Environmental Research Letters

LETTER • **OPEN ACCESS**

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

To cite this article: Jo Smith *et al* 2019 *Environ. Res. Lett.* **14** 085004

IOP Publishing Environ. Res. Lett. 14 (2019) 085004 https://doi.org/10.1088/1748-9326/ab2b1b

Environmental Research Letters

OPEN ACCESS

RECEIVED
22 February 2019

REVISED
14 June 2019

ACCEPTED FOR PUBLICATION
19 June 2019

PUBLISHED
26 July 2019

LETTER

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

Jo Smith[1], **Dali Nayak**[1], **Fabrizio Albanito**[1], **Bedru Balana**[2,11], **Helaina Black**[3], **Shiferaw Boke**[4], **Alison Brand**[1], **Anja Byg**[5], **Mengistu Dinato**[6], **Mulugeta Habte**[4], **Paul Hallett**[1], **Thomas Lemma Argaw**[6], **Wolde Mekuria**[7], **Awdenegest Moges**[6], **Alemayehu Muluneh**[6], **Paula Novo**[5,8], **Mike Rivington**[9], **Tewodros Tefera**[6], **May Vanni**[10], **Getahun Yakob**[4] and **Euan Phimister**[10]

[1] School of Biological Science, University of Aberdeen, Aberdeen, United Kingdom
[2] International Water Management Institute, Accra, Ghana
[3] Ecological Sciences, James Hutton Institute, Aberdeen, United Kingdom
[4] Department of Natural Resources, Southern Agricultural Research Institute, Hawassa, Ethiopia
[5] Social, Economic and Geographical Science Group, James Hutton Institute, Aberdeen, United Kingdom
[6] Environment, Gender & Development Studies, Hawassa University, Hawassa, Ethiopia
[7] International Water Management Institute, Addis Ababa, Ethiopia
[8] Land Economy, Environment & Society, Scotland's Rural College (SRUC), Edinburgh, United Kingdom
[9] Information and Computational Sciences, James Hutton Institute, Aberdeen, United Kingdom
[10] Business School, University of Aberdeen, Aberdeen, United Kingdom
[11] Current address: International Food Policy Research Institute (IFPRI), Abuja, Nigeria.

E-mail: jo.smith@abdn.ac.uk

Keywords: organic resource use, resilience, soil degradation, compost, bioslurry, biochar, El Niño

Supplementary material for this article is available online

Abstract

The use of limited organic resources to build resilience to drought in semi-arid regions was investigated using systems modelling. The study focused on Halaba in Ethiopia, drawing on biophysical and socio-economic data obtained from a survey of farms before, during and after the 2015/16 El Niño event. Using a simplified weather dataset to remove noise from weather fluctuations, a ten yearly El Niño was demonstrated to cause significant long-term degradation of soil, reducing crop yields by 9%–14% and soil carbon by 0.5%–4.1%; more frequent droughts would increase this impact. Farmers in Halaba usually apply manures to soils untreated. Counteracting the impact of El Niño on soil degradation is possible by increasing application of untreated manure, but would result in a small net cost due to loss of dung as fuel. By composting manure its recalcitrance increases, allowing soil degradation to be counteracted without cost. The best option investigated, in terms of both food and fuel security, for households with access to water and finances needed for anaerobic digestion (500–2000 US$), is to use manure to produce biogas and then apply the nutrient-rich bioslurry residue to the soil. This will result in a significant benefit of over 5000 US$ per decade from increased crop production and saved fuel costs. However, many households are limited in water and finances; in that situation, the much cheaper pyrolysis cook-stove (50 US$) can provide similar economic benefits without the need for water. The biochar residue from pyrolysis is highly recalcitrant, but pyrolysis results in loss of nutrients, so may result in lower yields than other uses of manures. This may be countered by using biochar to capture nutrients from elsewhere in the farm, such as from animal housing or compost pits; more work is needed to quantify the impact of treated biochar on crop yields.

1. Introduction

Smallholder farmers in low to middle income countries are particularly vulnerable to extreme weather conditions, because they are often living with a low baseline level of income and food security, and have limited capacity to adopt strategies that adapt to climate variability and change [1]. The warm phase of

El Niño Southern Oscillation is associated with a band of warm ocean water that develops in the central and east-central Pacific, and causes a shift in atmospheric and oceanic circulation, reducing rainfall in some areas while increasing it in others [2]. In June–September 2015, rainfall in many parts of Ethiopia was significantly less than normal; precipitation data indicated that this was one of the worst droughts in more than 50 years with the drought being exacerbated by the strong 2015 El Niño event [3]. It is estimated that 10.2 million people in Ethiopia were subject to food insecurity during and immediately after the exceptional drought in 2015 [4]. Here, we use a combination of socioeconomic and biophysical measurements, taken before, during and after the El Niño event, to understand how the drought and subsequent floods affected household resources in the Halaba district in the Ethiopian Rift Valley Lakes Basin. We use a novel systems modelling approach to use the data collected to determine the potential to use organic resources to build resilience to drought, and attempt to draw out lessons from this analysis to help increase preparedness of agricultural communities in Ethiopia and other low to middle income countries for future extremes in weather.

2. Materials and methods

2.1. The study area

A detailed description of the study area, Halaba Woreda (district) near Hawassa, in the Southern Nations, Nationalities and Peoples Regional State of Ethiopia, is given in the supplementary materials (S1.1) available online at stacks.iop.org/ERL/14/085004/mmedia. It is classified as being semi-arid and experienced an extreme drought during the main rainy season of 2015, followed by delayed rains in early 2016 and flooding in May 2016 [3]. 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’ [4]. However, it is an agricultural area with a high population density, where many farmers received food aid during 2015, and so there is potential for careful planning to help communities to find their own ways to cope with extreme weather. Changes to land 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 due to the more extreme conditions faced. 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 and wider population of Ethiopia.

2.2. Choice of on-farm measures to be assessed

Feedback from farmers in Halaba at focus group discussions and stakeholder workshops suggested that they do not necessarily need new methods to cope with extreme weather events, but instead want to know which of the existing methods are most likely to improve their resilience [5]. Therefore, the resilience building measures considered here are drawn from the coping strategies already adopted by farmers to deal with the droughts and floods experienced over recent years (table 1). Here, we focus on the use of organic fertilisers and compare changes in resilience achieved to the range of potential changes associated with soil and water conservation measures. Diversification of crops and changes in management practices are beyond the scope of this paper. Further discussion of the resilience building measures used in Halaba is given in S1.2.

Table 1. Resilience building measures to be considered.

Category	Practice
Use of organic fertilisers	- Increased use of untreated manures - Composting - Anaerobic digestion - Pyrolysis
Soil and water conservation measures	- Soil and stone bunds - Terracing, fences and drainage canals - Stabilising soil and water conservation structures with trees and grasses - Strip cropping - Contour ploughing - Water pumps for irrigation - Ponds to store water
Diversification of crops and management practices	- Planting extra maize for animal feeds - Early ploughing - Planting trees and grasses as forage crops - Early sowing - Growing early maturing crops - Growing crops with shorter growing seasons - Area closure

2.3. The modelling approach

2.3.1. Overview

A model of the whole farm system was adopted, based on the ‘Operational Research Assessment Tool for Organic Resources’ (ORATOR) (S1.3). This simple but comprehensive model is designed to account for the impact of different uses of farm resources on soil organic matter, crop production, animal production, water use, fuel availability, on- and off-farm labour, and farm income and expenditure (figure 1). The model uses process-based approaches to simulate the impact of changes in resource management on resilience. Different inputs of organic resources to the soil affect resource use in the whole system; increased inputs of carbon to the soil lead to increases in the soil

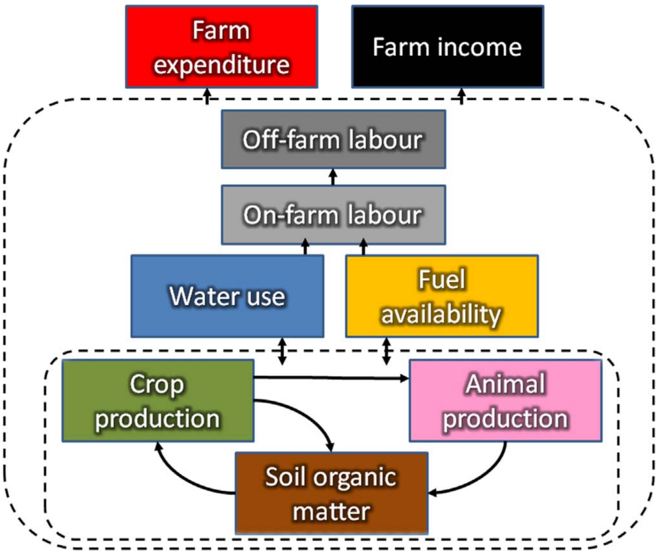

Figure 1. The structure of the ORATOR model.

organic matter, which impacts the water holding capacity and nutrients available in the soil. This affects crop production, which has an impact on the production of animals using feeds produced on-farm, or on the household expenditure on feed to maintain animals. The water holding capacity of the soil, and production of crops and animals all affect the requirements for water. The biomass production of crops determines the amount of crop residues available to feed to animals, and the availability of crop residues and dung for use as fuels. This impacts the labour or financial resources required to obtain additional fuels, such as wood or charcoal. The requirement for labour is also determined by water use, crop selection and the animals maintained on the farm. This has an impact on the amount of labour available for off-farm activities. The income and expenditure of the farm are a function of the purchases made by the household, such as food, feed, fuel and fertilisers, and the labour and products available within the household for sale, such as grain, milk and animals.

2.3.2. Impact of El Niño in Halaba

The ORATOR model was used to simulate the impact of El Niño on households in Halaba, using input data collected from January 2014 to December 2016. The mean characteristics of soils in Halaba were obtained from a survey of 196 soil samples collected from randomly selected farms across four different kebeles (districts) in Halaba [5, 6] (table 2). Comparison of mean total soil carbon content in 0–20 cm topsoil from the surveyed samples with data from the Harmonised World Soil Database for the five major soil types in the area [7] shows close agreement between average soil carbon contents (36 and 37 t ha^{-1}, respectively), providing confidence that the surveyed soils are representative of the soils found in Halaba. The use of these data within the model to simulate the impacts of the El Niño effect is described in more detail in S1.3.1 and S.1.3.2.

Table 2. Characteristics of soils in Halaba (depth 0–20 cm) measured in 196 soil samples collected from farms in Halaba [5, 6] and used as inputs to the ORATOR model.

Parameter	Mean	Standard error
Organic carbon, P_C (%)	1.61	0.04
Bulk density, D_{bulk} (g cm^{-3})	1.12	0.01
Total carbon[a], C_{meas} (t ha^{-1})	36.06	0.008
Clay, P_{clay} (%)	12.8	0.3
Sand, P_{sand} (%)	39.7	0.7
pH in water, $S_{\mathrm{pH},w}$	6.89	0.04
pH in[b] CaCl$_2$, S_{pH}	6.15	0.04

Note. Shaded values are calculated from the other parameters. Values are calculated as described in

[a] Equation (1) of online supplementary material.

[b] Equation (12) of online supplementary material.

2.3.3. Increased use of organic fertilisers

The potential impacts of increased application of organic fertilisers, applied as untreated animal manure (fresh waste), composts, bioslurry produced by anaerobic digestion or biochar produced by pyrolysis, were calculated using the simulations of the impact of El Niño in Halaba as the baseline. It was assumed that farmers could only apply up to the amount of manure available on their farms; the option to buy in or otherwise obtain organic wastes from neighbours or other sources was not considered. This equated to 3.1 t yr^{-1} applied over the area of land holding (1.0 ± 0.5 ha^{-1}), giving an average potential application rate of 3.1 t ha^{-1} yr^{-1}, but with 0.4 t yr^{-1} currently being used for cooking fuel (S1.3.3). The carbon and nitrogen content and recalcitrance of the organic wastes were determined according to the treatment method (S1.3.3). The impact on available

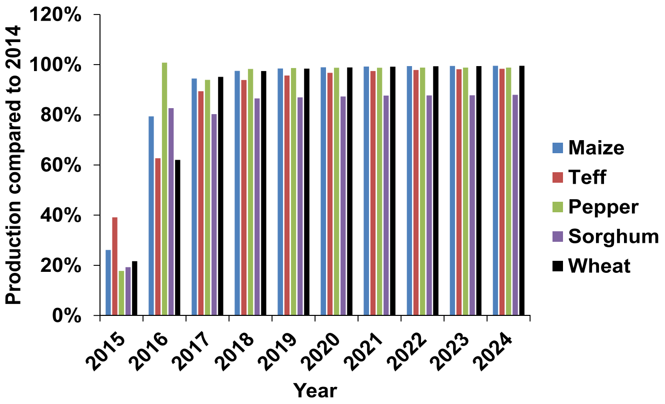

Figure 2. Simulated production of five major crops grown in Halaba District compared to 2014. Crops growing on soils with mean surveyed characteristics (table 2). Rainfall and air temperature used in steady state and post El Niño simulations were obtained from records for 2014. Actual weather data were used for years when El Niño effects were seen in 2015 and 2016.

fuel, labour and household expenditure of applying differently treated organic wastes to the soil was calculated as detailed in S1.3.4.

2.3.4. Installation of soil and water conservation structures

Site specific simulation of the impact of soil and water conservation structures on erosion requires detailed information on climate erosivity, soil erodibility, topography (slope length and steepness), and land use and management, which is not all available for the households surveyed in Halaba [8]. The potential reduction in soil carbon loss was instead calculated from the estimated soil losses by erosion, the observed reduction in erosion that can be achieved using soil and water conservation structures, and the carbon content of the eroded soil. This was calculated as described in S1.3.5, using carbon contents of soils drawn from table 2.

3. Results and discussion

3.1. The impact of El Niño in Halaba

3.1.1. Crop production

Production compared to the previous decade for five major crops grown in Halaba shows a complex picture, with variation in weather conditions between years resulting in year-on-year differences in yield superimposed on the impacts of El Niño; nevertheless, analysis of the results shows a significant decadal reduction in crop production of 2.2%. If the noise in the weather data is removed by running simulations assuming 2014 represents steady state, so using 2014 weather and yield data for the year before and after El Niño, the impacts of El Niño can be separated out from the noise in weather and a clearer picture emerges, with a decadal reduction in production averaging 12% (figure 2), and a reduction in revenue of 404 US$ ha^{-1} (11%) for maize, 790 US$ ha^{-1} (13%) for teff, 387 US$ ha^{-1} (9%) for pepper, 572 US$ ha^{-1} (14%) for sorghum, and 753 US$ ha^{-1} (13%) for wheat. This indicates that a significant long-term (decadal) negative impact on production and revenue can be attributed to El Niño for the five major crops grown in Halaba. If other years of weather data had been used to represent the steady state, the decadal reduction in production would have been different; the results are presented here for 2014, as this is the year that the soils were sampled and crop yields were measured, so provides the most realistic representation of the state of the system.

3.1.2. Factors contributing to loss of production

Depending on rooting depth and growing season, there are large differences in 2015 and 2016 compared to 2014 in plant available nitrogen and water stress; differences in growing degree days are relatively small (figure 3).

By disregarding each of these three factors in turn, it emerges that in 2015, the reduction in yield is attributable to water stress, whereas in 2016, nitrogen limitation plays a more important role (figure 4); the model suggests this is due to nitrogen being lost by leaching during the period of heavy rainfall in 2016. Unfortunately, no local measurements exist to confirm this result. The increase in the 2016 pepper yield can be attributed to the crop being planted earlier than other crops, giving it access to the higher early-season rainfall (April–May). This is reflected in the positive response of production to water stress in 2016 for pepper (figure 4(b)). Note the model takes no account of losses of yield that might occur due to the crop being damaged by floods.

3.1.3. Soil organic matter

The reduction in crop production, results in reduced plant inputs to the soil (figure 5), causing a decline in soil organic matter, as represented by the change in soil carbon (figure 6). Again, when real weather data is used from 2005 to 2016, the picture is noisy; a reduction in carbon that persists for more than a

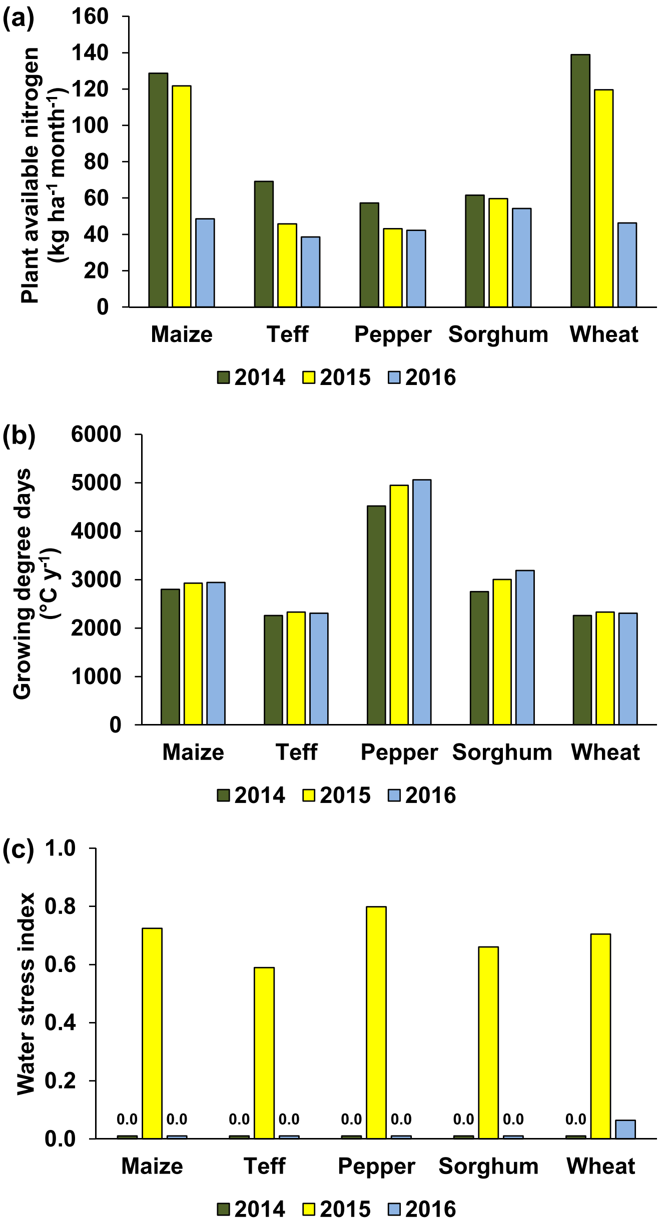

Figure 3. Factors contributing to simulated reduced crop production in 2015 and 2016 compared to 2014; (a) plant available nitrogen, calculated as the sum of nitrate and ammonium simulated in the soil during the growing season, (b) growing degree days, calculated as the sum of air temperature greater than 5 °C during the growing season, and (c) water stress index, calculated as the average ratio of actual to potential evapotranspiration during the growing season subtracted from 1 (so that a larger number indicates more water stress; no water stress = 0, maximum water stress = 1). If no bar is visible, the water stress was 0.

decade is apparent, although not all of this is attributable to the El Niño event. When the noise is removed by using 2014 weather data for the steady state and the post El Niño run, a sharp decline is seen in soil carbon in both 2015 and 2016, which remains 0.2 t ha^{-1} (pepper) to 1.5 t ha^{-1} (sorghum) below the 2014 soil carbon content at the end of the decade. Although this is a small percentage decline in soil carbon (0.5%–4.1% of the carbon content in 2014), it represents a long-term degradation of the soil resource. If left uncorrected by improved management, this will result in a permanent degradation of soil and reduced productivity of the farm. Furthermore, if the frequency (or severity) of future El Niño events increases, the soil carbon content will have less time to recover and the decadal decline will be even greater (figure 7).

3.2. Increased use of organic fertilisers

3.2.1. Untreated animal manure

The change in soil carbon per decade with increasing application of untreated animal manure is shown in figure 8. This plot reflects two effects; the direct impact of adding carbon to the soil, and the indirect impact of increasing available nitrogen on the plant inputs to the soil. Therefore, at lower rates of manure application, the slope is higher due to the manure replacing the lost nitrogen that is limiting crop yield; this is particularly apparent in sorghum which remained limited in

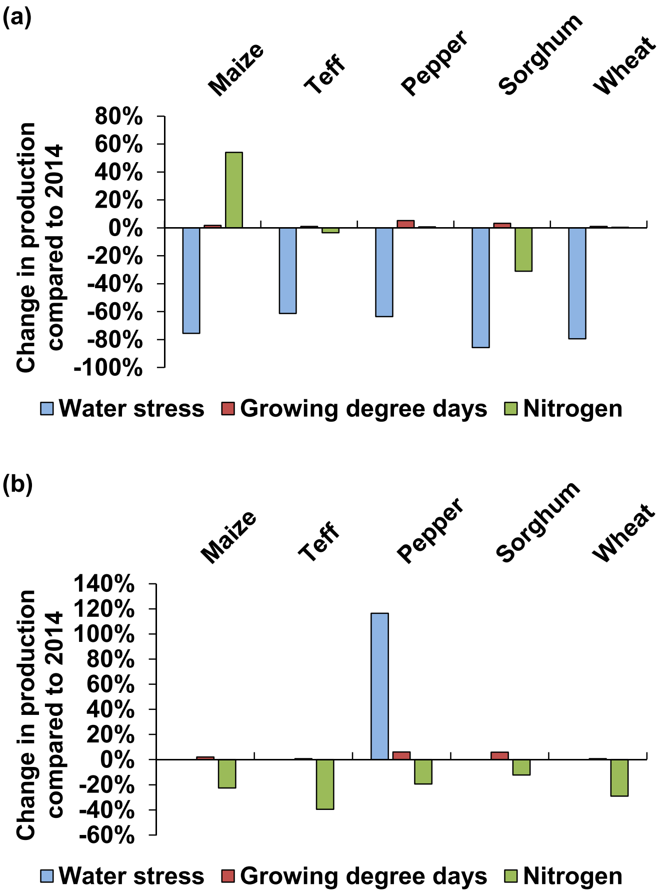

Figure 4. Contribution of different factors to change in crop production compared to 2014; (a) 2015; (b) 2016.

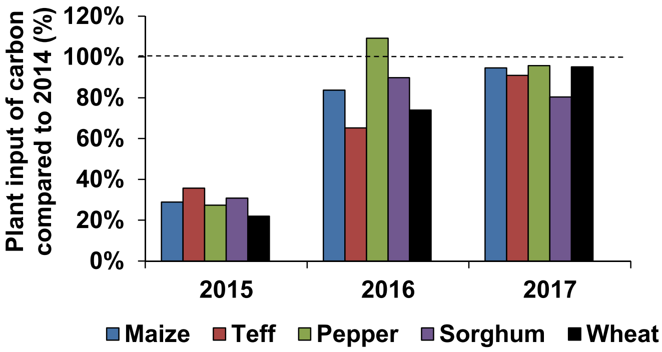

Figure 5. Plant input of carbon to soil compared to 2014 for five major crops grown in typical soils in Halaba.

nitrogen for longer than the other crops (figure 6). To counter the impacts of a 10 yearly El Niño event on soil carbon in a typical soil in Halaba, between 0.2 and 0.8 t ha^{-1} yr^{-1} additional organic manure would need to be applied, depending on crop type. This is approximately equivalent to the amount of manure currently used for cooking fuel (0.4 t yr^{-1} spread over 1.0 (±0.5) ha = 0.3–0.8 t ha^{-1} yr^{-1}).

Using the dung that is currently required for cooking in a typical farm household to apply to soils represents a loss of 0.4 t yr^{-1} cooking fuel with a calorific value of 5165 MJ yr^{-1}. Using the ratio of cooking energy provided by dung and fuelwood (0.66—see S1.3.4), this is equivalent to 0.3 t yr^{-1} fuelwood. On average, collecting this amount of fuelwood in Halaba would require an additional 0.5 (±0.3) hours of household labour every week. If the farmer instead needs to buy additional fuelwood, this would cost 19 (±2) US\$ yr^{-1}. In households that are already applying any dung not used for cooking to the soil, the change in revenue over the decade from crop production due to applying this amount of additional manure

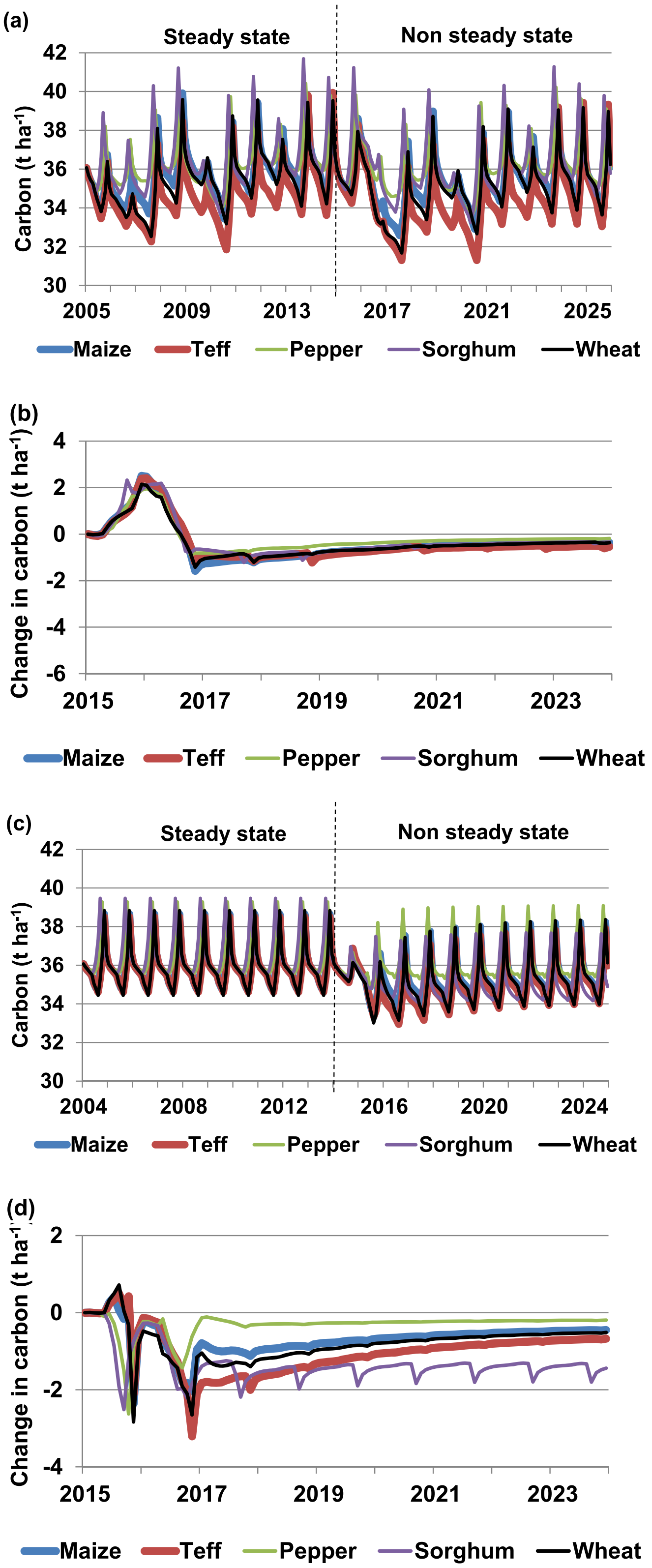

Figure 6. Impact of El Niño on soil carbon for major crops grown on typical soils in Halaba: for simulations using real weather data 2005–2016, (a) total carbon, (b) change compared to 2014; for simulations using 2014 weather data for steady state and post El Niño run, (c) total carbon, (d) change in carbon compared to 2014.

is small, ranging from 16 US$ (maize) to 150 US$ (sorghum). Therefore, in the first decade, the overall economic impact of applying manures to avoid the soil degradation associated with a 10 yearly El Niño event is a small cost, ranging from 40 US$ per decade (sorghum) to 174 US$ per decade (maize) (accounting for both increased revenue from crops and costs of replacing cooking fuel). The longer-term impacts on soils

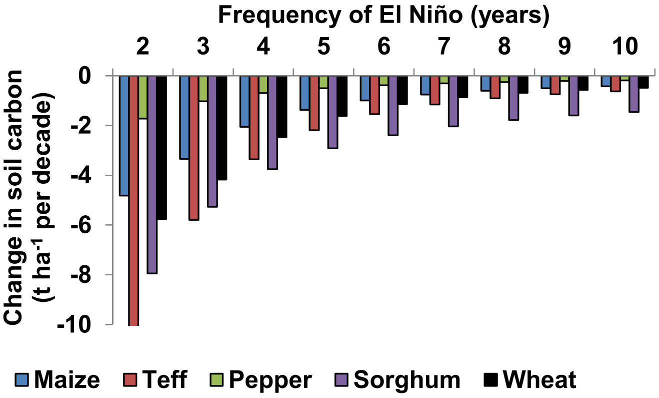

Figure 7. Impact of the frequency of El Niño events on loss of soil carbon over the decade. Simulations use 2014 weather data for steady state and post El Niño run and artificially adjust the frequency of the El Niño years (2015 and 2016).

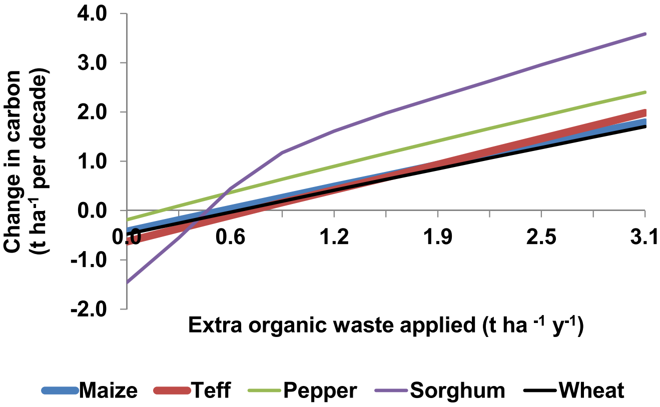

Figure 8. Change in soil carbon over the decade with annual application of untreated animal manure for five major crops grown in Halaba. Simulations assume 2014 weather data for steady state and post El Niño run.

and crop production, and the potential increased impact of more frequent droughts are given in S2.1.1 and S2.1.2.

3.2.2. Composted animal wastes and crop residues

A wider range of organic waste sources can be applied to soils if first composted, but to provide a conservative estimate, it was assumed here that the maximum amount of material available for composting is equivalent to the manure available on the farm. Composting organic wastes increases the recalcitrance of organic matter and increases the availability of nitrogen to the crops, but also results in a loss of carbon during the treatment process (S1.3.3). Despite this, less organic waste is used to produce the compost needed to counteract the losses in soil carbon due to the El Niño event than if untreated animal manure is applied directly; for a 10 yearly El Niño event, compost derived from an average of 0.5 t ha^{-1} yr^{-1} organic waste would need to be applied, compared to 0.6 t ha^{-1} yr^{-1} if the organic waste was applied untreated. Applying all the manure available on the farm as compost would sequester 2.3–4.1 t ha^{-1} of carbon per decade, compared to only 1.7–3.6 t ha^{-1} when applied untreated (figure 9). Furthermore, the improved availability of nutrients in the compost results in an increase in income, from an average cost across all crops of 124 US$ per decade using fresh waste to a small benefit of 67 US$ per decade using compost (accounting for both increased revenue from crops and costs of replacing cooking fuel). Therefore, by composting organic wastes instead of applying them fresh, the potential soil degradation due to a 10 yearly El Niño event can be countered without a cost to the household.

3.2.3. Bioslurry from anaerobic digestion

Household anaerobic digestion is usually limited to cattle or pig manure, although food wastes can also be used to feed digesters. The digestion process emits methane, which can be burnt as a cooking fuel, but therefore also reduces the carbon retained in the organic fertiliser and returned to the soil (S1.3.3). However, because the recalcitrance of the organic matter is increased by digestion, the carbon sequestered in the soil is similar to that when the organic

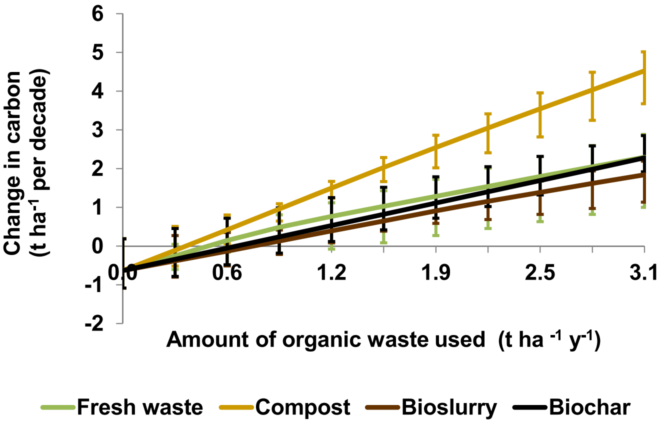

Figure 9. Change in soil carbon following a decade of application with differently treated organic wastes, accounting for losses during treatment and the different compositions of organic wastes following treatment. The line represents the average value and error bars represent the range of values under the five major crops grown in Halaba (maize, teff, pepper, sorghum and wheat).

waste is applied untreated (figure 9). Because the digester is a closed vessel, nutrient losses during digestion are small [9], so the bioslurry delivers greater levels of available nutrients to the crop than compost. This is reflected in a greater increase than for untreated wastes or composts in the decadal revenue from crop production. This gives a net benefit of 148–1086 US$ ha^{-1} compared to when no manure is applied, which is 52–412 US$ ha^{-1} greater than untreated waste, and 26–139 US$ ha^{-1} greater than compost. Note that these estimated responses to bioslurry need to be confirmed in controlled experiments in Ethiopia and Sub-Saharan Africa.

Added to this are the potential very important benefits of producing biogas. Digesting 3.1 t organic waste produces 99–124 m^3 yr^{-1} biogas, providing 12 000–15 000 MJ yr^{-1} cooking energy, and potentially reducing costs resulting from health problems associated with the particulate matter emitted by burning fuelwood or dung [10]. This is equivalent to 7.7–9.6 t yr^{-1} firewood, with a value of 509–636 US$ yr^{-1}, or requiring 1.9–2.4 h of labour every day to collect. The survey indicated that farmers collect or purchase between 1 and 20 t firewood every year [5, 6], so this will make a significant contribution to the household fuel requirement. The combined increase in income compared to application of untreated waste from crop production and savings on firewood purchases are high; 5142–6772 US$ per decade. However, the feasibility of achieving these considerable benefits depends on access to a nearby source of water; assuming the volume of water needed for anaerobic digestion is 5 dm^3 for every kg of manure [11], digestion of 3.1 t yr^{-1} manure would require 15 500 dm^3 yr^{-1}, equivalent to two jerry cans of water (volume 40 dm^3) per day. A typical family in Halaba takes 1.5 h to collect 20 dm^3 water in a non-drought year [5], so it will take 3 h to collect the additional water needed for the digester every day. Therefore, accounting for the potential reduction in woodfuel collection, a typical household in Halaba will require 0.6–1.1 h every day to run the digester in addition to time required for handling the manure. A further constraint is the ability of the household to invest in the biogas digester, which in Ethiopia, can cost between 500 and 2000 US$, depending on size and design [12].

3.2.4. Biochar from pyrolysis of crop residues

Since most of the crop residues in Halaba are already used for other purposes, such as animal feeds, the impact of incorporating biochar produced only from animal manures will be considered here. Pyrolysis cook-stoves separate combustible gases (primarily hydrogen, carbon monoxide and some carbon dioxide) from biomass by gasification, and then burn these gases as the fuel, producing a hot flame with a high thermal efficiency (38%–50%) and low emissions of particulates [13]. Burning carbon monoxide and carbon dioxide results in a high loss of carbon during pyrolysis (around 65%) (S1.3.3) [14]. There is some debate over the recalcitrance of the material remaining [14], which introduces uncertainty in the rate of sequestration in the soil. However, using best available information [14], incorporating biochar into the soil sequesters at least similar quantities of carbon as the untreated organic waste (figure 9).

The loss of nutrients during pyrolysis also tends to be high, with most of the remaining nutrients tightly bound in structural sites [9]. As a result, the increase in productivity compared to no application of manure is modest, with a decadal increase in revenue of 42–206 US$, and a loss of revenue compared to applying untreated waste (54–534 US$), compost (80–807 US$) or bioslurry (91–892 US$). However, biochar contains a large number of ion exchange sites, so there is potential to use it to deliver nutrients by treating it with urine or mixing with compost or bioslurry before application [15]. Furthermore, there is evidence that

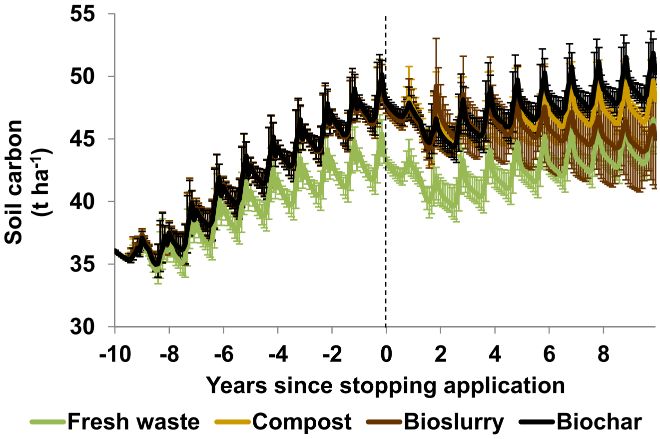

Figure 10. Soil carbon during a decade of application of 2.7 t ha^{-1} yr^{-1} organic wastes that have been untreated, composted, digested or pyrolysed before application, followed by a decade where applications are stopped. The line represents the average value and error bars represent the range of values under the five major crops grown in Halaba (maize, teff, pepper, sorghum and wheat).

especially low temperature biochars produced from manures can reduce the rate of losses of nitrogen by ammonia volatilisation from the soil, so crop yields may be significantly higher than predicted here [16]. However, there is some debate in the scientific literature [17], and so this is another area of uncertainty that requires further work in Sub-Saharan conditions.

If the household converted from a traditional to a pyrolysis cook-stove, with a thermal efficiency of 38%–50% [13] compared to a traditional stove of only 11% [18], a pyrolysis cook-stove would provide 4.5–5.9 times more cooking energy than using the traditional stove. If all the manure available on the farm was used for cooking on a pyrolysis cook-stove before incorporation into the soil, this would provide extra energy for the household equivalent to 8.9–11.8 t yr^{-1} of fuelwood, with a value of 588–779 US$ yr^{-1}, or requiring 2.2–2.9 h of labour every day to collect. The combined increase in income compared to applying untreated organic waste from changes in crop production and savings on firewood purchases are comparable to a biogas digester, 5346–7736 US$ per decade. Given that pyrolysis cook-stoves cost less than biogas digesters (~50 US$ [12]), require less maintenance and do not require a water supply, conversion to pyrolysis cook-stoves may be the more feasible option for both meeting energy demands and stopping soil degradation in Halaba. Furthermore, the carbon added to the soil in biochar is much more recalcitrant than the carbon added either as untreated waste, compost or bioslurry. Therefore, if soil amendment of organic waste is stopped, the carbon content of the soil may remain at a higher level for longer following application of biochar than following application of untreated waste, compost or bioslurry (figure 10). However, more work is needed to understand the factors controlling aggregation of biochar into a highly degraded soil, where lack of organic matter may allow biochar to be lost by erosion.

3.3. Installation of soil and water conservation structures

Given a range of soil erosion from 20 to 100 t ha^{-1} yr^{-1} and a reduction in erosion from 40% to 66% by implementing soil water conservation structures, the potential reduction in soil carbon losses in Halaba is 0.62 ($\pm$0.5) t ha^{-1} yr^{-1}, where the error term depends on the range of erosion rates that occur on sites with different slopes, soil textures and land uses. The potential annual changes in soil carbon after using all organic manure available on the farm are shown in figure 11 for the different treatments in comparison to changes achieved by implementing soil and water conservation structures. On steep slopes where rates of erosion are high, the potential carbon savings greatly exceed the potential carbon sequestration achieved by applying organic waste. This suggests that soil and water conservation structures should be installed on steep slopes before applying organic wastes; not doing so will result in all the potential soil carbon gain being washed downhill.

4. Conclusions

4.1. The impacts of El Niño on land degradation and livelihoods

The El Niño event during 2015 and 2016 had a significant long-term impact on crop yields and livelihoods in Halaba, Ethiopia. The largest reduction in crop yields occurred in 2015, owing to water stress, but, even without accounting for crops being destroyed by floods, in 2016 there was a significant loss of production due to nutrients being washed out of the soil by the heavy rainfall. This had a knock-on effect on soil organic matter (expressed as soil carbon), due to reduced plant inputs. Soil organic matter will remain at a lower level even ten years after the drought. This indicates the potential for the El Niño event to cause long-term soil degradation. Repeated El Niño events

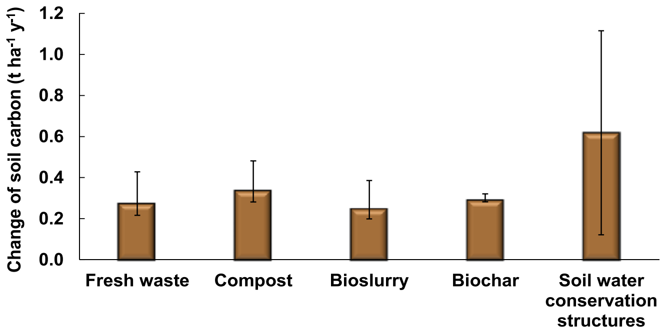

Figure 11. Comparison of average annual changes in soil carbon occurring over 10 years following introduction of different management options. Application of all organic waste available on farm (assumed 3.1 t ha^{-1} yr^{-1}) as fresh waste, compost, bioslurry or biochar compared to installation of soil water conservation structures. Error bars on organic waste treatments represents the range of results obtained for five major crops grown in Halaba (maize, teff, pepper, sorghum, wheat). The error bar on soil and water conservation structure represents the range of potential savings depending on slope, texture and land use type. Simulations assume consistent weather conditions represented by weather data for 2014.

Table 3. Summary of impacts on household resources of different organic fertiliser applications needed to counter soil degradation due to El Niño event.

	Fresh waste[a]	Compost[b]	Bioslurry[c]	Biochar[d]
Average change across all crops in…				
Soil carbon (t ha^{-1} yr^{-1})	0.29	0.36	0.25	0.29
Crop prod (%)	9	13	14	3
Water demand[e] (dm^3 d^{-1})	0	0	43	0
Energy (MJ d^{-1})	−14	0	330	394
Labour[f] (h d^{-1})	0.5	0	0.8	−2.6
Net revenue (US$ yr^{-1})	−124	64	610	676

[a] All manure available applied to soil as fresh waste.

[b] Only 2.7 ha^{-1} yr^{-1} applied to soil as compost and 0.4 t yr^{-1} used as cooking fuel.

[c] All manure available used to produce biogas and the bioslurry reside applied to the soil.

[d] All manure available pyrolysed to provide energy and the biochar residue incorporated in the soil.

[e] Assumed no water used for irrigation as this is not common in Halaba.

[f] Labour accounting for collection of fuelwood and water only (handling of organic manure is not included).

will lead to further soil degradation, with increased degradation associated with more frequent droughts.

4.2. Implications for reversing land degradation and improving livelihoods

On sloping sites at high risk of erosion, significantly more carbon can be retained in the soil by installing soil and water conservation structures than can be provided by the organic fertilisers available. Therefore, soil water conservation structures should be installed and maintained as a matter of priority on eroding slopes before attempting to improve productivity with organic fertilisers. This is an important finding because, although programmes to encourage soil and water conservation measures have been successfully implemented in different parts of Ethiopia over the last five decades, efforts have focused on common and highly degraded unfarmed land; implementation on farmed land has not met expected targets [19]. Therefore, more effort is needed to install soil and water conservation structures on farmed land and bring a larger area of the farm into productive use.

Additional manure should be applied to non-eroding soils (or slopes with soil and water conservation structures installed) to reduce degradation due to El Niño events. Applying the dung currently used in cooking could counter the impact of El Niño, with only a small cost to the household due to loss of fuel. If manure is composted, digested or pyrolysed before application to increase the recalcitrance of the carbon in the organic manure, soil degradation can be countered without a net cost (table 3). The greater recalcitrance of composted, digested or pyrolysed manure is well known [6]; the important finding for resource limited situations, where competing uses and number of animals limit the amount of manure available, is that if the same amount of manure is treated before application it will provide better soil improvement with net benefit to the household despite the losses in carbon and reduction in volume that occurs during the treatment process.

Composted manure has most potential to retain carbon and nutrients in the soil (table 3). Applying bioslurry provides a similar amount of nutrients to the crop as compost, and so similarly improves income and reduces the impact of El Niño on crop production. However, anaerobic digestion also provides biogas to the household, which will increase decadal income by over 5000 $US, easily paying back the cost of the digester within the decade. Therefore, if the household has access to the finances and water needed to invest in and run a biogas digester, this is a better long-term option than composting.

Applying biochar sequesters similar amounts of carbon in the soil as applying bioslurry, but loses a higher percentage of the nutrients during pyrolysis. Therefore, biochar is a less effective organic fertiliser than either bioslurry or compost (table 3). However, if all available animal dung was used as a fuel in a pyrolysis cook-stove, the extra fuel available to the household would have a value of well over 5000 $US per decade. Furthermore, the carbon in biochar is more recalcitrant than in bioslurry or compost, and so, as demonstrated by the simulations where inputs of organic fertilisers were stopped, applying biochar may result in more effective long-term improvement of the soil. The biochar also provides ion exchange sites that may retain plant available nitrogen, so there is potential to treat biochar with urine before application to the soil to make it a more effective nitrogen fertiliser. If this can be used to reduce other point source losses of nutrients within the livestock management system, the net impact on available nutrients could be positive. Given the relatively low cost of a pyrolysis cook-stove (~50 US$), this may be the most cost effective, low risk option for many households, especially where the water supply is limited. However, further work is needed to test particulate emissions from dung-fuelled pyrolysis cook-stoves to ensure that this does not have a detrimental impact on indoor air quality, and to consider the suitability of the hot flame produced by pyrolysis for the traditional cooking practices used in Ethiopia. Work is also needed to consider the subsequent use of biochar; if households decide to use the biochar produced as an additional fuel, rather than incorporating it into the soil, then carbon and nutrient returns to the soil will be greatly reduced and soils will be further degraded.

This work has considered the total availability of organic resources for reducing soil degradation; in practice, farmers usually apply more manure to areas close to the home where they grow more valuable crops and have easy access, leaving the distant fields with lower amendments and so more highly degraded soils [20]. The greatly reduced volume of all treated manures, but especially biochar, may encourage increased use of organic fertilisers in more distant fields, so bringing a larger area of land back into agricultural production.

4.3. Recommendations

The key messages for policy makers, extension workers and farmers emerging from this work are as follows:

1. Soil water conservation measures should always be installed on erosion vulnerable slopes before applying manures to avoid wasting this valuable resource;
2. If extra household energy is not needed, a low-cost option for countering soil degradation is to apply organic wastes as composts instead of fresh wastes;
3. If extra household energy is needed, and the household has access to the finances and water needed to invest in and run a biogas digester, applying organic waste as bioslurry will provide a significant additional benefit of saved expenditure on fuel or reduced labour for fuelwood collection;
4. If extra household energy is needed, but the water or finances needed for biogas are limiting, applying organic waste as biochar is a good alternative, providing a significant benefit of saved expenditure on fuelwood. However, measures should be taken to retain nitrogen from the farming system in the biochar so that it acts as an effective organic fertiliser.

Acknowledgments

We are grateful for support from the DFID-NERC El Niño programme in project NE P004830, 'Building Resilience in Ethiopia's Awassa region to Drought (BREAD)', the ESRC NEXUS programme in project IEAS/POO2501/1, 'Improving organic resource use in rural Ethiopia (IPORE)', and the NERC ESPA programme in project NEK0104251 'Alternative carbon investments in ecosystems for poverty alleviation (ALTER)'. We are also grateful to Anke Fischer (James Hutton Institute) for her comments on the paper.

References

[1] Douxchamps S *et al* 2016 Linking agricultural adaptation strategies, food security and vulnerability: evidence from West Africa *Reg. Environ. Change* **16** 1305–17

[2] Trenberth K E 1997 The definition of El Niño *Bull. Am. Meteorol. Soc.* **78** 2771–7

[3] Funk C, Harrison L, Shukla S, Hoell A, Korecha D, Magadzire T, Husak G and Galu G 2016 Assessing the contributions of local and east Pacific warming to the 2015 droughts in Ethiopia and southern Africa *Bull. Am. Meteorol. Soc.* **97** S75–80

[4] FAO 2016 Global Information and Early Warning System (http://fao.org/giews/countrybrief/country.jsp?code=ETH)

[5] Phimister E 2018 *Organic Resource Use in Rural Households in Ethiopia (Data Collection)* (Colchester: UK Data Archive) (https://doi.org/10.5255/UKDA-SN-853076)

[6] Smith J, Hallett P, Nayak D, Boke S, Habte M, Yakob G, Rivington M and 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/10.5285/024c5a61-5114-41a6-93b8-e3fb4d24622b)

[7] Harmonized World Soil Database 2018 (http://fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/)

[8] Renard K G, Foster G R, Weesies G A and Porter J P 1991 RUSLE revised universal soil loss equation *J. Soil Water Conservation* **46** 30–3

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

[10] Tumwesige V, Okello G, Semple S and Smith J 2017 Impact of partial fuel switch on household air pollutants in sub-Sahara Africa *Environ. Pollut.* **231** 1021–9

[11] Bansal V, Tumwesige V and Smith J U 2017 Water for small-scale biogas digesters in sub-Saharan Africa *Glob. Change Biol. Bioenergy* **9** 339–57

[12] Smith J U 2013 *The Potential of Small-Scale Biogas Digesters to Improve Livelihoods and Long Term Sustainability of Ecosystem Services in Sub-Saharan Africa* (http://r4d.dfid.gov.uk/Output/193337/Default.aspx)

[13] Kumar M, Kumar S and Tyagi S K 2013 Design, development and technological advancement in the biomass cookstoves: a review *Renew. Sustain. Energy Rev.* **26** 265–85

[14] Smith J, Abegaz A, Matthews R B, Subedi M, Orskov E R, Tumwesige V and 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 Bioenergy* **70** 73–86

[15] Thangarajan R, Bolan N S, Kunhikrishnan A, Wijesekara H, Xu Y, Tsang D C W, Song H, Okg Y S and Hou D 2018 The potential value of biochar in the mitigation of gaseous emission of nitrogen *Sci. Total Environ.* **612** 257–68

[16] Mandal S, Donner E, Vasileiadis V, Skinner W, Smith E and Lombi E 2018 The effect of biochar feedstock, pyrolysis temperature, and application rate on the reduction of ammonia volatilisation from biochar-amended soil *Sci. Total Environ.* **627** 942–50

[17] Gronwald M, Helfrich M, Don A, Fuß R, Well R and Flessa H 2018 Application of hydrochar and pyrochar to manure is not effective for mitigation of ammonia emissions from cattle slurry and poultry manure *Biol. Fertil. Soils* **54** 451–65

[18] Singh P, Gundimeda H and Stucki M 2014 Environmental footprint of cooking fuels: a life cycle assessment of ten fuel sources used in Indian households *Int. J. Life Cycle Assess.* **19** 1036–48

[19] EPA 2012 *National Report of Ethiopia, the United Nations Conference on Sustainable Development (Rio+20)* Federal Democratic Republic of Ethiopia, Addis Ababa (https://sustainabledevelopment.un.org/content/documents/973ethiopia.pdf)

[20] Zingore S, Murwira H K, Delve R J and Giller K E 2007 Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe *Agric. Ecosyst. Environ.* **119** 112–26