the *hinterland* of an urban area, the question remains as far as how the results are applicable to other areas in Uganda and beyond. First, other studies suggest that many areas in Uganda and countries in SSA face similar problems of negative soil nutrient budgets (e.g., Sheldrick and Lingard, 2004; Nkonya et al., 2005). Second, similar ambitions for MSW and human excrement recycling exist in other areas in Uganda and SSA (e.g., Cofie et al., 2009; Dagerskog et al., 2013; Andersson, 2014). These examples suggest that applying MFA in other areas in Uganda and SSA countries would be useful to answer similar research questions. In the case of Uganda, it is even possible to scale the results of this study since under a given recycling of rural household waste, the potential of unused MSW to improve soil fertility is determined by the share of urban population. The share of urban population in Busia and most other districts as well as the whole country is, according to UBoS (2011), similar (15–20%), and results of calculations for other districts or the whole country will not be too different from this case study. In the case of the SSA-region, population distributions among districts and countries vary widely, and the urban population share is 37% (World Bank, 2013). A comparison with other MFA case studies from SSA countries and districts considering a nutrient consuming urban population and the *hinterland* required to feed them would be interesting, not only due to different rural-urban population distributions, but also due to different recycling practices, such as in parts of West Africa (i.e. Mali) where larger quantities of urban MSW is recycled in agriculture (Wilson et al., 2012).

4.2.2. The potential and challenges of organic MSW from urban areas

The recycling of their own organic waste is widely practiced among Busia's farmers, which is beneficial for the intended increase of recycling urban organic MSW through the CDM composting program, as farmers already have some experience with waste utilization on agricultural land (World Bank, 2008). Though its contribution to reduce soil nutrient deficits is negligible, it can of course be meaningful from a waste management perspective since farmer's demand and a presumed willingness to pay for organic MSW compost can help to increase waste collection rates and decreases MSW management costs (Lederer et al., 2012). However, attention should be paid to the compost quality. While the content of heavy metals in all sampled composts in Uganda is comparatively low (Tumuhairwe, 2011), a survey with farmers who used this compost found low compost quality with lots of extraneous materials, such as injection needles or broken glass (Lederer et al., 2012).

4.2.3. The potential and challenges of human excrement

Human excrement recycling has a high potential to reduce soil nutrient deficits, and Uganda is seen as a pioneer in this field in SSA. However, most initiatives are small scale and progress seems to be slow. The explanations are manifold, and range from hygienic hazards of feces handling to costs for sanitation facilities and a lack of collection chains (Tumwebaze et al., 2011; Katukizaet al., 2012). These and other problems call for a revision of current sanitation and nutrient recycling strategies. As the fears of potential users of human excrement are not based on irrational cultural taboos, but on tangible hygienic concerns, the first possibility would be to exclusively focus on nutrients in relatively hygienic urine only (Andersson, 2014). However, if done so, there is still some demand for research concerning, for instance, suitability of soils for urine fertilization (Dagerskog et al., 2013; Andersson, 2014). The second option is to shift the focus from currently targeted poor urban households to rural farmers, which would not require the same extensive collection, transport, and treatment system.

4.3. Methodological aspects of MFA in nutrient management

Authors have critically discussed questions of methodology and usefulness of soil nutrient balancing (Cobo et al., 2010), and the same should be done for MFA.

4.3.1. MFA and soil nutrient balances

MFA follows the same basic principles as soil nutrient balancing, and from this point of view the added value of MFA is only the illustration and calculation (including uncertainties) by STAN. Yet the strength of MFA is that it allows the consideration of flows and processes beyond the usual system boundary of soil nutrient balances, which is relevant to show and quantify farm-external nutrient resources available. Furthermore, some flows are simply treated as in- and outflows in farm balances, like off-farm grazing or animal manure losses. Where these flows come from or go to and how they affect other compartments in the environment is often not considered. The flexible system boundary in MFA allows a further investigation of the impact of these flows. For instance, if there is an input through off-farm grazing, it is relevant where it is taking place since land is limited, and by balancing nutrient flows in Busia District it has been found that much more land than indicated by UBoS (2011) is used for agricultural purposes. Similarly, manure excretion during grazing, whether on pastures (on-farm) or non-agricultural grass land (off-farm), has to be treated differently than manure losses to unproductive soils. This and other unproductive nutrient stocks, like latrines, are local nutrient sources readily available, and their potential can be clearly shown by MFA. MFA should thus not be seen as an alternative, but as an addition to soil nutrient balancing.

4.3.2. The temporal systems boundary

Another issue of concern in MFA and soil nutrient balancing is the temporal system boundary. The dynamics and sometimes abrupt changes in natural and anthropogenic systems can only be considered if the time span of investigation is long enough.

For instance, the average growth of cattle population in Busia is around 10% p.a. (UBoS, 2003, 2010c). The temporal boundary of one year, as used in this but also other studies, is definitely too short to cover such dynamics. Nevertheless, this study should be considered as the first of several steps, to be followed by a dynamic long-term MFA model. An example for such a step wise approach is the one-year MFA of P flows in Austria by Egle et al. (2014), which was used by Zoboli et al. (2014) to develop their dynamic P-MFA modelled for a time span of 20 years. Zoboli and colleagues point out the relevance of the one-year model to establish the system understanding required for the dynamic 20 years model.

4.3.3. Dealing with uncertain data

Another issue of general concern is the consideration of uncertainties. In soil nutrient balances, as well as in MFA, the debate has been ongoing for years, particularly in two directions. The first concerns the assessment and classification of data sources for MFA due to their quality, and the second concerns modelling uncertain data, for instance by means of Monte Carlo simulations (Hedbrant and Sörme, 2001; Oenema et al., 2003; Lesschen et al., 2007; Egle et al., 2014; Laner et al., 2014). The approach used in this study, assuming normally distributed datasets, is clearly unsatisfactory. However, as with the time span considered, this work should be seen as a first step, followed by, for instance, another model that classifies uncertainties and aims to model different variations of distributions.

5. Conclusions

The MFA for nutrients performed for Busia District in Uganda showed a negative soil nutrient balance in agricultural land, and thereby confirms the results of other studies carried out in the country. Though the uncertainties associated with the determination of nutrient flows are remarkable, calling for more research on their nature and size in order to better understand and probably reduce them, the results show that recycling of hitherto unused MSW has a much lower quantitative potential than the recycling of human excrement to reduce soil nutrient deficits. What counts for both nutrient sources is that their utilization should not be in contradiction to other societal objectives, particularly protection of human health. That this point is more relevant for human excrements is shown by the fact that they are not used by farmers. In light of the various initiatives existing to increase the utilization of human excrement, a stepwise approach that first focuses on the collection and utilization of less hazardous urine rather than feces, as well as a focus on rural rather than urban areas, might be more successful than the current *recycle all* approach favored by so-called ecological sanitation. Even though this will only direct a smaller amount of nutrients to agricultural land, which means that other measures to increase agricultural productivity (e.g., erosion control, mineral fertilizer, crop rotation) should not be ignored, it can at least contribute to improved food security for a growing population, not only in Uganda, but also in most countries of SSA.

Acknowledgements

This work was funded by the Commission for Development Research (KEF) at the Austrian Exchange Service (OEAD), the International Solid Waste Association (ISWA), and Altstoff Recycling Austria (ARA), and carried out together with the NGO Youth Environment Service (YES) and the Busia Municipal Council.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2015.03.024.

References

Amoding, A., 2007. Supply Potential and Agronomic Value of Urban Market Crop Waste. Ph.D. Thesis. School of Agricultural Sciences, Makerere University, Kampala, Uganda.

Andersson, E., 2014. Turning waste into value: using human urine to enrich soils for sustainable food production in Uganda. J. Clean. Prod. doi:http://dx.doi.org/10.1016/j.jclepro.2014.01.070.

Antikainen, R., Lemola, R., Nousiainen, J.I., Sokka, L., Esala, M., Huhtanen, P., Rekolainen, S., 2005. Stocks and flows of nitrogen and phosphorus in the Finnish food production and consumption system. Agric. Ecosyst. Environ. 107, 287–305.

Bekunda, M., Manzi, G., 2003. Use of the partial nutrient budget as an indicator of nutrient depletion in the highlands of southwestern Uganda. Nutr. Cycl. Agroecosyst. 67, 187–195.

Belevi, H., 2002. Material flow analysis as a strategic planning tool for regional waste water and solid waste management. GTZ/BMZ and ATV-DVWK, 12. Europäisches Wasser-, Abwasser und Abfall-Symposium, IFAT 2002, Munich.

Brady, N.C., Weil, R.R., 1999. Elements of the Nature and Properties of Soils. Prentince Hall, Upper Sandle River, New Jersey.

Brunner, P.H., Rechberger, H., 2004. Practical Handbook of Material Flow Analysis. CRC Press LLC, Boca Raton, Florida.

Cencic, O., Kelly, J.D., Kovacs, A., 2012. STAN (subSTance flow ANalysis). Helmut Rechberger and Oliver Cencic, Institute for Water Quality, Resources and Waste Management. Vienna University of Technology, Vienna. http://stan2web.net.

Cencic, O., Rechberger, H., 2008. Material flow analysis with software STAN. J. Environ. Eng. Manag. 18, 3–7.

Chen, W.-Q., Graedel, T.E., 2012. Anthropogenic cycles of the elements: a critical review. Environ. Sci. Technol. 46, 8574–8586.

Cobo, J.G., Dercon, G., Cadisch, G., 2010. Nutrient balances in African land use systems across different spatial scales: a review of approaches, challenges and progress. Agric. Ecosyst. Environ. 136, 1–15.

Cofie, O.O., Drechsel, P., Agbottah, S., Veenhuizen, R.v., 2009. Resource recovery from urban waste: options and challenges for community-based composting in sub-Saharan Africa. Desalination 248, 256–261.

Dagerskog, L., Morgan, P., Still, D., Ochiro, B., Ekane, N., Henry, L., Harawa, K., 2013. Food security in Sub-Saharan Africa – What could be the contribution of productive sanitation? In: Cross, P., Coombes, Y. (Eds.), Sanitation and Hygiene in Africa: Where do We Stand? IWA Publishing, 67-76.

Egle, L., Zoboli, O., Thaler, S., Rechberger, H., Zessner, M., 2014. The Austrian P budget as a basis for resource optimization. Resour. Conserv. Recycl. 83, 152–162.

FAO, 2013. FAOSTAT. Food and Agriculture Organization (FAO), Rome.

Fellner, J., Aschenbrenner, P., Cencic, O., Rechberger, H., 2011. Determination of the biogenic and fossil organic matter content of refuse-derived fuels based on elementary analyses. Fuel 90, 3164–3171.

Giller, K.E., Cadisch, G., Ehaliotis, C., Adams, E., Sakala, W.D., Mafongoya, P.L., 1997. Building soil nitrogen capital in Africa. In: Buresh, R.J., Sanchez, P.A., Calhoun, F. (Eds.), Replenishing Soil Fertility in Africa. SSSA Special Publication Number 51. Soil Science Society of America (SSSA), Madison.

Hedbrant, J., Sörme, L., 2001. Data vagueness and uncertainties in urban heavy-metal data collection. Water Air Soil Pollut.: Focus 1, 43–53.

Henao, J., Baanante, C.A., 1999. Estimating Rates of Nutrient Depletion in Soils of Agricultural Lands of Africa. International Fertilizer Development Center, Muscle Shoals, USA.

Jarvis, A., Reuter, H.I., Nelson, A., Guevara, E., 2008. Hole-filled Seamless SRTM Data V4. International Centre for Tropical Agriculture (CIAT).

Jiang, B., 2013. GIS-based time series study of soil erosion risk using the Revised Universal Soil Loss Equation (RUSLE) model in a micro-catchment on Mount Elgon, Uganda. M. Sc. Thesis. Department of Physical Geography and Ecosystems Science, Lund University, Sweden.

Johansson, C., 2013. Performance of Dairy Cows and Calves in Agro-pastoral Production Systems. Department of Animal Nutrition and Management. Swedish University of Agricultural Sciences, Uppsala.

Katukiza, A.Y., Ronteltap, M., Niwagaba, C.B., Foppen, J.W.A., Kansiime, F., Lens, P.N. L., 2012. Sustainable sanitation technology options for urban slums. Biotechnol. Adv. 30, 964–978.

Komakech, A.J., Banadda, N.E., Kinobe, J.R., Kasisira, L., Sundberg, C., Gebresenbet, G., Vinnerås, B., 2014. Characterisation of municipal waste in Kampala, Uganda. J. Air Waste Manag. Assoc. 64, 1–9.

Laner, D., Rechberger, H., Astrup, T., 2014. Systematic evaluation of uncertainty in material flow analysis. J. Ind. Ecol. doi:http://dx.doi.org/10.1111/jiec.12143.

Lederer, J., Brunner, P.H., Ongatai, A., Nabassa, M., Otim, S., Rashid, H., Ondeda, D., Karungi, J., Ogwang, F., 2012. A User-focused Knowledge Base for Goal-oriented Solid Waste Management in Uganda (UGoS). Final Report. Vienna University of Technology, Youth Environment Service (YES), Makerere University, Vienna, Austria.

Geigy scientific tables. In: Lentner, C., Lentner, C., Wink, A. (Eds.), Units of Measurement, Body Fluids, Composition of the Body, Nutrition, 1. Ciba-Geigy Limited, Basle.

Lesschen, J.P., Stoorvogel, J.J., Smaling, E.M.A., Heuvelink, G.B.M., Veldkamp, A., 2007. A spatially explicit methodology to quantify soil nutrient balances and their uncertainties at the national level. Nutr. Cycl. Agroecosyst. 78, 111–131.

Liu, Y., Villalba, G., Ayres, R.U., Schroder, H., 2008. Global phosphorus flows and environmental impacts from a consumption perspective. J. Ind. Ecol. 12, 229–247.

McKinney, P., 2009. Comprehensive Food Security & Vulnerability Analysis (CFSVA) Uganda. World Food Programme, Uganda Country Office, Kampala, Uganda.

Meinzinger, F., Otterpohl, R., 2009. Material flow analysis as a tool for sustainable sanitation planning in developing countries: case study of Arba Minch, Ethiopia. Water Sci. Technol. 59, 1911–1920.

Mubiru, D.N., Coyne, M.S., 2009. Legume cover crops are more beneficial than natural fallows in minimally tilled Ugandan soils. Agron. J. 101, 644–652.

NEMA, 2004. Busia District State of Environment Report. National Environment Management Authority (NEMA), Kampala, Uganda.

Nkonya, E., Kaizzi, C., Pender, J., 2005. Determinants of nutrient balances in a maize farming system in eastern Uganda. Agric. Syst. 85, 155–182.

Obernosterer, M., 2006. Sanitation Master Plan Busia Town Council. German Development Service, Busia Town Council, Busia, Uganda.

Oenema, O., Kros, H., de Vries, W., 2003. Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. Eur. J. Agron. 20, 3–16.

Ogejo, J.A., Wildeus, S., Knight, P., Wilke, R.B., 2010. Technical note: estimating goat and sheep manure production and their nutrient contribution in the Chesapeake Bay Watershed. Appl. Eng. Agric. 26, 1061–1065.

Ojok, J., Koeck, M.K., Tole, M., Okot-Okumu, J., 2013. Rate and quantities of household solid waste generated in Kampala City, Uganda. Sci. J. Environ. Eng. Res. 2013, 6.

Otim, D., 2008. Drought Analysis for Busia District (Uganda). M. Sc. Thesis. Istituto Agronomico per l'Oltremare, Facoltá di Agraria. Università degli Studi di Firenze, Florence, Italy.

Powell, J.M., Fernández-Rivera, S., Höfs, S., 1994. Effects of sheep diet on nutrient cycling in mixed farming systems of semi-arid West Africa. Agric. Ecosyst. Environ. 48, 263–271.

Roussel, J.-M., 2012. Feasibility Study and Preparation of an Integrated Watershed Management Program and Investment Proposal for the SioMalaba-Malakisi Sub-Basin. Final Report – Investment Project Proposal. Nile Basin Initiative, Entebbe, Uganda.

Ruecker, G.R., Park, S.J., Brunner, A.C., Vlek, P.L., 2008. Assessment of soil redistribution on two contrasting hillslopes in Uganda using Caesium-137 modelling. Erdkunde 62, 259–272.

Scheren, P.A.G.M., Zanting, H.A., Lemmens, A.M.C., 2000. Estimation of water pollution sources in Lake Victoria, East Africa: application and elaboration of the rapid assessment methodology. J. Environ. Manag. 58, 235–248.

Sheldrick, W., Syers, J.K., Lingard, J., 2003. Contribution of livestock excreta to nutrient balances. Nutr. Cycl. Agroecosyst. 66, 119–131.

Sheldrick, W.F., Lingard, J., 2004. The use of nutrient audits to determine nutrient balances in Africa. Food Pol. 29, 61–98.

Smaling, E.M.A., Stoorvogel, J.J., Windmeijer, P.N., 1993. Calculating soil nutrient balances in Africa at different scales. II. District Scale. Fert. Res. 35, 237–250.

Snijders, P.J., Davies, O., Wouters, A., Gachimbi, L., Zake, J., Ergano, K., Abduke, M., Van Keulen, H., 2009. Cattle Manure Management in East Africa: Review of Manure Quality and Nutrient Losses and Scenarios for Cattle and Manure Management. Wageningen UR Livestock Research, Wageningen, Netherlands.

Snijders, P.J., Van der Meer, H., Onduru, D., Ebanyat, P., Ergano, K., Zake, J., Wouters, B., Gachimbi, L., Van Keulen, H., 2013. Effects of cattle and manure management on the nutrient economy of mixed farms in East Africa: a scenario study. Afr. J. Agric. Res. 8, 5129–5148.

Ssali, H., 2001. Soil fertility. In: Mukiibi, J.K. (Ed.), Agriculture in Uganda, General Information. Fountain Publishers/CTA/NARO, Kampala, pp. 104–135.

Stadlmayer, B., Charrondiere, R., Enujiugha, V.N., Bayili, R.G., 2012. West African Food Composition Table. Food and Agriculture Organization (FAO), Rome, Italy.

Stoorvogel, J., Smaling, E., 1990. Assessment of Soil Nutrient Depletion in Sub-Saharan Africa: 1983–2000, I and III. Winand Staring Centre, Wageningen, Netherlands.

Tamatamah, R.A., Hecky, R.E., Duthie, H., 2005. The atmospheric deposition of phosphorus in Lake Victoria (East Africa). Biogeochemistry 73, 325–344.

Tumuhairwe, J.B., 2011. Fresh Waste Characterisation and Chemical Analysis, Leachate Analysis and Rejects Characterisation for the Municipal Solid Waste Composting Project in Uganda. Department of Agricultural Production, College of Agricultural and Environmental Sciences, Makerere University, Kampala, Uganda.

Tumwebaze, I.K., Orach, C.G., Nakayaga, J.K., Karamagi, C., Luethi, C., Niwagaba, C., 2011. Ecological sanitation coverage and factors affecting its uptake in Kabale municipality, western Uganda. Int. J. Environ. Health Res. 21, 294–305.

UBoS, 2003. Uganda Census of Agriculture 2002. Ugandan Bureau of Statistics (UBoS).

UBoS, 2010a. Uganda census of agriculture 2008/2009. Agricultural Household and Holding Characteristics Report, III. Ugandan Bureau of Statistics (UBoS), Kampala, Uganda.

UBoS, 2010b. Uganda census of agriculture 2008/2009. Crop Area and Production Report. Agricultural Household and Holding Characteristics Report, Volume IV. Ugandan Bureau of Statistics (UBoS), Kampala, Uganda.

UBoS, 2010c. The National Livestock Census Report 2008. Uganda Bureau of Statistics (UBoS), Kampala, Uganda.

UBoS, 2011. 2011 Statistical Abstract. Uganda Bureau of Statistics (UBoS), Kampala, Uganda.

UNEP, 1987. Global resource information database (GRID): Uganda case study: a sampler atlas of environmental resource datasets within GRID. GRID Information Series. United Nations Environment Programme (UNEP), Nairobi.

USDA, 2011. USDA National Nutrient Database. United States Department of Agriculture (USDA), Beltsville.

Van den Bosch, H., Gitari, J.N., Ogaro, V.N., Maobe, S., Vlaming, J., 1998. Monitoring nutrient flows and economic performance in African farming systems (NUTMON): III. Monitoring nutrient flows and balances in three districts in Kenya. Agric. Ecosyst. Environ. 71, 63–80.

Wilson, D.C., Rodic, L., Scheinberg, A., Velis, C.A., Alabaster, G., 2012. Comparative analysis of solid waste management in 20 cities. Waste Manag. Res. 30, 237–254.

Wischmeier, W., 1978. USLE Handbook. United States Department of Agriculture (USDA), Washington, DC.

World Bank, 2008. Uganda Municipal Waste Compost Programme. World Bank – CDM Executive Board, Washington DC.

World Bank, 2013. Development Indicators: Population Growth (Annual%). World Bank Group, Washington DC.

Wortmann, C.S., Kaizzi, C.K., 1998. Nutrient balances and expected effects of alternative practices in farming systems of Uganda. Agric. Ecosyst. Environ. 71, 115–129.

Zoboli, O., Zessner, M., Rechberger, H., 2014. Added value of time series in MFA: the Austrian phosphorus budget from 1990 to 2011. Submitted to the Journal of Industrial Ecology, October 2014.