Treatment of organic resources before soil incorporation in semi-arid regions improves resilience to El Niño, and increases crop production and economic returns

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Received xxxxxx
Accepted for publication xxxxxx
Published xxxxxx

Supplementary materials

S1. Materials and methods

S1.1 The study area

The study area was Halaba Woreda (district) near Hawassa, in the Southern Nations, Nationalities and Peoples Regional State (SNNPRS) Ethiopia (Figure 1). Halaba is approximately 640 km² and located between 70 20” - 70 61” latitude and 380 5” – 380 44” longitude, 250 km South of Addis Ababa [1]. It is a “Special Woreda”, meaning that it has a higher degree of administrative autonomy than other woredas, with administration divided into 73 Peasant Associations and one town (Halaba) [2]. It is one of the more densely populated areas of Ethiopia, with a population of 449 people per km², nearly four times the national average [1]. Agriculture is the main source of income for 88 % of the population [1], with food crops (teff, maize, wheat, sorghum and beans) and cash crops (pepper and khat) being widely grown [3]. Forest cover is only 5.2 % of the woreda land area, and this is dwindling due to increasing population and the demand for agricultural land and wood fuel [3]. Halaba is classified as being semi-arid “Woina Dega” (literally translated from Amharic as “grape zone”), at an elevation of between 1,700 and 2,150 m above sea level [1]. The annual temperature varies from 17 to 25 °C [2], with
March usually being the warmest month (average temperature 16 – 18 °C) and June the coolest (average temperature 13 °C). Precipitation is typically between 857 to 1085 mm y⁻¹, with a small rainy season between March and April, and the main rains between July and September [2]. As the Bilate river is the only perennial river in Halaba, rainfall is a major limiting factor in agricultural production [1].

Halaba experienced an extreme drought during the main rainy season of 2015, followed by delayed rains in early 2016 and flooding in May 2016 [4]. Information was gathered from the study area before, during and after the 2015 drought and the 2016 floods. This included data on social, cultural and economic factors, and measurements of carbon, nitrogen and water in soils and the yield of crops [5][6]. Farmers in Halaba were not the worst affected by drought; during 2015 the area was categorised as “stressed”, where other areas of Ethiopia were categorised as in a state of “crisis” or “emergency” [1]. However, it is an agricultural area with a high population density, where many farmers received food aid during 2015, and there is potential for careful planning to help communities to find their own ways to cope with extreme weather. Changes to management practices are likely to have a greater impact than in less densely populated but worse affected areas, where measures are also less likely to succeed. Therefore, this study area was selected as an example location where improved practices could have a high impact on the food security of both the local population and wider population of Ethiopia.

Figure 1 – Location of Halaba Special District, Ethiopia

### S1.2 On-farm measures used in Halaba

#### S1.2.1 Increased use of organic fertilisers

Use of chemical fertilisers has steadily increased in Halaba since 1998, with chemical fertilisers now being used in 93% of households, farmyard manure in 88% and composting in only 26% [5][6]. The increase in the use of chemical fertilisers is associated with a decrease in reliance on organic methods to supply plant nutrients, with a concomitant detrimental impact on the organic matter content of the soil [7] and reduction in water holding capacity [8]. Therefore, the impact on typical smallholder households in Halaba of returning to higher use of organic fertilisers was assessed. This accounts for the knock-on effects of using more organic wastes as fertilisers on their availability for other important functions within the household, such as use of manures for fuel and crop residues for feeding animals.

#### S1.2.2 Installation of soil and water conservation structures

Use of soil and water conservation practices is also increasing in Halaba, with soil bunds, strip cropping and contour ploughing now being practiced in around 50% of households [5][6]. In soils with a low organic matter content on steep slopes, there can be very high levels of erosion during wet periods. Soil and water conservation measures have been observed to decrease sediment loss from soils in Ethiopia by 40 to 66%, depending on the slope and soil type [9]. Reduced sediment loss also reduces loss of soil organic matter and nutrients, so maintaining the ability of the soil to retain water. Interviewed farmers in Halaba considered they could have achieved greater resilience to droughts and floods by ploughing across the slope, installing terracing, fences and drainage canals, planting soil and water conservation structures with trees and grasses to strengthen them, using water pumps for irrigation and constructing ponds to store water [5][6]. Therefore, the potential impact of using these different soil and water conservation practices on household income was assessed, particularly accounting for the impact on labour and the land area available for crop growth.

#### S1.2.3 Diversification of crops and management practices

Diversification strategies used by farmers in 2015 to cope with droughts and floods included planting extra maize for animal feed, practicing early ploughing to make use of early rains, planting trees and grasses as forage crops, sowing early and growing early maturing crops [5][6]. The main causes of crop damage during extreme weather events in Halaba between 1998 and 2007 were due to too much rain, floods and hail [2]. The average crop losses due to drought...
over that time were only 3%, but when droughts did occur, the impacts were catastrophic; during 2007, crop production was significantly reduced with greatest loss in the staple food crop, maize, perhaps because it has the longest growing season [2]. Crops with shorter seasons, such as haricot beans and teff showed much less reduction in yield [2]. This suggests the need to diversify crops and management practices so as to build resilience to droughts and floods. However, because in good years maize is the most productive crop, this would result in a yield cost over the long term. Due to constraints on the length of this paper, the impact of such diversification of crops and production methods on household revenue were not considered here.

S1.3 The modelling approach

S1.3.1 Use of soil data in simulations. Data obtained from the Harmonized World Soil Database for the 5 major soil types in the area [10] are given in Table 1. The soil characteristics held in the database are generated using only typical characteristics for the different soil classes, so do not necessarily represent the actual soils in the area, but can be used to check soil data collected in the survey of 196 farms in Halaba. Close agreement between the total soil carbon calculated from the two datasets suggests the surveyed soils provide a good sample of soils contained in Halaba.

Table 1 – Characteristics of topsoil for soils in Halaba obtained from the harmonized world soil database [10].

| Topsoil (0-20 cm) | Andisol | Nitisol | Vertisol | Luvisol | Leptosol |
|------------------|---------|---------|----------|---------|----------|
| Organic carbon, PC (%) | 3.43 | 2.45 | 1.23 | 0.63 | 0.39 |
| Bulk density, DBulk (g cm⁻³) | 0.97 | 1.18 | 1.23 | 1.45 | 1.31 |
| Total carbon, Cmeas (t ha⁻¹) | 67 | 58 | 30 | 18 | 10 |
| Average total carbon (t ha⁻¹) | 37 |
| Clay, Pclay (%) | 7 | 49 | 54 | 27 | 28 |
| Sand, Psand (%) | 61 | 24 | 18 | 51 | 43 |
| pH in water, SpHw | 5.8 | 5.3 | 5.6 | 6.4 | 7.5 |
| pH in CaCl₂, Sph | 5.2 | 4.7 | 5.0 | 5.7 | 6.7 |

Note: Shaded values are calculated. Calculated as described in *equation 1, b equation 12

The surveyed soil data were used in the ORATOR model to estimate the rate of soil organic carbon turnover as described by Smith et al. [11]. For applications in low input tropical soils, Smith et al. [11] demonstrated that the simulations of soil organic carbon over-estimated the measured change by 9%. Therefore, it is likely that the changes of soil organic carbon simulated here are within ~10% of the actual changes that would be observed in the field.

The measured soil organic carbon, Cmeas (t ha⁻¹), was calculated from the percent organic carbon, PC (%), and bulk density, DBulk (g cm⁻³), as shown in equation 1,

\[ C_{meas} = P_C \times D_{bulk} \times d \]  

(1)

where \( d \) is the depth of measurement (cm), set to 20 cm.

After Coleman and Jenkinson [12], soil carbon was divided into pools of decomposable plant material (DPM), resistant plant material (RPM), rapidly (BIO) and slowly decomposing soil organic matter (HUM), and inert soil organic matter (IOM) that does not decompose at all. The relative sizes of these pools defines the activity of the organic matter in the soil; these pool sizes were determined by an iterative process described by Smith et al. [13], by assuming the soil organic matter is in steady state and adjusting plant inputs, \( C_P \) (t ha⁻¹), until the simulated soil organic matter content at equilibrium, \( C_{sim} \) (t ha⁻¹), was equivalent to the measured value, \( C_{meas} \).

\[ C_{P}^* = C_P \times \frac{C_{meas}}{C_{sim}} \]  

(2)

where \( C_{P}^* \) is the plant inputs after adjustment (t ha⁻¹).

Clay minerals provide physical protection to organic matter in the soil, so the percentage clay, \( P_{clay} \) (%), was used to determine the proportion of decomposing organic matter (BIO and HUM) retained, \( p_{BIO&HUM} \), as described by Coleman and Jenkinson [12],

\[ p_{BIO&HUM} = \frac{1}{\left(1 + 1.67 \left(1.85 + 1.6e^{(-0.0786P_{clay})}\right)\right)} \]  

(3)

The ratio of rapidly (BIO) to slowly (HUM) decomposing organic matter produced on decomposition was set within the model to 0.85 [12], allowing the decomposing carbon to be separated into rapidly and slowly decomposing components, \( p_{BIO} \) and \( p_{HUM} \) respectively, and carbon dioxide, \( p_{CO2} \), as follows

\[ p_{HUM} = \frac{p_{BIO&HUM}}{1 + 0.85} \]  

(4)

\[ p_{BIO} = p_{BIO&HUM} - p_{HUM} \]  

(5)

\[ p_{CO2} = 1 - p_{BIO} - p_{HUM} \]  

(6)
The percent clay was also used together with the percent carbon and percent sand, $P_{sand}$ (%), to determine the volumetric water content at field capacity, $\theta_{FC}$ (%), and at permanent wilting point $\theta_{PWP}$ (%) according to pedotransfer functions derived for Halaba [11].

$$\theta_{FC} = 4.442P_C - 0.061P_{sand} + 0.34P_{clay} + 22.821$$  \hspace{1cm} (7)

$$\theta_{PWP} = 1.963P_C - 0.029P_{sand} + 0.166P_{clay} + 11.74$$  \hspace{1cm} (8)

These were then translated into the depth of water in 20 cm soil at field capacity and permanent wilting point, respectively $V_{FC}$ and $V_{PWP}$ (mm), using the soil depth $d = 20 \text{ cm}$

$$V_{FC} = \frac{\theta_{FC} \times d}{10}$$  \hspace{1cm} (9)

$$V_{PWP} = \frac{\theta_{PWP} \times d}{10}$$  \hspace{1cm} (10)

Taken together with rainfall data for the region, $V_{FC}$ and $V_{PWP}$ were used to calculate the water content of the soil to the specified depth at each monthly time step, $V_{wat}$ (mm) [11].

The rate of aerobic decomposition of soil carbon was then modified according to soil water,

$$r_{wat} = \min(1, 1 - \frac{0.8(V_{FC}-V_{wat})}{(V_{FC}-V_{PWP})})$$  \hspace{1cm} (11)

where $r_{wat}$ is the moisture modifier for aerobic decomposition of soil carbon [12].

Soil pH was also used to modify the rate of soil organic matter turnover as

$$r_{ph} = 0.56 + \frac{\tan^{-1}(3.14 \times 0.45 \times (S_{PH}-5))}{3.14}$$  \hspace{1cm} (12)

where $r_{ph}$ is the pH rate modifier for aerobic decomposition of soil carbon, and $S_{PH}$ is the soil pH measured in 0.01M calcium chloride (CaCl$_2$) [14]. Data were only available for pH measured in water, $S_{PHw}$, so the measured values were converted using the linear equation provided by Minasny et al [15], assuming that in these non-saline soils, the electrical conductivity measured in 1:5 soil to water solution, $S_{EC}$, is close to zero,

$$S_{PH} = -0.05 + 0.9S_{PHw} \pm 0.14S_{EC}$$  \hspace{1cm} (13)

The rate of aerobic decomposition was further modified according to average monthly air temperature, $T_n$ (°C),

$$r_{temp} = \frac{47.91}{1 - \exp(106.06/(T_n+18.27))}$$  \hspace{1cm} (14)

where $r_{temp}$ is the temperature modifier for aerobic decomposition of soil carbon [12].

Air temperature and rainfall data were obtained from total monthly rainfall (mm) and average air temperatures (°C) recorded from January 2005 to December 2016 [16]. Potential evapotranspiration was calculated for this latitude (assumed mid-point 70 41”) from air temperature using the Thornthwaite equation [17]. The rainfall and air temperature data for 2005 - 2014 was used to run the model to steady state. The impact of the El Niño event was then assessed using weather data for 2015 and 2016, and then the simulation was continued for a further eight years to determine the decadal impact using weather data from 2007 - 2014. A simplified weather pattern, in which the steady state and post-El Niño ran used just one repeated year (2014), allowed the impacts of the El Niño event to be discerned from the noise in changes in soil carbon and crop production generated by normal fluctuations in weather conditions.

S1.3.2 Estimating changes in crop production. In addition to calculating the rate modifying factors described above, the soil moisture and air temperature were used to estimate the crop yield by adjusting yield according to water stress and growing degree days in the current year compared to the typical year, 2014, which was then further adjusted according to the availability of soil nutrients calculated from the decomposition of organic matter in the soil and nutrient loss processes [11]. For applications in low input tropical soils, Smith et al. [11] demonstrated that the change in crop yield was over-estimated by 21%. Therefore, it is likely that the changes in productivity simulated here is within ~20% of the actual changes that would be observed in the field.

Typical 2014 yields for the five major crops grown in Halaba, maize, teff, pepper, sorghum and wheat, were obtained from field trials run by the Southern Agricultural Research Institute (SARI). Field trials were used to provide crop yields because the survey of crop yields on working farms in Halaba was likely to be inaccurate due to small and irregularly shaped fields, opportunistic intercropping, use of non-standardised weighing units or total absence of measurement of yields. Typical sowing and harvest dates in Halaba were also obtained from SARI records. Farm gate prices were obtained for the Halaba area from SARI records for 2014 (Table 2).
Table 2. Farm gate price and typical yield for major crops in Halaba

| Crop    | a Farm gate price (US$ t⁻¹) | b Typical yield (t ha⁻¹) | a Sowing month | a Harvest month |
|---------|-----------------------------|--------------------------|----------------|----------------|
| Maize   | 144                         | 2.64                     | 7              | 11             |
| Teff    | 576                         | 1.05                     | 8              | 11             |
| Pepper  | 900                         | 0.49                     | 3              | 10             |
| Sorghum | 249                         | 1.64                     | 5              | 9              |
| Wheat   | 234                         | 2.51                     | 8              | 11             |

Note: a SARI records; b SARI field trials.

The historical yields were calculated compared to 2014 by initialising the model using 2014 weather data and then running the model using weather data for the given year in the first year after initialisation. The historical yields calculated in this way for 2005 to 2014 were then used for the steady state simulation, and future yields calculated by running the model forward using actual weather data for 2015 and 2016 and setting the weather data in 2017 to 2024 to the values in 2007 to 2014.

S1.3.3 Quantity and quality of organic fertilisers available in Halaba. The average number of livestock kept by farmers was obtained from a survey of 157 farmers in Halaba [5][6]. This was converted to the typical amount of manure produced per household by multiplying by the manure produced per head [18] (Table 3). Therefore, the amount of manure available for treatment (none, composting, anaerobic digestion or pyrolysis) was assumed to be 0 to 3.1 t y⁻¹ manure. On average, the 157 farmers surveyed grew crops on 1.0 (95% confidence interval ± 0.5) hectares of land [5][6], so this equates to an application rate of 0 to 3.1 t ha⁻¹ y⁻¹, ranging from 2.1 to 6.2 t ha⁻¹ y⁻¹ depending on size of land holding.

Table 3. Typical amount of manure produced by animals owned by farmers in Halaba District 2014

| Animal       | c No. animals owned | d Manure produced per head (t y⁻¹) | Total manure produced (t y⁻¹) |
|--------------|---------------------|-----------------------------------|-------------------------------|
| Dairy cattle | 1.5                 | 0.2                               | 1.1                          | 1.7 (± 0.2) |
| Beef cattle  | 1.4                 | 0.3                               | 0.5                          | 0.7 (± 0.2) |
| Calves       | 0.6                 | 0.1                               | 0.25 a                       | 0.2 (± 0.0) |
| Goats or sheep | 1.3               | 0.3                               | 0.2 b                       | 0.3 (± 0.1) |
| Equines      | 0.6                 | 0.1                               | 0.5 c                       | 0.3 (± 0.1) |
| Poultry      | 3.2                 | 0.5                               | 0.00                        | 0.0 (± 0.0) |
| Total        |                     |                                   | 3.1 (± 0.6)                 |

Note: CI95 is the 95% confidence interval, assumptions a 50% production of adult beef cattle, b equivalent to adult beef cattle, c negligible, d typical livestock production values for mixed rotation livestock grazing in arid / semi-arid areas of Eastern Africa [18], e from survey of farmers in Halaba [5][6].

The carbon and nitrogen contents of the differently treated organic wastes were determined using the percent carbon and the carbon to nitrogen ratio, and the applied carbon was partitioned into decomposable plant material and slowly decomposing organic matter in the soil according to the ratios provided by Smith et al. [19] (Table 4).

Table 4. Parameters used to describe differently treated organic wastes

| Organic waste treatment | Fresh waste | Compost | Bioslurry | Biochar |
|-------------------------|-------------|---------|-----------|---------|
| Carbon to nitrogen ratio| 23 a        | 9 b     | 6 c       | 150 d   |
| Ratio of DPM to HUM e   | 31.45       | 1.00    | 1.00      | 32.00   |
| IOM (%) c               | 0%          | 0%      | 0%        | 50%     |
| Carbon (%) d            | 47% a       | 50% a   | 47% c     |
| Carbon lost on treatment (%)e| 0%          | 63%     | 74%       | 65%     |

Note: DPM = decomposable plant material; HUM = slowly decomposing soil organic matter; IOM = inert soil organic matter, a typical values measured in Ethiopian manures [7], b typical values for composts in Sub-Saharan Africa [20], c typical values for bioslurries assuming conservation of nitrogen within the digester, d typical values for biochar produced from low nutrient materials [21], e values estimated for organic wastes in Sub-Saharan Africa [19].

S1.3.4 Impact of applying organic wastes to soils on available fuel, labour and household expenditure. Information from the survey of 157 farmers in Halaba [5][6] was used to calculate the impact of applying organic wastes to the soils on available fuel, labour and household expenditure to obtain cooking fuel. The survey indicated that 15% of household cooking fuel was typically obtained from dung, and 14% of the available dung is used for cooking. Therefore, it was assumed that 14% of the available manure (0.4 t y⁻¹) was used for cooking.

From the theoretical lower heating value, the net calorific value of dung cakes was assumed to be 11.90 MJ kg⁻¹ with a typical stovetop efficiency of 8.5% [22], whereas that of woodfuel was assumed to be 13.95 MJ kg⁻¹ with a typical stovetop efficiency of 11% [22]; this gives a ratio of cooking energy provided by dung cakes compared to woodfuel of 0.66. Therefore, it was assumed that 0.66 t of additional woodfuel
would be required for every tonne of manure applied to soil instead of using it as cooking fuel.

The survey also indicated that households in Halaba typically require 1.45 (±0.09) hours to collect one bundle of woodfuel, weighing 0.016 (±0.002) tonnes. Therefore, every additional tonne of woodfuel needed would take 91 (±6) hours to collect. Alternatively, additional woodfuel could be purchased; the survey determined that the average cost of woodfuel in Halaba was 30 Ethiopian Birr per bundle, just over 1 US$. Therefore, every additional tonne of woodfuel purchased would cost 66 (±8) US$.

Heegde and Sonder [23] estimated that 0.8 to 1.0 m³ biogas is produced per 25 kg dung. Therefore, it was assumed that every tonne of manure used to produce bioslurry would provide 32 to 40 m³ biogas. From the net calorific value of biogas, 216 MJ m⁻³ [24], and the minimum efficiency required for biogas stoves, 55% [25], the cooking energy provided by the biogas is assumed to be 118.8 MJ m⁻³, meaning that every tonne of manure used to produce bioslurry will provide 3802 to 4752 MJ.

**S1.3.5 Installation of soil and water conservation structures.** The potential reduction in soil carbon loss, \( \Delta C_{erode} \) (t ha⁻¹) was instead calculated from the estimated soil losses by erosion, \( S_{erode} \) (t ha⁻¹), the observed reduction in erosion that can be achieved using soil and water conservation structures, \( \Delta P_{erode} \) (%), and the carbon content of the eroded soil, \( P_C \) (%);

\[
\Delta C_{erode} = S_{erode} \times \Delta P_{erode} \times P_C
\]  

(15)

In the highlands of Ethiopia, Mulatie [26] estimated soil losses by erosion to average 20 t ha⁻¹ y⁻¹, and to be as high as 300 t ha⁻¹ y⁻¹ on steep slopes. The Ethiopian Highlands Reclamation Study estimated the average rate of erosion to be much higher, at ~100 t ha⁻¹ y⁻¹ [27]. Hurni [28] estimated average soil loss rates of 70 t ha⁻¹ y⁻¹ from permanently degraded land, 42 t ha⁻¹ y⁻¹ from arable land, 8 t ha⁻¹ y⁻¹ under perennial crops, and 5 t ha⁻¹ y⁻¹ under grazing, wood and bush land. Therefore, the range of potential soil losses by erosion \( S_{erode} \) was assumed to be 20 to 100 t ha⁻¹ y⁻¹ of soil. The reduction in soil erosion that is possible by installing soil and water conservation structures was estimated for the Highlands of Ethiopia to be 40 to 66% [29]; this was used as the range of possible values for \( \Delta P_{erode} \). The carbon contents of soils in Halaba were obtained from a survey of 196 randomly selected soil samples.

**S2. Results and discussion**

**S2.1 Increased use of organic fertilisers**

**S2.1.1 Frequency of droughts** As the frequency of droughts increases, the amount of manure needed to avoid soil degradation also increases; if droughts occur every 3 years, the amount of manure needed to prevent long term soil degradation exceeds that available on the farm for all crops except pepper and sorghum (Figure 2).

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**Figure 2 – Untreated animal manure needed to counter the impacts on soil carbon of El Niño events occurring with different frequencies for five major crops grown in Halaba. Simulations assume 2014 weather data for steady state and post El Niño run.**

52.1.2 Longer term impacts of manure application If manure application had started in the first year of the El Niño event, with application of all the manure available on the farm, crop production is increased by 3% (maize) to 33% (sorghum) in 2015, and by 3% (maize) to 21% (sorghum) over the decade as a whole, with an associated increase in income over the decade of between 107 and 726 US$ ha⁻¹ (Figure 3). If applications had started 10 years earlier, the loss of yield in 2015 would have been further reduced, increasing yield compared to no manure application by between 9% (maize) and 79% (sorghum) in 2015, and by between 6% (maize) and 26% (teff) over the decade, with an associated increase in income over the decade of between 205 and 904 US$ ha⁻¹.

In households that use dung for cooking, applying all of the manure available to crops represents a loss of 0.4 t y⁻¹ cooking fuel with a calorific value of 5165 MJ y⁻¹, which using the ratio of cooking energy provided by dung to woodfuel (0.66), is equivalent to 0.3 t y⁻¹ woodfuel. On average, collecting this amount of woodfuel in Halaba would require 0.5 (± 0.3) hours every week, or just under 5 minutes a day. If the farmer instead needs to buy additional woodfuel, this would cost 19 (± 2) US$ y⁻¹. Therefore, the economic impact of applying all organic waste to the crops over 10 years ranges from a net cost of 83 (±24) US$ (maize) to a net benefit of 536 (±24) US$ (sorghum) in decade 1, and a net benefit of 15 US$ (maize) to 714 US$ (sorghum) in decade 2. Therefore, unless woodfuel is readily available, household income is likely to be improved by applying untreated animal manure only up to the rate not required for household cooking (2.7 t y⁻¹). This is sufficient to avoid soil degradation down to a frequency El Niño events of every 5 years (Figure 2), and provides an increase in net...
income of 96 to 674 US$ in decade 1 and 194 to 851 US$ ha⁻¹ in decade 2 with no additional cost for fuel.

Figure 3 – Increased income due to applying all manure available on farm (3.1 t ha⁻¹ y⁻¹) as untreated animal manure for five major crops grown in Halaba. Manure applications starting in the year of El Niño event, assuming 2014 weather data for steady state and post El Niño run.

References

[1] Tarfasa S, Balana BB, Tefera T, Woldeamanuel T, Moges A, Dinato M, Black H 2018 Modeling smallholder farmers’ preferences for soil management measures: A case study from South Ethiopia Ecological Economics 145 410-9
[2] Getnet K, Tekuria W, Langan S, Rivington M, Novo P, Black H 2017 Ecosystem-based interventions and farm household welfare in degraded areas: Comparative evidence from Ethiopia Agricultural Systems 154 53-62
[3] CSA (Central Statistics Agency) 2014 Key findings of the 2013/2014 (2006 E.C.) agricultural sample surveys. In: Country SummaryFederal Republic of Ethiopia, Central Statistical Agency, Addis Ababa http://www.csa.gov.et/index.php?option=com_phocadownload&view=category&id=270&Itemid=270
[4] Funk C, Harrison L, Shukla S, Hoell A, Korecha D, Magadzire T, Husak G, Galu G 2016 Assessing the contributions of local and east Pacific warming to the 2015 droughts in Ethiopia and southern Africa Bulletin of the American Meteorological Society 97 S75-S80
[5] Phimister E, 2018. Organic resource use in rural households in Ethiopia. [Data Collection]. Colchester, Essex: UK Data Archive. 10.5255/UKDA-SN-853076.
[6] Smith JU, 2019. Building resilience to drought in Ethiopia’s Awassa region. [Data Collection]. Colchester, Essex: UK Data Archive. Website to be confirmed.
[7] Negash D, Abegaz A, Smith JU, Araya H, Gelana B 2017 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 Global Change Biology Bioenergy 9 1588-601
[8] Smith J, Hallett P, Nayak D, Boke S, Habte M, Yakob G, Rivington M, Phimister E 2019 Biophysical measurements from Ethiopia’s Awassa region during the drought and subsequent floods of 2015-2016 NERC Environmental Information Data Centre https://doi.org/10.5285/024c5a61-5114-41a6-9fbb-e3fbd762b2b
[9] Gebremichael A, Yakob G 2016 On-farm quantification and demonstration of the extent of soil erosion and nutrient loss from slope farmland under millet production in Kafa Zone, Ethiopia. Journal of Natural Science Research 6 77-86
[10] Harmonized World Soil Database 2018 http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/
[11] Smith J, Nayak D, Albaniito F, Balana B, Black H, Boke S, Brand A, Byg A, Dinato M, Fischer A, Habte M, Hallett P, Lemma T, Tekuria W, Moges A, Mulunehe A, Novo P, Rivington M, Tefera T, Vanni M, Yakob G, Phimister E 2018 A new model of the impact of organic resources on smallholder farms in Sub-Saharan Africa. Environmental Modelling and Software. Submitted.
[12] Coleman K, Jenkinson DS 1996 RothC-26.3. A model for the turnover of carbon in soil. In: Powlsion DS, Smith P, Smith JU, editors. Evaluation of soil organic matter models using existing long-term datasets. NATO ASI Series I, Springer, Berlin 38 237–46.
[13] Smith JU, Smith P, Wattenbach M, Zaehle S, Hiederer R, Jones RJA, Montanarella L, Roussseuil MDA, Reginster I, Ewert F 2005 Projected changes in mineral soil carbon of European croplands and grasslands, 1990-2080. Global Change Biology 11 2141–52.
[14] Parton WJ, Mosier AR, Ojima DS, Valentine DW, Schimel DS, Weier K, Kulmala AE 1996 Generalized model for N₂ and NO production from nitrification and denitrification. Global Biogeochemical Cycles 10 401-12.
[15] Minasy N, McBratney AB, Brough DM, Jacquer D 2011 Models relating soil pH measurements in water and calcium chloride that incorporate electrolyte concentration. European Journal of Soil Science 62 728–32.
[16] Ethiopian National Meteorological Agency 2016 http://www.ethiomet.gov.et/
[17] Thorntwhaite CW 1948 An approach toward a rational classification of climate. Geographical Review 38 55–94.
[18] Herrero M, Havlik P, Valin H, Notenbaert A, Rufino MC, Thornton PK, Blümmel M, Weiss F, Grace D, Obersteiner M 2013 Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proceedings of the National Academy of Science 110 20888–93.
[19] Smith J, Abegaz A, Matthews RB, Subedi M, Orskov ER, Tumwesige V, Smith P 2014 What is the potential for biogas digesters to improve soil carbon sequestration in Sub-Saharan Africa? Comparison with other uses of organic residues. Biomass and Bioenergy 70 73-86.
[20] Kabore TW-T, Houot S, Hien E, Zombré P, Hien V, Masse D 2017 Effect of the raw materials and mixing ratio of
composted wastes on the dynamic of organic matter stabilization and nitrogen availability in composts of Sub-Saharan Africa. Bioresource Technology 101 1002-13.

[21] Smith J, Abegaz A, Matthews RB, Subedi M, Orskov ER, Tumwesige V, Smith P 2014 What is the potential for biogas digesters to improve soil fertility and crop production in Sub-Saharan Africa? Biomass and Bioenergy 70 58-72.

[22] Singh P, Gundimeda H, Stucki M 2014 Environmental footprint of cooking fuels: a life cycle assessment of ten fuel sources used in Indian households. International Journal of Life Cycle Assessment 19 1036-48.

[23] ter Heegde F, Sonder K 2007 Domestic biogas in Africa; a first assessment of the potential and need. The Netherlands: SNV; http://www.snv.org/?publication=348.

[24] AEBIOM 2009 A biogas road map for Europe. Belgium: European Biomass Association; http://www.aebiom.org/IMG/pdf/Brochure_BiogasRoadmap_WEB.pdf.

[25] Khandelwal KC, Gupta VK 2009 Popular summary of the test reports on biogas stoves and lamps prepared by testing institutes in China, India and the Netherlands. The Netherlands: SNV.

[26] Mulatie M 2009 Soil erosion assessment, runoff estimation and water harvesting site selection using GIS and remote sensing at Debre Mewi Watershed (West Gojam). MSc thesis, Bahri Dar, University, Bahir Dar.

[27] Ethiopian Highlands Reclamation Study 1986 Ethiopian highland reclamation study, final report, Vol. 1, FAO, Rome.

[28] Hurni H 1985 Erosion-Productivity-Conservation systems in Ethiopia. In: Proceedings 4th international conference on soil conservation, Maracay, Venezuela, p 654–674.

[29] Gebremichael A, Yakob G 2016. Journal of Natural Science Research 6 77-86.