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Household energy and recycling of nutrients and carbon to the soil in integrated crop-livestock farming systems: a case study in Kumbursa village, Central Highlands of Ethiopia

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Abstract

Soil amendment with organic wastes in the Highlands of Ethiopia has been greatly reduced by widespread use of dung cakes and crop residues as fuels. This study assessed the interaction between household energy and recycling of nutrients and carbon to the soil using household survey, focus group discussions, key informant interviews, direct observations and measurements between 2014 and 2015 in Kumbursa village (Central Highlands of Ethiopia). All surveyed households were entirely dependent on biomass fuel for cooking, with production and consumption rates directly related to wealth status, which significantly varied ($P < 0.001$) among three farm wealth groups (poor, medium and rich). Crop residues and dung cakes accounted for 80(±3)% by energy content and 85(±4)% by dry mass weight of total biomass fuel consumption. Mean losses were 59 (±2) kg ha^{-1} yr^{-1} nitrogen (109(±8) kg yr^{-1} per household), 13.9(±0.3) kg ha^{-1} yr^{-1} phosphorus (26 (±2) kg yr^{-1} per household), 79(±2) kg ha^{-1} yr^{-1} potassium (150(±11) kg yr^{-1} per household) and 2100 (±40) kg ha^{-1} yr^{-1} organic carbon (3000(±300) kg yr^{-1} per household). Rich farmers lost significantly more carbon and nutrients in fuel than farmers in other wealth groups. However, these losses were spread over a larger area, so losses per land area were significantly higher for medium and poor than for rich farmers. This means that the land of poorer farmers is likely to become degraded more rapidly due to fuel limitations than that of rich farmers, so increasing the poverty gap. The estimated financial loss per household due to not using dung and crop residues as organic fertilizer was 162(±8) US$ yr^{-1}. However, this is less than their value as fuels, which was 490(±20) US$ yr^{-1}. Therefore, farmers will only be persuaded to use these valuable assets as soil improvers if an alternative, cheaper fuel source can be found.

Keywords: biomass fuel, crop residues, dung cakes, Ethiopian Highlands, household energy, soil fertility

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Introduction

Reliance on traditional biomass fuel in sub-Saharan Africa and Ethiopia

The energy mix of sub-Saharan African countries, including Ethiopia, is dominated by traditional biomass fuels. Biomass fuel constitutes about 90%–98% of the total residential fuel consumption in most of sub-Saharan countries, and Ethiopia ranks second, only preceded by Nigeria in terms of biomass fuel consumption rate (Idiata *et al.*, 2013). Biomass fuel reportedly makes up over 90% of the total energy demand of Ethiopia (Dawit, 2012; Gwavuya *et al.*, 2012; EUEI, 2013; Getamesay *et al.*, 2015; Gudina & Nonhebel, 2015), providing almost all of the energy demand of rural households and accounting for approximately 85% of the total cooking fuel consumed by urban households in Ethiopia (Abebe *et al.*, 2011).

Such excessive reliance on biomass fuels and inefficient combustion technologies have resulted in adverse consequences including land degradation, deforestation, increased emissions of greenhouse gases, desertification, loss of biodiversity and health problems (Idiata *et al.*, 2013). Fuelwood collection is one of the primary causes

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of deforestation and forest degradation (Elizabeth *et al.*, 2014), while exposure to the smoke from biomass burning is responsible for the deaths of ~600 000 people in sub-Saharan Africa annually (SEI, 2015). Extensive removal of biomass resources for fuel has also exacerbated environmental degradation and restricted socioeconomic development in Ethiopia (Wolde-Giorgis, 2002; Abebe *et al.*, 2015). Dwindling firewood supplies due to deforestation and the consequent switch to dung cakes and crop residues for fuel in the Highlands of Ethiopia has jeopardized agricultural productivity (Zenebe *et al.*, 2006).

Determinants of household energy choice in developing countries

Identifying major bottlenecks of the transition to more efficient household energy in developing countries is crucial for designing sustainable and environmentally benign household energy alternatives. There is little consensus in the literature on the factors determining choice of household fuel because fuel choice and consumption characteristics are highly specific to the local context.

The most commonly used theoretical frameworks for analyzing household energy transition are the 'energy ladder' and 'fuel stacking' models which, respectively, refer to the perfect and partial substitution of one energy source with another one (IEA, 2014). The energy ladder model refers to complete abandonment of the inferior fuel, and hence a total shift to the superior fuel; it assumes universal access to all energy sources among which consumers rationally choose based on their income (Risseeuw, 2012). The fuel stacking model, on the other hand, refers to addition of new energy sources and superior fuels upon existing fuels, hence resulting in multiple fuel use; it considers multiplicities of fuel choice and consumption dictating factors, among which, income is only one (Treiber, 2012; IEA, 2014; Remigios, 2014).

The fuel stacking model better explains energy use behavior in sub-Saharan African countries as households tend to use multiple fuels instead of abandoning previous fuel sources due to unreliable supply and limited affordability (Alemu & Kohlin, 2008; Treiber, 2012; Ogwumike *et al.*, 2014). Moreover, universal access to all fuel sources is rare and consumers are far from being rational in fuel choices; a number of noneconomic factors (sociocultural, institutional and environmental) can influence fuel choice and consumption.

The consumption of 'dirty' fuels, including biomass fuels, which result in poor indoor air quality, tends to decrease with increasing household income (Masera *et al.*, 2000; Onoja & Anthony, 2012; A.J. Omojolaibi, unpublished). There is generally a positive correlation between the adoption of new energy sources and household wealth status (SEI, 2008; IEA, 2014), but Samuel (2002) in Ethiopia, and Jan *et al.* (2012) in Pakistan, found no significant positive relationship between wealth status and uptake of modern energy. In India, R. Hanna & P. Oliva (unpublished) observed that even where cleaner alternative energy sources were available, rich households tended to use more cow dung than the poor because they owned more cattle. Because use of biomass fuels is so deeply ingrained in the cultures of many rural societies of developing countries, transition to modern energy sources is often delayed (Risseeuw, 2012). Households may persistently use biomass fuels, despite adequate access to modern energy sources (Jan *et al.*, 2012). Unreliable supply of modern energy sources, such as electricity, may also result in households reverting to biomass fuels (Treiber, 2012; Ogwumike *et al.*, 2014; Mulu *et al.*, 2016). Furthermore, price fluctuations may force households to shift from dirty fuels (firewood) to dirtier fuels (cattle dung and crop residues) (Treiber, 2012; R. Hanna & P. Oliva, unpublished). Poor energy policies and institutional frameworks are another possible hurdle to successful rural energy development (EUEI, 2013); the attention given to rural energy development by the Ethiopian government is very little compared to rural road construction, education and health (Wolde-Giorgis, 2002).

This study tries to assess fuel choice and consumption characteristics of farm households in Kumbursa village in line with the fuel stacking model by focusing on variation in resource endowment of farm households as determinant factor. Other factors were assumed to be the same for all farm households of the study area.

Implications for recycling of nutrients and carbon to the soil in the Highlands of Ethiopia

In the Ethiopian Highlands, dwindling woody biomass supplies have resulted in the widespread shift toward using cattle dung and crop residues as fuels at the expense of applying them to farmland (Woldeamlak, 2003; Kassahun *et al.*, 2013; Abebe *et al.*, 2015). The estimated total annual production potential of dung and crop residues in Ethiopia is 33.0 and 22.4 million tons, respectively; 60% of this, 22.8 and 10.3 million tons, respectively, are used as fuel (EUEI [European Union Energy Initiative], 2013). This large-scale switch to using dung cakes and crop residues for fuel has become a serious limitation to the success of the Ethiopian government targets to intensify agriculture and build a green economy through promotion of organic fertilizers (FDRE, 2011). The prevailing intense competition between use for fuel and fertilizer of cattle dung and crop residues (Gwavuya *et al.*, 2012; Smith *et al.*, 2014; Abebe *et al.*, 2015) has severely threatened agricultural productivity in many areas (Aklilu, 2006; Assefa *et al.*, 2007; Dawit, 2012); for instance, the use of cattle dung for fuel instead of using it as fertilizer is estimated to have reduced agricultural gross domestic product (GDP) by ~7% (IFRI, 2010).

Unfortunately, it is also likely that the demand for locally sourced biomass fuels, including livestock manures and crop residues, will keep increasing into the foreseeable future. Based on business-as-usual scenario projections, the mean annual firewood deficit of Ethiopia will be 5.6 million tons by the year 2030 (EUEI [European Union Energy Initiative], 2013). Increased firewood scarcity (Dawit, 2012; Getamesay *et al.*, 2015), poor efficiency of the use of available biomass fuel resources (Dagninet *et al.*, 2015; Getamesay *et al.*, 2015) and limited access to alternative modern energy sources (Kassahun *et al.*, 2013; Smith *et al.*, 2014) have generally contributed to the ever increasing demand for dung cakes and crop residues as fuels at the expense of application to farmland to improve soil fertility.

Today there emerges an inextricable downward spiral in household income due to the link between household energy and agricultural productivity in the Ethiopian Highlands; this suggests the need for joint efforts to address food security and energy challenges (Hailemariam, 2011; Gwavuya *et al.*, 2012). For this reason, the present study focuses on the competition between the use as fuel and fertilizer of crop residues and dung. The underlying premise is that any improvement in biomass fuel use efficiency and/or transition to modern energy is likely to enhance the availability of manure and crop residues for use as organic fertilizers, which, in turn, contributes to the enhancement of agricultural productivity (Assefa *et al.*, 2007; Alemu & Kohlin, 2008; Smith *et al.*, 2014)

This study was instigated because there is a paucity of empirical literature, in the Central Ethiopian Highlands, on household energy use and the associated impacts on soil nutrients and carbon recycling in typical rural villages, where farm households almost entirely depend on their respective landholdings for food, feed and fuel. Most studies of household energy have so far emphasized implications for indoor air pollution and related health impacts (Avery *et al.*, 2014; Semple *et al.*, 2014; Yongabi *et al.*, 2014), deforestation (Badege, 2001; Subedi *et al.*, 2014; Fekadu, 2015; Mulu *et al.*, 2016) and loss of biodiversity (Debela, 2007; Adugnaw, 2014), determinants of allocating dung for fuel and fertilizer (Alemu & Kohlin, 2008), and the impacts of the shadow price on allocating farmyard manure for multipurpose uses (Hailemariam, 2011), while only gross implications for soil nutrient loss have been addressed (Aklilu, 2006; Kassahun *et al.*, 2013; Smith *et al.*, 2014). Experimental measurements on household energy use and its implications for nutrients and carbon recycling in sub-Saharan Africa, as a whole, are scarce. The outputs from this study should help to inform policymakers on strategies for sustainable use of household energy that simultaneously allow sustainable recycling of nutrients and carbon within the farming systems.

Objectives of the study

There are two objectives of this study. The first objective focuses on identification of household energy sources and analysis of their consumption patterns among different farmer wealth groups using the fuel stacking model. The second objective is to quantify losses of nutrients and carbon from farming systems with removal of crop residues and dung cakes for household energy, assessing the implications of this for soil nutrients and carbon recycling in integrated crop-livestock farming systems in the different wealth groups. This work was done in Kumbursa village in the Central Highlands of Ethiopia.

Materials and methods

The study site

Kumbursa village is situated in Ude Kebele (the smallest administration unit in Ethiopia), Ada'a District in East Shoa Zone, Oromia National Regional State, Ethiopia. The village is located between 8°41′05″N and 8°42′49″N latitude and 39°00′29″E and 39°01′44″E longitude (Fig. 1). The altitude of the village ranges between 1878 m and 1892 m above sea level with flat to slightly undulating topography covering the total area of nearly 1000 ha. The village is located at a distance of about 55.5 km south-east of Addis Ababa along the Addis Ababa – Adama old highway.

The rainfall distribution pattern of the village is unimodal with 74% of the mean annual precipitation occurring between June and September and a total annual average of 839 mm (Minase *et al.*, 2015). The average monthly temperatures range from 17.2 °C (in December) to 20.7 °C (in May), with a mean annual record of 18.9 °C (Minase *et al.*, 2015).

The farming system in the study site is denoted by close interdependence and integration of crop cultivation and animal husbandry, where the production and productivity of one is inextricably related to the other.

There is no communal land for livestock grazing or firewood collection in Kumbursa village. Therefore, farm households of the village almost entirely depend on resources collected from their farmlands and homesteads for food, feed, fuel and cash.

Household survey

A single time cross-sectional survey of farming households was undertaken between December 2014 and March 2015 to

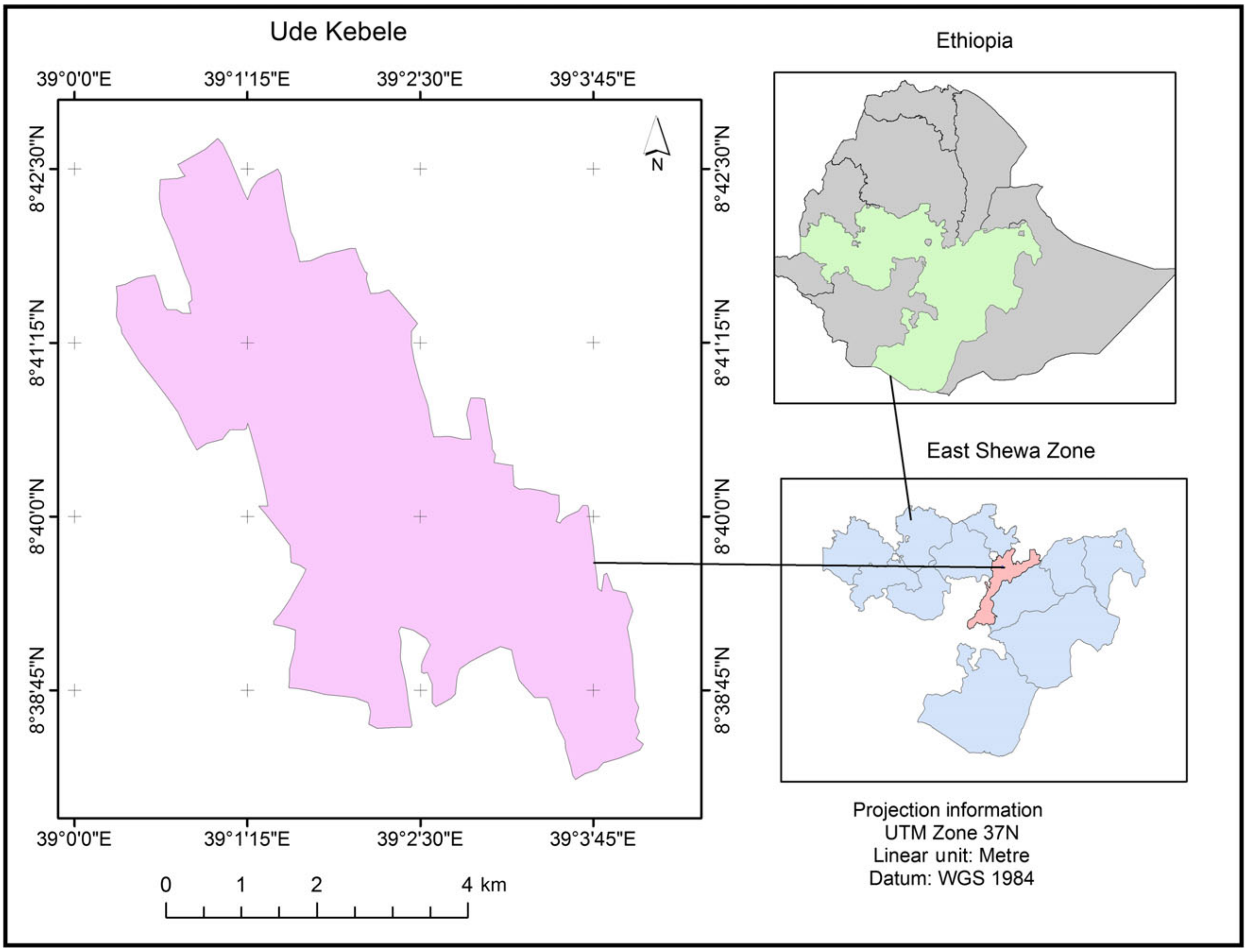

Fig. 1 Map of Ude Kebele.

collect data on the family size, resource endowment (landholding size, livestock number and amounts of annual crop production) and household energy (sources of energy and consumption rates). A semistructured interview questionnaire was used for the survey. The questionnaire was pretested using the split-half method with 10% of the sample respondents to check for internal consistency (Drost, 2011). The sex and age composition of the respondents was 97 (81%) male and 22 (19%) female, with minimum and maximum ages of 28 and 78, respectively, and average age of 48. The household survey data were supplemented by key informant interviews, focus group discussions, and observations and measurements.

Preliminary surveys indicated that farm households in Kumbursa village were relatively homogenous, all of them being engaged in mixed crop-livestock farming, and being dependent on biomass resources from their own landholding for the majority of their household energy. However, differences were observed in wealth status, so this was used as a criterion for purposeful sampling. Furthermore, the objectives of the study were to focus on the relationship between wealth status and fuel use, so sampling by wealth status was required. Spatial variation was not considered because the study village covers a total area of nearly 1000 ha with very small altitudinal variation (between 1878 m and 1892 m above sea level) and a flat to slightly undulating topography. Therefore, using a participatory wealth ranking method (Balesh, 2005; Assefa *et al.*, 2007), households of the village were stratified into three wealth groups (rich, medium and poor) based on (i) number of oxen owned, (ii) landholding size and (iii) amount of annual crop production available for household consumption, sale and stockpiling. Households with one ox or no oxen at all, up to 1.25 ha landholding size, and not enough annual agricultural production to feed members of their household throughout the year were categorized as being in the poor wealth group. Households with two to three oxen, 1.26–2.00 ha landholding size, enough annual agricultural production to feed members of their household throughout the year and sell part of their produce, but not enough to stockpile for the following years were categorized in the medium wealth group. Households with greater than three oxen, >2.00 ha landholding size, and enough annual agricultural produce to feed members of their household throughout the year and sell part of their produce with surplus to stockpile for following years were categorized as rich. In order to be categorized as rich, medium or poor, a farm household was expected to satisfy at least two of the three criteria listed above. Using a proportionate-stratified-random sampling procedure over the wealth groups (Balesh, 2005; Assefa *et al*., 2007), 120 farm households (i.e., 45%) were selected out of the total 258 households of Kumbursa village.

Sampling crop residues and dung cakes

Composite samples were collected for laboratory analysis for crop residues and dung cakes as shown in Table 1, with each composite sample consisting of seven subsamples. The residue samples were taken from the three major crops (teff, chickpeas and wheat), which together constituted more than 95% of the cropped area in the village. Equal allocation (Mathew *et al*., 2013) was used to sample residues and dung cakes; hence samples were evenly distributed across the three farm wealth groups (poor, medium and rich) as well as the three major crops (teff, chickpeas and wheat). This is a small number of crop residue and dung cake samples compared to the number of farm households and the total area of the village, but care was taken to ensure that samples obtained were representative of the typical situation in the village. As is common practice in Ethiopia, the crops belonging to the household from different areas were brought to one place during threshing; this results in mixing of residues, making them relatively homogenous, and allowing representative samples to be obtained immediately after threshing. To enhance the representativeness of the sampling, seven subsamples were taken and bulked together to provide a composite sample for analysis. Dung cakes are made by collecting and mixing cattle dung, resulting in homogenous nutrient concentrations; again seven subsamples were taken and mixed to provide a composite sample. As it is expected that the nutrient concentrations of residues and dung cakes vary across different farm wealth groups due to differences in agricultural inputs and field management, the samples were evenly distributed across the three farm wealth groups.

Quantification of household fuel consumption

The household head and the person responsible for cooking were asked to specify the amounts of dung cakes, firewood and charcoal used to cook meals each day and each week. The respondents expressed these quantities as the number of dung cakes used per meal, number of sacks of dung cakes, crop residues or charcoal used per week, and number of bundles of firewood used per week. The weights of a single dung cake, a single sack of dung cakes, crop residues or charcoal, and a typical bundle of firewood were measured using a weight balance across a sample size of 42. This provided weights of 0.45(standard error = ±0.02) kg per dung cake, 21(±1) kg per sack of dung cakes, 10(±0.4) kg per sack of crop residues, 16(±0.7) kg per sack of charcoal, and 28(±2) kg per bundle of fuelwood. This allowed the average weight of fuel used each year to be quantified for each farm wealth category.

Determination of the amounts of crop residues produced by farm households

Data on grain yields were collected through the household survey, while the amounts of dry matter in crop residues were indirectly determined for each crop using mean harvest indices; the total amounts of dry matter in crop residues produced by the farm households were quantified using the following equation:

$$M_{\mathrm{res},x} = \frac{\sum_{n}\left(\frac{M_{\mathrm{grain},x}}{H_{i,x}} - M_{\mathrm{grain},x}\right)}{n} \qquad (1)$$

where $M_{\mathrm{res},x}$ is the mean dry matter produced by a typical household in crop residues for crop x (kg yr^{-1}), x stands for any of the three crops (teff, wheat and chickpeas); $H_{i,x}$ is the harvest index for crop x, $M_{\mathrm{grain},x}$ is grain yield of crop x (kg yr^{-1}), and n is the number of households in the wealth group. Harvest indices were assumed to be 0.24 for teff (Ketema, 1997; EARO, 2001), 0.41 for wheat (Bayeh, 2010) and 0.37 for chickpeas (Tilahun *et al*., 2015).

Laboratory analysis of crop residue and dung cake samples

The collected crop residues and dung cake samples were analyzed in the soil and plant analysis laboratory of Debre Zeit Agricultural Research Center, Ethiopia, to quantify total nitrogen (N), phosphorus (P), potassium (K) and organic carbon (OC) contents. The Kjeldahl method, which involves wet digestion, distillation and titration, was used for analysis of total N (Anderson & Ingram, 1993). Following the dry-ashing method (Sahlemedhin & Taye, 2000), P and K contents of crop residues and dung cakes were determined by spectrophotometry and atomic absorption. Organic carbon was determined from the

Table 1 Summary of the number of households, sample size and number of composite samples of crop residues and dung cakes in each farm wealth group

Farm wealth group	Number of household heads in each wealth group	Sample household heads in each wealth group	Composite crop residues and dung cakes samples			
			Teff	Wheat	Chickpea	Dung cakes
Rich	47	22	3	3	3	3
Medium	157	73	3	3	3	3
Poor	54	25	3	3	3	3
Total	258	120	9	9	9	9

ash by comparing weight before and after oxidation (Sahlemedhin & Taye, 2000).

Quantification of carbon and nutrient loss through removal of crop residues and dung cakes

The annual nutrient and OC losses for each household were obtained from the total dry matter in crop residues and dung cakes and the average nutrient contents of each product as follows:

$$L_{\mathrm{res},y} = \frac{\sum_1^{n_h}\left(\sum_x \left(M_{\mathrm{res},x} \times p_{y,x}\right)\right)}{n_h} \quad (2)$$

$$L_{\mathrm{dung},y} = \frac{\sum_1^{n_h}\left(M_{\mathrm{dung}} \times p_{y,\mathrm{dung}}\right)}{n_h} \quad (3)$$

where $L_{\mathrm{res},y}$ is the average loss of y (where y is N, P, K or OC) in crop residues and $L_{\mathrm{dung},y}$ is the average loss in dung (kg y^{-1}); $M_{\mathrm{res},x}$ is the amount of crop residue x used by a household for energy(where x refers to the crop type; teff, chickpeas or wheat) and M_{dung} is the amount of dung cakes used by a household for energy (both within the household and sold) (kg yr^{-1} dry matter); $p_{y,x}$ is the proportion of y in crop residue x, and $p_{y,\mathrm{dung}}$ is the proportion of y in dung; and n_h is the number of households in each farm wealth group (rich = 22, medium = 73, and poor = 25).

The Tropical Livestock Unit (TLU), which represents a hypothetical animal of 250 kg live weight, was used to determine livestock number, which was needed to determine the wealth group; conversion factors 0.01, 0.1, 0.5, 0.7, 0.8 and 1.1 TLU were used for chickens, sheep/goats, donkeys, heifers, cows and oxen, respectively (Gryseels, 1988).

Market values of inorganic fertilizers in Kumbursa village in 2015 were used to determine the fertilizer equivalent monetary values of the crop residues and dung cakes removed for household energy; diammonium phosphate = 15 Ethiopian Birr (ETB) kg^{-1} (0.72 US$ kg^{-1}) and urea = 13 ETB kg^{-1} (0.62 US$ kg^{-1}).

Local market prices of different fuels in March 2015 were used to determine fuel monetary values; firewood = 1.8 ETB kg^{-1} (0.09 US$ kg^{-1}), charcoal = 10 ETB kg^{-1} (0.5 US$ kg^{-1}), crop residues = 2.1 ETB kg^{-1} (0.1 US$ kg^{-1}), dung cakes = 2 ETB kg^{-1} (0.1 US$ kg^{-1}) and (kerosene = 16 ETB dm^{-3} (0.76 US$ dm^{-3}). The energy contents of different fuel sources were determined using their corresponding conversion factors; wood = 16.2 MJ kg^{-1}; dung cakes = 10.8 MJ kg^{-1}; cereal straw = 14.4 MJ kg^{-1}; charcoal = 25.2 MJ kg^{-1} and kerosene = 36 MJ dm^{-3}) (INFORSE, 2006).

Statistical analysis

Quantitative data obtained from the farm household survey, field observations and measurements, and laboratory analyses were averaged and summarized in tables and graphs. One way analysis of variance (ANOVA) was used to compare mean energy consumptions of the three farm wealth groups, while Pearson correlation coefficient was used to analyze the relationships between energy consumption and farm household resource endowment, as well as the relative consumption rates of different biomass fuels. The Statistical Package for Social Sciences (SPSS) version 20 was used for ANOVA and Pearson correlation coefficient, while all the graphical analyses were carried out using MICROSOFT OFFICE EXCEL 2007. Qualitative data generated from key informant interviews, focus group discussions and personal observations were used as supplementary for household survey data and analyzed using narration under different themes.

Results

Major sources of household energy in Kumbursa village

The major biomass fuel sources in decreasing order of local use for all the three farm household wealth groups were dung cakes, crop residues, firewood and charcoal with corresponding mean consumption rates per household of 4300(±150) kg yr^{-1} (46 000(±1600) MJ yr^{-1}), 1800(±70) kg yr^{-1} (26 000(±1000) MJ yr^{-1}), 920(±30) kg yr^{-1} (14 800(±500) MJ yr^{-1}) and 150(±4) kg yr^{-1} (3700(±100) MJ yr^{-1}), respectively (Table 2). Kerosene is used for lighting and its mean consumption rate per household was 40(±1) dm^3 yr^{-1} (1500(±40) MJ yr^{-1}) (Table 2).

In terms of consumption by energy content, dung cakes and crop residues together provided 80(±3)% of the total energy used for cooking, while the share of firewood and tree litter was 15.9(±0.6)%, and that of charcoal was only 4.1(±0.4)% (Fig. 2).

Biomass fuel production and consumption patterns among the three farm wealth groups

Both biomass fuel production and consumption were directly related to the size of landholding, livestock number and family size, and significantly varied among the three farm wealth groups ($P < 0.001$; Table 2). This suggests that rich farm households were producers of higher amounts of biomass fuels as they had larger landholdings (3.3 ± 0.2 ha) compared to the medium (1.5 ± 0.1 ha) and poor (1.1 ± 0.1 ha) wealth groups (Table 2). Rich farm households also had a higher number of livestock (8.4 ± 0.3 TLU) compared to the medium (4.1 ± 0.2 TLU) and poor (2.5 ± 0.1 TLU) households (Table 2), and this implies higher availability of cattle dung for dung cake preparation.

It was observed that rich households had also more eucalyptus trees for firewood production in their homesteads and more acacia trees scattered in their farmland for charcoal production compared to the medium and poor households.

Consumption of a given biomass fuel was also found to be related to consumption of the other biomass fuels, availability of biomass resources and family size (Table 3). Rich farm households had larger families (7.2 ± 0.3 people per household) compared to the medium (5.9 ± 0.4 people per household) and poor farm households (5.5 ± 0.3 people per household). Per capita biomass fuel consumption also significantly varied among the three farm wealth groups ($P < 0.001$; Table 2); this was higher for the rich (63 ± 4 MJ d^{-1}) compared to the medium and poor wealth groups, which, respectively, consumed (33 ± 2 MJ d^{-1}) and (26 ± 2 MJ d^{-1}) (Table 2).

Among the 120 households, 82 (68.3%) were using three stone open fires, 21 (17.5%) mud-stoves, 10 (8.3%) improved solid biomass stoves, 3 (2.5%) both biogas stoves and mud-stoves, and 4 (3.3%) both biogas stoves and improved solid biomass stoves.

As shown in Table 3, consumption rates of the different biomass fuel sources (dung cakes, charcoal, firewood and crop residues) were positively and significantly correlated ($P < 0.01$). This is because different biomass fuel sources were used as complementary and not as substitutes for each other. For instance, it was observed during the field survey that both dung cakes and crop residues were used together for 'injera' (traditional pancake-like bread) baking for increasing burning efficiency and as mechanism of adapting to fuel scarcity. There was also a tendency to use specific biomass fuels for specific cooking purposes and hence higher consumption rates of one biomass fuel source led to corresponding higher consumption rates of other biomass fuel source (Table 3). For instance, baking more 'injera' required more dung cakes and crop residues which obliged farm households to prepare more 'wot' (traditional sauce eaten with 'injera') which in turn required more firewood.

Kerosene consumption rates also significantly varied among wealth groups (Table 2); this was highest for the rich (58(±1) dm^3 yr^{-1} per household) followed by the medium (38(±0.8) dm^3 yr^{-1} per household) and the poor (31(±0.7) dm^3 yr^{-1} per household). It was determined from focus group discussions and key informant interviews that families with alternative sources of energy for lighting, such as biogas, battery and solar energy consumed lower amounts of kerosene compared to families without alternative light sources.

Amounts of nutrients and organic carbon loss with use of dung cakes and crop residues for fuel

Using the measured nutrient contents (Table 4), the mean loss across all wealth groups of nutrients and OC due to using dung cakes and crop residues for fuels

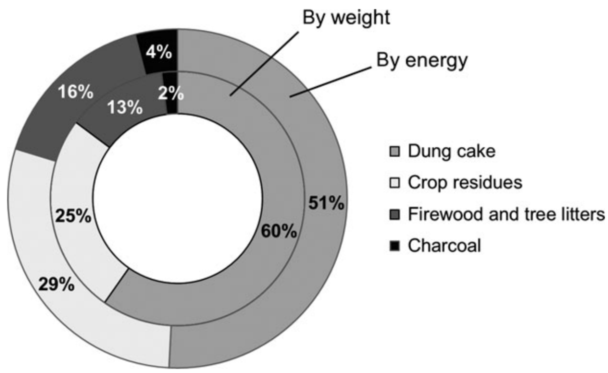

Fig. 2 Proportion on dry base weight (inner circle) and by energy content (outer circle) of different biomass fuels used in Kumbursa village.

Table 2 Farm households' energy consumption rates and resources endowment by wealth group

Wealth groups (N = 120)	Dung cakes (kg yr^{-1})	Crop residues (kg yr^{-1})	Firewood (kg yr^{-1})	Charcoal (kg yr^{-1})	Kerosene (dm^3 yr^{-1})	Landholding size (ha)	Livestock number (TLU)	Dung cake huts (number)	Fuel consumption rate (MJ ($capita^{-1}$ d^{-1})
Rich (n = 22)	7700 (±300)	2500 (±100)	1520 (±50)	190 (±5)	58 (±1)	3.3 (±0.2)	8.4 (±0.3)	4.4 (±0.2)	63 (±4)
Medium (n = 73)	3800 (±100)	1800 (±70)	810 (±30)	150 (±4)	38 (±0.8)	1.5 (±0.1)	4.1 (±0.2)	2.5 (±0.1)	33 (±2)
Poor (n = 25)	2800 (±100)	1240 (±50)	690 (±20)	90 (±3)	31 (±0.7)	1.1 (±0.1)	2.5 (±0.1)	1.3 (±0.1)	26 (±2)
Mean (n = 120)	4300	1800	920	150	40	1.9	5.0	2.7	41
Standard deviation	1677	409	292	42	1.2	1.2	2.5	1.5	19
Coefficient of variation (%)	39	22	32	29	34.9	67.8	57.3	53.1	47
Standard error	150	70	30	4	1	0.1	0.2	0.1	2.5
P-value	0.000**	0.000**	0.000**	0.000**	0.000**	0.000**	0.000**	0.000**	0.000**

Notes: kg $capita^{-1}$ d^{-1} includes only dung cakes, crop residues and firewood; **significant at 0.001 level; TLU = Tropical Livestock Unit; n = the number of samples; standard errors are given in brackets.

Table 3 Bivariate correlation coefficients between different biomass fuel consumption rates and resource endowment of the farm household

	Dung cakes (kg)	Charcoal (kg)	Firewood (kg)	Crop residues (kg)	Landholding size (ha)	Family size (capita)	Livestock number (TLU)
Dung cakes (kg)	1.00						
Charcoal (kg)	.654**	1.00					
Firewood (kg)	.994**	.628**	1.00				
Crop residues (kg)	.936**	.764**	.910**	1.00			
Landholding size (ha)	.651**	.461**	.652**	.597**	1.00		
Family size (capita)	.197*	.160*	.211*	.189*	.194*	1.00	
Livestock number (TLU)	.792**	.593**	.789**	.782**	.508**	.155*	1.00

Notes: TLU = Tropical Livestock Unit; ** and * indicate significant correlation at $P < 0.01$ and $P < 0.05$, respectively.

was 59(±2) kg ha^{-1} yr^{-1} N, 14(±0.5) kg ha^{-1} yr^{-1} P, 79 (±2) kg ha^{-1} yr^{-1} K and 1540(±20) kg ha^{-1} yr^{-1} OC (Figs 3 and 4). The nutrients concentrations of dung cakes and crop residues for the rich farm households were found to be higher than that of the medium and the poor (Table S1). These losses of nutrients are higher than has been measured by other researchers working in the Central Highlands of Ethiopia; Aklilu (2006) measured nutrient losses of 21 kg ha^{-1} yr^{-1} N, 4.5 kg ha^{-1} yr^{-1} P and 20.7 kg ha^{-1} yr^{-1} K due to the use of dung cakes as fuels, and Kassahun *et al.* (2013) measured nutrient losses of only 13.2 kg ha^{-1} yr^{-1} N, 3.3 kg ha^{-1} yr^{-1} P and 15.8 kg ha^{-1} yr^{-1} K due to the use of both dung cakes and crop residues for fuel. The differences in the observations may be due to larger areas of landholding per household in the areas selected in the earlier studies, resulting in the same household fuel use causing smaller nutrient losses per area of land. This is reflected in the losses of nutrients and OC observed for the different wealth categories, with the losses per area of land from the rich wealth group being significantly lower than from the medium or poor wealth categories.

If the losses are considered across the whole household, the mean losses across all wealth groups of nutrients and OC through the use of dung cakes for fuel are estimated to be 90(±7) kg yr^{-1} N, 24(±2) kg yr^{-1} P, 120 (±10) kg yr^{-1} K and 2000(±200) kg yr^{-1} OC per household, and due to use of crop residues as fuels to be 19 (±1) kg yr^{-1} N, 2.4(±0.2) kg yr^{-1} P, 30(±1) kg yr^{-1} K and 980(±50) kg yr^{-1} OC per household (Figs 5 and 6). This gives a total nutrient loss due to using dung and crops residues as fuels of 110(±8) kg yr^{-1} N, 26 (±2) kg yr^{-1} P, 150(±10) kg yr^{-1} K and 3000 (±300) kg yr^{-1} OC per household.

Contrary to the result per area of landholding, the rich farm wealth group was found to use significantly more dung and crop residues for fuel than the medium and the poor farm wealth groups (Fig. 6).The mean consumption of OC in dung cakes and crop residues per household was 2000(±200) kg yr^{-1} and 1000 (±60) kg yr^{-1}. The highest loss of OC with the dung cakes was recorded for the rich farm wealth group (162% of the losses from the medium farm wealth group and 223% of the loss from the poor farm wealth group) (Fig. 6). The nutrient loss due to use of dung cakes for fuel was significantly higher (90(±7) kg yr^{-1} N, 24(±2) kg yr^{-1} P, 120(±10) kg yr^{-1} K) than that of the crop residues (19(±1) kg yr^{-1} N, 2.4 (±0.2) kg yr^{-1} P, 30 (±2) kg yr^{-1} K) (Fig. 5). This is because crop residues are mostly used for feeding to the livestock.

It was reported by key informants that there had been a general switch to dung cakes and crop residues due to fuelwood scarcity, not only for domestic consumption, but also for sale. Apart from dung cakes, farm households of Kumbursa do not usually have surplus fuel to sell. The average value of dung cakes sold by a household was 2686(±127) ETB yr^{-1} (128(±6.1) US$ yr^{-1}) per household.

Discussion

The study in Kumbursa in the context of Ethiopia

Typical of rural villages in Ethiopia, farm households in Kumbursa were almost entirely dependent on biomass fuels for all household energy requirements (Fig. 2), with the exception of lighting. However, unlike many rural farm households in the Ethiopian Highlands, which often at least partly depend on community forests for fuelwood (Badege, 2001; Abebe *et al.*, 2011; Dawit, 2012; Fekadu, 2015), almost every farm household surveyed in Kumbursa was dependent on dung and crop residues collected from their own holdings (cropland and homestead) for fuel. There was neither a community forest for firewood nor communal grazing lands for dung collection. As such, Kumbursa represents the situation in an Ethiopian Highland village after the community forest has been depleted; a situation that will become more common as community forests become increasingly deforested due to population growth and overuse. Kumbursa villagers now only obtain 16(±0.6)% and 4.1(±0.2)% of their energy requirements from fuelwood and charcoal, respectively, the remainder being obtained from dung and crop residues (Fig. 2; Table 2) which would formerly have been applied to farmland for soil fertility amendment. This has seriously threatened a generations old practice of carbon and nutrient recycling within the farming systems through application of animal manures and crop residues in the smallholder crop-livestock integrated farming systems of the Ethiopian Highlands in general and in Kumbursa village in particular.

Field observations at the study site showed that almost all of the crop residues were used to feed livestock, while dung produced by cattle was a major source of fuel. Dung cakes and crop residues together made up 80(±4)% of the total biomass fuel consumption by energy content and 85(±4)% by dry mass weight (Fig. 2). As determined by key informant interviews and focus groups discussions, all the available dung was collected and made into dung cakes, while crop residues were largely used as feed for livestock. It was also observed during the field survey that the partially decomposed crop residues that are not suitable for feeding to livestock and any residues left over from livestock feed were almost exhaustively collected to either mix with the dung for dung cake preparation or to use directly as a fuel for cooking. In line with this finding, Aklilu (2006) observed that farm households in Beressa

Table 4 Average nutrients and carbon concentrations of crop residues and dung cakes samples

		Average nutrient concentration (%)			
Sample	Farm wealth group	Nitrogen	Phosphorus	Potassium	Organic carbon
Teff	Rich	1.14 (±0.03)	0.18 (±0.02)	1.04 (±0.05)	55 (±1)
	Medium	1.06 (±0.02)	0.15 (±0.01)	0.85 (±0.04)	52 (±0.9)
	Poor	1.04 (±0.02)	0.13 (±0.01)	0.82 (±0.03)	49 (±0.8)
	Mean	1.08 (±0.02)	0.16 (±0.01)	0.90 (±0.04)	52 (±0.9)
Chickpeas	Rich	1.18 (±0.03)	0.15 (±0.02)	3.16 (±0.1)	57 (±0.7)
	Medium	1.14 (±0.02)	0.14 (±0.02)	2.84 (±0.09)	54 (±0.7)
	Poor	1.07 (±0.01)	0.11 (±0.02)	2.61 (±0.08)	54 (±0.7)
	Mean	1.13 (±0.02)	0.13 (±0.01)	2.87 (±0.08)	55 (±0.6)
Wheat	Rich	1.04 (±0.03)	0.13 (±0.02)	1.16 (±0.02)	52.5 (±0.4)
	Medium	0.96 (±0.03)	0.12 (±0.01)	1.14 (±0.01)	51.4 (±0.4)
	Poor	0.84 (±0.02)	0.09 (±0.01)	1.13 (±0.01)	50.5 (±0.4)
	Mean	0.95 (±0.03)	0.11 (±0.01)	1.15 (±0.01)	51.5 (±0.4)
Dung cakes	Rich	2.5 (±0.1)	0.67 (±0.05)	2.89 (±0.04)	48.4 (±0.4)
	Medium	2.1 (±0.1)	0.58 (±0.03)	2.73 (±0.04)	47.2 (±0.3)
	Poor	1.7 (±0.1)	0.42 (±0.02)	2.64 (±0.03)	46.5 (±0.3)
	Mean	2.1 (±0.1)	0.56 (±0.04)	2.75 (±0.04)	47.4 (±0.4)

Note: Standard errors are shown in brackets.

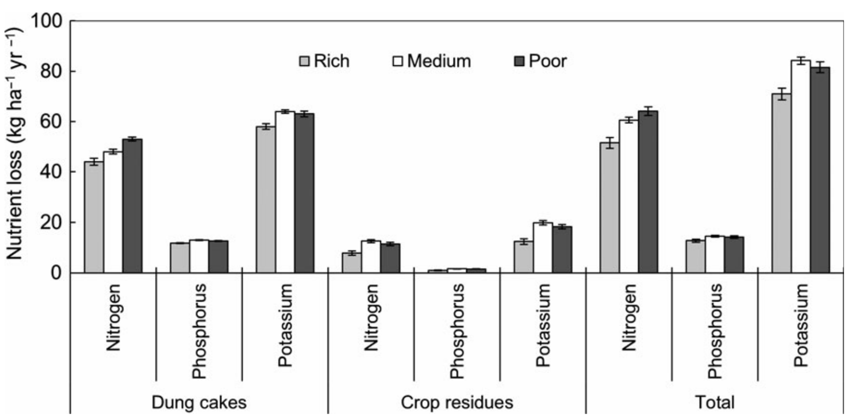

Fig. 3 Mean loss of nutrients by area of landholding due to use of dung cakes and crop residues separately as well as in combination as fuel. Note: Nutrient losses both through consumption by the households and sale were included. Error bars show standard errors.

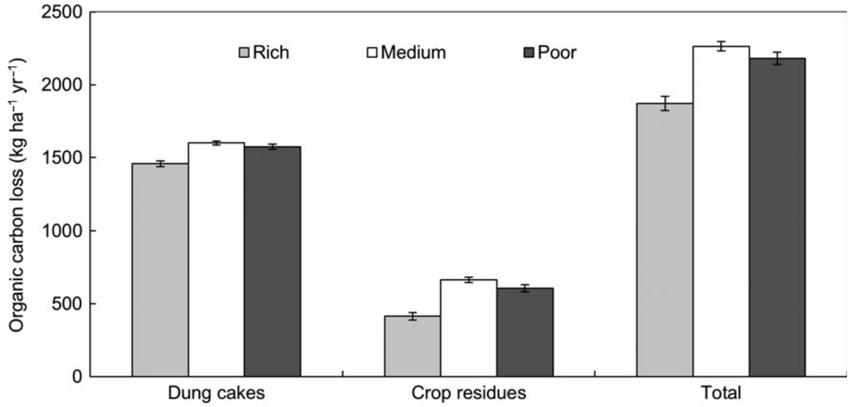

Fig. 4 Mean loss of organic carbon by area of landholding with use of dung cakes compared to crop residues for fuel for farm wealth groups. Note: Organic carbon loss both through consumption by the households and sale were included. Error bars show standard errors.

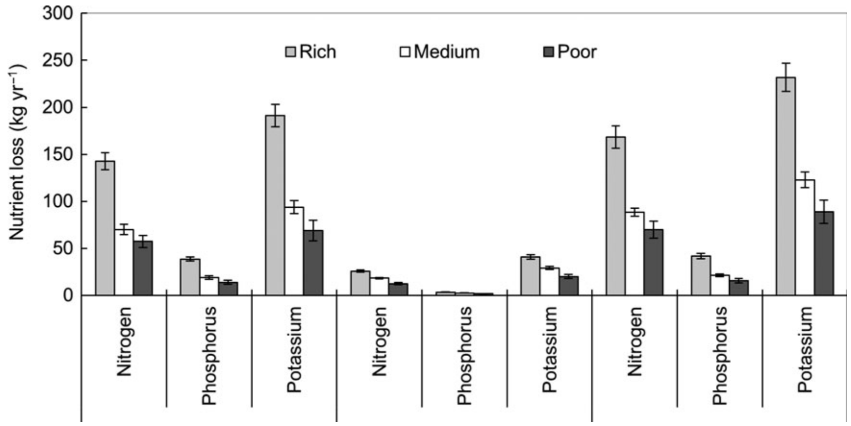

Fig. 5 Mean loss of nutrients for the household by wealth group due to the use of dung cakes and/or crop residues as fuel. Note: Nutrient losses both through consumption by the households and sale were included. Error bars show standard errors.

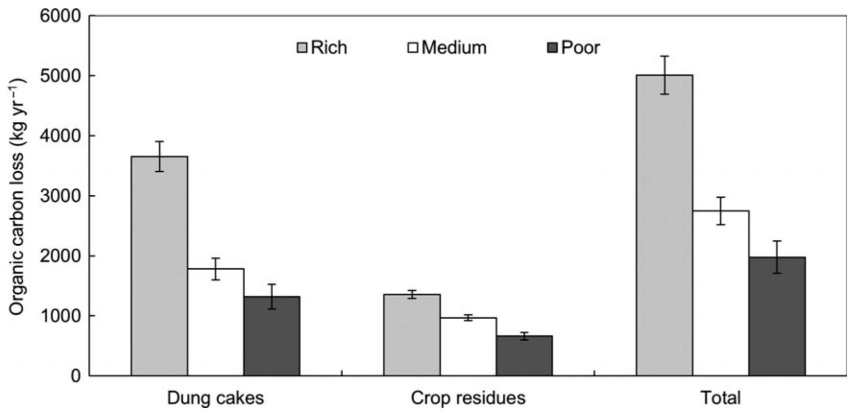

Fig. 6 Loss of organic carbon for the household by farm wealth groups due to use of dung cakes and/or crop residues for fuel. Note: Organic carbon loss both through consumption by the households and sale were included. Error bars show standard errors.

Watershed of the Central Highlands of Ethiopia prepared about 90% of their cattle manure into dung cake. EUEI [European Union Energy Initiative] (2013) also suggested that ~60% of dung and crop residues are used for household energy in the Highlands of Ethiopia. This suggests that the use of both animal manure and crop residues for improving soil fertility in Kumbursa, and Ethiopia as a whole, is very low, resulting in high loss of nutrients and carbon from the farming systems.

The situation today compared to the situation in the past

Interviews conducted with key informants also indicated that, in the past, firewood was abundant and large tracts of communal lands were available for livestock grazing. As a result, crop residues were left on farmland and animal manure was recycled into the farming system; this provided a significant contribution to soil fertility improvement. In the past, application of chemical fertilizers to cropland was rarely practiced by farmers of Kumbursa. However, farm households have now changed their practices to use dung cakes and crop residues for household energy instead of applying them to farmlands. As a result, it is suggested here that farmlands have become increasingly infertile and crop production without chemical fertilizer has become difficult.

Relationship between wealth status and tendency to use multiple fuels

In an effort to reduce the gap in the empirical literature on household energy and its interaction with carbon and nutrient recycling within the farming systems, this study has assessed biomass fuel production and consumption patterns among the different farm wealth groups. More specifically, the study has quantified the loss of nutrients and organic carbon from the farming systems with removal of crop residues and dung cakes for fuel, and explored its implications for sustainability of agricultural productivity.

There tends to be a positive relationship between resource endowment and fuel stacking. However, sometimes this relationship becomes unclear because noneconomic factors, which could be sociocultural and/or geographical, can also influence the tendency to use multiple fuels, so it is important to clarify the degree of relationship.

Wealth status, which is based on resource endowment, had little or no impact on farm households' energy choice in Kumbursa village as all of the three wealth groups (rich, medium and poor) were dependent on biomass fuel for cooking (Table 2). In other words, higher wealth status/resource endowment did not lead to energy stacking or partial energy switching. The focus group discussions suggested that some farm households were not willing to pay for alternative energy sources for cooking as long as dung cakes and crop residues were available, while others mentioned lack of access to alternative fuel sources as an underlying constraint to energy stacking. There also seemed to be little awareness or promotion of the benefits of modern cooking fuels over traditional biomass fuels in the area.

Overall, the impact of household resource endowment in dictating fuel choice and energy stacking was found to be insignificant. Based on focus group discussions and key informant interviews, multiple fuel use appeared to be curtailed by (1) inadequate awareness of the benefits of alternative fuel sources, and (2) limited access to the clean and safe energy alternatives which can serve to substitute or supplement biomass fuels. Therefore, under the present situation, the finding of this study does not follow the 'Energy Stacking' model as it fails to establish positive correlation between resource endowment and multiple fuel use.

Implications of large-scale removal of agricultural wastes for fuel

The loss of nutrients (N, P and K) from croplands through removal of crop residues was very high. Only small amounts of crop residues from stubble (approximately 10% based on a rough visual estimate) were left in situ for recycling back to the soil and this was further exposed to losses by livestock grazing after crop harvest. In the case of chickpeas, even the underground plant biomass was removed as harvesting was usually undertaken by uprooting. Abebe *et al.* (2015) also reported that less than 10% of manure and crop residues produced by smallholder farmers in Ethiopia were recycled into croplands for soil fertility amendment. Other studies have reported a shift to using animal manure and crop residues for household energy at the expense of applying them to croplands (Woldeamlak, 2003; Assefa *et al.*, 2007; EUEI [European Union Energy Initiative], 2013). Studies undertaken in several Ethiopian Highlands show high loss of organic matter from farming systems due to widespread conversion of households to dung cakes and crop residues for fuel in response to dwindling firewood supply (Aklilu, 2006; Dawit, 2012; Gwavuya *et al.*, 2012; Kassahun *et al.*, 2013; Getamesay *et al.*, 2015).

There were large differences among the three wealth groups in the total amount of nutrients and carbon lost due to use of organic resources as fuel. Although the total household loss of nutrients and OC was higher for the rich than the medium or poor farmers (Figs 5 and 6), when the loss was calculated per area of landholding, the losses were higher for the poor and the medium wealth groups than for the rich farmers (Figs 3 and 4). This suggests that depletion of soil, due to not incorporating dung and crop residues, will have a greater impact on the land belonging to poor and medium wealth class farmers than on land belonging to rich farmers, resulting in a cycle of decreasing soil fertility that increased poverty levels particularly in the farmers who are already poor.

The mean annual loss of N and P with use of crop residues and dung cakes for fuel was equivalent to 156(±7) kg diammonium phosphates and 80(±3) kg urea per household. In financial terms, the average loss for all the three farm wealth groups was estimated to be 3380 (±160) ETB yr^{-1} (162(±7.6) US$ yr^{-1}). However, this is less than their value as fuels, which was 10 297(±483) ETB yr^{-1} (490(±23) US$ yr^{-1}). Therefore, farmers will only be persuaded to use these valuable assets as soil improvers if an alternative, cheaper fuel source can be found. Of course it is worth noting that the value of organic fertilizers can be far higher than this if the value of all the nutrients (both macro and micro), and the effects of increasing soil organic matter and water holding capacity are taken into account.

The sale of dung cakes to provide household cash income also contributed to the removal of OC and nutrients from the farming system. Because Kumbursa is close to the capital city (Addis Ababa) and several small urban centers, such as Bishoftu, Dukam and Galan, there is an increased market demand for dung cakes; and this has caused farm households to collect almost all the available dung for dung cake preparation leaving little for application to farmland for soil fertility amendment. Aklilu (2006) also suggested that the farm households in the Central Ethiopian Highlands obtain cash income from the sale of dung cakes in the nearby towns. A study undertaken by Abebe *et al.* (2015) in the suburbs of Addis Ababa reported that up to 10% of household income is generated from the sale of dung cakes.

Generally, the prevailing switch to the widespread use of agricultural wastes both for domestic consumption and sale as fuel was identified as serious hurdle to the recycling of carbon and nutrients back to soils. This suggests that the already inadequate application of inorganic fertilizers (typically 49 kg ha^{-1} N and 46 kg ha^{-1} P) is rarely supported by recycling of nutrients from agricultural wastes; this jeopardizes the long-term sustainability of agricultural production.

What can be done?

The availability of cattle dung and crop residues for soil amendment could be increased through use of fuel-efficient improved cookstoves or increased use of multiple energy alternatives, such as small-scale biogas digesters or solar energy; these have the added advantage of being clean and sustainable. Chemical fertilizer should be used to complement, not as a substitute for, organic fertilizers; organic fertilizers provide organic matter as well as nutrients to the soil, improving soil structure and increasing the water holding capacity. Therefore policy makers should work toward encouraging farmers to use chemical fertilizers in combination with organic fertilizers instead of using chemical fertilizer alone.

Further work

Although this study was conducted in only one village, the findings and recommendations are likely to be representative of wider rural areas of Ethiopian Highlands that have switched to agricultural wastes for fuel in response to dwindling woody biomass supply, shrinking communal lands for livestock grazing and firewood collection. We recommend further studies to evaluate the long-term changes in soil nutrient status in Ethiopia, and the sustainable limit to the amounts of dung cakes and crop residues that can be removed for fuel. We also suggest the need for studies on the challenges and opportunities for improving biomass fuel use efficiency, noneconomic factors constraining the uptake of multiple fuels and the actions needed to make fuel use sustainable in Ethiopia.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Table S1 Nutrient and carbon loss by fuel and farm wealth group in Kumbursa village, Central Highlands of Ethiopia