REVIEW ARTICLE

Potential for soil organic carbon sequestration in grasslands in East African countries: A review

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Abstract

Grasslands occupy almost half of the world's land area. Soil organic carbon (SOC) is a key indicator of soil fertility and grassland productivity. Increasing SOC stocks (so-called SOC sequestration) improves soil fertility and contributes to climate change mitigation by binding atmospheric carbon dioxide (CO_2). Grasslands constitute about 70% of all agricultural land, but their potential for SOC sequestration is largely unknown. This review paper quantitatively summarizes observation-based studies on the SOC sequestration potential of grasslands in six East African countries (Burundi, Ethiopia, Kenya, Rwanda, Tanzania and Uganda) and seeks to identify knowledge gaps related to SOC sequestration potential in the region. In the studies reviewed, SOC stocks in grasslands range from 3 to 93 Mg C/ha in the upper 0.3 m of the soil profile, while SOC sequestration rate ranges from 0.1 to 3.1 Mg C ha^{-1} $year^{-1}$ under different management strategies. Grazing management is reported to have a considerable impact on SOC sequestration rates, and grassland regeneration and protection are recommended as options to stimulate SOC sequestration. However, a very limited number of relevant studies are available (n = 23) and there is a need for fundamental information on SOC sequestration potential in the region. The effectiveness of potential incentive mechanisms, such as payments for environmental services, to foster uptake of SOC-enhancing practices should also be assessed.

KEYWORDS
GHG emission, grassland, grazing, management practices

1 | INTRODUCTION

Grasslands are areas where the vegetation is dominated by grasses (Poaceae family). They are an intrinsic part of both rangelands and pasturelands and constitute about half of the global land area. Grassland provides different functions, such as livestock feed, environmental regulation, sequestration of soil carbon, biological diversity and maintenance of soil health (Carlier, ROTAR, Vlahova, & Vidican, 2009; Hönigová et al., 2012; Ribeiro, Fernandes, Dalila Espırito-Santo, 2014). Soil organic carbon (SOC) content is a key indicator of soil fertility and grassland productivity, and SOC sequestration is considered a means to mitigate climate change through

reducing the carbon dioxide (CO_2) concentration in the atmosphere (Conant, 2010; Conant, Cerri, Osborne, & Paustian, 2017; Freibauer, Rounsevell, Smith, & Verhagen, 2004; Ghosh & Mahanta, 2014; Mengistu & Mekuriaw, 2014). Thus, understanding the capacity of grassland soils to store organic carbon is vital in developing climate change mitigation strategies and in addressing soil health issues (Gray, Bishop, & Wilson, 2015).

Globally, grasslands contain more than one-third of aboveground and belowground stocks of organic carbon (Allen-Diaz et al., 1996; Mengistu, 2006). Fisher et al. (1994) and Mishra, Ranade, Joshi, and Sharma (1997) highlight the potential for SOC sequestration by deep-rooting African grasses, such as *Andropogon gayanus* and *Brachiaria humidicola*. Guo and Gifford (2002) estimated that the conversion of cropland to grassland increases SOC by about 19%, while recent meta-analysis shows an increase of 3%–5% (Conant, Paustian, & Elliott, 2001; Conant et al., 2017. The higher SOC stocks in grasslands are due to their perennial nature which results in constant carbon inputs from aboveground vegetation and the large quantities of carbon to the subsoil via root exudates and decomposing deep roots (Zimmermann, Dauber, & Jones, 2012). However, grassland management practices have substantial effects on the turnover rates of soil organic matter, carbon inputs and soil nutrients (Blair, Lefroy, & Lisle, 1995), leading to varying effects on SOC.

For instance, Dlamini, Chivenge, Manson, and Chaplot (2014) reported a 90% decline in SOC in the heavily grazed highlands of KwaZuluNatal in South Africa. Globally, the increased grassland degradation caused by overgrazing has been shown to substantially reduce SOC, mainly in the dry climates, with between 1.2% and 4.2% of the grassland SOC stocks likely to be lost (Dlamini, Chivenge, & Chaplot, 2016). Grassland rehabilitation through adopting improved management has been suggested as one way to reverse this loss. Chaplot, Dlamini, and Chivenge (2016) show that, compared to traditional free grazing, livestock enclosures where the livestock intensity is increased in one area for short duration increases SOC in Southern Africa.

About 75% of Eastern Africa is dominated by managed grassland systems. However, at the regional level little is known about the types of grassland managements and their impacts on SOC, with the existing studies focussing on small localized areas. Given the large land size of grasslands in East Africa, there is a yet untapped potential for C storage in the grasslands as an option to mitigate climate change. However, there is a need to review studies undertaken in the past to better understand the current and future potential effects of grassland management practices. Therefore, the aim of this study was review observation-based studies on grassland systems in East African countries (Burundi, Ethiopia, Kenya, Rwanda, Tanzania and Uganda (Figure 1)) in order to: (a) assess the SOC sequestration potential of existing management practices; (b) assess the key drivers affecting SOC sequestration in grasslands in the region; and (c) identify the knowledge gaps regarding SOC sequestration potential in East African grasslands and provide recommendations for further studies.
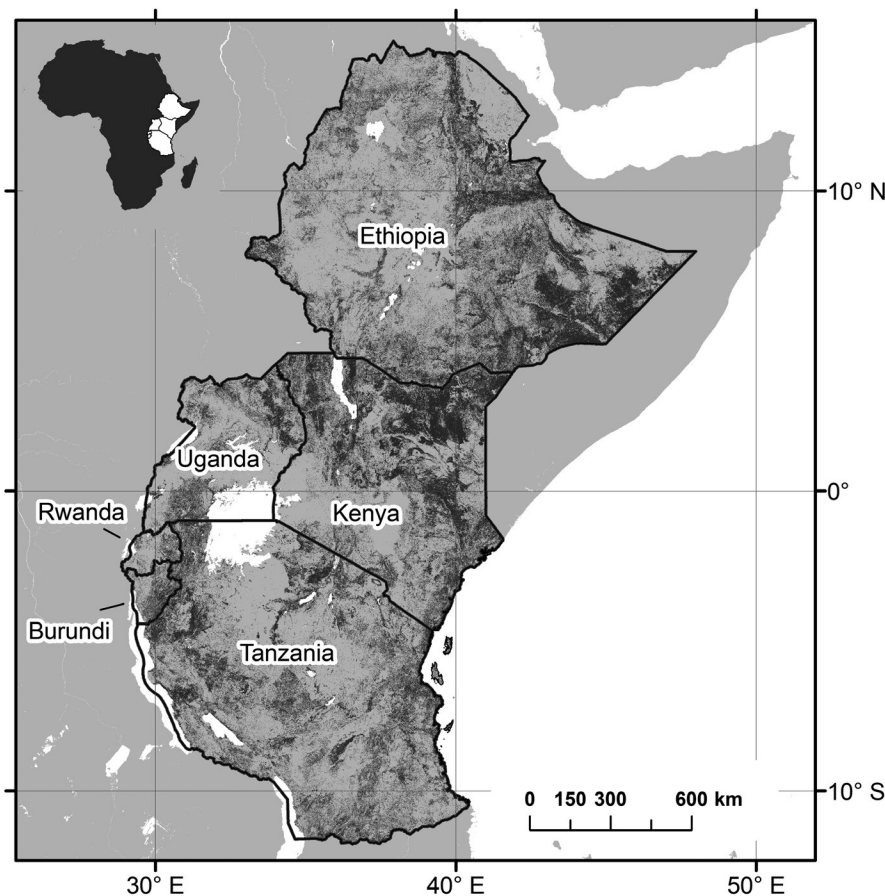

FIGURE 1 Study area. The six countries in East Africa covered by the reviewed publications on SOC in grasslands and converted grasslands. Grasslands are represented by dark areas (data from ESA 2015: © ESA Climate Change Initiative – Land Cover project 2017)

2 | MATERIALS AND METHODS

2.1 | Key terminology

Terminology referring to grasslands varies based on context. For instance, in some cases rangeland and grassland are used interchangeably, while in others grasslands are considered part of different land use classes, e.g., rangelands and pasturelands. The terminology used in this review paper was as follows:

Rangelands

Land on which the native vegetation is predominantly grasses, grass-like plants, forbs or shrubs. This includes land revegetated with such species naturally or artificially by routine management, mainly through manipulation of grazing.

Pasturelands

Enclosed tracts used for grazing distinguished by periodic cultivation to maintain introduced (non-native) forage species and use of agronomic inputs such as irrigation and fertilization (Holechek, Pieper,& Herbel, 2001).

Grasslands

Areas where the vegetation is dominated by grasses (plants of the Poaceae family) and which are an intrinsic part of rangelands and pasturelands.

2.2 | Study area

The present study covered six countries (Burundi, Ethiopia, Kenya, Rwanda, Tanzania and Uganda) in East Africa (Figure 1). The total grassland coverage in this area is an estimated 80 Mha (ESA, 2017). Ethiopia, Tanzania and Kenya have the largest coverage, with 32 Mha, 23 Mha and 20 Mha, respectively, while the total grassland areas is smaller in Uganda (5 Mha), Burundi (1 Mha) and Rwanda (<1 Mha) (ESA, 2017).

2.3 | Literature search and selection

A systematic literature search was undertaken using Google Scholar and key terms such as: "SOC" and "grasslands," combined with country names. The results were compiled in a database for further analysis. From the total number of hits in each search, subsets were derived in three steps by applying criteria on the title (subset 1), applying criteria on full-text availability (subset 2) and applying criteria on the full text itself (subset 3). *Subset 1* was derived by discarding papers where the title clearly indicated that the study covered another geographical region or another land use. *Subset 2* was derived by discarding publications for which no full-text version was available via the Swedish University of Agricultural Sciences (SLU, Uppsala, Sweden), or open access. *Subset 3* was derived by discarding papers where the full text indicated that the study covered another geographical region or another land use and including only publications presenting quantitative data on SOC or SOC change over time. Only publications in the English language were considered.

When sorting results according to relevance, older publications were considered more relevant because of more citations. To ensure recent publications were equally included, separate searches restricted to the previous 11 years (2007–2017) were performed. In addition to this systematic literature search, other publications reporting on SOC stocks in East Africa were identified from the reference lists of publications or were known from previous work by the authors.

The results of the literature search are presented in Table 1. In total, 23 publications that quantified SOC concentration and/or SOC sequestration potential, or for which we could derive those values, were identified. No research work was found for Burundi, and extractable data were only available for Ethiopia, Kenya, Uganda and one regional study for East Africa as a whole. Of the total number of studies, seven reported data from before-after intervention cases, so sequestration rates were computed.

The fact that only 23 relevant publications were located indicates a scarcity of hard data on the SOC sequestration potential of grasslands in the region. About half of the studies were carried out in Kenya (8 studies) and Ethiopia (6 studies) (Table 2), which indicates a geographical bias in empirical evidence on SOC sequestration potential. Moreover, the selected countries differ in size and are therefore not directly comparable. In addition, a language bias could have excluded studies produced in French- and/or non-English-speaking countries (e.g., Burundi and Rwanda). In the retrieved publications, eight different management practices were examined: enclosure; improved management (using rotations and by adding different inputs such as manuring, fertilizer, etc); free grazing; light grazing; heavy grazing; fencing; restoration measures; and conversion from natural forest to grazing.

2.4 | Variables and formulae used to calculate SOC stocks and sequestration rates

In the analysis, direct SOC stock and C sequestration rate values were used if these were available in the studies reviewed. In the absence of values on stocks and sequestration rates, SOC concentration (SOC%) and bulk density (BD) were used to calculate SOC stock for the soil layer specified. Total SOC stocks (Mg C/ha) were then calculated as a product of SOC%, BD and sampling depth (Equation 1). The sequestration rate of SOC was calculated by dividing the SOC stock by the number of years since establishment of

TABLE 1 Documentation of the literature search using Google Scholar, December 7–9, 2017

Search ID	Search string	Time period restriction	Hits ([#])	Subset 1 ([#])	Subset 2 ([#])	Subset 3 ([#])
1	Ethiopia AND "soil organic carbon" AND grasslands	–––	13,500	16	14	3
2	Kenya AND "soil organic carbon" AND grasslands	–––	17,300	19	15	6
3	Tanzania AND "soil organic carbon" AND grasslands	–––	10,900	12	11	3
4	Uganda AND "soil organic carbon" AND grasslands	–––	7,430	17	11	4
5	Rwanda AND "soil organic carbon" AND grasslands	–––	2,950	13	13	4
6	Burundi AND "soil organic carbon" AND grasslands	–––	1,430	5	5	3
7	Ethiopia AND "soil organic carbon" AND grasslands	Since 2007	8,960	25	24	9
8	Kenya AND "soil organic carbon" AND grasslands	Since 2007	12,000	17	17	5
9	Tanzania AND "soil organic carbon" AND grasslands	Since 2007	6,750	13	13	5
10	Uganda AND "soil organic carbon" AND grasslands	Since 2007	4,480	14	14	5
11	Rwanda AND "soil organic carbon" AND grasslands	Since 2007	1,710	10	10	4
12	Burundi AND "soil organic carbon" AND grasslands	Since 2007	936	9	8	1
1–12	No. after removal of duplicates	30				
1–12	No. after removal of studies presenting insufficient information for the Excel table	23				

[#] = number of publications. ––– = no restriction

each specific management practice/intervention (Equation 2). In the absence of bulk density data, an average BD value for the respective countries (~1.4 g/cm^3 on average for all countries) was taken from the global soil mapping database SoilGrids.org (ISRIC, Wageningen, the Netherlands).

$$SOC\,(Mg/ha) = BD \times SOC\% \times Depth \qquad (1)$$

$$SOC\left(Mg\,ha^{-1}year^{-1}\right) = \frac{SOC\,(Mg/ha)}{Age\,(year)} \qquad (2)$$

3 | RESULTS

3.1 | SOC sequestration potential of grasslands in East Africa

The SOC sequestration potential reported in the 23 publications is summarized in Table 3. There was great variation in both the reported amount of SOC in the soil and the SOC sequestration rate under different management options. This may be due to the small number of studies available, supporting the need for additional experiments and/or observational studies for accurate assessments of SOC sequestration potential in grassland soils in countries in East Africa.

The SOC amounts and the rate at which SOC is sequestered in grasslands under different management interventions in the selected East African countries are presented in Table 3. Soil sampling depths behind the reported data were not uniform in the papers reviewed, and therefore, it was difficult to draw comparisons between countries and management intervention measures. Three different

soil depth categories (0–0.1 m, 0–0.3 m and 0–1.0 m) were covered specifically by the soil samples analyzed in the 23 papers reviewed. However, no soil depth values were mentioned for the SOC values reported in three papers.

From the reported data, we inferred that the SOC stocks at 0–0.3 m soil depth in grasslands range from 3 Mg C/ha (Ethiopia) to 93 Mg C/ha (Kenya) (Table 3). The reported impact of management interventions on SOC sequestration rate varied from 0.1 to 3.1 Mg C ha^{-1} year^{-1} for 0–1.0 m soil depth in Kenya, while lower sequestration rates (0.10 Mg C ha^{-1} year^{-1}) were reported in general for some management practices in Ethiopia. The highest rate was reported for fencing (3.10 Mg C ha^{-1} year^{-1} for 7–10 year fenced grasslands in Kenya), followed by conversion from natural forest to grazing (2.4 ± 2.1 Mg C ha^{-1} year^{-1} in Uganda) and enclosure (1.8 ± 0.2 Mg C ha^{-1} year^{-1}). The extent to which grazing is practiced was also reported to affect the sequestration rate, e.g., light grazing (0.77 ± 0.4 Mg C ha^{-1} year^{-1}), giving a higher sequestration rate than heavy grazing (0.9 ± 0.5 Mg C ha^{-1} year^{-1}) for 0–0.1 m soil depth in Ethiopia.

3.2 | Factors affecting SOC stocks

3.2.1 | Geographical location, soil and climate

Two factors are important for increasing the amount of carbon sequestered in grasslands: 1) Carbon input to the soil by net primary production, and 2) the rate of organic matter decomposition (US Department of Energy, 1999). More than two-thirds of the carbon stored in grasslands is located below ground (Burke et al., 1989; Parton, Schimel, Cole, & Ojima, 1987). Grassland SOC stocks

TABLE 2 Studies summarized, and number and type of interventions identified per country

Country	No. of studies	No. of interventions	Intervention(s)
East Africa	1	1	Enclosure
Ethiopia	8	5	Enclosure; restoration measures; improved management; heavy grazing; light grazing
Kenya	6	2	Fencing; free grazing
Uganda	3	1	Natural forest to grazing
Tanzania	4	–	–
Rwanda	1	–	–
Burundi	–	–	–
Total	23	8	

TABLE 3 Soil organic carbon (SOC) stocks and sequestration potential under grassland following different management interventions

Country/area	Intervention	Soil layer (m)	Initial SOC (t C/ha)	SOC sequestration rate (t C ha^{-1}year^{-1})	Studies
East Africa	Enclosure	0–30	43.80 ± 6.30	1.77 ± 0.18	Feyisa et.al., (2017)
Ethiopia	Enclosure	–	3.00	0.30	Niles et.al (2010)
	Restoration measures	–	7.40	0.10	Girmay, Singh, Mitiku, Borresen, & Lal, (2008)
	Improved management	–	5.30	0.10	Girmay et.al (2008)
	Heavy grazing	0–10	32.20 ± 13.90	0.77 ± 0.40	Tessema, de Boer, Baars, & Prins, (2011)
	Light grazing	0–10	36.40 ± 15.80	0.88 ± 0.50	Tessema et.al, (2011)
Kenya	Fencing	0–100	26.10	3.10	Svanlund (2014)
	Free grazing	0–30	92.90	–	Svanlund (2014)
	Free grazing	0–100	77.80	–	Dabasso, Taddese, & Hoag, (2014)
Uganda	Conversion (Natural forest to grazing	0–30	20.10 ± 12.50	2.40 ± 2.10	Twongyirwe et.al (2013)

are primarily determined by climate factors such as temperature and rainfall (Gray et al., 2015), with SOC stocks typically being higher under a cool humid climate. However, in some cases, soil chemical and physical problems can negate this effect (McKenzie & Mason, 2010). There are some positive feedbacks to the currently observed elevated atmospheric CO_2 concentrations and increased temperatures that may be an advantage for growing grasses, and thus for carbon sequestration in the soil (Steffen & Canadell, 2005). Howden et al. (1999) suggest that warmer temperatures are also likely to lead to increased pasture growth, higher biomass yields and SOC sequestration. However, (Taboada, Rubio, Chaneton, Hatfield, & Sauer, 2011) claim that increasing temperature could lead to a decrease in total SOC, due to an increase in decomposition.

3.2.2 | Grass productivity

The production and decomposition of plant biomass can influence a number of ecosystem processes (Windham, 2001). Hence, plant

biomass production and decomposition can determine carbon inputs to the soil profile. Moreover, plant allocation between aboveground and belowground parts, and between shallow and deep roots, can leave distinct imprints on the distribution of soil carbon with depth (Jobbágy & Jackson, 2000). The high carbon input derived from high plant root biomass production in grassland systems can provide the potential to increase soil organic matter content, which is a key factor for enhanced SOC storage in grasslands (Farage et al., 2004). Therefore, maximizing productivity and root inputs in grassland systems is crucial in increasing their SOC sequestration (Trumbmore, Davidson, Barbosa de Camargo, Nepstad, & Martinelli, 1995). However, some studies report that a large root biomass supports substantial soil microorganism populations and their metabolic processes, thus contributing significantly to soil organic matter decomposition and carbon turnover (Kuzyakov, 2002). Accumulation of SOC in grasslands is also a function of the length of time for which the land remains under grasses (Neill et al., 1997). Therefore, regardless of technologies or mechanisms, grassland age must be considered when assessing longer-term carbon storage potential.

3.2.3 | Grazing management

Managing grasslands is crucial, since grasses are the main feed source for livestock production systems (Conant et al., 2001; Ni, 2002). Grazing management aims at optimal use of grasslands for animals, which can be achieved by manipulation of one or more of three variables: species/type(s) of animals, number of animals and distribution of animals. Grassland grazing systems are classified as continuous, seasonal or rotational (Pratt & Gwynne, 1977). Rotational grazing is the typical grazing management system for grasslands in East Africa and gives the land time to recover from past overgrazing (Pratt & Gwynne, 1977).

Poor management of grasslands, such as excessive free grazing, has a major negative influence on grassland C cycling, affecting not only transfers between vegetation and soil compartments, but also ecosystem input and output flows (Franzluebbers et al., 2012; Holechek et al., 2001; Scurlock & Hall, 1998). In the long run, these alterations may have important consequences for the capacity of managed grasslands to store SOC (Holechek et al., 2001). In contrast, improved grazing management is reported to increase SOC storage in grasslands (Conant et al., 2017; Schuman, Janzen, & Herrick, 2002).

3.2.4 | Land conversion

In the past two centuries, 70% of grasslands worldwide have been cleared or converted to agricultural land (Banwart, Noellemeyer, & Milne, 2015; FAO, 2015; Foley et al., 2011). This tremendous pressure on grasslands is expected to continue (Banwart et al., 2015; Holechek et al., 2001; Searchinger et al., 2015; Victoria et al., 2012). In Africa, increased human and livestock populations on a shrinking land area, in combination with drought, which has always been a part of Africa's climate, have intensified ecological degradation of terrestrial ecosystems, resulting in food shortages and famines (Holechek et al., 2001; SIDA, 2010). East African countries, particularly Ethiopia, Kenya and Tanzania, have some of the highest population growth rates in the world (Solomon et al., 2015), which could potentially force more intensive land use and increasingly shift farming onto grasslands (Holechek et al., 2001; SIDA, 2010).

Degradation of remaining grasslands as a consequence of land conversion has become a major concern, as grasslands support nearly a billion domestic animals worldwide (Mengistu, 2006). In sub-Saharan Africa, grassland degradation is much more obvious around watering points because of overstocking (SIDA, 2010). Hence, maintaining and improving the health of grassland ecosystems is a major challenge (Holechek et al., 2001).

Grasslands in dryland areas of East African countries are generally degraded (Farage et al., 2004). Conversion of grasslands to marginal agriculture causes low productivity, which leads to SOC losses by erosion and decomposition (Franzluebbers et al., 2012; Scurlock & Hall, 1998). According to FAO (2004), as a consequence of cropland conversion to grasslands in dryland areas, SOC sequestration rate declines from 0.17 Mg C ha^{-1} year^{-1} in the first 25 years to 0.04 Mg C ha^{-1} year^{-1} in the next 25 years. On the other hand, Sanderman, Farquharson,

and Baldock (2009) estimated a 0.3–0.6 Mg C ha^{-1} year^{-1} increase as a result of cropland conversion to permanent pasture in Australia.

4 | DISCUSSION

4.1 | SOC sequestration potential of grasslands in East Africa

For many years, crop breeders and growers have been selecting specifically for tropical grasses with deep, large root systems that can exploit nutrients and water in deeper soil layers (Fisher et al., 2007). Deep root penetration into the subsoil and deposition of root biomass are believed to be the primary vehicle for SOC sequestration (Kell, 2011; Kuzyakov, 2002; McKenzie & Mason, 2010; Nguyen, 2003). Hence, deep-rooting perennial grasses contribute significantly to the SOC pool via biomass inputs (litter and exudates). In addition, mineralization processes are slower in deeper soil layers, so SOC losses are lower (Lorenz & Lal, 2005; Monti & Zatta, 2009; Rumpel & Kögel-Knabner, 2011).

Studies at various locations have shown that the average annual organic matter input to grassland soils is about twice that to cropped soils (Clifton-Brown, Breuer, & Jones, 2007; Jenkinson & Rayner, 1977; McKenzie & Mason, 2010; Schwenke et al., 2014). Even grasslands subjected to controlled grazing have higher SOC levels than croplands, primarily due to the lower losses of SOC that occur when the soil is not tilled (Farage et al., 2004). However, estimates of carbon inputs from biomass in grassland savannah vary significantly, from 0 Mg C ha^{-1} year^{-1} in dry periods to between 5 and 15 Mg C ha^{-1} year^{-1} in the rainy season (Vågen, Lal, & Singh, 2005).

Grasslands can play a significant role in carbon sequestration if grazing management is optimized. Alternatively, if grasslands are exposed to prolonged overgrazing and soil degradation, the consequence is high SOC losses (Conant, 2012; Farage et al., 2004). Improved grazing management has been estimated to increase SOC storage in US rangelands by 0.1–0.3 Mg C ha^{-1} year^{-1}, while newly established grasslands have been shown to sequester as much as 0.6 Mg C ha^{-1} year^{-1} (Conant et al., 2017; Schuman et al., 2002). There is much less empirical evidence available for East Africa and elsewhere in Africa, but the data at hand indicate that pasture improvements, including fertilization, liming, irrigation and sowing of more productive grass varieties, generally result in relative gains of 0.1–0.3 Mg C ha^{-1} year^{-1} (Sanderman et al., 2009).

Grasses also have the potential to sequester carbon in previously degraded soil. For example, in a study where switchgrass (*Panicum virgatum* L.) was grown on degraded land, SOC sequestration rate increased by an estimated 12% over 10 years (Garten & Wullschleger, 2000). Clifton-Brown et al. (2007) estimated the total mitigation potential of *Miscanthus* grass-dominated rangelands through carbon sequestration, soil and belowground biomass, combined to be 5.2–7.2 Mg C ha^{-1} year^{-1} after 15 years. *Miscanthus* grass has been shown to accumulate significant quantities of new carbon to 1.0 m soil depth (Schneckenberger & Kuzyakov, 2007; Zimmermann et

al., 2012). Poeplau and Don (2013) observed a mean C_4 plant-derived SOC sequestration rate of 0.19–0.78 Mg C ha^{-1} year^{-1} under *Miscanthus* and found that the rate increased with increasing mean annual temperature. A study conducted by International Center for Tropical Agriculture (CIAT) scientists on gamba grass (*Andropogon gayanus*), which has a root system penetrating to 1.0 m depth in tropical soils, revealed outstandingly high SOC sequestration rates of up to 195 Mg C ha^{-1} year^{-1} (Vietmeyer,1997).

Grasslands are the basis of livelihood for East African communities, which depend heavily on livestock (Mengistu, 2006). Animal numbers are expanding in the region to meet the needs of the growing human population and the animals are depending on a shrinking rangeland area, which is putting rangelands under pressure (Holechek et al., 2001). In addition, the high demand for different kinds of products from rangeland causes frequent modification of land use, which results in changes in the relative area of different rangeland uses (Mengistu, 2006). In East Africa, a great number of wild animals depend on rangelands that they must share with humans and their herds and flocks (Figure 2). Grasslands of East Africa therefore need careful management, because they have great potential for feed production and SOC storage (Mengistu, 2006).

4.2 | Opportunities for governance of grasslands in East Africa

African soils in general have great potential for storing SOC, provided that appropriate land management practices and carbon input measures are undertaken (Solomon et al., 2015). In Ethiopia, agricultural production and land productivity remain low, due to ever-increasing human population pressure on land resources, in combination with unfavorable land policies (small land holdings and land ownership issues). Shiferaw, Hurni, and Zeleke (2013) report some success for the Ethiopian Sustainable Land Management Program (SLMP), which aims at improving soil quality and productivity by restoring degraded lands, including grasslands, using best land management practices and climate change mitigation and adaptation measures (https://

FIGURE 2 Wildlife on Kapiti Ranch of the International Livestock Research Institute, ILRI, south of Nairobi, Kenya

www.giz.de/en/worldwide/18912.html). The program reflects the goals of the growth and transformation plan for Ethiopia, one of which is to enhance SOC stocks in Ethiopian soils, including grassland soils (SIDA, 2010; Solomon et al., 2015).

In the studies reviewed in the present analysis, it is widely suggested that rangeland/grassland regeneration and protection practices could be a sustainable option for SOC sequestration, contributing to climate change mitigation at both national and regional level. In addition to the climate change benefit, storage of carbon in grassland soils through improving the productivity of grass biomass offers economic returns (Singh, Guleria, Rao, & Goswami, 2011). However, grasslands are complex ecosystems. For instances, restoring and sequestering carbon may come at the cost of reduced feed availability when free grazing is restricted, negatively affecting pastoralists in the short-term. Similarly, while conversion of grasslands into cropland may benefit smallholder farmers, this land use conversion can entail further losses of SOC.

4.3 | Knowledge gaps

4.3.1 | Data availability

Field studies on the SOC sequestration potential of rangeland systems in East Africa form only a small part of research on the subject globally (Tubiello, Soussana, & Howden, 2007). There have been no such studies in Burundi and few in the other five East African countries included in the present study. There is a need for sound empirical data on the SOC sequestration potential of grasslands in East Africa in general, and the potential or limitations for carbon sequestration in response to climate change in particular. For example, there is a critical need for data on SOC stock changes caused by conversion from grasslands to agricultural lands. It is also important to determine the quantitative impact of factors affecting SOC concentrations in grassland soils. Field experiments and computer modeling work examining the effects of management practices on SOC sequestration are required to understand underlying mechanisms at multiple scales, as there is considerable variation in SOC concentrations and soil bulk density under grasses, depending on factors such as soil type and elevation (Chan & McCoy, 2010; Easter et al., 2007; Wilson, Koen, Barnes, Ghosh, & King, 2011; Young, Wilson, McLeod, & Alston, 2005; Zimmermann et al.,2012).

4.3.2 | Financing mechanisms

Sequestration of SOC in grassland soils is not currently eligible for payments under the Clean Development Mechanism (CDM) of the Kyoto Protocol, due in particular to issues of permanence and verification (SIDA, 2010). Therefore, there is also a need to review current and potential financing mechanisms, such as voluntary carbon markets, for grassland improvement and adoption of management practices that enhance SOC in grasslands. Some possibilities for investment and policy support are currently opening up, such as the 4p1000 initiative (Minasny et al., 2017).

4.3.3 | Deep soil SOC sequestration potential

Consideration of SOC stocks to soil depths of 1–2 m, or the entire root zone if deeper, may be required for accurate assessment of SOC sequestration and SOC storage potential (Olson, Al-Kaisi, Lal, & Lowery, 2014). However, there is a severe lack of SOC content data for most soils at 0.5–1.0 m depth or below (see also Olson (2013). In the tropics, current knowledge about SOC stocks below 0.2 m depth is very limited, although there are some occasional measurements down to 4.0 m (Fisher et al., 1994) or even down to 6.0 m (Carvalheiro & Nepstad, 1996; Sommer, Denich, & Vlek, 2000). In addition, variations in the vertical and horizontal distribution of SOC in tropical, subtropical and temperate soils need to be assessed.

4.3.4 | SOC sequestration rates under planted cut and carry forages

Another knowledge gap concerns SOC sequestration rates under planted cut and carry forages on cropland, which was not part of this review. Little is known about the SOC dynamics in these systems, and measuring C sequestration is a challenge, as the areas planted are patchier and integrated with other (food) crops. Hence, computer modeling might play a role. This could be linked to the interventions/technologies CIAT is working on in Africa, which focus on cut and carry because rangelands are often communally managed and there is no individual incentive to introduce improvement measures.

5 | CONCLUSIONS

Grasslands have great potential to sequester SOC due to their fast establishment, growth and perennial biomass production, and improved management of grasslands can increase this potential, particularly on degraded soils. However, this review revealed a lack of published studies on the SOC sequestration potential of grasslands in East Africa, so it is difficult to draw any firm general conclusions. Overall, it was found that:

- More studies are needed on the SOC sequestration potential of East African grasslands when promising management practices are adopted.
- There are tremendous variations in reported SOC sequestration rates. In combination with the low number of individual studies, this is likely to lead to biased and uncertain estimates of SOC sequestration potential.
- The effects of grass type and management practices on SOC storage potential need to be fully quantified, including extending soil sampling to greater depths and under deep-rooted perennial grasses.
- Ways of stabilizing carbon stored in soils so that it is not released by management-induced disturbances need to be identified.

Given the vast areas under grasslands worldwide and the tendency for grassland systems to store more carbon in soils, their carbon sequestration potential should be compared with that of other land use systems. This could help improve decision making on prioritizing SOC-enhancing measures and policies.

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