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Can local nutrient-circularity and erosion control increase yields of resource-constraint smallholder farmers? A case study in Kenya and Uganda

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ABSTRACT

As many regions in sub-Saharan Africa, the border region of Kenya (KE) and Uganda (UG) has faced a declining soil fertility for decades, resulting from soil erosion, intensely managed agricultural soils due to population pressure and small inputs of mineral and organic fertilizers. With limited financial means, farmers need measures and/or technologies that effectively reduce nutrient losses or increase inputs at a low cost. In this study, four such measures are in focus, namely erosion reduction practices, vermicomposting of animal manure, collection of human urine in jerry cans and, collection of human excreta in urine-diverting dry toilets. Current soil nutrient balances in five districts in the Sio-Malaba-Malakisi River Basin and the potential of these measures to reduce the soil nutrient deficit are studied using the method of material flow analysis and the software STAN. Furthermore, crop-nutrient-response functions are used to determine their potential impact on maize harvests. Overall, results reveal that there exists a non-negligible and exploitable potential of local resources to reduce the soil nutrient deficit, improve harvests and in turn food security of the smallholder farmers in the region. Soil nutrient deficits could be reduced by 20–30%, 23–42% and 9–15% for nitrogen (N), phosphorus (P) and potassium (K), respectively. Subsequently, maize harvests could be increased by 8–40%, depending on the applied technology and area. This research provides useful insights for agricultural extension workers, politicians and researchers alike, highlighting that simple and easily available technologies can harness similar amounts of nutrients as more complex and expensive ones if all specific technology-constraints are adequately incorporated in the analyses.

1. Introduction

Countries in sub-Saharan Africa (SSA) face one of the lowest food-self-sufficiency rates in the world (van Ittersum et al., 2016; Wichern et al., 2017). Declining soil-fertility, low labour productivity rates (Ritzema et al., 2017), a lack of institutional markets, marginal technology-uptake and access rates (Vanlauwe et al., 2017) as well as excessive population growth and in consequence a decrease in farm size per household (Schreinemachers, 2006) are only a selection of important contributors to food-insecurity in the region. Even by closing the existing crop-yield-gap in SSA, a projected two- to threefold population increase by 2050 is expected to offset these gains in productivity, and will demand an increase in irrigated areas (Badian and Collins, 2016) and cropping intensity (Loison, 2015; van Ittersum et al., 2016). In

Abbreviations: MFA, material flow analysis; UDDT, urine-diverting dry toilets; SSA, sub-Saharan Africa; N, nitrogen; P, phosphorus; K, potassium; KE, Kenya; UG, Uganda; USLE, Universal Soil Loss Equation; MSW, mixed solid waste; gSP, generalized support practices

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this light, research and governmental efforts to increase agricultural productivity should remain high.

Declining soil-fertility has been and still is the single-most researched factor related to food-insecurity in SSA (Vanlauwe et al., 2017). Underlying issues for this decline are manifold, e.g. high erosion rates (Schürz et al., 2020), limited input of external and inadequate management of on-farm nutrient sources and organic matter (Andersson, 2015; Castellanos-Navarrete et al., 2015), reduced time of land laying fallow due to population pressure (Tittonell et al., 2008) and a high dependency on rainfall (Barasa, 2014; Epule et al., 2017). Potential technologies and management practices of all forms, sizes and costs have been studied to cope with these issues, from simple reduction of erosion by reduced tillage (Kaizzi et al., 2007) to complex and cost-intensive biogas technology with the use of digestate as a fertilizer (Walekhwa et al., 2009; Clemens et al., 2018).

Regarding research and dissemination of soil-fertility-conservation technologies two issues have to be addressed. First, existing research shows a tendency to focus on an improbable maximum potential that is unlikely achieved by technology diffusion (see for example Okello et al., 2013; Lederer et al., 2015). In contrast, after technologies have been installed on-site, a reduced use or efficiency is however often observed (see e.g. Kariko-Buhwezi et al., 2011; Barnard et al., 2013; Kwiringira et al., 2014; Silveti and Andersson, 2019). Similarly, testing of recycled nutrients in plot trials is often done at or close to recommended nitrogen-application rates (Chikowo et al., 2004; Kihara et al., 2016; Amoah et al., 2017), disregarding that organic resources of nutrients on farms are limited and that recommended application rates can rarely be achieved. There therefore exists a demand for reality-driven research that adequately represents technology constraints and resource availability.

Second, recent research by Vanlauwe et al. (2017) has highlighted the drivers involved in the uptake of soil-fertility-related technologies, namely integrating local farmers from the start (e.g. through Science Technology Backyards, see: Zhang et al., 2016; Cui et al., 2018), establishing functioning institutions to enable continuing access to markets and credits, as well as setting-up or including existing stakeholder-platforms and extension agents to enhance insight into problems-faced and long-term dissemination efforts. In addition, the socio-economic status of smallholder farmers should increasingly be taken into account when reaching for wide-spread adoption of new technologies (Recha, 2018). Recent post-evaluations of biogas plants and EcoSan toilet dissemination projects showed that smallholder farmers are often lacking financial means and local repair options, leading to the decay of said installations (Lwiza et al., 2017; Schneider, 2019). Therefore, with limited investment into agricultural extension services available, it is crucial to prioritize the dissemination of technologies that are tailored to regional requirements and demands, thereby accounting for the large heterogeneity of SSA farming systems (Badian and Collins, 2016; Recha, 2018).

Considering those insights, this study bids farewell to the 'one-size-fits-all'-approach and attempts to take a closer look into how regional preconditions control the potential of technologies to improve soil-fertility and in consequence food-security. A major contributor to the declining soil-fertility is the soil–nutrient-deficit (nitrogen (N), phosphorus (P), potassium (K) and micronutrients). Many proposed technologies aim at reducing this deficit to further close the crop-yield-gap. Soil–nutrient-balances, a widely used method to determine the rate of nutrient-depletion in SSA (see e.g.: Wortmann and Kaizzi, 1998; Sheldrick et al., 2003; Nkonya et al., 2005; Snijders et al., 2009; Lederer et al., 2015), are therefore set-up in this study to determine the potential impact of technologies on soil-fertility and the crop-yield-gap. The following research questions are formulated:

(i) What are the main current inputs and outputs of nutrients in agricultural soils in SSA and to what extent can these differ in regions of close proximity?

(ii) How does the potential of different technologies to improve soil–nutrient-balances differ based on the preconditions in a region?

(iii) What gains in closing the crop-yield-gap can be expected if different technologies reach widespread adoption, depending on regions' preconditions?

Three groups of preconditions can be identified, namely (i) the natural prevalent landscape, (ii) prior existing agricultural practices (crop varieties and rotation, livestock possession, fertilizer use, land sizes) and (iii) the socio-economic structure of smallholder households. The Sio-Malaba-Malakisi River Basin in Kenya (KE) and Uganda (UG) is chosen as a case study, as the region is highly diverse in topography and depicts two different economies which in turn impacts household structures, financial capacities and agriculture (see Section 2). Three technology (groups) are selected based on their simplicity, a diversity in addressed issues, optimistic results from dissemination projects and cost-effectiveness, to account for the limited financial means of smallholder farmers (Kaizzi et al., 2007; Andersson, 2015). These are (i) erosion reduction practices on agricultural land, (ii) management of livestock manure by vermicomposting and (iii) human urine collection and storage in jerrycans. In addition, urine-diverting dry toilets (UDDTs) are chosen as a means to compare a simplistic measure that does not exploit the whole nutrient potential of human excrements (urine collection), to a more cost-intensive measure that does.

2. Study area

The case study area of the Sio-Malaba-Malakisi River Basin lies at the border of Kenya and Uganda, delimited by Lake Victoria in the South and Mt. Elgon in the north (Fig. 1). Two counties from the Kenyan side (Bungoma, Busia) and three districts from the Ugandan side (Busia, Manafwa, Tororo) are chosen as individual research units,[1] as they depict areas with varying proneness to erosion (Fig. 1(b)), agricultural practices and livestock ownership (Fig. 1(c)), as well as socio-economic structures (Fig. 1(d)) (see also Table 1).

The Sio-Malaba-Malakisi River Basin is dominated by agricultural land (Fig. 1(a)) and is one of the poorer regions of Kenya and Uganda , with around 30–40% living below the respective national poverty line (KNBS, 2018; UBOS, 2019). In terms of GDP per capita, and therefore financial opportunities, households on the Kenyan side are generally better off than those in the Ugandan districts (KNBS, 2019b; Wang et al., 2019). Approximately 90% of all households use pit latrines, and levels of improved sanitation (urine collection, urine-diverting-dry-toilets, ventilated pit latrines) is < 5 and < 1% for Kenya and Uganda, respectively.

Main soil-types in the region are low to medium fertility ferralsols and acrisols in the southern part and high fertility nitisols in the northern part (Sombroek et al., 1982; NARO & NARL, 2017). While the southern units of Busia (UG), Busia (KE) and Manafwa show only gentle inclinations, the northern units of Bungoma and Manafwa at the foot of Mt. Elgon feature moderate to steep slopes and a higher soil loss (ESA, 2017; Schürz et al., 2020). More than 80% of households are engaged in agriculture (ASDSP et al., 2014; MoALF, 2016; UBOS, 2016a) and the share of cropland on total area ranges between 55% in Busia (KE) to 82% in Manafwa. More than half of the agricultural households on the Kenyan side use mineral fertilizer, while use on the Ugandan side is low. Livestock ownership of households in the units varies between 13 to 46% for cattle and 57 to 70% for chicken (Table 1).

[1] Districts and counties, if mentioned collectively, are hereby referred to as 'units' for reasons of simplicity.

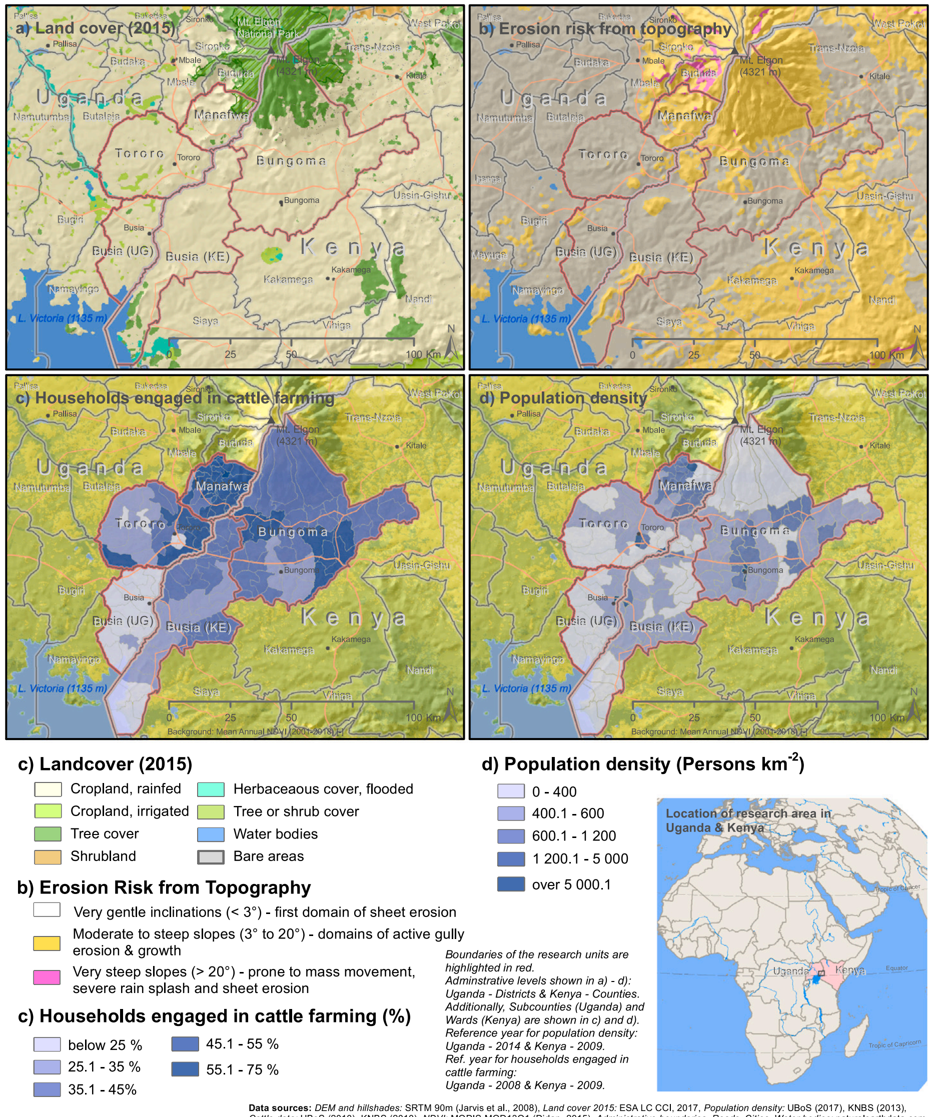

Fig. 1. Study area in the border region of Kenya and Uganda between Lake Victoria and Mt. Elgon. A land cover classification with reference year 2015 (ESA, 2017) (a), a classification of the soil erosion risk following Ebisemiju (1988) (b), the households engaged in cattle farming (KNBS, 2010; UBoS, 2010) (c), and the population density (KNBS, 2013; UBoS, 2017) (d) are plotted to characterize some spatial properties of the study region. The boundaries of the studied administrative units are shown with red outlines. MODIS NDVI is plotted as background in (c) and (d) as a proxy for vegetation cover. Darker green colours represent areas with higher vegetation cover. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Methods and data

3.1. Material flow analysis & uncertainty management

The method of material flow analysis (MFA; Austrian Standards, 2005 *ÖNORM S 2096*) is chosen to analyse current nutrient flows (N, P and K) into and out of agricultural land in the case-study region. MFA is a widely used method to systematically analyse material and/or substance flows into, within and out of a system with defined spatial and temporal boundaries (Brunner and Rechberger, 2016). A variety of nutrient flow analyses across many different scales (i.e. plots, farms, regions, countries) have been realized through the use of MFA (Cobo et al., 2010; van der Wiel et al., 2020), notably also in the region of SSA (Meinzinger et al., 2009; Lederer et al., 2015). To implement and calculate the MFA for this study, the freeware STAN (subSTance flow ANalysis) (Cencic and Rechberger, 2008) is used. STAN is a software that allows easier implementation of MFAs through the use of a graphical interface. Further, it can impute unknown flows by linking them to related flows and by creating mathematical dependencies between these flows.

The quality of the used data can highly vary. An appropriate uncertainty management is therefore a key element of this analysis. If more than four data sources are available for one flow, the uncertainty of that flow is calculated using the mean μ and standard deviation σ, assuming a normal distribution. In contrast, if four or less data sources are found, the maximum deviation from μ is used instead. For each flow, the initial values (mean and uncertainty) are entered in STAN. To achieve the best fit for all flows, the final value and uncertainty of each flow is then determined by (i) considering the mean and uncertainty of the initial value, (ii) the mathematical dependencies of interacting flows, (iii) the concept of Gaussian error propagation to determine the uncertainty produced by interacting flows and (iv) data reconciliation to correct the data for random errors (Cencic and Rechberger, 2008).

3.2. Status quo system definition and data for the material flow analysis

Many studies in SSA focus on farm-level and/or scenario-based case-studies to determine the availability and management of nutrients

Table 1
Overview of socio-economic, landscape, agricultural and livestock statistics in the five analysed units in the Sio-Malaba-Malakisi River Basin.

Indicator	Unit	Bungoma (Kenya)	Busia (Kenya)	Busia (Uganda)	Manafwa (Uganda)	Tororo (Uganda)	Total or weighted arithmetic mean	Source
Socio-Economics								
Population in 2014	inh.	1,519,481	815,401	323,662	353,825	517,082	3,529,451	Projected from KNBS (2010b) and UBOS (2016a)
Population density	inh. km^{-2}	500	480	440	660	430	497	–
Rural population	%	84	88	83	86	86	86	KNBS (2010b) and UBOS (2016a)
Mean household size	no.	4.8	4.6	5	4.9	5	5	KNBS (2010b, 2019a) and UBOS (2016a)
GDP in 2014	USD	730	1000	270	110	560	672	KNBS (2019b) and Wang et al. (2019)
Poverty rate	%	36	69	~30	~35	~30	42	KNBS (2018) and Baryahirwa (2019)
Landscape								
Total area	km^2	3012	1805	755	525	1186	7283	ESA (2017)
Wetlands/waterbodies	km^2	13	170	11	0	17	211	ESA (2017)
Land area	km^2	2999	1635	744	525	1169	7072	ESA (2017)
Cropland	%	68	55	68	69	82	67	UBOS (2010b), KNBS (2015a,b) and Turinawe et al. (2018)
Pastures and fallow land	%	5.5	36	25	12	11	16	Turinawe et al. (2018)
Forests	%	21	5.9	1.9	16	2.9	12	ESA (2017)
Other land	%	5.7	3.5	4.7	2.9	4.7	5	Calculated
Mean slope agricultural land	°	6.5	3.8	2.7	9.7	2.8	5.1	ESA (2017)
Mean soil loss	t ha^{-1} a^{-1}	52	33	12	75	9.2	38	Schürz et al. (2020)
Agriculture								
Agricultural households	%	86	80	79	86	89	84	ASDSP et al. (2014), MoALF (2016) and UBOS (2016a)
Main crops planted		Maize, Beans, Plantain	Maize, Cassava, Beans	Maize, Cassava, Sweet Potato, Soy(Beans)	Plantain, Maize, Beans	Maize, Cassava, Millet, Rice		UBOS (2010b), KNBS (2015a,b) and Turinawe et al. (2018)
Mean size of cropland	ha hh^{-1}	0.75	0.63	0.98	0.58	1.00	0.78	Calculated from cropland
Mean size of maize area	ha hh^{-1}	0.26	0.28	0.34	0.17	0.25	0.26	Calculated from cropland
Share of households using mineral fertilizer	%	85	55	22	22	22	57	MALDM et al. (2002), MoALF (2016), Turinawe et al. (2018) and UBOS (2020)
Livestock								
Share of households owning cattle	%	40	30	13	46	36	35	Wiesmann et al. (2014), KNBS (2010a) and UBOS (2010a)
Mean no. of cattle per cattle owning household	no. hh^{-1}	3.1	3.6	3.2	2.3	3.2	3.1	KNBS (2010a) and UBOS (2010a)
No. of cattle per ha of agricultural land	no. ha^{-1}	1.7	1.3	0.39	1.8	1.1	1.4	KNBS (2010a) and UBOS (2010a)
Share of households owning chicken	%	66	67	57	70	66	66	KNBS (2010a) and UBOS (2010a)
Mean no. of chicken per chicken owning household	no. hh^{-1}	6.9	7.6	11	8.7	8.7	7.8	KNBS (2010a) and UBOS (2010a)

in smallholder farms (see e.g. Wortmann and Kaizzi, 1998; Lekasi et al., 2001b; Nkonya et al., 2005; Rufino et al., 2007; Tittonell et al., 2008; Snijders et al., 2009; Cobo et al., 2010; Castellanos-Navarrete et al., 2015). In contrast, this study uses a top-down approach by (i) determining county/district-wide nutrient flows and (ii) dividing these flows by the agricultural land area to normalize flows to a functional unit of 1 ha of agricultural land. This procedure is seen as advantageous for the depiction of regional differences in soil-erodibility potential and agricultural management practices as well as for implementing the limits to recycling brought forth by population and livestock densities.

A MFA is set-up for each individual unit, resulting in five analyses based on the same model structure (Fig. 2). The MFA is based on the model of Lederer et al. (2015), which was applied in the Busia district for the year 2010. The spatial boundary of the system is defined as the individual units' border. The temporal boundary of the MFA is set to the year 2014, therefore all flows are based on one year. The main processes are defined according to van der Wiel et al. (2020) as: *PR1 — agricultural land*, *PR2 — animal husbandry*, *PR3 — food distribution*, *PR4 — food consumption* and *PR5 — sanitation* (see Fig. 2), which are divided into 15 sub-processes with multiple associated flows.

3.2.1. PR1 – agricultural land

Fig. 3 shows the model for the process agricultural land, including the sub-processes *PR1.1 cultivated cropland, fallow and pasture*, *PR1.2 distribution of crop residues* and *PR 1.3 collection of animal fodder*. Flows in process PR1 are modelled as follows: *Mineral fertilizer (F1.im1)* is calculated after national consumption data from Godfrey and Dickens (2015), FAO (2019a) and IFA (2019) and adjusted to units by their share of cropland on total national cropland (see Appendix A Table A.1). *Nitrogen fixation (F1.im2)* is estimated from crop area of N-fixating crops multiplied by a constant N-fixation factor per ha after Stoorvogel et al. (1990), Wortmann and Kaizzi (1998), Giller (2001), Lesschen et al. (2007) and Brady et al. (2008) and compared to results from crop production data multiplied by a factor of %N derived from N_2 fixation after Ojiem et al. (2007) (see Table A.2). Calculation of flows *F2.2., F2.3, F3.3, F4.1, F5.1, F5.2* is explained in the respective sections (S3.2.2, S3.2.3, S3.2.4 & S3.2.5).

Soil loss by water erosion is one of the main output flows from agricultural land. The Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978; Renard et al., 1997) is implemented to calculate spatially distributed estimates of water induced soil erosion for the study area. The USLE is an empirical model that is, due to its simplicity, frequently implemented to estimate soil erosion on large scales and data scarce regions (for applications in East Africa see e.g., Fenta et al., 2020; Karamage et al., 2017; Tamene and Le, 2015; Lufafa et al., 2003). Schürz et al. (2020), however, illustrated that a soil loss estimation with the USLE is highly uncertain and strongly depends on the implemented methods to calculate the individual USLE inputs. To account for uncertainties in the calculation of soil erosion, two different soil losses for the study area units were calculated according to Schürz

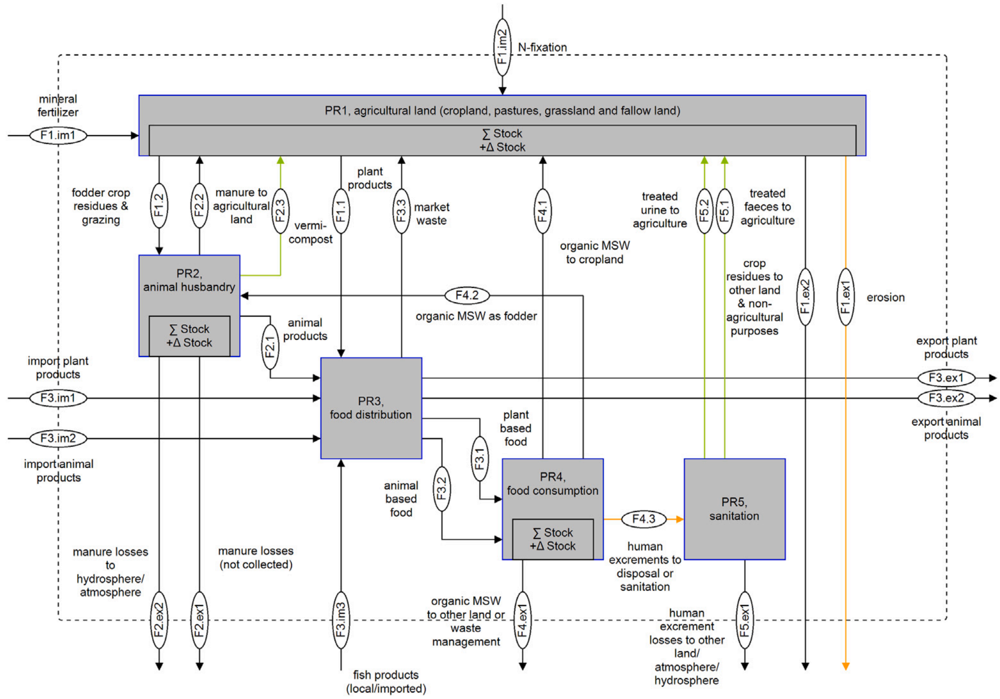

Fig. 2. Depiction of the material flow analysis model set-up, the studied processes and flows in the analysed units.

et al. (2020) (For a detailed description see Appendix A. Page 3). Apart from large uncertainties, the USLE only estimates the gross erosion and does not account for deposition processes (Evans, 2013).

To estimate the transport of eroded soil material to other land uses or rivers and its redistribution on agricultural land requires additional assumptions. First, agricultural land in the units is divided into three groups of slope prevalence, namely $\leq 5°$, > 5–$\leq 10°$ and $> 10°$, and the percentage of area belonging to each group is determined (Table A.6). Second, based on the soil redistribution model from Claessens et al. (2007) and sediment loading data from Barasa (2014), it is assumed that 10, 20 and 30% of gross eroded material from areas with $\leq 5°$, > 5–$\leq 10°$ and $> 10°$, respectively, terminates in rivers. Third, the remainder is distributed between agricultural land and other land or forests based on the land use in the units (Table 1). For this, it is estimated that eroded soil is twice as likely to be deposited on other land or forests than on agricultural land, due to a higher friction and impediments (Ruecker et al., 2008).

Most forest land in Bungoma and Manafwa lies on the slopes of Mt. Elgon and therefore above most agricultural plots. Therefore, 70 and 50%, respectively, of forest area is assumed as not available for deposition of eroded material from agricultural land (determined from slope distribution of agricultural and forest land; ESA, 2017). Finally, the nutrients removed through *erosion (F1.ex1)* are calculated using the amount of material eroded to rivers and other land multiplied with the respective soil–nutrient-concentration (Wortmann and Kaizzi, 1998; Makokha et al., 2001; Blomme et al., 2005; Ojiem et al., 2007; Lederer et al., 2012; see Table A.7) and an nutrient enrichment factor (from Stoorvogel et al., 1990; Wortmann and Kaizzi, 1998; Lesschen et al., 2007; see Table A.8).

Crop production in the units is computed based on crop area and yield factors from UBOS (2014), KNBS (2015a,b), Oseko and Dienya (2015) and UBOS (2020) (see Tables A.9 and A.10). Initial analysis of crop areas from national reports indicated an under- or overestimation of crop areas for some crops. In addition, national data is therefore compared to results from an agricultural households survey (sample size = 506 households) which was conducted as part of the CapNex project (Capacity Building on the Water–Energy–Food Security Nexus through Research and Training in Kenya and Uganda) in the five units of interest (Turinawe et al., 2018). Final crop areas are then chosen based on estimated demand for consumption in the regions (see *PR4.1*).

Output of *plant products (F1.1)* is calculated using the derived crop production estimates and nutrient-concentrations in harvested products from literature (Lentner, 1981; Van den Bosch et al., 1998; Wortmann and Kaizzi, 1998; Smaling et al., 1993; Stoorvogel et al., 1990; USDA, 2011; Stadlmayr, 2012; FAO & GoK, 2018; see Tables A.11, A.12, A.13). Nutrient flows from *total crop residues (F1.i2)* are computed using crop-residue-to-product ratios from Lal (1995b) and Okello et al. (2013) (see Table A.14), the crop production estimates, as well as nutrient concentrations in crop residues from Stoorvogel et al. (1990), Nyambati et al. (2003) and Schreinemachers (2006) (see Table A.15). Distribution of total crop residues to flows *crop residues as fodder (F1.i3), crop residues as mulch (F1.i4)* and *crop residues to other land & non-agricultural purposes (F1.ex2)* is assumed after values for Kakamega county (bordering Bungoma and Busia (KE)) presented in Duncan et al. (2016) with 34, 36 and 30% respectively. Flows *fodder from fallow and pasture (F1.i1)* and consecutively *fodder crop residues and grazing (F1.2)* are calculated by the MFA model derived from animal feed demand as explained in Section 3.2.2. Atmospheric deposition and leaching of nutrients are neglected in this study for two main reasons. Firstly, both flows are associated with a high uncertainty due to a low data availability for the region. Secondly, the influence of farmers on these flows is very limited.

3.2.2. *PR2 – animal husbandry*

The process of animal husbandry (Fig. 4) includes four sub-processes: *PR2.1 animal feeding, PR2.2 manure diversion process, PR2.3 manure losses consolidation process* and *PR 2.4 manure processing (vermi-composting)*. First, livestock numbers are estimated from KNBS (2010a, 2015b), GoK & KNBS (2015), UBOS (2010a, 2016b, 2017), UBOS & ICF (2018), Turinawe et al. (2018) and FAO (2020a) (see Table A.16). Second, nutrient flows in *animal products (F2.1)* are determined by comparing national and county statistics for production and livestock numbers (from UBOS, 2010a; ASDSP et al., 2014; KNBS, 2015a,b; FAO, 2020b; see Table A.17) and multiplying it with nutrient concentrations in animal products from literature (Lentner, 1981; Smaling et al., 1993; Van den Bosch et al., 1998; Wortmann and Kaizzi, 1998; USDA,

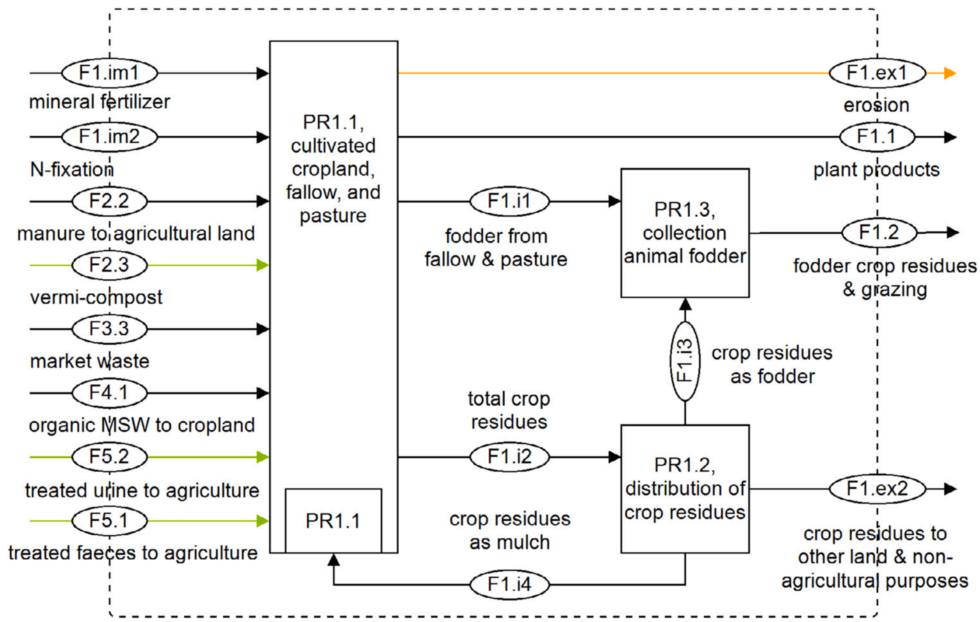

Fig. 3. Depiction of the material flow analysis model structure including flows and sub-processes of the process PR1 agricultural land.

2011; Stadlmayr, 2012; FAO & GoK, 2018; see Tables A.11, A.12 and A.13). Third, faecal excretion of nutrients from livestock in the different units is computed by taking livestock numbers, yearly faecal excretion rates (Fernandez-Rivera et al., 1995; Rufino et al., 2007; Williams, 2010; Onduru et al., 2008; Njuki et al., 2011; Castellanos-Navarrete et al., 2015; Ngwabie et al., 2018; see Table A.18), and nutrient concentrations in fresh faeces (Woomer et al., 1999; Onduru et al., 2008; Sanginga et al., 2009; Sileshi et al., 2017; Zhu et al., 2020; see Table A.19).

Then, urine excretion is estimated from faeces excretion using values on the share of nutrient excretion between urine and faeces from CAST (1996) (see Table A.20). The sum of urine and faeces excretion then gives *F2.i1 excretion*. Finally, total animal feed demand is back-calculated from nutrient excretion, assuming a simplified 10% / 90% share between nutrient uptake and excretion for all animal types, respectively (expert guess based on data from Rufino et al. (2006) and Lekasi et al. (2001a) and animal production and excretion flows). Animal feeding in the river basin is achieved by supplying *organic mixed solid waste (MSW) (F4.2)* (explained in Section 3.2.4) and crop residues or by letting animals graze on agricultural or communal lands. *Fodder from crop residues & grazing (F1.2)* is determined by subtracting *F4.2* from total feed demand.

Management of manure in the region is poor, with nutrient losses occurring from a failure to collect manure and an inadequate storage of manure. The diversion of excreted nutrients to flows *manure to agricultural land (F2.2)*, *manure losses (not collected) (F2.ex1)*, *manure losses (inadequate management) (F2.i2)* and *manure to processing (F2.i3)* is based on a set of assumptions: (i) At nighttime, animals are kept in an open stall (boma) or tethered in the homestead with nighttime excretion accounting for 43% (Schlecht et al., 1998; Thomas et al., 2013). (ii) During daytime animals spend 90% of their time on agricultural land and the remaining 10% on other land. (iii) Of faeces excreted at the boma, 90% are collected and stored; urine excreted in the boma is lost. (iv) Stored faeces, and urine and faeces excreted on agricultural land are subjected to heat, rain and decomposition. The resulting losses are based on data from Sheldrick et al. (2003), Tittonell et al. (2008), Rufino et al. (2006, 2007), Snijders et al. (2009), Sileshi et al. (2017) and Casu (2018) with final assumptions for the MFA given in Table 2. (v) Amounts of manure that undergo further processing is set to zero for the year 2014; scenarios for vermicomposting and the determination of flows *F2.i4, F2.3* and *F2.i5* is explained in Section 3.3.

Table 2
Assumptions on nutrient losses from animal excreta during excretion and storage (in percent of total inputs).

% - losses from ...	N	P	K
Faeces deposited on agricultural land	20	0	0
Urine deposited on agricultural land	5	0	0
Faeces in storage	50	30	30

3.2.3. PR3 – food distribution

In Fig. 5 the model for the process food distribution is given, consisting of the sub-processes *PR3.1 distribution of plant products* and *PR2.2 distribution of animal products*. First, gross consumption (supply) of plant and animal and fish products is calculated from national consumption data (FAO, 2019b,c) and regional adjustment factors. For plant products, this regional factor is determined by dividing the average numbers of days that a food item was consumed in the region by national values; for animal products, livestock numbers per capita according to regional data was divided by those of national data (see Table A.21 for details). Flows *(F3.1 plant based food, F3.2 animal based food and F3.im3 fish products)* are then established by multiplying gross consumption data with the respective food nutrient concentrations (see Tables A.11, A.12, A.13).

Second, import and export of plant and animal products (*F3.im1, F3.im2, F3.ex1 and F3.ex2*) is estimated by comparing production data to consumption behaviour. If gross consumption of a product exceeds production in the unit, the net difference is assumed to be imported and, if vice versa, to be exported. Generation of *market waste (F3.3)* is taken from Lederer et al. (2015) (= 0.08 kg cap^{-1} d^{-1} wet weight, only urban population) and multiplied with nutrient concentrations in organic waste (from Amoding, 2007; Komakech et al., 2014; Lederer et al., 2015; see Table A.22).

3.2.4. PR4 – food consumption

The process food consumption (Fig. 6) entails two sub-processes, namely *PR4.1 food preparation and consumption* and *PR4.2 household waste*. Uptake of nutrients from consumed food (Stock *PR4.1*) is assumed as 15, 5 and 5% for N, P and K, respectively. Of gross food consumption (*F3.1* and *F3.2*; Section 3.2.3) 0.23 kg cap^{-1} d^{-1} wet weight of *organic household waste (F4.i1)* are produced (data from Busia (UG)

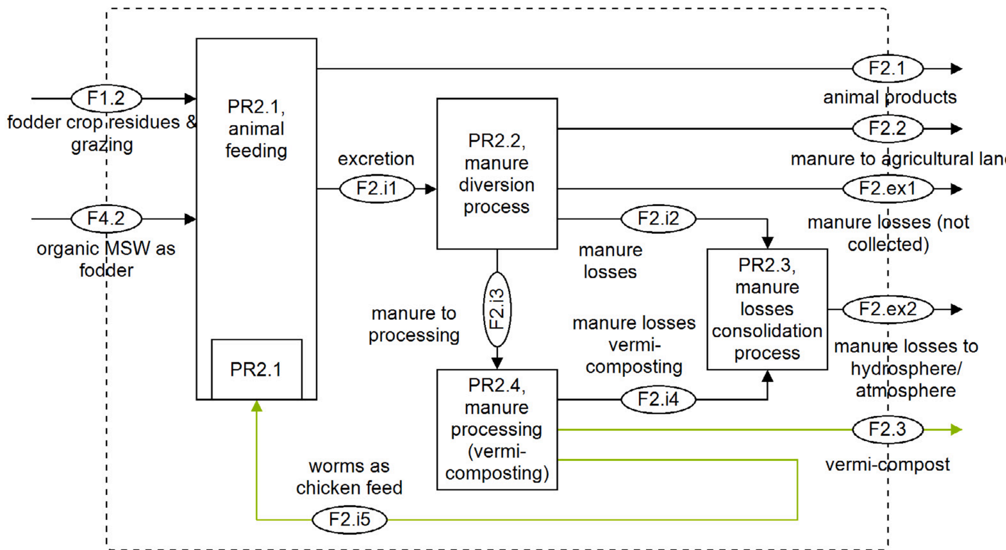

Fig. 4. Depiction of the material flow analysis model structure including flows and sub-processes of the process PR2 animal husbandry.

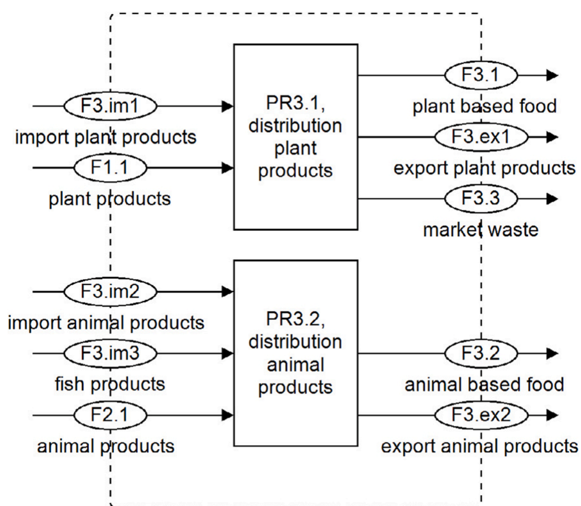

Fig. 5. Depiction of the material flow analysis model structure including flows and sub-processes of the process PR3 food distribution.

gathered by Lederer et al., 2012). The same nutrient concentrations as in market waste apply. In accordance with Lederer et al. (2012, 2015) 15% of organic waste generated in urban households is diverted to *F4.1 organic MSW to cropland* and 85% to *F4.ex1 organic MSW to other land or waste management*. In rural households 80% are diverted to cropland and the remaining 20% to *F4.2 organic MSW as fodder*. Excretion of nutrients via urine and faeces (*F4.3*) is calculated using nutrient excretion factors per g of protein consumed from Jönsson et al. (2004), national data on protein supply from FAO (2019b,c) (see Table A.23) and the regional adjustment factors as used for food consumption (see Section 3.2.3).

3.2.5. PR5 – sanitation

Fig. 7 shows the model for the process sanitation. Common sanitation facilities in the area are pit latrines (*F3.i2*). Few households have access to improved pit latrines, sceptic tanks and sewers (*F5.i3*), and extremely poor households practice open defecation (*F5.i1*). A small number of households have an UDDT (*F5.i4*) or collect their urine (*F5.i5*). Human excrement is distributed (*PR5.1 excrements distribution process*) according to official statistics (GoK, 2013b,a; GoK & KNBS, 2015; UBOS, 2017; UBOS & ICF, 2018; see Table A.24). All nutrients in excreta diverted to pit latrines, sewers, sceptic tanks or by open defecation are assumed to be lost (*F5.ex1*). Flows associated with UDDTs or urine collection in jerry tanks (*F5.i6, F5.i7, F5.i8, F5.1 and F5.2*) are explained in Section 3.3.

3.3. Scenario definition

For this study, four measures and technologies that have the potential to return or keep nutrients in agricultural soils are selected for further analysis (Fig. 8). *Measure I* entails the widespread implementation of erosion reduction practices on-site by the smallholder farmers themselves. The considered practices are grouped into 3 classes ('generalized support practices' (gSPs)), namely linear, extensive, and intensive practices. Assumptions on realistic adoption rates for these gSPs are based on farmers' data from the agricultural surveys by Mwanake et al. (in preperation) and Turinawe et al. (2018). Here, the 99th top percentile of the regionalized farmer survey data ('best-management farmers') within a region are taken as representative for the ambitious implementation rate of erosion reduction practices. A detailed description and methodology for the calculation of this scenario is documented in Appendix A.1.

Measure II involves the vermicomposting of animal faeces. Vermicomposting is a technology that biodegrades fresh organic material by the use of earthworms and microorganisms (Chew et al., 2019). Organic matter, like cattle manure, and water is continuously added to a wooden crate that contains earthworms, thereby producing fertilizer with stable nutrient concentrations after a period of three months (Lalander et al., 2015). For the scenarios, first, it is assumed that farmers collect all faeces excreted by their animals at the boma or the homestead at night (= 43%). Second, collected faeces are added to a vermicomposting unit continuously and vermicomposted for a minimum of three months (*F2.i3*). Values for losses of N, P and K through volatilization and leaching (*F2.i4*) – 18, 0 and 0% respectively – are taken from experiments conducted by Jjagwe et al. (2019). 7.0, 2.4 and 1.3% of N, P and K are taken up by earthworms (*F2.i5*) and used as chicken feed, and the remaining nutrients are applied via the finished product to the farmers agricultural plots (*F2.3*).

Measure IIIa is centred around an increased collection of human urine in jerrycans. The ease of adoption of this measure, as a rather simple and cost-effective method, has been tested by Andersson (2015) in the Sio-Malaba-Malakisi River Basin with positive results. Human urine is collected through a funnel in a jerrycan and stored for at least

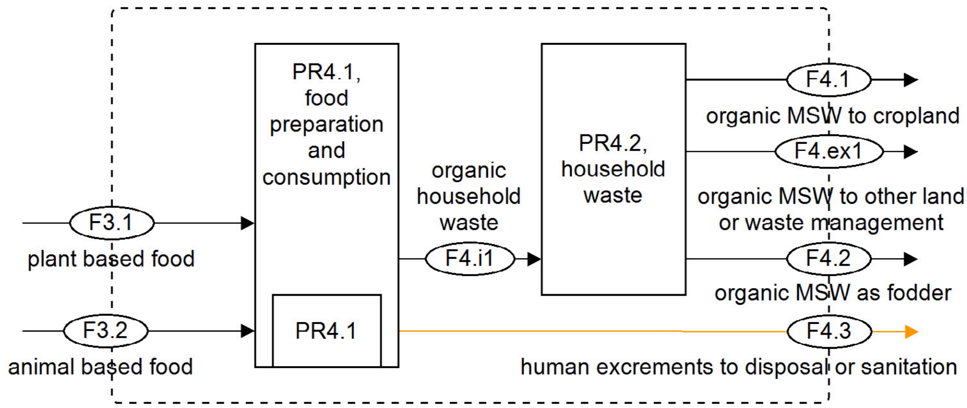

Fig. 6. Depiction of the material flow analysis model structure including flows and sub-processes of the process PR4 food consumption.

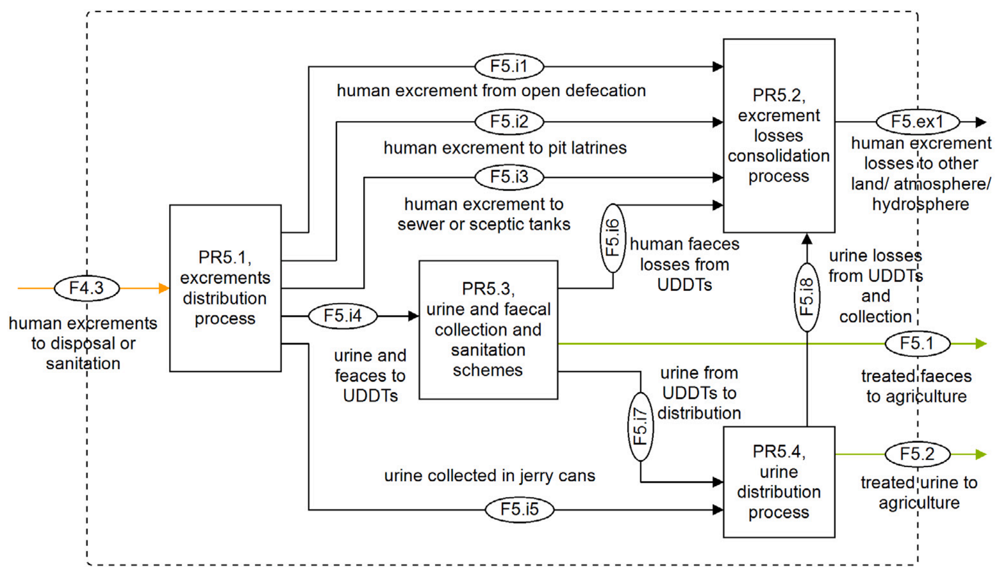

Fig. 7. Depiction of the material flow analysis model structure including flows and sub-processes of the process PR5 sanitation.

two weeks up to six months (Schönning and Stenström, 2004; Semalulu et al., 2011).

In contrast, *measure IIIb* revolves around the simultaneous but separated collection of urine and faeces in so called urine-diverting dry toilets (UDDTs). More nutrients can be reclaimed by this technology than by simple urine collection (considering N losses from storage theoretically up to 85% vs. 79% of all excreted N, 100% vs. 76% for P and 100% vs. 80% for K; based on data from Jönsson et al., 2004). However, it is also associated with higher initial and maintenance costs, and material shortages for certain parts have been experienced in the Sio-Malaba-Malakisi River Basin (Wakala, 2019). As a post-evaluation-study of UDDTs in Bungoma has shown, sanitation is a big driver of this technology and around 10% of households with functioning UDDTs do not use their fertilizer products (Schneider, 2019).

Based on experiences and data from Schneider, the following assumptions are made for scenarios IIIa and IIIb: (i) only a part of household members can use the UDDTs or collect their own urine; the elderly cannot because they experience problems with squatting, and children due to problems with handling. Realistically, the remaining amounts to about 80% of all household members. (ii) Of urine collected through jerrycans, all urine is applied to fields, as this is the main driver for collection. (iii) Of urine and faeces harvested through UDDTs, 72 and 80%, respectively, are used on agricultural plots. Losses of N from faeces and urine storage through volatilization are assumed with 50 and 10%, respectively (Jönsson et al., 2004). No losses of P and K are expected as faeces and urine are stored under dry conditions and/or in closed containers.

For reasons of simplicity, only two scenarios are defined, as measures I, II and IIIa/IIIb are addressing different aspects of the nutrient cycle and do not contradict each other. These are S.1 (combination of measure I, II and IIIa) and S.2 (combination of measure I, II and IIIb). In addition, S.0 is defined as the baseline scenario (= status quo).

3.4. Harvest response to nutrient application

After setting up the MFA for the status quo as well as for the scenarios, soil–nutrient-balances are determined by comparing input and output flows into agricultural land. The net nutrient input into agricultural soils is then inserted into nutrient response functions developed by Wortmann and Keith (2017) to analyse the impacts of an improved nutrient management on harvests. Following the method of Wortmann and Keith (2017), the theoretically achievable harvest (*yield*) is determined by the response coefficients *a*, *b* and *c* (derived from observational data), and the elemental nutrient rate *r* (net nutrient input in kg ha^{-1}; see Formula (1)).

$$Yield = a - bc^r \quad (1)$$

Maize is the main staple and the prevalent crop in most smallholder farms in the Sio-Malaba-Malakisi River Basin (cultivated by around 95% of farmers; UBOS, 2016a) and is therefore chosen as a reference

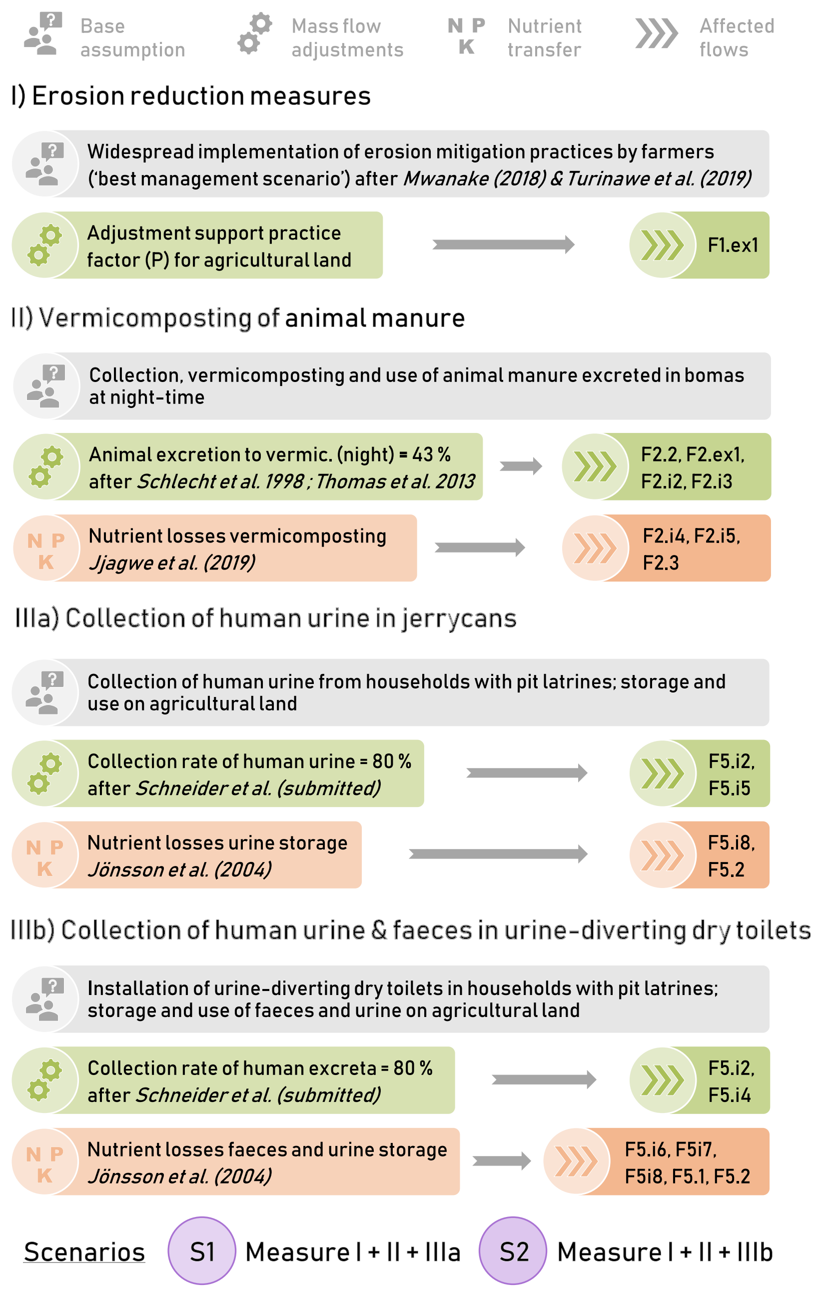

Fig. 8. Definition and overview of the analysed measures and scenarios as used in the material flow analysis.

crop. Further, the response coefficients given for the *Central Region — Lake Victoria Crescent* and *Eastern Uganda: 1400–1800 m.a.s.l. (Mt. Elgon High Farmlands)* (Tables 15.5a and 15.5c in Wortmann and Keith, 2017) are selected as being representative for the analysed units (values given in Table A.25). Thereby a maximum yield of 3.7 tonnes ha^{-1} season^{-1} can be achieved in this region with the available maize varieties. No values are available for K in those regions, therefore the response coefficients are taken from the *Western Kenya Lower (< 1400 m.a.s.l.)* region (Table 7.2f).

Before the yield response to net nutrient inputs can be calculated, the resulting flows from the MFA (both status quo and scenarios) need to be analysed for their relevance for the cultivation of maize. Analysis of data from Turinawe et al. (2018) shows, that 70, 70 and 20% of N, P and K in mineral fertilizer (*F1.im1*), respectively, are applied to maize fields; the rest to other crops. N-fixation (*F1.im2*) through maize is zero, and the effect of intercropping in maize fields is neglected for this analysis. For manure (*F2.2*), only the amount deliberately taken from the boma and applied to agricultural fields is considered. Data shows that around 50% of manure is spread on maize plots (Turinawe et al., 2018). The same share of usage is assumed for the other organic wastes (*F3.3* and *F4.1*). For the products gained by implementing the analysed technologies (*F2.3, F5.1* and *F5.2*), it is assumed that all is used for maize cultivation. Of crop residues, only those resulting from maize production are considered.

The total sum of nutrient inputs into maize plots is then reduced by the share of nutrients removed through erosion. For that, it is assumed that nutrient inputs are incorporated into the soil – and therefore evenly distributed – up to a depth of 20 cm (= topsoil). With a topsoil density of 1.5 g cm^{-3}, the share of eroded material on the topsoil layer is then calculated. Then, to determine the amount of nutrient inputs readily removed through erosion, this share is multiplied with the inputs per g of the topsoil layer and the nutrient enrichment factors from Section 3.2.1 .

Table 3
Nutrient balances in Uganda and Kenya in kg ha^{-1} yr^{-1} for scenarios S.0 (status quo), S.1 (erosion reduction + vermicomposting + urine collection) and S.2 (erosion reduction + vermicomposting + urine-diverting dry toilets) as determined by the material flow analysis.

Scenario	N			P			K		
	S.0	S.1	S.2	S.0	S.1	S.2	S.0	S.1	S.2
Bungoma	−110	−81	−83	−15	−10	−9.8	−150	−130	−130
Busia (KE)	−57	−40	−42	−8.1	−4.9	−4.7	−88	−75	−75
Busia (UG)	−31	−24	−25	−5.7	−4.4	−4.2	−43	−38	−37
Manafwa	−150	−110	−120	−24	−18	−18	−180	−150	−150
Tororo	−38	−28	−30	−6.4	−4.8	−4.6	−54	−49	−49

As the nutrient response functions are determined for fully plant available nutrient sources (= mineral fertilizer), the effectiveness of each waste and product has to be determined and accounted for. Factors used for the plant availability of the different sources are taken from literature (Jönsson et al., 2004; Shah et al., 2012; Duboc et al., 2017; Kratz et al., 2019) and can be found in Table A.26.

4. Results

4.1. Nutrient balances for agricultural soils in the Sio-Malaba-Malakisi River Basin

The nutrient balances for the five units and for the reference year 2014 were successfully calculated by reaching a flow equilibrium in STAN. Final balances of the processes and stocks, and flow results can be found in Table 3 and Appendix B Table B.1 ff. Inputs and outputs into agricultural soils, as well as the net balance and uncertainty for each unit are shown in Fig. 9. Negative nutrient balances have been found for all three nutrients, N, P and K, and in each unit. The soil nutrient deficit ranges between −30 to −150 kg ha^{-1} yr^{-1} for N, from −6 to −24 kg ha^{-1} yr^{-1} for P and from −43 to −180 kg ha^{-1} yr for K, thereby revealing large differences in the analysed units. In comparison with nutrient balances from Uganda (see e.g. Wortmann and Kaizzi, 1998; Sheldrick et al., 2003; Nkonya et al., 2005; Lederer et al., 2015), this study shows much higher net soil nutrient deficits at least for some of the units (literature values: −11 to −35 kg N ha^{-1} yr^{-1}, −1 to −16 kg P ha^{-1} yr^{-1} and −18 to −60 kg K kg ha^{-1} yr^{-1}). As can be seen from the following results, these differences are mainly attributed to high erosion rates, as some of the analysed units show a much higher risk than the units studied in the mentioned literature.

Results can only be taken as indicative, as the uncertainty for the net balances lies between 27 and 66% depending on the unit and nutrient. In general, the biggest input of nutrients into soils is the application of manure. Inputs of mineral fertilizer (mainly N and P) vary widely among the five units, with farmers using significantly more fertilizer on the Kenyan side. Inputs from N-fixation or organic wastes and crop residues are less pronounced and mainly play a role for K inputs. Animal feeding (fodder from fallow & pasture) and erosion are the two biggest output flows, however their importance for the units differs. While, as expected, the hilly and steep units Bungoma and Manafwa experience high outputs of nutrients through erosion, the results reveal it being less of a problem for Busia (UG) and Tororo. Units with a higher livestock density – Bungoma, Busia (KE) and Manafwa – experience high outputs from soils through fodder. Outputs through plant products and crop residues vary depending on the agricultural productivity of the units, but are in general attributed with a lower impact than the prevalent landscape (erosion) and livestock ownership.

4.2. Uncertainty of the material flow analysis results

Uncertainties for selected flows are given in Fig. 10. Close to half of all flows (45%) exhibit an uncertainty of less than 25%, and another 36% an uncertainty of 25–50%. Few flows are attributed with a high uncertainty of > 50%, mainly those connected with import and export of nutrient containing products (low to no data availability). Furthermore, nutrient flows by erosion, especially for P and K, show a higher uncertainty than most flows.

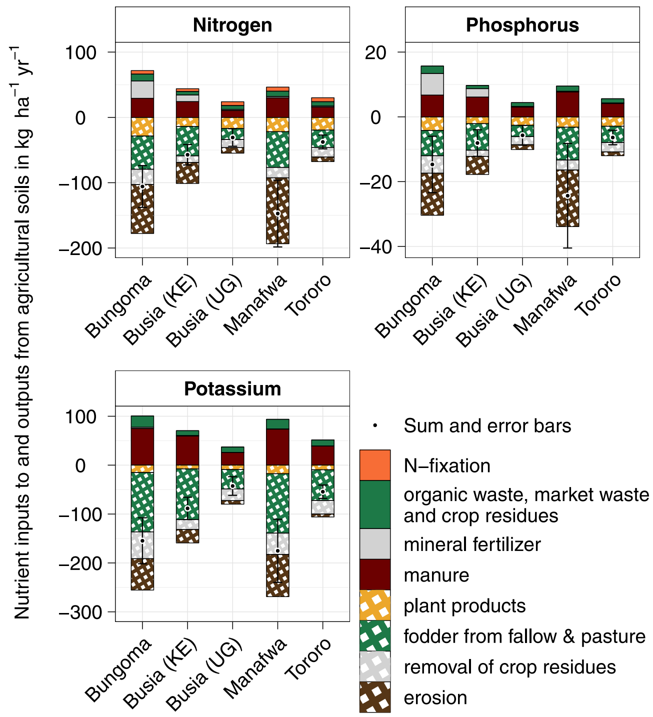

Fig. 9. Results for nutrient out- and inputs into agricultural land (arable, grassland and fallow) for the different units in Uganda and Kenya and the status quo (S.0) in kg ha^{-1} yr^{-1}. Flows F1.i4 + F3.3 + F4.1 are aggregated to *organic, market waste and crop residues* for reasons of clarity. Flows F2.2, F5.1 and F5.2 are excluded for S.0.

4.3. Improvement of the nutrient balances by implementation of the analysed measures

Overall, by implementing the proposed measures, the soil nutrient deficit in the units could be reduced by 20–30%, 23–42% and 9–15% for N, P and K, respectively (see Table 3). Both Scenarios S.1 and S.2 show a very similar rate of improvement, and, considering the uncertainty of the data, no significant difference can be found. Thus, when social restrictions and the reduced accessibility of UDDTs for elderly is taken into account (Section 3.3), a similar amount of nutrients can be collected via urine collection as with UDDTs.

The county Busia (KE) has the highest relative potential to lower its losses. This is likely attributed to the fact that it is both hilly and has a high rate of population to agricultural land, and ideal preconditions for the implementation of erosion reduction practices and urine and/or faeces collection. The steep units Bungoma and Manafwa exhibit the highest absolute potential for improvement. It can be gathered from Fig. 11 that this is due to a high susceptibility of these units to erosion reduction practices. In general, it can be seen that the application of urine and erosion reduction practices can contribute slightly more nutrients to agricultural land than vermicomposting, however importance varies highly between the units and nutrients. The application of treated faeces is only relevant for P and K, but urine remains the main source in excrement for these nutrients. In the flat districts of Busia (UG) and Tororo, urine collection and treatment, and vermicomposting clearly have a higher potential than erosion reduction practices.

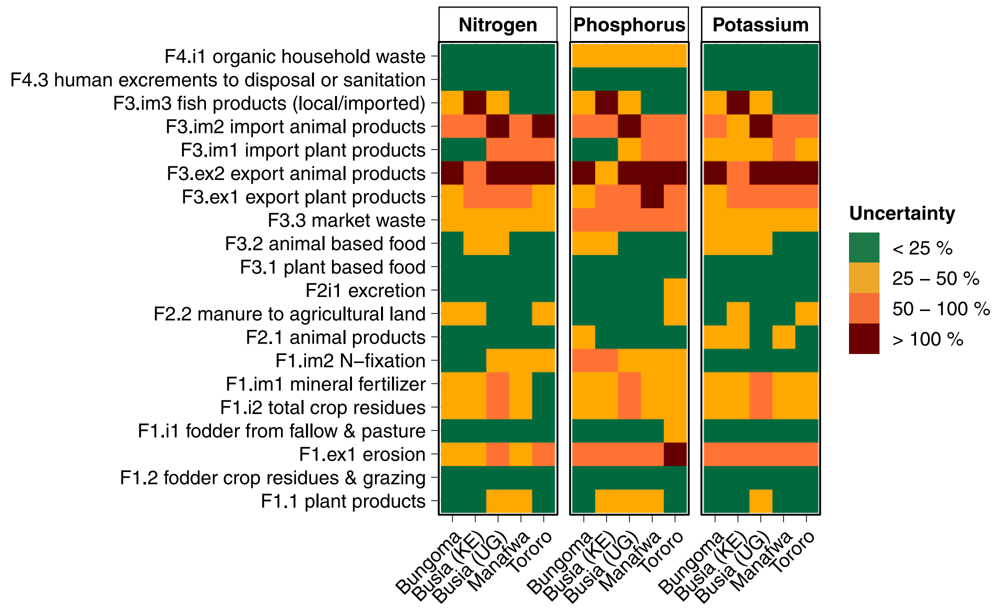

Fig. 10. Range of uncertainty of the calculated flows depicted for selected flows and for each unit and nutrient.

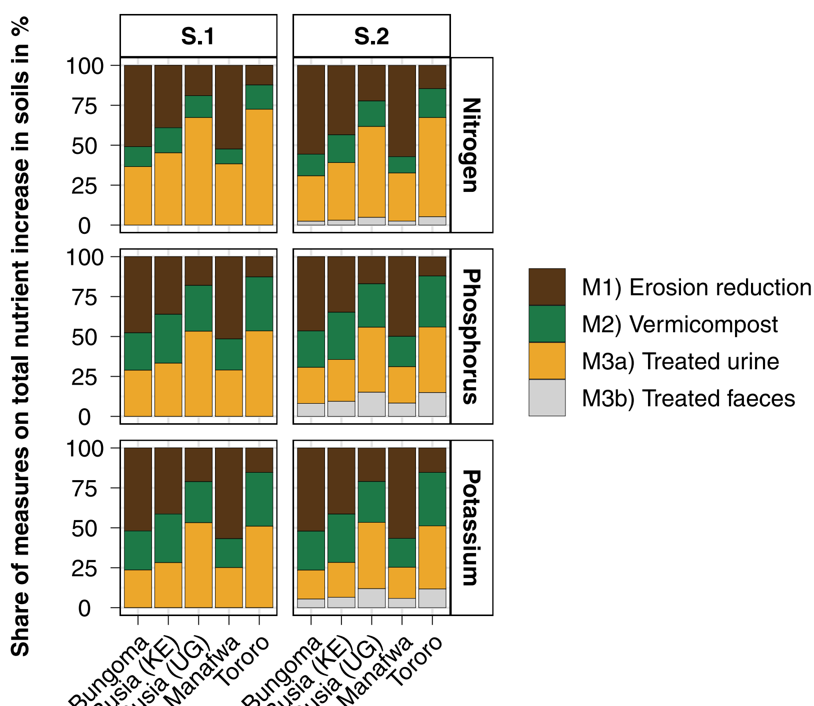

Fig. 11. Contribution of the analysed measures to the total improvement of the nutrient balance in the agricultural soils of selected districts and counties in Uganda and Kenya as analysed for scenarios S.1 and S.2. given in % of improvement.

4.4. Harvest response

The mean maize harvest of the Status Quo (S.0), as a function of the currently applied nutrients and modelled with the crop–nutrient-response functions from Wortmann and Keith (2017), lies between 2.3–3.3 t ha^{-1} $season^{-1}$. This theoretical maize harvest is thereby significantly higher than the actual range of 0.8– 1.5 t ha^{-1} $season^{-1}$ as reported in official data for the analysed units (KNBS, 2015a,b; UBOS, 2020). As other farming practices or environmental factors are not considered in this study, it is necessary to mention that the response given is likely overestimated by the model, even though the crop response functions were derived from field trials in the region.

According to the analysis, N is the limiting nutrient for maize harvests in the region (Table 4) and P and K are already applied in sufficient amounts for maize growth (Table B.6). Therefore, the potential yield increases for the scenarios are derived from an increase in N application. In the Kenyan counties, especially Bungoma, the impact on maize yield by the implementation of the analysed measures is limited (8–20%), as farmers already apply medium amounts of N-fertilizer. In contrast, on the Ugandan side, an about 30–40% higher harvest is estimated by the model for both scenarios, as inputs are generally low.

Looking at the impact of the different measures on the increase of maize harvests (Fig. 12), the pattern of importance changes in

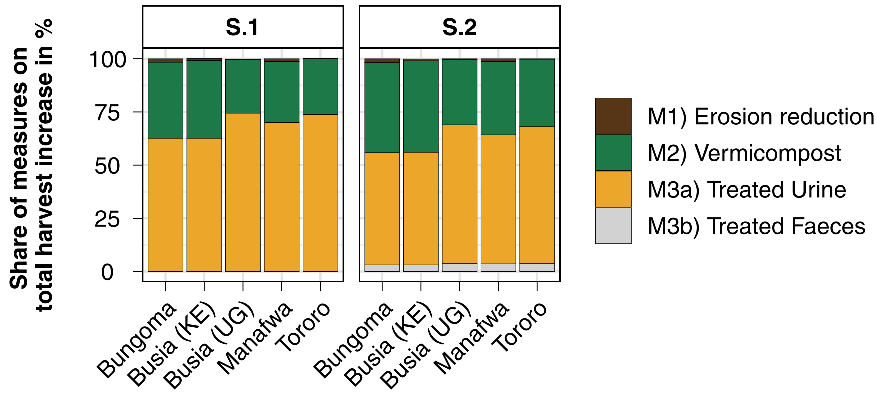

Fig. 12. Contribution of the analysed measures to the total increase of maize harvests as analysed for scenarios S.1 and S.2. given for each studied district/county in Uganda and Kenya in %.

Table 4
Results for the mean harvest response of maize to nitrogen application in selected districts or counties in Uganda and Kenya in t ha^{-1} $season^{-1}$ for the status quo S.0 and the scenarios S.1 and S.2 given for each analysed district/county.

Scenario	S.0	S.1	S.2
Bungoma	3.3	3.6 (+8.3%)	3.5 (+7.5%)
Busia (KE)	2.9	3.4 (+20%)	3.4 (+18%)
Busia (UG)	2.3	3.1 (+33%)	3 (+29%)
Manafwa	2.5	3.5 (+42%)	3.4 (+39%)
Tororo	2.4	3.3 (+40%)	3.2 (+36%)

comparison to that of the nutrient balances. Crops will preferentially take up the newly added and easily available nutrients from the soil matrix. Erosive forces however, remove only a small amount of the freshly applied and easily available nutrients, the higher share will be from less-available nutrient-deposits. This is due to the fact, that fresh sources are typically worked into the soil up to a depth of 20 cm, therefore erosive forces removing the topsoil layer can simultaneously only remove the share of freshly available nutrients found in the top few millimetres. As modelled in this study, the influence of erosion reduction practices on harvests is therefore negligible, especially if N is the limiting nutrient.

Similarly, in this case, faeces' contribution is small, as they contain only the minority of N in excrements. In contrast, a combination of urine collection and vermicomposting of manure on an average smallholder farm would lead to the highest yield increases resulting from N availability.

5. Discussion

5.1. Model choices

Choosing small units with high diversity on the district level provided much needed information on the range of soil nutrient deficits that can be expected in Uganda and Kenya. This diversity is mainly attributed to differences in the landscape, rain and erosion, but other factors, like the economic ability of farmers to buy fertilizers or livestock numbers, played a part as well. In addition, regional resource restrictions (livestock manure, human excreta) could be adequately depicted by studying the districts as a whole entity.

However, as stated by Droppelmann et al. (2017) and Vanlauwe et al. (2017), the high diversity of farmers production systems needs to be accounted for when looking at the potential for technology adoption. Here, the current district-wide analysis poses a significant drawback, and future research should therefore try to scale the results to different farming systems as done in Ritzema et al. (2017) and Wichern et al. (2017). Current erosion and deposition models should be improved to better track and trace erosion without the need for data- and time-intensive models.

Combining 'traditional' nutrient balances with a harvest model proved highly insightful. While the results for the nutrient deficit and the potential harvest increase in the units vary based on the preconditions, the harvest model shows that treated urine and vermicomposting are the most effective measures in all five units if only the nutrient supply is considered. While many material flow analyses for the western world focus solely on P (Wichern et al., 2017), adding K and especially N to the analysis proved valuable since (i) N is rarely applied in excess in SSA and (ii) the importance of different input and output flows for the different nutrients varied highly. Unfortunately, including organic matter in MFAs still poses a big challenge due to severe data limitations (van der Wiel et al., 2020). Especially from a long-term-perspective, the strong focus solely on nutrients thereby likely underestimates the need of erosion reduction practices in steep areas and of organic matter from faeces and manure.

While MFAs typically focus on maximum potentials of different measures using all available resources (van der Wiel et al., 2020), this study tried to include realistic expectations on what amount of resources (in this case manure and human excreta) could be indeed allocated to new technologies. It was revealed that only about 60 and 30% of N in human urine and faeces and 30% of N in manure could be directed to agricultural land through urine collection, UDDTs and vermicomposting respectively. Further, using data on the currently used erosion reduction practices of the 'most ambitious' farmers in the area showed that nutrient losses through erosion could realistically be reduced by 20%, an indication that a higher reduction is unlikely. Determining these achievable values is seen as an important aspect to adequately represent a technologies' limitation to farmers, ensuring that its widespread adoption is not hampered by unmet expectations (Vanlauwe et al., 2017).

5.2. Data availability and uncertainties

Three major sources of uncertainty surfaced during the analysis. First, crop data from the region, though generally available, often lack in quality. As the careful processing of the statistical reports showed, both crop areas and crop harvests are often unrealistic and unreliable. Statistical crop data is usually gathered by questioning farmers on their production and crop areas. It is assumed, that the intermixing of the units 'ha' and 'acres' creates confusion with the smallholder farmers and thereby creates potential for errors in the final results. As much of the farmers' produce is used to fulfil the households food requirements, farmers also have less need to keep track of their harvests. To address the first issue, it is suggested that future agricultural surveys do additional hands-on measurements of farmers land in some households, to at least determine the associated rate of error. Also, while intercropping is advantageous for the farmers, it remains difficult to include this process in nutrient balances. A special focus of future surveys on intercropping could provide needed insights into this issue.

Second, not all data was available for every flow on a regional level. Whenever possible, data was adjusted with regional factors, however for some (e.g. mineral fertilizer application) only national mean values could be applied. For future research, it is suggested to improve the knowledge on actual fertilizing rates. Nevertheless, the high difference between the use of fertilizer in Kenya and Uganda is well depicted by the current data, and certainly provides some indication of reality.

Third, determining the rate of erosion and the outputs of nutrients continues to prove difficult, as reflected in the high uncertainty determined in this study. For one, calculating the potential soil loss through the use of the USLE can give highly varying results depending on the provided input parameters (Schürz et al., 2020). Since many results from erosion studies in SSA on the plot scale only provide anecdotal information, the net soil loss from agricultural land can currently only be a crude estimate. Until more sophisticated and detailed spatial models are available, this will remain a challenge.

5.3. Potential impact of the analysed measures on food security

The four analysed measures use the locally available resources human excrement and animal manure or erosion reduction to improve nutrient inputs or reduce nutrient losses. It is shown, that all measures can contribute to improve the soil nutrient deficit, but only urine and vermicomposting have an intermediate effect on maize harvests. A few inferences can be drawn from this information.

First, it is revealed that the swiftly implemented measure of urine collection in jerry cans has the same potential to increase food security as the collection of urine and faeces through UDDTs. Financial means are highly limited in the resource-constraint smallholder farms in the region, and a main obstacle to UDDT access are the economic capabilities of households (Tumwebaze et al., 2011). It is therefore clear that nutrient recycling – an aspect that UDDTs are often promoted for Jönsson et al. (2004) and Langergraber and Muellegger (2005) – cannot be a vital driver for the implementation of UDDTs in the area as also shown by Schneider (2019). Further, human urine is an environmental friendly fertilizer (Malila et al., 2019) and its use is both safer and more easily accepted than human faeces (Andersson, 2015). Therefore, while efforts to improve sanitation in those areas should continue, efficient nutrient recycling can be more easily achieved through simpler interventions.

Second, vermicomposting of manure can significantly improve the current typical manure management of partial collection and storage, using only locally and easily available building materials. However, the bottleneck for this technology remains the labour force required to collect the spread out excreta of freely roaming cattle and other animals. As on-farm labour availability is limited in smallholder farms (Schreinemachers, 2006), this needs to be taken into account when promoting vermicomposting as a strategy for livestock owners. The added-value of harvesting not only vermicompost, but also worms that can be used as a protein-source in smallholder poultry production (Lalander et al., 2015; Nalunga et al., 2021), may aid in overcoming this problem .

Third, the reportedly high effect of soil erosion on yields in SSA (see e.g. Lal, 1995a) could not be underpinned by the short-term nutrient response model. If nutrient inputs are well mixed into the first 20 cm of soil, as modelled in this study, the amount of freshly available nutrients removed through erosion is generally low, as only about 1% of the top soil layer is eroded each year. Therefore, by studying the effect of erosion on the soil nutrient deficit alone, its effect on harvests is potentially overstated. This is not a call to underestimate the impact of erosion both on yields, and on rivers and lakes (e.g. river water quality for drinking water supply) in SSA. However, other models and field observations (e.g. long-term plot scale trials) are needed to appropriately address this issue.

6. Conclusions and prospects

The nutrient balances performed in this study by the use of MFA showed highly varying soil nutrient deficits for district and counties of close vicinity in the border region of Kenya and Uganda. The soil nutrient balance for the steeper part of the Sio-Malaba-Malakisi-River-Basin exposed much higher deficits than previous studies have found for other regions in Uganda, a fact mostly attributed to a high susceptibility for erosion. Next to erosion, the requirements of fodder for animals, the (non)use of mineral fertilizer and the amounts of manure being excreted or applied on agricultural land are the biggest factors involved in the severity of the deficit. In general, uncertainties in the model were mainly attributed to inconsistencies in official crop statistics, lacking data on import and export flows, and a difficulty to validate the modelled erosion rates.

Overall, there exists a non-negligible potential of local resources to reduce the soil nutrient deficit, improve harvests, and in turn, food security of the smallholder farmers in the Sio-Malaba-Malakisi River Basin. It was shown that simple and easily available technologies like urine collection and vermicomposting can often harness similar amounts of nutrients and improve yields as well as more complex and expensive ones. If all of the specific technologies drawbacks are adequately taken into account, e.g. the non-use of UDDTs by elderly people, a better comparison of different technologies and their contribution to the analysed goals can be achieved.

Agricultural extension workers and governmental subsidies should therefore focus on supplying the right technologies to those who need it and account for the regional variation in agroecological and socio-economical perspectives of smallholder farmers. In unison, future research should continue to include regional preconditions, local variety of smallholder farming systems and the factual access of farmers to resources and markets into their work. Further, there is a strong need for improved and long-term erosion measurements in these areas, to rightly enable the quantification of soil losses, negative impacts and reduction potentials.

CRediT authorship contribution statement

Arabel Amann: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Mathew Herrnegger:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Jeninah Karungi:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition. **Allan John Komakech:** Data curation, Supervision, Project administration. **Hope Mwanake:** Formal analysis, Investigation, Data curation. **Lea Schneider:** Formal analysis, Investigation, Data curation. **Christoph Schürz:** Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Gabriel Stecher:** Formal analysis, Investigation, Writing – review & editing. **Alice Turinawe:** Investigation, Data curation, Supervision, Project administration. **Matthias Zessner:** Methodology, Supervision. **Jakob Lederer:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.128510. Materials include tables and description of input data, numeric results from the MFA and the harvest response analysis.

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