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Management of harvested C in smallholder mixed farming in Ethiopia

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ABSTRACT

Increasing the share of the harvested C ending up in food and returned to soil could contribute to climate change mitigation and food security. The aim of this study was to quantify empirically the proportion of the harvested C ending up in food and soil and the C losses occurring when managing harvested C in smallholder mixed farming systems in Ethiopia. Four case farms were explored; one resource-limited and one better-off farm, in two socio-ecologically contrasting regions important for food production. Material flow analysis (MFA) was used to determine the flows of harvested C. The losses of harvested C, from the livestock, compost and household energy use were quantified based on C balances. The C flows were estimated as means for two growing seasons, 2008/2009 and 2009/2010, with low and average precipitation, respectively. Analysis was founded on semi-structured interviews and sampling, supplemented with information from databases and the literature. From the total harvested C, 9–16% was allocated to food and 4–12% to agricultural soil. Since the residues are utilized apart from human excreta with a negligible significance, increasing the proportion of harvested C used for food and returned to soil is in these farming systems only possible by reducing the gaseous C losses. The largest losses of the harvested C occur through biomass burning (15–60%), animal metabolism (16–44%) and composting (5–23%). The large C loss through the replaceable residue burning seems to offer the most accessible remedy to smallholder management of harvested C. Consequently, the proportion of harvested C used for fuel appears as the main determinant for the proportion of harvested C ending up in soil and food. Energy substitutes for manure and straw, improved manure management and more stable food and fodder supply to reduce the requisite number of animals are all keys to close C cycles in the farming systems. Quantification of the organic C flows using MFA is useful in revealing the allocation of harvested C and losses occurring in its management in farming systems when measurement of gaseous emissions and leaching are not feasible.

1. Introduction

Climate change poses a threat to food security in sub-Saharan Africa (SSA), where economies are highly dependent on agriculture (IPCC, 2007). Thornton et al. (2011) estimated a 24–71% decrease in crop yields by 2090, and in places a shift from crop production to livestock husbandry, although these figures imply a high degree of uncertainty. Simultaneously, high population growth and soil degradation exert pressures to increase agricultural productivity. Carbon (C) sequestration in agricultural soils has the greatest potential to mitigate climate change in SSA agriculture (Smith et al., 2008), and to increase agricultural productivity (Lal, 2004). In farming systems, food security and C sequestration can be enhanced by allocating a high share of harvested C to food and agricultural soil. Such development can be contributed to by reducing C losses before harvested C ends up in food or soil.

In agriculture, carbon dioxide (CO_2) is assimilated during photosynthesis in crops and rangelands. Part of this C is released back into the atmosphere during plant and soil respiration or fire, part of it being stored in soil organic matter (SOM) and in harvested biomass and animal products, and part being liable to erosion and leaching as dissolved organic and inorganic carbon and methane. Biomass C is harvested as crops and through grazing of livestock and collecting fuel wood. Harvested C can also be imported into the farm as fodder, food, fuel, construction material and organic soil amendments. The quantity of harvested C lays the ground for availability of food and soil amendment, but there are also other competitive uses for these resources.

Agriculture in Ethiopia is characterized by low-input and low-output production (Devereux, 2000). The pressure to satisfy the need of the growing population for food and fuel has decreased holding size, intensified agriculture, and reduced forest cover

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(Bationo et al., 2007; Pohjonen and Pukkala, 1990) to a current 4% of the land area (Berhanu, 2005). The decrease in forest resources has led to the use of dried cow dung for fuel, while crop residues are mainly used as fodder for livestock (Corbeels et al., 2000). Therefore, return of residue C to the soil is reduced, which in turn reduces soil productivity.

Allocation of a higher share of harvested C in food would directly improve food security. Further, returning a higher share of harvested C not used as food to soil would contribute to increasing soil C storage (Girmay et al., 2008) and improve soil nutrient supply and water holding capacity, and consequently soil productivity and stability of food supply (Lal et al., 2011).

About 72% of greenhouse gas (GHG) emissions in Ethiopia originate from agriculture (WRI CAIT, 2013). Most of the emissions comprise methane (CH_4), enteric fermentation being the largest source, totalling 28,077,000 tonnes of (CO_2) equivalent (Tadeke, 2001). More than twice as large emissions occur in biomass burning in households totalling over 66,000,000 tonnes of CO_2 (Tadeke, 2001). Emissions from bioenergy are not, however, added to inventories of national emissions reported to UNFCCC as they are considered "carbon–neutral", corresponding to the amount of C bound from the atmosphere in photosynthesis (Metz, 2007). On farms, however, fuel use and soil amendment compete for the scarce resource of residue C.

Material flow analysis (MFA) (Brunner and Rechberger, 2004) allows direct tracing of C material flows and indirectly also the gaseous losses from these flows through C balance counting, and thus quantification of the proportion of harvested C used for food and soil. Such analysis provides valuable information that further research can exploit to assess the impacts of changes in C management practices on household welfare and potential to sequester C. Such a C budget approach has strengths and weaknesses analogous to those of nutrient budget approaches (Oenema et al., 2003; Öborn et al., 2003), an important strength being accessibility of the primary data to the researcher. To date, there are few empirical data on the use of harvested C for food and soil amendment, or about the potential to improve the resource-use efficiency in farming systems. To our knowledge, organic C flows and C losses in East African farming systems have not been studied before. Empirical quantitative case studies of the flows of harvested C and losses occurring in its management in Ethiopian farming systems provide in-depth understanding of the use of this valuable, scarce resource and of the significance and causes of the various losses.

The aim of the study was to increase understanding about the potential to enhance the use of harvested C for food and soil amendment on mixed smallholder farms in East Africa. The examination focused on the losses of harvested C reducing the share ending up in food and soil. The following research questions were posed: What is the proportion of harvested C allocated to food and soil in smallholder mixed farming systems in the Ethiopian highlands? What are the major losses of harvested C reducing the proportion allocated to food and soil? What are the determinants for the proportion of harvested C used for food and soil and of the C losses? The usefulness of MFA to indicate C the proportion of the C use and C losses in farming systems was also discussed. Smallholder mixed case farms with Good Agricultural Practices (GAP) (FAO, 2003) in the Ethiopian highlands, with limited and greater resources were studied in two regions contrasting in agroecological and socioeconomic conditions.

2. Materials and methods

An instrumental case study approach was used, where the cases were explored to understand causal relations and mechanisms of the phenomenon (Creswell, 2007; Stake, 1995). Documents and data from the national and local archives and agricultural offices were used in addition to interviews, sampling and published literature (Yin, 2003). Two representative but contrasting case regions and two farms in each region were selected for this collective study (Stake, 1995) to facilitate generalization (Yin, 2003).

2.1. Case characteristics

The topography of Ethiopia varies since the East African Great Rift Valley divides the high plateau diagonally. The Ethiopian economy relies on agriculture, which accounts for 43% of total GDP (CountrySTAT, 2012) and employs 85% of the population (CIA, 2012). Around 60% of Ethiopian farms cultivate less than 0.9 ha and 40% less than 0.5 ha (Taffesse et al., 2011). The present study was carried out in Kobo, on the border of the cool semi-arid and warm semi-arid agroecological zones, and Sire, on the border of cool semi-arid and cool sub-humid agroecological zones (Harvest Choice/IFPRI, 2009), on the slopes of the Great Rift Valley (Fig. 1). The sites represent relatively food-insecure and food-secure regions of Ethiopia, respectively (See Appendix A). Kobo is characterized by severe soil degradation and low soil fertility, small land holding size, high water stress and low crop yields compared with Sire (World Bank, 2004) (Appendix A). Low income, due to lack of off-farm employment opportunities, has worsened poverty and hindered access to food. At the turn of the 21st century the number of people receiving food aid ranged between 27% and 50% of the total population (Ali, 2002). Sire represents an area of greater potential for food production as it has higher precipitation and more land available. Both districts represent important food production areas in Ethiopia (Taffesse et al., 2011). Due to local variation in precipitation and lack of weather station data for rainfall intensity we relied on farmer descriptions (Regassa et al., 2010) of the annual weather relative to the long-term average (Appendix A). According to farmers, 2008/2009 was low and 2009/2010 average in precipitation, on all of the case farms.

Highland temperate mixed farming prevails in both case regions. It is the most common farming system type in Ethiopia and is conducted on approximately a third of the land area, a share similar to that allocated to pastoralism. In East Africa this farming system covers 5% of the land area (Dixon et al., 2001; FAOSTAT, 2011). Livestock represents financial security, draft power, transportation, fuel and cultural values. Animals graze freely on communal rangeland and on field plots after harvesting. Poor livestock nutrition due to lack of forage limits productivity and increases emissions per product unit. In Kobo, subsistence production dominates and is constrained by erratic rainfall and lack of inputs. In contrast to Sire, sorghum (*Sorghum bicolor* L.) is widely cultivated in Kobo for its drought tolerance. In Sire, crop rotations are more diverse than in Kobo, and include cash crops such as pulses and vegetables. Agroforestry is practised around the homesteads on many farms. The agroecological and socioeconomic characteristics of the case regions were described in detail by Kahiluoto et al. (2012).

As available resources substantially influence the use of inputs in cropping (Mwaniki, 2005), in each of the two regions we selected one case farm with limited resources and another with greater resources, compared with the average for the district (Table 1). Farmers with limited resources participated in the Productive Safety Net Programme, a social protection scheme under the national Food Security Program, addressing chronically food-insecure people (Negatu, 2008). Better-off farms with greater resources had more field area and livestock and more advanced agroecological management practices than on average for the region. All four case farms applied GAPs (Table 1). Farms representative of size, number of livestock, degree of food aid, and applied management were selected from within each of the

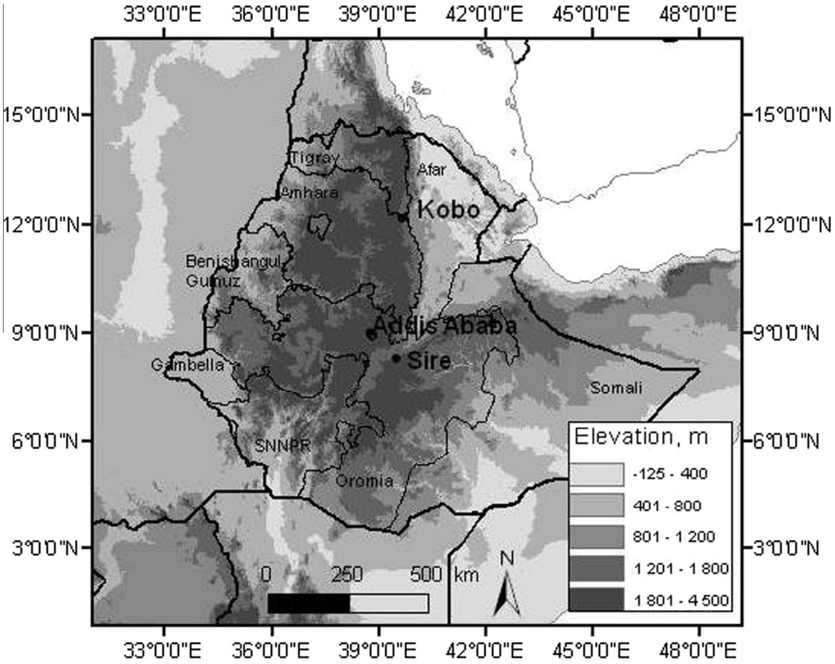

Fig. 1. Location of the case regions in Ethiopia (Kahiluoto et al., 2012).

two socioeconomic groups of each region. The selection was done with the help of local agricultural advisers with broad local expertise.

2.2. Definition of the studied system

The farming system, defined on a functional basis, composed of cropping, livestock raising and grazing, composting and household food and energy consumption (Fig. 2). The harvested C produced in the crop fields were grain for food, and straw for fodder and fuel, and in the rangeland hay for livestock fodder and for compost-making and fuel wood for the household energy. In addition, harvested C was supplemented from markets, neighbors and charity. The livestock included the animals of the farm that produced animal products for household consumption and for sale, and manure and urine for fuel and compost. The study focused on the flows of the harvested C (i.e., the C management system), to quantify the proportion of harvested C allocated to food, soil and C losses (Fig. 2).

2.3. Material flow analysis

MFA was used to trace the C material flows and to quantify the proportion of harvested C used for food and soil. C losses occurring before harvested C ended up in food or soil were calculated based on material C balances for processes of livestock raising, composting and household biomass burning. The C flows were quantified through semi-structured interviews and sampling, and complemented and double-checked with information from the published literature (see Section 2.3.1). The C contents of flows were calculated by multiplying the mass of the flow per single year by its C concentration. To get an average estimation, flows were studied over two one-year periods. The results were reported as the mean of the two years. There was no fire or significant construction work on the farms during the study years.

2.3.1. Calculation of the C flows

2.3.1.1. Cropping. The quantity of imported seeds (Se) and compost (Co), as well as the quantity of exported crops was based on farmer estimation. The crop (Cr) and straw (St) yields estimated by the respondents for the 2009/2010 growing seasons were double-checked by sampling. Crop yields were manually sampled at harvest time of the main growing season in October–November 2010. Two 1 m^2 plots in each cultivated field were harvested. The fresh weight of grain and straw were recorded. Three replicate samples were separated from each plot sample for further analyses. The DM% (w/w) was measured by drying at 105 °C for 12 h at Melkasa Ethiopian Institute of Agricultural Research. Since the export of wheat (*Triticum L.*) and teff [*Eragrostis tef* (*Zucc.*) *Trotter*] from Ethiopia was forbidden, estimations of their C concentrations were based on previously reported figures (Table 2). C concentrations for seeds (Se) were based on measurement if a particular species was analyzed or from the literature. C concentration for grain and straw of haricot bean (*Phaseolus vulgaris L.*), barley (*Hordeum vulgare L.*) and sorghum were determined using a Leco CN analyzer at the laboratory of MTT Agrifood Research Finland (Table 3).

2.3.1.2. Grazing. The quantity of manure (Ma) and urine (Ur) that remained in the rangeland during grazing was estimated at 40% of the total manure production (Haileslassie et al., 2005; Manlay et al., 2004). The DM content of rangeland hay (Ha) was estimated at 93% (Kabaija and Little, 1988). C concentration for hay was based on reported figures (Table 2).

2.3.1.3. Livestock raising. The livestock population was converted into tropical livestock units (TLU). The conversion factors were 0.7 for cattle and mules, 0.15 for sheep and goats, 0.5 for donkeys, 0.01 for chickens, 0.8 for horses, and 1 for camels (Jahnke, 1982). The daily feed intake was estimated by multiplying the DM weight of manure by feed digestibility (Ibrahim and Olaloku, 2000), as: $DM\ intake\ (\text{g/day}) = 100/(100 - digestibility) * DM\ weight\ of\ manure$, where digestibility is given as a percentage. The digestibility of feed was estimated at 50% (Preston and Leng, 1987; FAO, 1999) and the production of manure (Ma) of one TLU at 3000 g DM per day for cattle (Haileslassie et al., 2009; FAO, 1999). The daily feed intake was estimated at 6000 g DM/day/TLU. To double-check this result we compared the figure with the assumption of daily feed intake of 2% of body weight reported by FAO (1999). Our result differed from the previously reported value by 4–17%.

Table 1
Characteristics of the resource-limited and better-off case farms in Kobo and Sire regions.

	Kobo		Sire	
	Resource-limited	Better-off	Resource-limited	Better-off
Holding size[a], ha	0.75	1.5	2.5	6.25
Number of household members	4	6	7	7
Number of TLU's[b]	0.85	5.3	5.0	13.2
Number of oxen	1	2	2	7
Crop rotation	Teff–sorghum	Teff–sorghum–onion	Wheat/barley–teff–haricot bean/wheat	Onion–wheat–haricot bean–teff
GAP's[c]	Farmland terracing, area enclosures[d]	Farmland terracing, area enclosures[d]	Composting	Agroforestry since 2001, ploughing against slope, composting
Sources of livelihood apart from farming	Carpenter	Grain broking	Sale of grain and animals	House renting

[a] Includes owned and rented land.
[b] TLU = Tropical livestock unit.
[c] Good agricultural practices.
[d] Areas preserved from human and animal interruption.

The quantity of imported straw (St) from cropping and markets, and live animals (La) from markets were based on farmer estimations. The amount of grazed hay (Ha) was estimated by subtracting the fodder consumed at the farm from the total estimated feed intake. The DM content of straw (St) purchased from the markets was assessed on the basis of measurements. The production of cattle urine (Ur) was estimated at 530 g DM per day (Tesfaye et al., 2006). The urine production per TLU of other animals was estimated to correspond to that of cattle. The quantities of exported milk (Mi) and live animals (La) were based on farmer estimations. The quantity of egg (Eg) production was estimated at 60 eggs per 10 mature birds per year (Dessie and Ogle, 2001). C concentrations of manure (Ma), urine (Ur), milk (Mi), eggs (Eg), and live animals (La) (Table 2) were based on figures reported in the literature.

2.3.1.4. Composting. The quantities of imported manure (Ma) and hay (Ha) were based on farmer estimations. C concentration was based on reported values (Table 2). The quantity of produced compost (Co) was based on farmer estimation.

2.3.1.5. Household food and energy consumption. The quantity of imported crops (Cr), seeds (Se), live animals (La), meat (Me), milk (Mi), eggs (Eg), straw (St), energy sources, including manure (Ma), straw (St) and wood (Wo), and the quantity of marketed crops (Cr), live animals (La) and Milk (Mi) were based on farmer estimations. The live and carcass weights of animals were based on figures reported in the literature (Table 4). The annual production of human faeces was estimated at 50 kg (20% DM) and urine at 500 kg (4% DM) per person (Heinonen-Tanski and Van Wijk-Sijbesma, 2005; Jönsson et al., 2004; Malkki, 1999). In the analysis, human faeces and urine were reported jointly as excreta (Ex). The quantity of faeces and urine of children below 15 years of age was estimated to be half that of adults. C concentrations of crops (Cr) were based on measurements or reported figures, and those for live animals (La), meat (Me), milk (Mi), eggs (Eg), wood (Wo), human faeces and urine were based on previously reported information (Table 2).

2.3.2. Calculation of the proportion of harvested C used for food and soil and C losses

The proportion of harvested C used for food and soil was calculated as: The quantity of harvested C ending up in food and soil (kg)/The quantity of total harvested C produced on farm and imported to the farm (kg)$*$100.

C losses were calculated as the difference between C imports and exports of each process following harvesting and imports. For the livestock the C loss was calculated as: (hay + straw + live animals) – (manure + urine + live animals + milk + eggs). The positive balance indicated C loss through animal metabolism. For the compost C loss was calculated as: (hay + manure) – (compost). And for the household energy use the C loss was calculated as: straw + manure + wood. We also estimated C losses from untapped human excreta and offal. However, these losses occurred after the harvested C had ended up in food. C loss regarding the untapped human excreta was calculated as: faeces + urine and C loss regarding offals exported to wildlife as: 0.5$*$offal. The rest was exploited at the household system.

2.4. Interviews

Adult household members who participated in farm work were included in the interviews, comprising one to three participants. The interviews were conducted at the producers' associations in October 2010 by two local socioeconomic researchers from the national agricultural research system, trained by the authors. The interviews, conducted in Amharic in Kobo and Oromia in Sire, were tape-recorded, transcribed and translated into English. The length of the interviews ranged between three and six hours. The interview guide included detailed questions about the farm characteristics and resources, land use history, agricultural management practices at field plot level, including specific questions about crop rotation, use of manure, crop residues and other inputs, composting, harvesting losses, livestock management and grazing, household diet and acquisition of food, cash crops and exports of animals, use of fuel wood and management of organic household waste within the farming system in 2008/2009 and 2009/2010.

2.5. Uncertainty analysis

The model of Hedbrant and Sörme (2001), developed for uncertainty analyses of MFA, was used to estimate the uncertainties of the MFA data and the results. The uncertainty factors, which define the rate of uncertainty of the data, were determined based on Hedbrant and Sörme (2001), applied by Antikainen et al. (2005) and Danius (2002). The data sources were classified into five uncertainty intervals (Table 5) on the basis of uncertainty by comparing the types of data in this study to Antikainen et al. (2005) and Danius (2002). For example, the number of cattle on the farm was given an uncertainty factor of 1.1 and the quantity of manure used as fuel an uncertainty factor of 2, meaning that quantification of manure included substantially more uncertainty than quantification of the number of cattle.

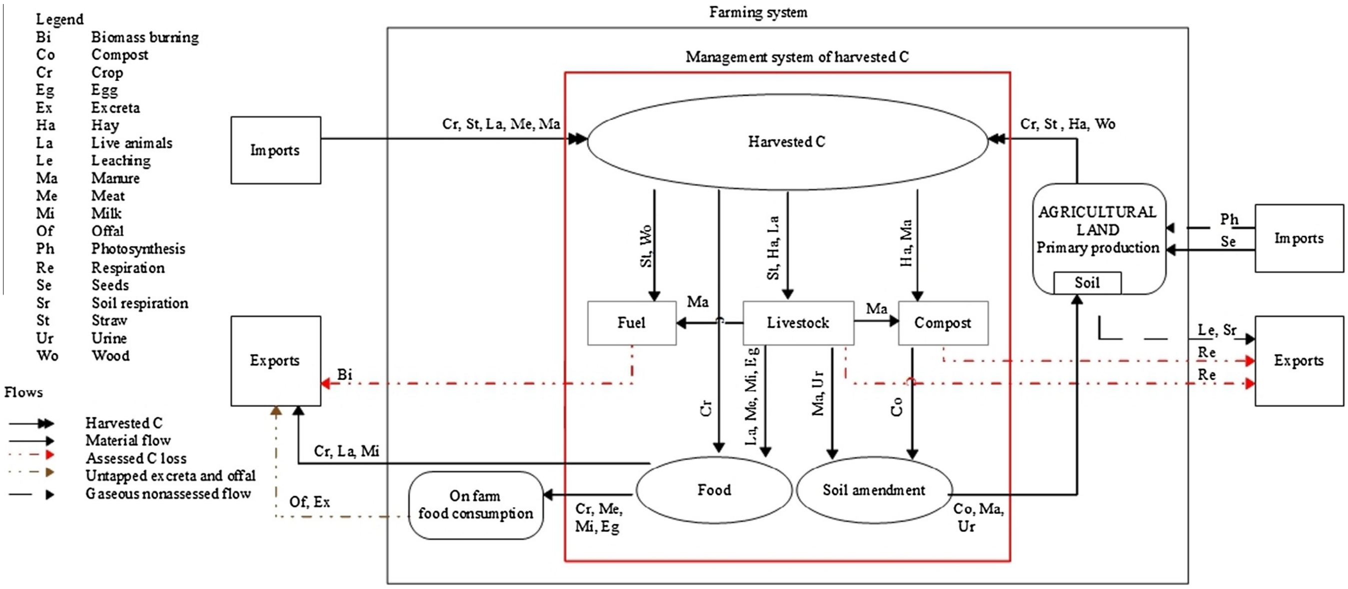

Fig. 2. The conceptual model of the farming system processes with their flows and stocks of C. The red boundary frames the management system of harvested C explored in this study. Material C flows, represented as black solid line were quantified directly. C losses occurring in the management system of harvested C, represented as red scattered line were calculated indirectly based on balance counting of fuel use, livestock and composting.

When calculation of a flow requires multiplication of data, the uncertainty increases (Hedbrant and Sörme, 2001). An example of the multiplication is calculation of the quantity of C in manure produced per day. In the case of the better-off farm in Kobo, the number of TLU's is 5.26, the amount of produced manure 3 kg DM and the C concentration of manure 35%. The likely value (m) for C content in manure produced per day is calculated as:

$$m_{a^*b^*c} = m_a^* m_b^* m_c \qquad \text{i.e.}$$

$$m = 5.26 * 3\ \text{kg} * 0.35 = 5.5\ \text{kg C}.$$

The uncertainty factors are determined for each type of data (Table 5). In this case, the number of TLUs was given an uncertainty factor of 1.1, the amount of produced manure factor 2 and the C concentration of manure factor 1.33.

The uncertainty factor (f) is calculated according to Hedbrant and Sörme (2001) as:

$$f_{a^*b^*c} = 1 + ((f_a - 1)exp2 + (f_b - 1)exp2 + (f_c - 1)exp2)exp0.5$$

i.e. in our example the uncertainty factor (f) is calculated as:

$$f = 1 + ((1.1 - 1)exp2 + (2 - 1)exp2 + (1.33 - 1)exp2)exp0.5 = 2.06$$

The C content in the daily manure production is very likely to be 5.5 kg*/2.06. Thus, the C content probably lies between 2.7 and 11.3 kg. The analyses were performed using Microsoft Office Excel 2007.

In addition, we conducted a sensitivity analysis to test whether the uncertainty range influenced our conclusions about the order of the greatest C losses.

3. Results

3.1. The proportion of harvested C used for food and soil

The flows of harvested C were generally notably larger in Sire than in Kobo and on the better-off farms than on the resource-limited ones (Fig. 3a–d). The major flows of C were hay from the rangeland for fodder, and straw from the cropland for fodder and fuel. In total, 16–28% of the harvested C was used for food and soil. The share used for food was 9–16% and for soil amendment 4–12%. The share of food used at household level was higher on the resource-limited farms (Fig. 4a). All of the farms prepared compost. The use of manure for compost was higher on the better-off farms (Fig. 4b). The application rate of compost on the resource-limited farms was 53 and 176 kg ha^{-1} and on the better-off farms 264 and 1320 kg ha^{-1} on average, in Kobo and Sire, respectively. A larger share of harvested straw was used for cattle fodder in Sire.

3.2. C losses

The share of the total C loss was slightly higher in Kobo, 83–84% than in Sire, 72–76% (Fig. 3a–d). The largest C loss was animal metabolism, except for the resource-limited farm in Kobo where the largest loss was caused by biomass burning for household energy. The loss from the animal metabolism was larger on the better-off farms than on the resource-limited farms. On the resource-limited farms, a greater portion of manure was used for fuel than on the better-off farms (Fig. 4b). Composting caused larger C losses on the better-off farms than on the resource-limited farms. During composting the quantity of C was reduced by 96–97% on the resource-limited farms and by 66–97% on the better-off farms. Burning of biomass caused more C losses on the better-off farm than on the resource-limited farm in Sire and vice versa in Kobo (Fig. 3a–d). The main sources of fuel were dried manure, straw and wood (Fig. 4c). On all farms human excreta was not recycled as fertilizer for the field but was dug into the soil on wasteland soil. In addition, the inedible share of offal was thrown to hyenas. These losses occurred however after harvested C was managed to food and represented a negligible losses (excreta 36–63 kg C and offal 0.2–6 kg C) from the system.

4. Discussion

4.1. Determinants for the proportion of harvested C ending up in food and soil

The share of the harvested C ending up in food and soil in total was slightly higher in Sire than Kobo. The regions differed in use of

Table 2
C concentrations of the organic material flows (for full references see Appendix B).

Material	C%	Source
Teff, grain	43.0	[ae,ao,ap,aq]
Teff, straw	45.0	[ae,ap,ar,as,at,au,ax]
Wheat, grain	43.0	[ae,ao,ap,aq]
Wheat, straw	45.0	[ae,ap,ar,as,at,au,av]
Corn cob	49.0	[ar,au]
Corn stover	45.0	[at,au,av,ax]
Onion	45.0	[ay,az]
Pasture hay	50.0	[at,bb,bc,bd]
Manure	35.0	[ar,be,bf]
Cow urine	1.0	[ba,bg]
Compost	25.0	[be,bf,bh]
Milk	45.0	[ar,bi,bj,bk]
Meat	56.0	[ar,bi,bl,bm,bn]
Egg	56.0	[bi,bn,bo,bp]
Offal	56.0	[ar,bi,bm,bn]
Live animals	56.0	[ar]
Wood	50.8	[at,au,bq]
Human faeces	50.0	[br,bs,bt]
Human urine	20.0	[bs,bt,bu]

[ae] Primary data (2010).
[ao] Mengesha (1966).
[ap] Merah et al. (1999).
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Table 3
Dry matter (DM) and carbon (C) concentrations of the cultivated plants on the case farms.

Material	DM%	C% in DM	
		Mean	Range
Sorghum, grain ($n = 12$)	93	41.14	40.61–41.86
Sorghum, straw ($n = 12$)	71	40.40	38.77–42.27
Barley, grain ($n = 12$)	88	41.14	40.83–41.56
Barley, straw ($n = 12$)	96	41.15	39.78–42.28
Haricot bean, grain ($n = 6$)	78	40.93	40.66–41.24
Haricot bean, straw ($n = 6$)	53	40.39	39.92–40.59

Table 4
Live and carcass weights used for the domestic animals. Half of the offal was assumed to be consumed by the households (for full references see Appendix B).

Animal species	Live weight (kg)	Carcass weight (kg)
Camel	400[af]	
Cattle	250[ag,ah]	108[ai]
Calf at weaning stage	50[aj]	
Donkey, mule, horse	105[ak]	
Goat, sheep	14[al]	8[al]
Chicken	1[am]	0.6[an]
Chicken egg	0.04[am]	

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[am] Dana (2011).
[an] Mogesse (2007).

harvested C for fuel. The use of straw for fuel was higher in Kobo than in Sire due to reduced availability of fuel wood, the result of heavy deforestation in the North and unavailability of alternative energy sources. The use of straw as fuel reduced the use for fodder and thus the share of harvested C ending up in food. In Sire where the use of straw for fodder was higher, the use of manure as fuel was greater so that in both cases the lack of alternative energy sources reduced the allocation of organic materials to agricultural soil. In Sire, the shorter cultivation history, larger holding size, legumes in the rotation and larger amount of manure through greater number of animals may have contributed to higher soil fertility and thus higher yields. In previous studies (e.g. Elias et al., 1998; Berry, 2003) the share of crop residues used for soil amendment ranged from 10% to 30% in Ethiopia. Our study indicates even lower utilization rates, possibly due to negative development in resource availability during the last decade. The quantity of compost used on fields estimated by the present study, ranging from 53 to 1320 kg ha^{-1} a^{-1}, and use of 10–48% of manure for fuel, was in line with reports of Mekonnen and Köhlin (2008), and Corbeels et al. (2000), but lower than that of Edwards et al. (2007), who reported use of 5000–15,000 kg ha^{-1} on fields in Ethiopia.

The higher crop production and more diverse crop species enabled crop sales on the better-off farms whereas on the resource-limited farms the major share of edible plant biomass produced was consumed on farm. Grazing on the communal rangeland, and on fields after harvesting, represented a critical fodder supply in the case regions. The largest harvested C flow of the farming systems was hay to the livestock system; however a notably small share of fodder was converted into animal products in all farms.

4.2. C losses

The greatest C losses occurred from the livestock system, probably due to the need to have a high number of cattle in relation to the quantity of available fodder, to serve as draft power and insurance against crop failure. Sufficient high-quality fodder could reduce C losses from livestock metabolism by improving animal productivity and indirectly through reducing the requisite number of animals (Abegaz et al., 2007). Management of grazing intensity could enhance grassland productivity (Schönbach et al., 2011) and integration of trees producing fodder in the cropping system could diversify and stabilize fodder supply. Further, more stable and diverse income sources could critically reduce the need for large herd size as insurance.

In the present study, the calculated C loss from composting was 20–30% higher than reported in previous studies (Tittonell et al., 2010; Tiquia et al., 2002; Sommer, 2001). High C losses may be

Table 5

Uncertainty factors with sources of data and examples. The input data (X) may range from X divided by uncertainty factor (Y) (X/Y) to X multiplied by Y ($X * Y$) (Hedbrant and Sörme, 2001; Antikainen, 2005; Danius, 2002) (for full references see Appendix B).

Level	Factor	Data source	Type of data	Source
1	1.1	Interviewees	Number of people and animals, area of agricultural land	
		Measured	C concentrations of haricot bean, barley, sorghum	
		Literature	C concentrations of wheat, corn, onion, pasture hay, milk, eggs	[ao,ap,aq,ar,as,at,au,av,ax,ay,az,bb,bc,bd,bi,bj,bk,bn,bo,bp]
2	1.33	Literature	C concentrations of live animals, meat, manure, urine, offal, compost, wood, human faeces, human urine	[ar,at,au,ba,be,bf,bg,bh,bi,bl,bm,bn,bq,br,bs,bt,bu]
3	1.5	Measured	Grain and straw yields	
4	2	Literature	Straw and hay intake, quantity of produced manure, urine and human excreta, animal weights	[af,ag,ah,ai,aj,ak,al,am,an,ap,ar,as,at,au,ax,bb,bc,bd,bs,bt,bu]
		Literature on crop characteristics extrapolated to other crops	C concentrations of teff	[ao,ap,aq,ar,as,at,au,ax]
		Interviewees	Quantity of grain and straw yields, imported food aid, crops, meat, seeds, manure, straw and live animals, use of grain and straw, hay, compost, manure, woods, milk, eggs and live animals, quantity of harvesting losses, exported crops, live animals, milk, excreta, offal and skin	
5	4	Interviewees	The amount of fuel wood woman and donkey can carry	

[af] Kurtu (2004).
[ag] Abdelhadi and Babiker (2009).
[ah] Osuji and Capper (1992).
[ai] FAOSTAT (2011c).
[aj] Sidibé-Anago et al. (2008).
[ak] Gebreab et al. (2000).
[al] Legesse and Abebe (2008).
[am] Dana (2011).
[an] Mogesse (2007).
[ao] Mengesha (1966).
[ap] Merah et al. (1999).
[aq] Woldeab et al. (1991).
[ar] Kahiluoto et al. (2011).
[as] Lehtomäki et al. (2008).
[at] Ptasinski et al. (2007).
[au] Demirbas (1997).
[av] Preston and Leng (1987).
[ax] Tolera and Sundstol (2000).
[ay] Raines et al. (2009).
[az] Furlan and Bernier-Cardou (1989).
[ba] Edwards and Araya (2010).
[bb] Kabaija et al. (1989).
[bc] Kabaija and Little (1988).
[bd] Ibrahim and Olaloku (2000).
[be] Lekasi et al. (2001).
[bf] Paul et al. (2009).
[bg] Tegegne et al. (2007).
[bh] Bierwirth (2001).
[bi] Fineli (2011).
[bj] Zublena et al. (1997).
[bk] WHFoods (2011).
[bl] Malek et al. (2009).
[bm] USDA (2011a).
[bn] USDA (2011b).
[bo] Matt et al. (2009).
[bp] FAO (2003).
[bq] Toky and Singh (1995).
[br] Fry (1973).
[bs] Jönsson et al. (2004).
[bt] Heinonen-Tanski and Van Wijk-Sijbesma (2005).
[bu] Malkki (1999).

due to CH_4 production resulting from anaerobic conditions in dense compost piles (Pel et al., 1997), from rapid degradation of organic material at high temperature (Sánchez-Monedero et al., 2010) or due to leaching as dissolved organic carbon. Part of the C may also be sequestrated in soil below the compost pile. Our previous findings regarding health problems due to gaseous emissions while turning and transporting compost (Kahiluoto et al., 2012) support the present conclusions of high C losses. However the results include uncertainty as the biomass output from the composting was based on farmer estimation.

Contrary to livestock metabolism and composting losses, C losses from residue burning are totally avoidable when producing food and soil amendment. Availability of alternative energy sources to substitute for manure and straw as fuel would likely increase their use as soil amendment. Introduction of new technologies using less fuel would conserve harvested C so that it could be used to improve soil C stocks and productivity. Anaerobic digestion in manure handling could reduce nutrient and C losses and also improve food safety and utilization. Integration of trees in the farming system could totally avoid residue use as fuel. C loss from

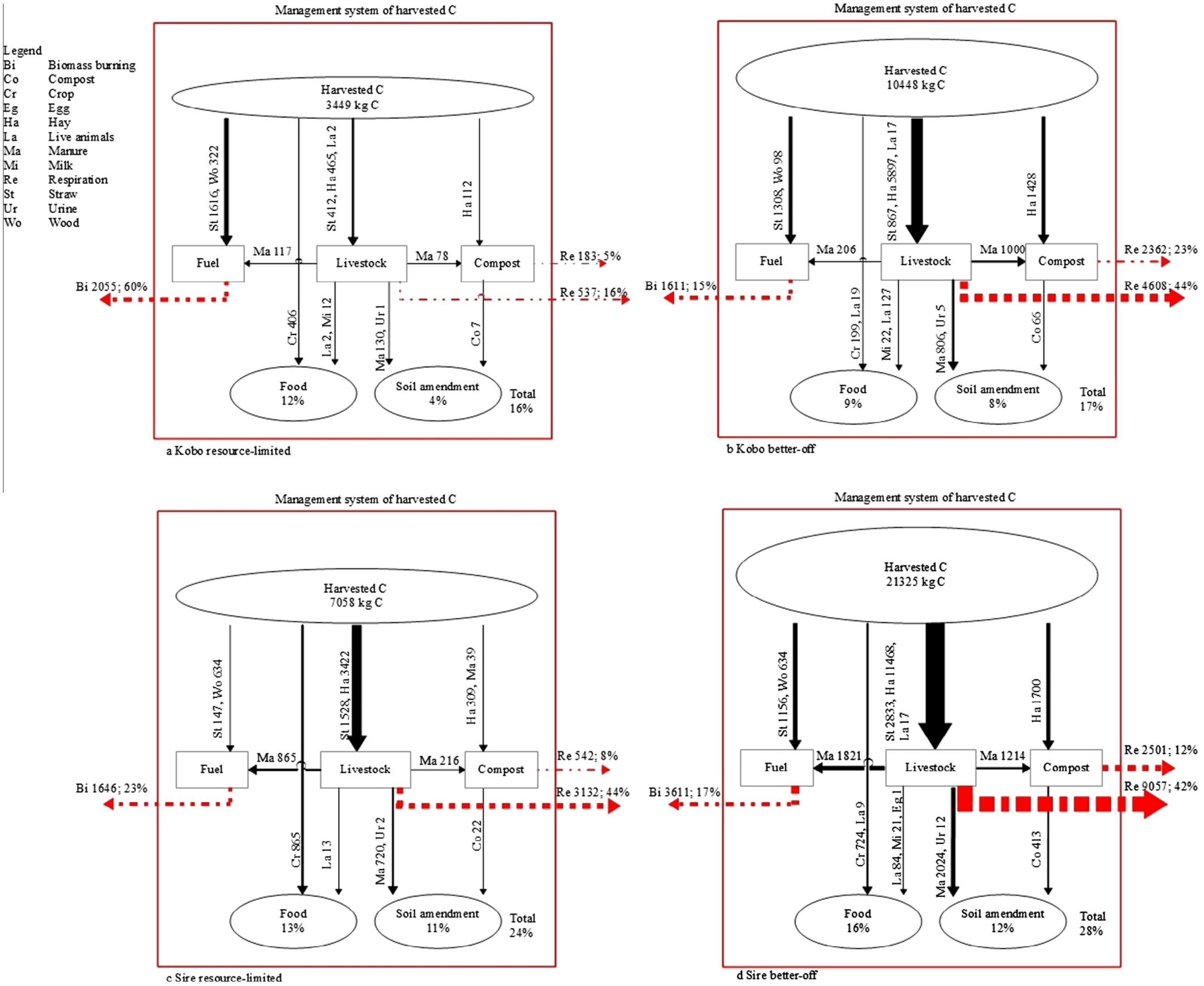

Fig. 3. (a–d) Allocation of harvested C (kg per year) to food, soil and losses on the case farms. The harvested C flows are represented as black solid lines and C losses as red scattered lines. Values are means of 2008/2009 and 2009/2010. The uncertainty ranges for the allocation of harvested C flows to food and soil are presented in Appendix C and for the C losses in Appendix D.

the fuel use was of the same size in all the farm households, indicating that preventing that loss could offer a constant reduction in C losses on smallholder farms. Human excreta and offal were the only untapped recyclable C source in the farming system, representing a negligible proportion of harvested C in mixed farming.

4.3. Generality and reliability

The contrasting case regions in the highlands of the Central Rift Valley, highly important for food production in Ethiopia, and the smallholder mixed farming systems, exemplifying a broad range of resource availability and the most common farming system type in the country, make the results representative of Ethiopian food production. The fact that the results were relatively similar among the contrasting farms supports this generality. Empirical data from two different years together covering a representative range of weather variation provide a strong basis for unique estimates of flows and losses of harvested C in East African mixed farming systems.

Interviews and partial reliance on the literature, as methods to collect data, imply uncertainty. However, the results were double-checked by using several data sources to decrease errors. Estimations of C flows that are based on multiplicand data, such as consumption of rangeland hay, the use of manure, compost application, and use of animal products, result in the greatest uncertainty. In contrast, for results that originate from our measurements, e.g. yields, the uncertainty is smaller. There are undoubtedly uncertainties of the order of greatest C losses (Appendix D).

4.4. MFA in calculating the use of harvested C and identifying C losses

MFA includes a systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner and Rechberger, 2004) and as such offered a useful tool to quantify flows and allocation of the harvested C and indicate the efficiency in its use for food and soil. MFA allowed quantifying the C losses including the gaseous ones, through calculation of the C balance of the processes (Pires et al., 2011) within the harvested C management system. The analysis is not a practical method to illustrate the entire carbon cycle or carbon budget of the farming system due to restrictions in accounting for gaseous exchange among the

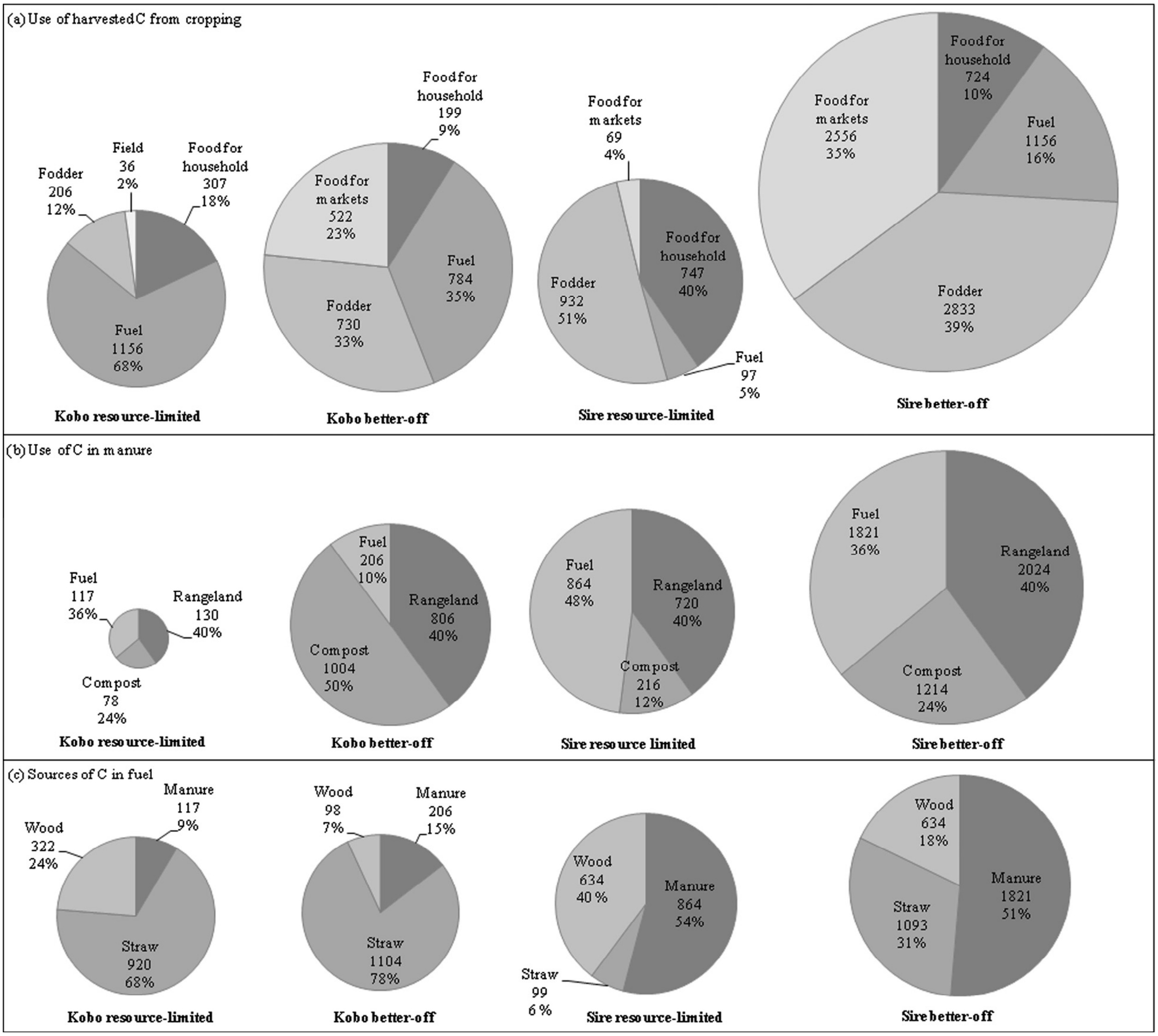

Fig. 4. (a–c) Use of (a) harvested C from cropping and (b) use of C in manure, and (c) sources of C in fuel (kg per year) on the case farms. The size of each pie represents the total amount of C managed in each farm.

atmosphere, plants and soil. The analysis of the C losses indicates low utilization of farm resources and forms the basis for further research to assess different means to prevent losses of C from farming systems. MFA seems a suitable tool to guide management of organic materials on farms. These uses could be facilitated through development of standard procedures and guidelines in C budgeting and uncertainty analyses in an analogy to nutrient budgeting approaches (Oenema et al., 2003).

5. Conclusions

This study suggests that the residue biomass is carefully utilized in these farming systems and consequently the main C losses are gaseous. The major C losses in smallholder mixed farms occur in animal metabolism and burning of biomass. The large and constant C losses through the entirely replaceable residue burning offer the most accessible remedy to smallholder management of harvested C. Consequently, the proportion of harvested C used for fuel appears as the main determinant for the proportion of harvested C ending up in soil and food. Creation of energy substitutes for manure and straw, improved manure management through, e.g. anaerobic digestion of residues and more stable food and fodder supply to reduce the requisite number of animals are all keys to close C cycles in the farming systems. Quantification of the flows of harvested C is a useful approach that reveals the use and losses of harvested C when measurement of gaseous emissions is not feasible. Such assessments are of a great value in guiding sustainable management of harvested C in smallholder farms.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agsy.2014.06.003.

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