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Soil organic carbon in agricultural systems of six countries in East Africa – a literature review of status and carbon sequestration potential

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Cropland soils are considered to have the potential to sequester atmospheric CO₂ through agronomic best management practices (BMPs). To estimate this potential in East Africa, the authors reviewed 69 published studies from Ethiopia, Kenya, Rwanda, Tanzania, Uganda, and Burundi assessing the effect of land use conversion from native vegetation to cropland on soil organic carbon (SOC) and the extent to which carbon sequestration is feasible through BMPs. Reported losses of SOC in the top 30 cm of the soil profile in short (<10 years), medium (10–25 years), and long (>25 years) term were 6.7 ± 6.0, 13.0 ± 9.2, and 2.8 ± 1.0 t C ha⁻¹ year⁻¹, respectively, for forest-to-cropland; and 16.0, 2.1 ± 2.2 and 0.3 ± 0.8 t C ha⁻¹ year⁻¹ respectively, for woodland-to-cropland conversion. Duration to steady-state SOC was 21–38 years for forest-to-cropland conversion. Short-term SOC sequestration (t C ha⁻¹ year⁻¹) in the 0–30 cm layer as a result of BMPs was 19.7 ± 3.9 from crop residues, 14.8 ± 8.7 from farmyard manure, 3.5 ± 4.5 from inorganic fertilizers, 2.7 from agroforestry, and 2.5 from improved fallow. However, the studies reviewed were mostly short-term and concentrated to a few locations. Future research should address these gaps.

Keywords: best management practices; cropland; East Africa; soil organic carbon

Introduction

Soil carbon sequestration is considered to be a promising way of mitigating climate change by taking up atmospheric carbon dioxide (CO₂) through plants and storing it as soil organic carbon (SOC) in decomposable plant residues, living biomass, and recalcitrant organic matter (Johnson et al. 2007; Shelukindo et al. 2014; Paustian et al. 2016). At the 2015 Climate Change Conference of Parties (COP 21), a program was launched to mitigate climate change by increasing SOC stocks by 0.4% per year (the '4 per mille' initiative), through maintaining or enhancing carbon stocks in agricultural soils while preserving carbon-rich soils (Rhodes 2016). Following conversion of native vegetation to cropland, soils are reported to lose SOC, which reaches a lower equilibrium of about 25–75% less carbon than in undisturbed native vegetation (Lal 2004). Studies in East and southern Africa estimate the time to reach this new equilibrium at 30 to 100 years (Lobe et al. 2001; Dominy et al. 2002; Moebius-Clune et al. 2011).

Soil organic carbon loss in cropland is mainly due to disturbance of soil aggregates through cultivation, which accelerates soil microbial activity, organic matter oxidation and mineralization (Six et al. 1999; Loke et al. 2012; Swanepoel et al. 2016). Soil erosion, runoff, and leaching lead to further loss of SOC from cropland (Roose and Barthes 2001). The degree of SOC loss due to these processes is influenced by many factors, including climate

conditions (Bispo et al. 2017), altitude (Lemenih and Itanna 2004; Pabst et al. 2013), soil texture (Tiessen et al. 1984; Bruun et al. 2015), and soil structure (Nsabimana et al. 2009; Canarini et al. 2017).

Adoption of best agronomic management practices (BMPs) can be expected to lead to SOC sequestration, with an estimated potential of 0.90–1.85 billion tons of carbon per year (t C year⁻¹) over 20 years globally (Zomer et al. 2017). The main BMPs for sequestering SOC are crop residue retention, use of cover crops, inorganic fertilizer addition, organic manure addition, agroforestry, crop rotation, and reduced tillage. However, estimates of attainable SOC sequestration through use of BMPs vary widely. Some studies report large potential, e.g., 0.23 t C ha⁻¹ year⁻¹ from cover crops (Poeplau and Don 2015); 0.20 and 0.57 t C ha⁻¹ year⁻¹ from crop rotation and no tillage, respectively (West and Post, 2002); and 0.27–0.80 t C ha⁻¹ year⁻¹ from conservation tillage and addition of crop residue mulch, compost, and manure (Lal 2004). Other studies report negligible SOC gains from e.g., conservation agriculture (Giller et al. 2009), or slightly reduced SOC losses from e.g., addition of manure or inorganic fertilizers (Nandwa 2001), integrated soil fertility management or conservation agriculture (Sommer et al. 2018). In degraded soils, the potential build-up of carbon is reported to be quite low (Guo and Gifford 2002; West and Post 2002; González-Sánchez

et al. 2012). Therefore, given the uncertainties in SOC losses and sequestration potential, if expectations of climate mitigation via SOC sequestration in cropland are to be realistic, there is a need for conclusive evidence on whether nett SOC sequestration is possible.

In the present study, we conducted a systematic literature review of existing evidence on SOC responses to BMPs in cultivated soils of East Africa, focusing on Ethiopia, Kenya, Rwanda, Tanzania, Uganda, and Burundi (Figure 1). These countries have similar rain-fed cropping systems on small (<2 ha) land holdings with intense cultivation, often without fallowing and with low fertilizer input (Kapkiyai et al. 1999; Wasige et al. 2014; Gelaw et al. 2014; Rapsomanikis 2015). Hence, SOC stocks in the soil are low compared with the levels before conversion from native vegetation, due to losses associated with frequent cultivation, soil erosion, and leaching (Solomon et al. 2000; Vågen et al.

2005; Yimer et al. 2007; Wasige et al. 2014). In this review, we examined current evidence on the extent to which BMPs can increase SOC stocks and whether nett SOC sequestration is attainable in this region. We also sought to identify knowledge gaps and make recommendations for future research.

Materials and Methods

Relevant studies were obtained by searches in Google Scholar and Science Direct databases using the key words: 'soil organic carbon', 'soil carbon sequestration', 'soil carbon loss' or 'soil carbon emission', combined with 'Kenya', 'Ethiopia', 'Tanzania', 'Rwanda', 'Burundi', 'Uganda', or 'East Africa' and 'best management practices', 'soil management', 'agriculture', 'cropland', 'cultivation', 'agroforestry', 'tillage', 'conservation agriculture', 'mulching', 'manuring' or 'fallow'.

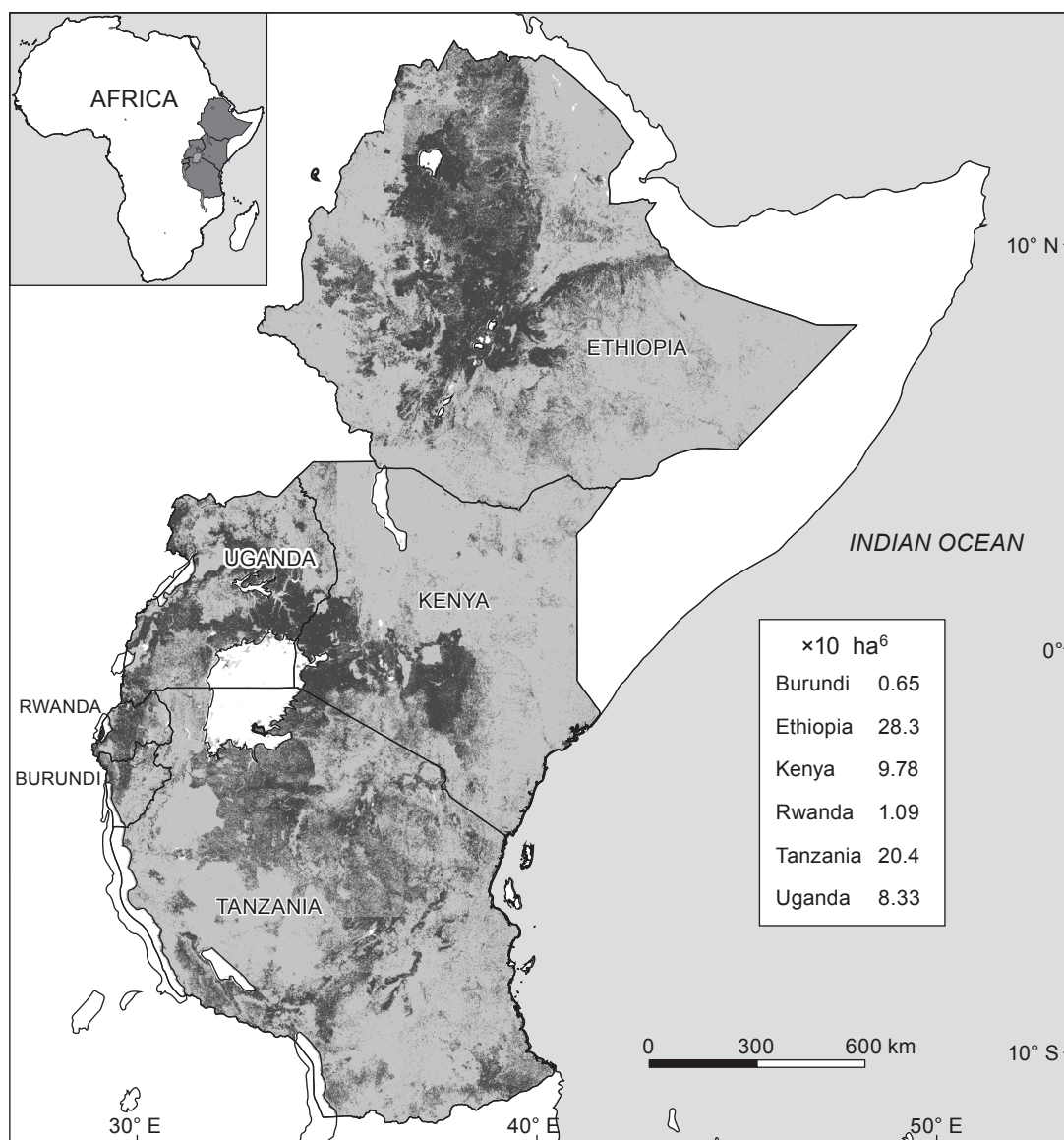


Figure 1: The study area, indicating cropland - the black color; the blacker the higher percentage of cropland. Data source: ESA (2016).

Reference lists of studies identified were used to find additional information. All studies quantifying the impact of BMPs and conversion from natural vegetation to cropland on SOC were included, without setting time limits. Relevant studies for inclusion were those which provided information on:

- Soil organic carbon stocks under various land uses and environmental conditions
- Impacts of land use change from native vegetation to cropland on SOC stocks
- Impacts of BMPs on SOC stocks in cropland.

The socio-economic challenges that may be associated with adopting BMPs (e.g., Knowler and Bradshaw 2007; Giller et al. 2009; Jaleta et al. 2013) were not included in this review.

The total number of studies that satisfied the selection criteria was 69, including peer-reviewed journal articles ($n = 55$), technical reports ($n = 4$), Master's or doctoral theses ($n = 7$), meeting proceedings ($n = 2$), and a working paper ($n = 1$). All showed a comparable degree of rigor in determining the impact of land use change and BMPs on SOC. Of the 69 studies identified, 62 (90%) were published after 1999. Land-use terms used in this review are defined in Table 1. Most studies ($n = 54$) determined SOC values from laboratory observations of soil samples and only a few were based on modeling ($n = 8$) or reviews ($n = 4$) (Table 2).

Data management

Information was extracted detailing independent variables grouped as environmental factors, land use before intervention, land use after intervention, type of BMP implemented, and years since the intervention took place. Environmental factors included climate (rainfall and temperature), location, altitude, soil type, bulk density,

and texture (clay and sand content). Climate conditions were categorized, based on mean annual rainfall (mm year⁻¹), as semi-arid (<600), sub-humid (601–1200), moist sub-humid (1201–1500), or humid (>1500), using climate classifications in Brouwer and Heibloem (1986).

Sites were categorized as lowland (<1500 m above sea level (a.s.l.)) or highland (≥1500 m a.s.l.). The period after which changes in SOC were measured was categorized as short-term (<10 years), medium-term (10–25 years), and long-term (>25 years). SOC values were summarized for the following soil depth intervals: 0–30 cm, 0–50 cm, and 0–100 cm. When SOC stock values were reported for other depth intervals, they were converted to one of these intervals by Equation 1:

$$SOC_i = SOC_j \times \frac{i}{j} \quad (1)$$

where SOC_i is the SOC stock in the new soil depth interval (i) and SOC_j is the SOC stock for the depth interval (j) specified in the study in question. The SOC content is not expected to be homogeneous with depth, but we believe it is sufficiently accurate for the present purpose.

Retrieved data from the collected studies were: SOC stock in metric tonnes of carbon (t C ha⁻¹) before and after intervention, and SOC sequestration (t C ha⁻¹ year⁻¹). Values of SOC provided as percentages were converted to SOC stock by Equation 2 (e.g., Marín-Spiotta and Sharma 2013):

$$SOC_i = SOC \times BD \times D \quad (2)$$

where SOC_{st} is SOC stock (t C ha⁻¹), SOC is SOC concentration (%), BD is soil bulk density (g cm⁻³), and D is depth interval (cm).

Table 1: Definitions of land use categories from publications included in the review

Land use	Definition
Cropland	Land cultivated with annual crops for food and fibre – maize (<i>Zea mays</i> L.), potatoes (<i>Solanum tuberosum</i> L.), beans (<i>Phaseolus vulgaris</i> L.), cassava (<i>Manihot esculenta</i> Crantz.), sorghum (<i>Sorghum bicolor</i> L.), wheat (<i>Triticum</i> spp. L.), teff (<i>Eragrostis tef</i> (Zucc.) Trotter) and barley (<i>Hordeum vulgare</i> L.), vegetables and sugarcane (<i>Saccharum officinarum</i> L.).
Agroforestry	Tree-crop mixtures including banana/coffee: <i>Musa</i> spp. with <i>Coffea americana</i> L. or <i>Coffea canephora</i> ; <i>Faidherbia</i> /annual crop: <i>Faidherbia albida</i> (Delile) A. Chev.) with annual crop; coffee/enset: Coffee with <i>Ensete ventricosum</i> (Welw.) Cheesman; or mixtures of coffee, enset, banana, mango (<i>Mangifera indica</i> L.) and avocado <i>Persea meridiana</i> (Mill.).
Improved fallow	Rotation of cropland with nitrogen-enriching tree species including <i>Cajanus cajan</i> , <i>Leucaena leucocephala</i> , <i>Sesbania sesban</i> , <i>Cassia grahamiana</i> , <i>Cassia paulina</i> , <i>Acacia crassicaarpa</i> , <i>A. nilotica</i> , <i>A. mangium</i> , <i>A. polyacantha</i> and <i>Gliricidia sepium</i> . Fallow cycle: 1–1.5 years.
Crop residue addition	Addition of organic matter from crops, including maize, sugarcane, millet or sorghum stover. Application rate: 0.75–1.5 t ha ⁻¹ year ⁻¹ .
Farmyard manure addition	Addition of farm yard manure including cow manure and compost from <i>Tithonia bagasse</i> and filtermod. Application rate: 1–2 t ha ⁻¹ year ⁻¹ .
Forest	Natural closed canopy tree community.
Grassland	Land predominantly covered by grass vegetation.
Perennial crop	Land cultivated with perennial crops – banana, coffee, enset, tea (<i>Camelia sinensis</i> (L.) Kuntze), sisal (<i>Agave sisalana</i>) or fruit trees.
Forest plantation	Planted trees.
Shrubland	Shrubs < 2 m forming > 40% canopy cover over herbaceous or grass vegetation.
Woodland	Natural open canopy tree community.
Native vegetation	Vegetation occurring naturally with little or no agricultural management. This includes forest, woodland, shrubland and grassland.

Table 2: Number of studies on soil organic carbon in croplands in East Africa

Key study consideration	Category	Number of observations
Soil depth (cm)	Top (0–30)	105
	Shallow (0–50)	31
	Deep (0–100)	30
Time scale (years)	Short (< 10)	72
	Medium (10–25)	44
	Long (> 25)	49**
	Not specified	2
Climate (mm year ⁻¹)	semi-arid (< 400–600)	26
	Sub-humid (600–1200)	84
	Moist, sub-humid (1200–1500)	16
	Humid (> 1500)	40
Elevation (meters above sea level)	Lowland (< 1500)	115
	Highland (> 1500)	51
Type of study	Observation	140
	Modeling	23
	Review	2
Location*	Ethiopia	58
	Kenya	67
	Rwanda	15
	Burundi	0
	Tanzania	21
	Uganda	4
	Regional	1
Land management	Land use change	37
	Agronomic management	78
	Land use change + Agronomic management	14

* Numbers indicate number of locations where studies were conducted. Some papers covered multiple locations.

** of which two were modeling studies

The SOC values were recorded as reported in the publications and converted to SOC stock (t C ha⁻¹) using bulk density values provided in the source article. Where such values were not provided, we used a value of 1.33 g cm⁻³ for the 0–30 cm depth interval in cropland, derived for the target East African countries from the global soil database SoilGrids250m by ISRIC-World Soil Information (Hengl et al. 2017). The cropland area was identified using the 20-m spatial resolution prototype land cover maps released for the African continent by the European Space Agency (ESA, 2016) (Figure 2). Soil organic matter was converted to SOC using a conversion factor of 1.724 (Stevenson et al., 1999).

Soil organic carbon sequestration or loss was calculated as the difference in stock before and after intervention with BMP or land use change, divided by the number of years since the intervention was implemented. Nett SOC sequestration was calculated as the difference in SOC stock between historical native vegetation and cropland

when BMPs were implemented. If a study gave multiple values for different locations or management interventions, each was considered a separate data point in the analysis. When studies presented multiple values of SOC within the same location, the mean was used. When values were presented as ranges, the median was calculated as the sum of the lower value and half the difference between the maximum and the minimum. The impact of BMPs on soil carbon emissions and on crop yield was also recorded.

Data analysis

Several of the studies provided multiple SOC data points, resulting in a total of 170 prior to conversion to croplands and 110 points after implementing BMPs. Mean and standard deviation of SOC stock values for different land uses and for SOC sequestration after land use change was calculated. Mean values based on few data points ($n < 5$) or with standard deviation greater than the mean were excluded from the analysis. Such values related to SOC changes due to terracing, removing fallow, converting from grassland or shrubland to cropland, and comparing BMP impact on SOC to that in original native vegetation. There is one particular outlying high SOC loss value (~20 times higher than the mean of the other values, see Namirembe et al. (2020)). This value was excluded from summary statistics (averages, etc.) to avoid having a disproportionately large impact on the results.

The data that support the findings of this study are openly available in Harvard Dataverse at <https://doi.org/10.7910/DVN/3BLW7E>

Results

Soil organic carbon stocks in cropland and other vegetation types

In the 0–30 cm depth interval, SOC stock (t C ha⁻¹) in cropland ranged from 36.3 ± 27.7 to 116.3 ± 37.1 in semi-arid and sub-humid conditions, respectively, and was significantly lower than that in forests (range 111.7 ± 15.1 to 193.9 ± 89.0). For the 0–100 cm depth interval in semi-arid conditions, SOC stock (t C ha⁻¹) was 404.1 ± 164.8 in forests and 81.3 (single value found) in cropland (Table 3).

In sub-humid conditions, SOC stock (t C ha⁻¹) in the 0–30 cm depth interval in cropland (50.8 ± 29.0) was not significantly different from that in woodland and grassland (83.4 ± 67.8 and 96.9 ± 33.4, respectively). Similarly, SOC stock (t C ha⁻¹) in cropland did not differ from that in agroforestry for the depth intervals 0–50 cm (126.6 ± 52.5 and 178.0 ± 171.3, respectively) and 0–100 cm (225.5 and 206.5 ± 75.6, respectively).

Influence of environmental conditions on SOC stock

For each land use type, SOC stock in the 0–30 cm depth interval did not differ significantly under different rainfall regimes (for land use type definitions, see Table 1). However, SOC stock in the 0–100 cm interval in cropland tended to be higher under higher rainfall regimes (Table 3). No difference was observed between lowland and highland SOC stock in the 0–30 cm depth interval for all land uses (Figure 3), although some studies associated

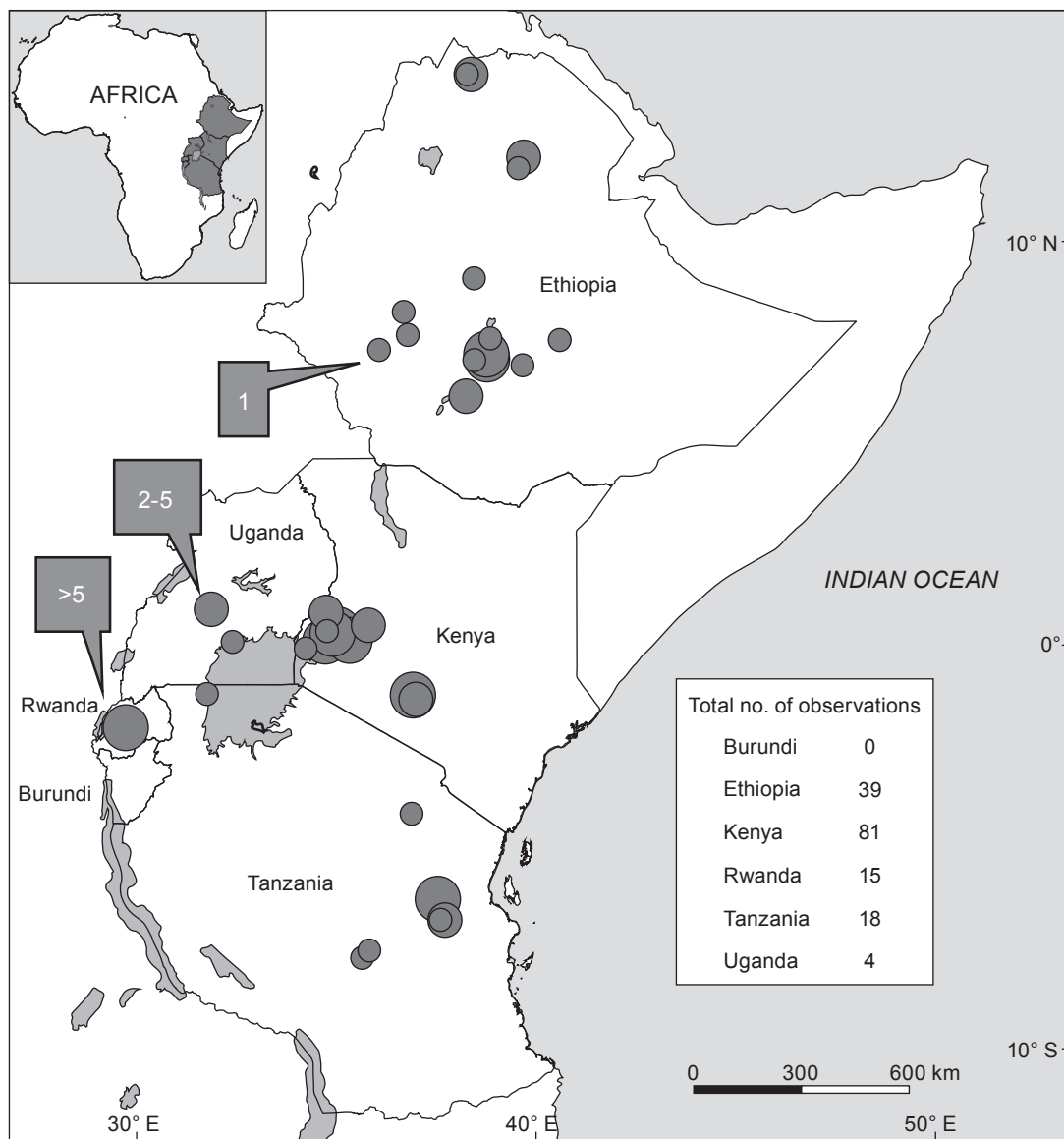


Figure 2: Spatial distribution of the accessed values on SOC sequestration rates. The number of observations per country is presented in the table. The observations for which a location name or location coordinates were provided were mapped. The sizes of the circles reflect the number of observations for a specific location. N.B. the numbers of observations are not the same as the number of publications. Most publications contained multiple observations, sometimes from different locations. Overall, it was possible to map 84 % of the observed SOC sequestration rate values.

variations in SOC stock with elevation (Lemenih and Itanna 2004; Shelukindo et al. 2014; Meliyo et al. 2016; Tesfaye et al. 2016).

Effect of converting native vegetation to cropland on SOC
 Conversion from forest to cropland resulted in an SOC loss ($t\ C\ ha^{-1}\ year^{-1}$) in the 0–30 cm depth interval of 6.7 ± 6.0 in the short term, 13.0 ± 9.2 in the medium term, and 2.8 ± 1.4 in the long term. Steady-state SOC stock following forest-to-cropland conversion was obtained only for western Kenya and was estimated at $36.0\ t\ C\ ha^{-1}$ at 0–10 cm depth (Berazneva et al. 2019). The time to SOC steady state after forest-to-cropland conversion was reported to be

21–38 years in Kenya (Solomon et al. 2007), 25 years in Rwanda (Wasige et al. 2014), and 20–34 years in Ethiopia (Lemenih et al. 2005).

Woodland-to-cropland conversion generally resulted in an SOC loss ($t\ C\ ha^{-1}\ year^{-1}$) in the 0–30 cm depth interval of 16.0 (single value), 2.1 ± 2.2 , and 0.3 ± 0.8 in the short, medium, and long term, respectively (Table 4; Figure 4). However, the data points were few and varied widely, with SOC loss indicated in some studies (Glaser et al. 2001; McDonagh et al. 2001; Pardo et al. 2012) and SOC sequestration in others in the short (Lemenih 2004) and long term (Nord 2008). Converting from forest to agroforestry (Negash and Kanninen 2015) or from

Table 3: Soil organic carbon concentration ($t\ C\ ha^{-1}$) in different land use systems in East Africa. Values are averages \pm standard deviations; number of observations in parentheses. Rainfall regime: semi-arid ($< 400\text{--}600\text{ mm}$), sub-humid ($600\text{--}1200\text{ mm}$), moist sub-humid ($1200\text{--}1500\text{ mm}$) and humid ($>1500\text{ mm}$ mean annual rainfall).

Soil depth (cm)	0–30				0–50				0–100			
	Humid	Moist sub-humid	Sub-humid	Semi-arid	Humid	Moist sub-humid	Sub-humid	Semi-arid	Humid	Moist sub-humid	Sub-humid	Semi-arid
Cropland	69 \pm 13 (24)	116 \pm 37 (6)	51 \pm 28 (35)	36 \pm 28 (5)	– (0)	– (0)	127 \pm 53 (6)	130 \pm 13 (6)	– (0)	225 (1)	81 (1)	28 \pm 4 (8)
Agroforestry	238 \pm 25 (2)	– (0)	74 \pm 9 (4)	– (0)	914 (1)	– (0)	178 \pm 171 (7)	– (0)	465 (1)	207 \pm 76 (7)	54 (1)	19 (1)
Forest	194 \pm 89 (22)	111 \pm 15 (3)	137 \pm 57 (4)	112 \pm 15 (3)	– (0)	– (0)	372 \pm 255 (8)	– (0)	489 \pm 302 (3)	586 (1)	– (0)	404 \pm 165 (2)
Grassland	85 \pm 9 (2)	94 \pm 47 (3)	97 \pm 33 (7)	– (0)	– (0)	– (0)	349 \pm 130 (2)	36 \pm 0 (2)	– (0)	– (0)	– (0)	– (0)
Shrubland	– (0)	60 \pm 7 (2)	45 \pm 9 (3)	– (0)	– (0)	– (0)	74 (1)	– (0)	– (0)	– (0)	39 \pm 5 (11)	– (0)
Woodland	– (0)	65 \pm 7 (2)	83 \pm 68 (15)	77 \pm 13 (6)	– (0)	– (0)	163 \pm 151 (6)	– (0)	– (0)	– (0)	88 \pm 41 (3)	– (0)

grassland to cropland (Birch-Thomsen et al. 2007) had a negligible long-term effect on SOC.

Effect of BMP on SOC stock

Adding crop residues to soil resulted in SOC sequestration ($t\ C\ ha^{-1}\ year^{-1}$) in the 0–30 cm depth interval of 16.9 ± 5.9 and 0.8 ± 0.9 in the short and medium term, respectively. In a study in the Tanzanian sub-humid highlands, McDonagh et al. (2001) estimated that 10 years of continuous application of cereal crop residues could restore SOC stock to that of previous woodland.

Farmyard manure (FYM) addition also led to SOC sequestration, of $14.8 \pm 8.7\ t\ C\ ha^{-1}\ year^{-1}$ in the 0–30 cm depth interval in the short term (Table 5; Figure 4). Studies that observed gains in SOC from FYM addition were mostly conducted in sub-humid conditions ($n = 17$ out of 23). However, in semi-arid conditions, FYM addition was reported to cause an SOC loss of $0.3\ t\ C\ ha^{-1}\ year^{-1}$ in the short term (Nandwa 2001) and $1.2\ t\ C\ ha^{-1}\ year^{-1}$ in the medium term (Kapkiyai et al. 1999). In the medium term, applying FYM to soil was reported to leave a nett SOC deficit in the 0–30 cm depth interval of $4.0\ t\ C\ ha^{-1}\ year^{-1}$ compared with previous forest and $1.1\ t\ C\ ha^{-1}\ year^{-1}$ compared with previous woodland (Solomon et al. 2000; Glaser et al. 2001). Compared with previous grassland, a deficit of $0.6\ t\ C\ ha^{-1}\ year^{-1}$ in the 0–100 cm depth interval was reported in the long term (Lemenih 2004). However, modeling studies have shown that, in the long term, FYM application could lead to nett SOC sequestration in cropland compared with previous shrubland (FAO 2004).

Short-term SOC sequestration in the 0–30 cm depth interval was also reported for fallowing, with the gain ranging from $1.6\ t\ C\ ha^{-1}\ year^{-1}$ under natural fallow to $4.3\ t\ C\ ha^{-1}\ year^{-1}$ using legume trees (Kimaro et al. 2011). Modeling studies have shown that fallowing can potentially lead to long-term SOC sequestration ($t\ C\ ha^{-1}\ year^{-1}$) of 0.3 ± 0.2 in the 0–30 cm depth interval (Stene 2007) and 0.6 in the 0–100 cm interval (FAO 2004).

The short-term effect of applying inorganic fertilizers on SOC sequestration in the 0–30 cm depth interval was relatively low, $3.5 \pm 4.5\ t\ C\ ha^{-1}\ year^{-1}$ (FAO 2004; Cebula 2013; Mbau et al. 2015; Chemutai 2016). Some studies reported no significant effect (Havlin et al. 1990; Nandwa 2001). Studies on agroforestry and terracing were very few, but they indicated SOC sequestration ($t\ C\ ha^{-1}\ year^{-1}$) in the 0–30 cm depth interval of 2.7 and 0.5, respectively, in the short term (Rimhanen et al. 2016).

Combining fertilizer with FYM was reported to result in short-term SOC sequestration of $19.9 \pm 8.7\ t\ C\ ha^{-1}\ year^{-1}$ in the 0–30 cm depth interval (Cebula 2013; Chemutai 2016). However, in the 0–50 cm depth interval, this combination was reported to leave a short-term SOC deficit of $0.3\ t\ C\ ha^{-1}\ year^{-1}$ compared with continuous agriculture (Nandwa 2001). Combining crop residues with fertilizer, or with fertilizer and FYM, gave SOC sequestration ($t\ C\ ha^{-1}\ year^{-1}$) in the 0–30 cm depth interval of 0.1 and 0.5, respectively, in the medium term (Kapkiyai et al. 1999). Models comparing SOC stock to that in previous shrubland showed that combining FYM with fallow left a SOC deficit of $0.4\ t\ C\ ha^{-1}$ in the 0–100 cm depth interval in the long term (FAO 2004).

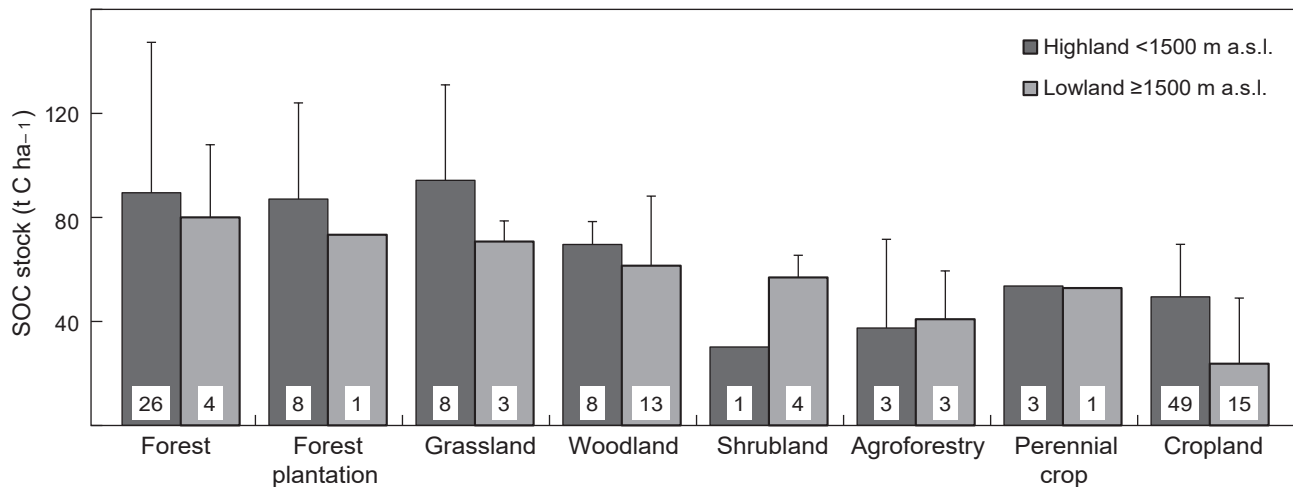


Figure 3: Soil organic carbon (SOC) concentration at 0–30 cm depth (mean of different studies, discretized by elevation). Error bars show standard deviations. Data labels show the number of observations for which the mean value was calculated. a.s.l. = above sea level.

Table 4: Soil organic carbon sequestration rates (t C ha⁻¹ year⁻¹) from land use change, categorized by period of time after which SOC changes were observed. Values are averages ± standard deviations; number of observations in parentheses.

Type of change	<10 years	10–25 years	>25 years	Depth (cm)
Forest to cropland	-6.7 ± 6.0 (6)	-13.0 ± 9.2 (2)	-2.8 ± 1.4 (4)	0–30
Woodland to cropland	-16.0 (1)	-1.9 ± 2.4* (2)	-0.3 ± 0.8* (3)	0–30
Agroforestry to cropland	- (0)	-1.7 ± 0.8 (3)	- (0)	0–30
Shrubland to cropland	- (0)	- (0)	-0.1 (1)	0–50
Grassland to cropland	- (0)	- (0)	0.2 (1)	0–50
Continuous cropland	- (0)	-1.4 (1)	- (0)	0–30

*wide variations in findings from different studies (SD > mean).

Impact of BMPs on soil carbon emissions

The impact of BMPs on soil carbon emissions was reported in only a few of the studies reviewed and it varied widely. Some studies reported no significant effect of BMPs, e.g., FYM did not affect CO₂ emissions (Glaser et al. 2001) and agroforestry did not affect CH₄ emissions (Kim et al. 2016). However, of the total carbon added to the soil through crop residues, about 30% was reported to be emitted back into the atmosphere as CO₂ in Tanzanian drylands (Sugihara et al. 2012) and about 70–90% in sub-humid western Kenya (Nyberg et al. 2002).

Impact of SOC changes on crop yield

Only eight of the studies reviewed reported on the impact of BMPs on SOC and crop yield. In semi-arid conditions, FYM addition and fertilizer addition were reported to lead to a short-term SOC loss of 1.1 and 1.7 t C ha⁻¹ year⁻¹, respectively, in the top 0–30 cm of soil and a loss in maize yield of 0.2 and 0.7 t ha⁻¹ year⁻¹, respectively. In the medium term, combined fertilizer and FYM addition in semi-arid conditions gave an SOC loss of 1.0 t C ha⁻¹ year⁻¹ in the 0–30 depth interval, corresponding to an increase in maize yield of 0.5 t ha⁻¹ year⁻¹ (Table 6). However, in sub-humid conditions, BMPs were reported to increase both

SOC sequestration in the 0–30 cm depth interval and maize yield. Fertilizer addition and FYM addition increased SOC sequestration (t C ha⁻¹ year⁻¹) by 3.3 and 14.5, respectively, in the short-term, with a corresponding increase in maize yield (t ha⁻¹ year⁻¹) of 1.9 and 1.5, respectively. Fertilizer addition resulted in medium-term SOC sequestration of 0.8 t C ha⁻¹ year⁻¹, corresponding to a 2.3 t ha⁻¹ year⁻¹ increase in maize yield.

Discussion

The aim of this review was to obtain quantitative evidence of SOC loss due to conversion from native vegetation to cropland and to determine the potential for increasing SOC sequestration in cropland through BMPs in East Africa. The evidence obtained was mostly based on observations for the 0–30 cm depth interval in soil, which had many data points (105 of 289). However, evidence from the few studies that looked at deeper soil profiles (0–50 cm and 0–100 cm) is also discussed.

SOC stock under different land uses

We started by examining whether the available evidence supported the view that SOC stock in cropland is lower

than that in native vegetation. We found that SOC stock (t C ha^{-1}) in the 0–30 depth interval was significantly higher in forests (range 111.1 to 203.8) than in cropland (range 36.3 to 87.2). The SOC range for cropland is consistent with the 57 t C ha^{-1} in the 0–30 cm soil layer reported for eastern and southern African cropland by Zomer et al. (2017). However, the SOC range for forest was much higher than

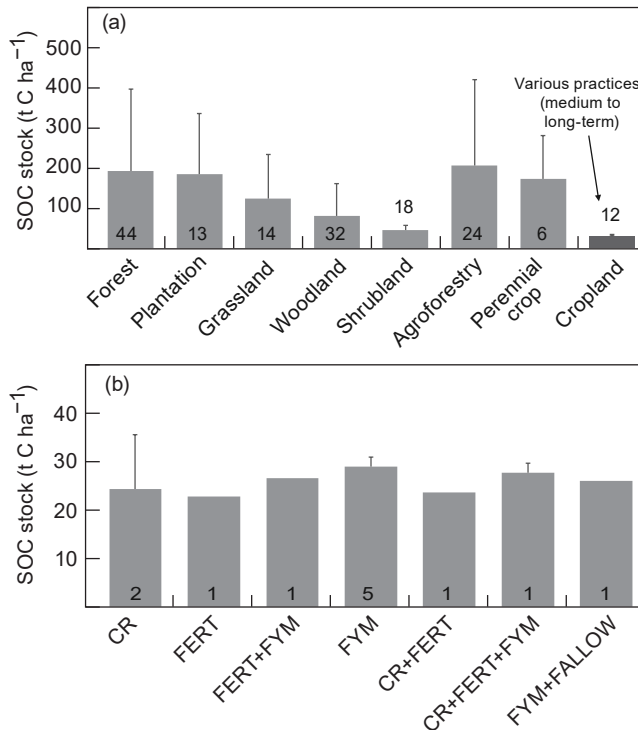


Figure 4: Average soil organic carbon (SOC) concentration under a) different cover types and b) cropland agronomic management practices observed after medium (10–25 years) and long (>25 years) time intervals. Error bars show standard deviations and data labels show number of observations. CR = crop residue addition; Fert = fertilizer addition; FYM = farmyard manure addition

the 38.9 t C ha^{-1} in the 0–30 cm soil layer in African forests reported by Henry et al. (2009) and the $73\text{--}83 \text{ t C ha}^{-1}$ in the 0–40 cm layer in tropical forests reported by Don et al. (2011). This is possibly because those studies included data from semi-arid forests, whereas in the studies reviewed here these were generally categorized as woodland. Tropical SOC stock estimates are generally reported to be associated with high uncertainty (Malhi and Grace 2000; Penman et al. 2003).

However, we found no significant difference in SOC stock in the 0–30 depth interval between cropland and grassland or woodland, possibly due to the small number of studies reviewed and high variation in the data. For example, the range of SOC stock found for grassland in this review was very wide (43.7 to $158.0 \text{ t C ha}^{-1}$) compared with that reported by Batjes (2004) for East African savannah (37 to 39 t C ha^{-1}). The greater difference in SOC stock in the 0–30 cm depth interval between cropland SOC and forest than between cropland and grassland or woodland SOC could be because of the greater distribution of SOC in topsoil under forest than under other native vegetation (Jobbágy and Jackson 2000). It could also be because of soil erosion, which is common on woodland and shrubland (Vågen and Winowiecki 2013).

Within each land use, no clear trends were observed relating SOC stock in the 0–30 cm depth interval with rainfall or elevation, again possibly because available studies were too few and highly variable. In a study in South Africa, Feral et al. (2003) found a weak influence of rainfall regime on SOC stock overall, but found that cropland SOC stock at 0–100 cm depth was higher under higher rainfall conditions. In contrast, Jobbágy and Jackson (2000) found a weakening association with climate conditions with increasing depth in soil.

Effect of land use conversion on SOC

Long-term (>25 years) SOC loss due to forest-to-cropland conversion in the studies reviewed was $2.8 \pm 1.4 \text{ t C ha}^{-1} \text{ year}^{-1}$ in the 0–30 cm depth interval, which was higher than the $0.7 \text{ t C ha}^{-1} \text{ year}^{-1}$ loss reported for a similar soil layer and similar period in tropical countries (Don et al.

Table 5: Soil organic carbon sequestration rates ($\text{t C ha}^{-1} \text{ year}^{-1}$) at 0–30 cm depth from agricultural land management, categorized by time interval after which SOC concentration changes were observed. Values are averages \pm standard deviations; n = number of observations in parentheses. CR = crop residue addition; Fert = fertilizer addition; FYM = farmyard manure addition

Land use practice	BMP Intervention	Soil organic carbon sequestration at 0–30 cm ($\text{t C ha}^{-1} \text{ year}^{-1}$)					
		< 10 years	n	10–25 years	n	> 25 years	n
Cropland	CR	16.9 ± 6.0	14	$0.8 \pm 0.9^*$	2	-	0
Cropland	FYM	14.8 ± 8.7	5	-0.2	1	-	0
Cropland	Fert	$3.5 \pm 4.5^*$	5	-0.02	1	-	0
Cropland	Fallows	2.4 ± 1.4	17	-	0	0.3 ± 0.2	2
Cropland	Agroforestry	2.7	1	-	0	0.2	1
Cropland	Legume intercrop	25.6	1	-	0	-	0
Cropland	Terracing	0.49	1	-	0	-	0
Cropland	Fert + FYM	19.9 ± 8.7	2	-0.6 ± 0.2	2	-	0
Cropland	CR+ Fert	-	0	$-0.6 \pm 0.9^*$	2	-	0
Cropland	CR+ Fert.+ FYM	-	0	-0.5	1	-	0
Forest	Cropland +FYM	-	0	-4.02	1	-	0
Woodland	Cropland + FYM	-	0	$-1.1 \pm 1.8^*$	5	-	0

*wide variations in findings from different studies (SD > mean).

Table 6: Impact of best management practice (BMP) on SOC at 0–30 cm depth* and maize crop yield

BMP	Climate	Time Interval (Years)	Impact on SOC (tC ha ⁻¹ year ⁻¹)	Impact on maize yield (t ha ⁻¹ year ⁻¹)
None	Semi-arid	< 5	-1.1	-1.3
	Sub-humid	10–25	-1.4	0
Crop residue (CR)	Semi-arid	< 5	11.6	2.3
	Humid	< 5	19.1	1.3
Fertilizer (Fert)	Semi-arid	< 5	-1.7	-0.2
	Sub-humid	< 5	3.3	1.9
Farm-yard manure (FYM)	Semi-arid	< 5	-1.1	-0.7
	Sub-humid	< 5	14.5	1.5
Fert + FYM	Semi-arid	10–25	-1.0	0.5
	Sub-humid	< 5	13.3	2.7
CR + Fert	Sub-humid	10–25	0.8	2.3
CR + Fert + FYM	Sub-humid	10–25	0.5	4.1

*Values of SOC are all scaled down to 0–30 cm depth using a linear conversion.

2011), and the 0.0–0.5 t C ha⁻¹ year⁻¹ reported for Ghana (Bruun et al. 2015). This could be due to the higher initial forest SOC stock substrate of 111.7 ± 15.1 to 203.8 ± 86.9 t C ha⁻¹ in semi-arid and humid conditions in the studies reviewed, compared with 83 ± 9 t C ha⁻¹ in Don et al. (2011). Differences in soil type (Torn et al. 1997) and climate conditions (Yang et al. 2015) may also explain the variation. The time taken to reach steady-state equilibrium after forest-to-cropland conversion was reported to be 21–38 years in Kenya, Rwanda, and Ethiopia, which is consistent with estimates for South African soil of 30–50 years (Lobe et al. 2001; Dominy et al. 2002).

Minor long-term losses in SOC (t C ha⁻¹ year⁻¹) were observed for shrub-to-cropland conversion (0.1 for 0–100 cm) and grass-to-cropland conversion (0.02 for 0–50 cm). However, these values were from single studies. Studies elsewhere reported SOC losses and gains due to grassland-to-cropland conversion. High SOC losses were reported in some cases, e.g., -4.8 t C ha⁻¹ year⁻¹ over 18 years in Nigeria (Jones 1971), -0.3 t C ha⁻¹ year⁻¹ over 22 years in tropical areas (Don et al. 2011), a high rate of loss of -50% after 50 years in East Africa (Birch-Thomsen et al. 2007) and -59% after 30–50 years globally (Guo and Gifford 2002). Other studies report SOC gain in cropland adjacent to homesteads and possibly enriched with organic inputs from other sources, e.g., Manlay et al. (2004) in a study in western Africa and Vågen et al. (2005) in a study in sub-Saharan Africa.

Effect of BMPs on SOC

Compared with continuously cultivated cropland, SOC sequestration from BMPs in the 0–30 cm depth interval ranged from 1.0 to 19.7 t C ha⁻¹ year⁻¹ in the short term (<10 years) and from 0.0 to 0.4 t C ha⁻¹ year⁻¹ in the long term (>25 years). Long-term SOC sequestration from using BMPs reported in the studies reviewed was lower than the SOC sequestration potential estimated for cropland (0.55 and 1.13 t C ha⁻¹ year⁻¹ for East Africa and southern Africa, respectively) (Zomer et al. 2017) and 0.02–0.76 t C ha⁻¹ year⁻¹ globally (Lal 2004). Regarding potential long-term SOC sequestration rate from specific BMPs, the mean values reported in the studies reviewed for addition of crop residues or FYM (0.0 to 2.0 t C ha⁻¹ year⁻¹ in the 0–30 cm depth interval) were consistent

with the attainable rate of 0.1–0.4 t C ha⁻¹ year⁻¹ in the 0–10 cm soil layer reported for sub-Saharan Africa by Vågen et al. (2005). For agroforestry, the long-term SOC sequestration of 0.3 ± 0.2 t C ha⁻¹ year⁻¹ reported in the studies reviewed is in agreement with observations by Scharlemann et al. (2014), but much lower than the 1.5–3.5 t C ha⁻¹ year⁻¹ in topsoil reported by Montagnini and Nair (2004).

In low rainfall conditions (<1000 mm year⁻¹), addition of crop residues, FYM, or fertilizer led to SOC sequestration of -0.02 to 0.70 t C ha⁻¹ year⁻¹ in the medium term (10–25 years) compared with continuous cropping (Nandwa 2001). These rates are in agreement with Halvorson et al. (1999) and with estimates of -0.04 to 0.15 t C ha⁻¹ year⁻¹ over 50 years for Sudan and Nigeria (Farage et al. 2007). No studies were found on longer-term effects (>10 years) of crop residues, FYM, or fertilizer on SOC in high rainfall conditions (>1000 mm) in East Africa. However, the difference in the effects of BMPs between high and low rainfall conditions may be small, as shown by Ogle et al. (2005), who reported an increase in SOC after 20 years of crop residue addition of 1.34 and 1.38 t C ha⁻¹ in the 0–30 cm soil layer in dry and moist conditions, respectively.

Combining crop residues, FYM, and/or fertilizer was reported to increase SOC sequestration in the 0–30 cm depth interval by 0.1–0.4 t C ha⁻¹ year⁻¹ over 10–25 years compared with when these were applied separately, but the increase was not cumulative (additive). In a study in Niger, Bationo and Buerkert (2001) also reported low SOC gain following 14 years of combined fallow and crop residues and fertilizer addition, compared with continuous cultivation.

The magnitude and persistence of the effects of adding crop residues and FYM on SOC over time depended on quantities added. The studies reviewed reported an annual application of 5.0–7.8 t ha⁻¹ for crop residues and 0.8–10.0 t ha⁻¹ for FYM. However, the impact of FYM and crop residues on SOC is reported to be short-term (Torn et al. 1997; Spaccini et al. 2002), sustained through continuous application (Solomon et al. 2000; Bationo and Buerkert 2001). Moreover, when used as a soil additive these organic materials are then not available for other uses, such as construction material and livestock feed (Corbeels et al. 2014) and cooking fuel (Bationo et al. 2007).

Studies comparing long-term (20–25 years) SOC change following soil amendment to the stock under previous vegetation have observed nett losses in the top 0–30 cm (e.g., for FYM addition -4.0 , -2.1 , and -1.1 t C ha⁻¹ compared with forest, plantation forest, and woodland, respectively). Torn et al. (1997) also showed that, in comparison with original grassland and shrubland in semi-arid lands, BMPs could only reduce, and not reverse, SOC loss even after 35 years. Nevertheless, potential for BMPs to increase SOC stock to levels that surpass that under previous vegetation has been reported, e.g., by Nord (2008) (intensive agriculture SOC > forest SOC) and Swaine and Hall (1983) (fallow SOC > humid forest SOC).

Potential to achieve the 4 per mille target

Based on the SOC stock values reported in the studies reviewed here, the 4 per mille SOC sequestration rate (t C ha⁻¹ year⁻¹) in 0–30 cm depth interval for East African cropland would be 0.06 for semi-arid areas and 0.20 for both sub-humid and humid areas. This target rate was reported to be surpassed in the short term (<10 years) by fertilizer addition (3.5 ± 4.5 t C ha⁻¹ year⁻¹), improved fallow (2.5 ± 1.8 t C ha⁻¹ year⁻¹), FYM addition (14.8 ± 8.7 t C ha⁻¹ year⁻¹), agroforestry (2.7 t C ha⁻¹ year⁻¹), terracing (0.5 t C ha⁻¹ year⁻¹), and addition of crop residues (19.7 ± 3.9 t C ha⁻¹ year⁻¹). However, for time scales longer than 10–25 years, it was only met by the SOC sequestration rate (t C ha⁻¹ year⁻¹) for agroforestry (0.2), improved fallow (0.3 ± 0.2), terracing (1.5), and combinations of crop residues, FYM, and fertilizer (0.5) or FYM and fertilizer (0.4 ± 0.0). Other BMPs failed to meet the 4 per mille target, e.g., crop residue addition (0.1 ± 2.0 t C ha⁻¹ year⁻¹), FYM addition (-1.2 t C ha⁻¹ year⁻¹), and fertilizer addition (-1.4 t C ha⁻¹ year⁻¹).

Can BMPs lead to nett SOC sequestration in East Africa?

In the studies included in this review, SOC losses in the 0–30 cm soil depth interval as a result of native-vegetation-to-cropland conversion ranged from 6.7 to 16.0 t C ha⁻¹ year⁻¹ in the short-term, 2.1 to 13.0 t C ha⁻¹ year⁻¹ in the medium term, and 0.1 to 2.8 t C ha⁻¹ year⁻¹ in the long-term. Reported SOC change (t C ha⁻¹ year⁻¹) from various BMPs was 2.7 to 25.6 in the short term, -1.4 to 0.1 in the medium term, and 0.2 to 0.3 in the long term. Therefore, although BMPs brought about a reduction in SOC losses under cropland, their potential to compensate for the losses due to land use change was low. The quantity, but also the quality, of SOC is important, as SOC originating from forest cover is known to persist for a relatively long time after forests are converted to cropland (Leminh 2004; Lemma et al. 2006; Kim et al. 2016), whereas that from crop residues is reported to be labile (Spaccini et al. 2002).

Although restoring SOC stocks to the level prevailing under the previous vegetation is not necessarily the goal of building up SOC in cropland, what is interpreted as SOC sequestration is complex, depending on the reference site (i.e., continuous cropping or pristine land) and the timespan required to reach SOC steady state after a management change. This is illustrated in Figure 5, where t_0 indicates the time when land use was converted from native vegetation to cropland, followed by a reduction in SOC stock towards

a steady-state condition (blue line) (e.g., Kinyangi 2008). The green line represents the trend if some BMP is implemented. A snapshot of the SOC stock at t_1 , without knowledge of the status of SOC at t_0 , would usually indicate that the BMP is able to sequester carbon. A common counterfactual conclusion is that this land has sequestration potential if appropriate BMPs are adopted. However, beyond t_1 , SOC loss continues (red dotted line in Figure 5) up to t_4 , when SOC stabilizes to the steady state for the particular BMP. Long-term observation of trends is therefore essential to manage expectations of SOC sequestration from BMPs. Nevertheless, at t_1 BMPs would show avoided losses of carbon, as has been reported e.g., for western Kenya (Sommer et al. 2018). Only after t_2 years since the start of new land use can nett carbon sequestration be observed (yellow line in Figure 5). Sequestration in that case would proceed for v years. However, avoiding SOC losses and true SOC sequestration both qualify as climate change mitigation, as they contribute to reducing atmospheric CO₂ concentrations.

Effect of SOC changes on crop yield

Besides mitigating climate change, increasing SOC is associated with improvement in soil functional properties such as cation exchange and sorption functions, aggregation, porosity, moisture retention (Mulumba and Lal 2008), long-term storage of elements, biological processes (Feller et al. 2000), and improved crop response to mineral fertilizer addition (Musinguzi et al. 2015). The minimum SOC increase needed to improve the crop yield response to fertilizer addition is estimated to be 1.9 t C ha⁻¹ or 3% for East Africa (Okalebo et al. 2002), although this value varies with soil texture, topography, and climate (Musinguzi et al. 2013).

Although only a few of the studies reviewed reported on the impact of BMPs on SOC and crop yield. The available studies, especially in relatively high rainfall conditions (> 600 mm), showed a positive correlation between SOC stock in the crop rooting zone (top 100 cm) and crop yield (Kapkiyai et al. 1999; Nandwa 2001; Mbau et al. 2015). Lal (2006) estimated an increase of 20 kg ha⁻¹ in maize yield for each metric tonne increase in SOC in degraded land. A positive impact of BMPs on crop yield has been reported in other studies in the region, e.g., for agroforestry (Akyaempong et al. 1999; Nyadzi et al. 2003), mulching (McIntyre et al. 2000), intercropping (Van Asten et al. 2011), crop residue addition (Nziguheba et al. 2000), FYM addition (Rutunga and Neel 2006), and improved fallow (Kwesiga and Coe 1994; David and Raussen 2003).

Knowledge gaps

In the studies reviewed, 140 observations were made directly on soil samples, of which 116 were made over a time scale of less than 25 years (Table 2). The studies covering longer time scales (>25 years) were modeling studies or had time lapses in data since a change took place, which various authors estimated by interviewing locals or referring to past documents. Short-term field experiments tend to have stronger statistical power to demonstrate effects, even when the effect size is small.

When summarizing the average SOC stocks across various studies of medium- to long-term practice, it became

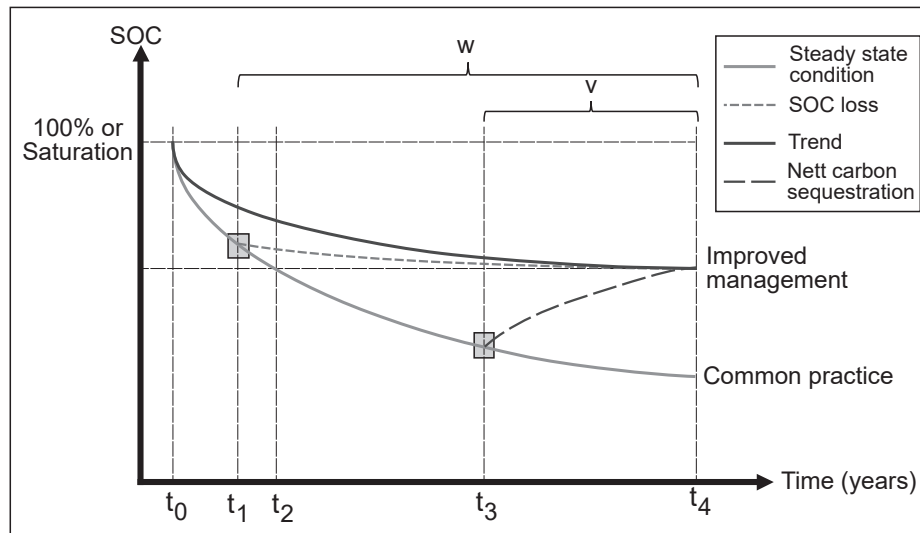


Figure 5: Schematic view of changes of soil organic carbon (SOC) after conversion from pristine lands to croplands. SOC sequestration occurs at t_3 whereas improved management at t_1 rather results in 'avoided in loss'. v is the period over which true SOC sequestration occurs; w is the period over which differences in SOC between cropland and improved management are observed.

obvious that the differences between the BMPs examined were negligible compared with the differences in SOC stocks between cropland and native vegetation. Therefore, there is little data available on what effects on SOC to expect from BMPs in the long run, or in deeper soil layers. Although soil carbon emissions need to be accounted for when estimating SOC sequestration potential from different BMPs, the number of studies reviewed ($n = 5$) that provided actual values was too small to discuss this with confidence. Nevertheless, agriculture is necessary and there is all reason to choose the best practices according to current knowledge.

The spatial distribution of the reported SOC sequestration rates reflected research hotspots in western and central Kenya, central Ethiopia, eastern Tanzania, and western Rwanda, with fewer observations from elsewhere (Figure 2). Considering the distribution of cropland in the region (Figure 1), some areas are 'unresearched'. Semi-arid areas are rarely researched (only 7 of the 69 studies identified), yet they cover about 69% of the East African region (UNDP/UNSO, 1997). No studies were found for Burundi, possibly due to research predominantly being published in French.

Conclusions

This review sought to use available evidence to establish whether SOC in cropland can be built up through BMPs. Analysis of the results in 69 relevant studies showed that it is agronomically possible to increase SOC stocks in East African cropland in the short term (<10 years). The few long-term studies found reported potential to increase SOC using BMPs involving trees, addition of crop residues combined with fertilizer, and addition of crop residues combined with FYM. As it probably takes longer than a decade to reach a new SOC steady state (equilibrium) in cropland soils after a management change, this means that there is little hard evidence available on

the total magnitude of the potential for SOC sequestration through BMPs. The studies reviewed also tended to be spatially concentrated in research hotspots, which means that little is known on the effects under conditions prevailing in other areas in East Africa. Future research and/or monitoring programs should aim to improve the spatial representation of East African cropland and make long-term measurements.

The available evidence on effects of BMPs on SOC concentration indicates that:

Inconsistent or unknown effects:

- There is no consistent effect on SOC of adding FYM or inorganic fertilizer. The mechanisms behind the effects may be slow, complex, and/or governed by local conditions.
- Reduced tillage is often considered to mitigate SOC loss, but we found no studies reporting evidence of this.

Likely effects:

- Addition of crop residues was more often than not associated with increased SOC stocks in the short term (<10 years).

Proven effects:

- Converting cropland to improved fallow or agroforestry consistently increased the SOC stocks in the soil.

In this theoretical exercise, we demonstrated that, in a dynamic system such as soil, it is necessary to make observations over time in order to distinguish between true SOC sequestration and mere retardation of ongoing SOC loss from the soil compared with an initial reference SOC stock. Therefore, recommendations on BMPs to farmers cannot be based solely on their effect on SOC stocks. Farming systems are complex and bio-physical aspects need to be considered together with socio-economic aspects, not least the effects on crop yield and quality.

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