Geoderma 370 (2020) 114342

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Soil health and ecosystem services: Lessons from sub-Sahara Africa (SSA)

J. Kihara[a,*], P. Bolo[a], M. Kinyua[a], S.S. Nyawira[a], R. Sommer[b]

[a] Alliance of Bioversity International and the International Center for Tropical Agriculture (CIAT) c/o International Centre of Insect Physiology and Ecology (ICIPE), Duduville Campus Off Kasarani Road P.O Box 82300621, Nairobi, Kenya

[b] World Wide Fund for Nature (WWF), Reinhardtstrasse 18, 10117 Berlin, Germany

ARTICLE INFO

Handling Editor: Morgan Cristine L.S.

Keywords:
Carbon
Provisioning
Regulation
Biological activity
Greenhouse gases
Leaching
Soil loss

ABSTRACT

Management practices to improve soil health influence several ecosystem services including regulation of water flows, changes in soil biodiversity and greenhouse gases that are important at local, regional and global levels. Unfortunately, the primary focus in soil health management over the years has been increasing crop productivity and to some extent the associated economics and use efficiencies of inputs. There are now efforts to study the inter-relationship of associated ecosystem effects of soil health management considering that sustainable intensification cannot occur without conscious recognition of these associated non-provisioning ecosystem services. This review documents the current knowledge of ecosystem services for key management practices based on experiences from agricultural lands in sub-Sahara Africa (SSA). Here, practicing conservation agriculture (CA) and Integrated Soil fertility management (ISFM) have overall positive benefits on increasing infiltration (> 44), reducing runoff (> 30%) and soil erosion (> 33%) and increases soil biodiversity. While ISFM and Agroforestry increase provisioning of fuelwood, fodder and food, the effect of CA on the provisioning of food is unclear. Also, considering long-term perspectives, none of the studied soil health promoting practices are increasing soil organic carbon (SOC). Annual contributions to greenhouse gases are generally low (< 3 kg N_2O ha^{-1}) with few exceptions. Nitrogen leaching vary widely, from 0.2 to over 200 kg N ha^{-1} and are sometimes inconsistent with N inputs. This summary of key considerations for evaluating practices from multiple perspectives including provisioning, regulating, supporting and cultural ecosystem services is important to inform future soil health policy and research initiatives in SSA.

1. Introduction

Land degradation characterized by soil erosion, nutrient depletion, loss of biological diversity and decreasing quality and quantity of water is a major problem facing many countries in sub-Saharan Africa (SSA; Swift et al., 2006). About 65% of the agricultural land in SSA is degraded due to poor management practices, which induce declines in soil biological, chemical and physical quality; reducing the capacity of the soil to support crop production and provide other ecosystem service (ES; Oldeman et al., 1991; Zingore et al., 2015). Annual nutrient depletion in year 2000 were estimated to reach 38 kg ha^{-1} (i.e., 26 kg N, 3 kg P, 9 kg K; FAO and ITPS, 2015), leaving soils with serious fertility and other constraints (FAO, 2002). Such degraded lands reduce the annual agricultural productivity by nearly 3% (Zingore et al., 2015), costing the SSA region about USD 68 billion annually. The degradation has stagnated or even declined yields levels of cereal and legume crops (Obalum et al., 2012) at a time when the region's population is rapidly rising. Meeting the growing demand for food, while also supporting livelihoods of 70% of the households in the region depending directly or indirectly on agriculture (FAO, 2002), will be a big problem if the current trend of degradation continues. Furthermore, poverty and malnutrition are likely to worsen as the population grows. Therefore, to address the prevalent problem of degradation, improving soil health, especially in agricultural lands, is a key priority. Soil health is defined as the continuous capacity of soils to function as a vital living ecosystem, within ecosystem and land use boundaries, to sustain biological productivity, maintain the quality of air and water, and promote plant, animal and human health (Doran and Zeiss, 2000). Because it considers the full range of ecosystem services, soil health is broader than soil fertility which mostly considers only the capacity of a soil to grow crops (Vanlauwe et al., 2010).

Soil health-improving practices such as conservation agriculture (CA), integrated soil fertility management (ISFM) and agroforestry practices positively affect not only the often measured crop production but also contribute to other ES (Blum, 2005). CA is a farming system that minimizes soil tillage, maintains a permanent soil cover of at least

* Corresponding author.
E-mail address: j.kihara@cgiar.org (J. Kihara).

https://doi.org/10.1016/j.geoderma.2020.114342
Received 23 July 2019; Received in revised form 10 March 2020; Accepted 22 March 2020

30%, and cultivates a diverse range of plant species in rotation or intercropping to improve soil health. ISFM is the combined use of mineral fertilizers and locally available soil amendments and organic matter in crop production while agroforestry is a land use management system involving growing trees or shrubs among crops. Recognizing that soil health affects other ES, it was proposed that management of agricultural soils must address not only productivity but also environmental effects, such as greenhouse gases, air and water quality (Lal, 2000). Ecosystem services provided by soils include regulation of the atmosphere and climate, primary production, nutrient conservation, carbon sequestration, water purification and erosion control (Millennium Ecosystem Assessment (MEA), 2005). These ES have been grouped into four broad categories namely: provisioning, regulating, supporting and cultural services. The recognition of linkages between soil health and broader ES is not new in SSA. As early as the 1970s, Rapp (1977) appreciated that dense vegetative soil cover under CA can be as effective as forests in controlling soil erosion; a major problem of agricultural landscapes in the region and contributes to high sedimentation of reservoirs (Dunne, 1977).

Over the past several decades different studies in SSA have assessed the impacts of some of the common soil health improving agronomic management practices on one or more ES, with major focus on the provision of food and climate regulation. The existing global reviews have focused on linking soils to ES in general, based on the soil physical and chemical properties such as organic carbon and water holding capacity (Adhikari and Hartemink, 2016), and examining the relationship between CA and ES (Palm et al., 2014; Giller et al., 2015). However, there are few studies providing a thorough review on how soil health relates to ES in all defined broad categories in SSA. Given that the promotion and adoption of improved management practices to enhance soil health is gaining momentum in SSA, it is important to understand the impacts of these practices on ES. The objective of the review is to provide current state of knowledge on effects of soil health management on delivery of ecosystem services for human well-being within SSA (See Table 1).

2. Methodology

This review focused on evaluation of the influences of soil health on ecosystem services in SSA. The region is characterized by high food insecurity, high levels of land degradation and increasing population in addition to the uncertainty of global climate change. Governments in the region have committed to improve land productivity through increased use of fertilizers along with incorporation of soil health promoting practices (like CA, ISFM, or agroforestry).

The data and information used in this study was obtained from a literature search conducted from November 2018 to July 2019. There were no restriction placed on publication dates because there are not many studies on ecosystem services in SSA, especially those touching on the regulating, supporting and cultural aspects. Initially, the search in Google Scholar search engine using key words of “soil health”, “ecosystem services” and “sub-Sahara Africa” returned 95 publications. Some of the publications were unsuitable as they did not provide the key indicators of interest. The search was therefore refined to include the specific indicators measured as part of ecosystem services targeting the different sub-sections of our study. The keywords included in the refined search in combination with “soil health” and “sub-Sahara Africa” are food production, fodder production, freshwater soil loss, nutrient leaching, fuelwood production, climate regulation, pest and diseases, pathogens, greenhouse gas, nitrous oxide, soil organic carbon, agroforestry, firewood, bioremediation, erosion, conservation agriculture, provisioning services, cultural services, regulating services and supporting services. In each case, the publications were screened to retain only those relating to effects of soil health management interventions. In the end, a total of 93 publications were used in this review, covering 1970–2019. These cover the key management practices used in the region such as CA which consists of reduced or zero tillage, crop residue retention and crop rotations including cover crops (Hobbs et al., 2008), ISFM involving the combination of inorganic fertilizers and organic resources, and agroforestry systems. The publications also cover a wide range of geographies with the extracted data in Tables and Figures covering Kenya, Nigeria, Mali, Burkina Faso, Zambia, Zimbabwe, Ethiopia, Mali, Tanzania and Togo besides several other countries discussed within the text (Fig. 1).

Data on specific soil physical, chemical and biological characteristics used in the Tables and Figures were extracted directly from the publications only when several manuscripts contained the data, otherwise the information or data was mentioned within the text. Extraction of carbon data involved retrieving information from graphs, tables or real values reported in different publications. Some data conversions were undertaken for reporting in this study. For example, soil organic carbon (SOC) data was reported for variable periods, from 1 to 40 years. Where necessary, e.g. in Partey et al. (2017) study, we recalculated and presented the SOC data in per annual increments in the text, i.e., equivalent quantities of carbon per hectare on annual basis. For long-term trends, SOC data derived from four research studies conducted in Kenya, Nigeria and Togo were fitted into simple linear regression curves with time of measurement since trial establishment as the x-variable.

For systems that had been sufficiently studied or where thorough

Table 1
Effects of conservation agriculture on soil loss, runoff, infiltration rates and associated yield change relative to conventional tillage systems in different parts of SSA.

Source	Country/ year	Soil type	Rainfall (mm)	Soil loss (t/ha/yr)		Runoff (mm)		Infiltration rate (mm h-1)		Yield change
				CA	CT	CA	CT	CA	CT	
Araya et al. (2011)	Ethiopia 2007	Vertisol	230	5.2	24.2	46.3	98.1	n.d	n.d	+wheat (*Triticum aestivum*) −Teff (*Eragrostis tef*)
Thierfelder and Wall (2009)	Zimbabwe 2006	Arensol & Luvisols	1036	8	12	n.d.	n.d	47	32	No change (maize)
	Zimbabwe 2007	Arensol & Luvisols	534	0.9	2.4	n.d	n.d	75	52	+ maize (Zea mays)
	Zambia 2006	Lixisols	734	n.d	n.d	n.d	n.d	53	34	+ maize (*Zea mays*)
	Zambia 2007	Lixisols	550	n.d	n.d	n.d	n.d	47	25	None (maize)
Lal (1997)	Nigeria 1981	Alfisols	n.d	0.25	1.03	26.3	68.1	n.d	n.d	− maize
	Nigeria 1981	Alfisols	n.d	0.16	0.63	33.3	79.1	n.d	n.d	None (cowpea; *Vigna unguiculata*)
	Nigeria 1984	Alfisols	n.d	0.78	6.64	137	197	n.d	n.d	None (Soybean [*Glycine Max.*])
	Nigeria 1984	Alfisols	n.d	0.76	3.79	87.5	115.3	n.d	n.d	+ cowpea; *Vigna unguiculata*

CT = conventional tillage; CA = conservation agriculture (direct seeding under mulch and no till except for Araya et al. (2011) which used permanent raised bends with furrow); n.d = no data was available; + =positive yield change; − =negative yield change.

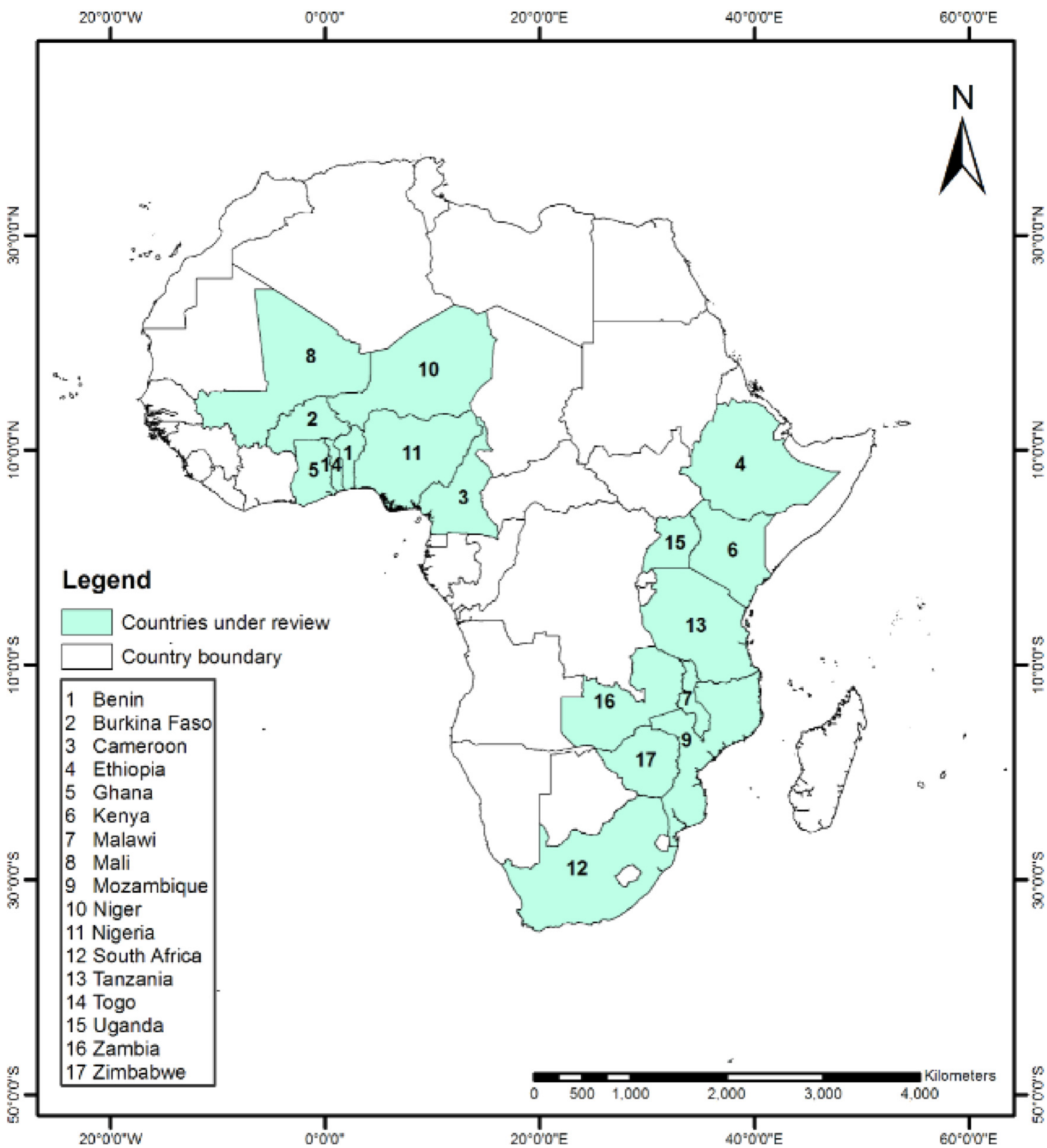

Fig. 1. Map of countries where data and information from peer reviewed journals on the different ecosystem services in sub-Saharan Africa were extracted. Source is the Global Administrative Boundaries Map (GADM).

review already existed, reference to these studies was made without going into a lot of details. The contribution of agroforestry to fuelwood and to other indicators of ecosystem services, such as SOC, have for example been undertaken in Malawi and Zambia by Kaczan et al. (2013) and other sub-Saharan countries by Partey et al. (2017). Under such contexts, only general distributions or average contributions are presented.

3. Results and discussion

3.1. Soil health and provisional ecosystem services:

3.1.1. Effects on food, fodder, and fuelwood production

Improved soil health is often associated with improved crop and fodder productivity (Vanlauwe et al., 2015; Njoroge et al., 2017; Ichami et al., 2019). ISFM technologies are known to increase yields and sometimes tripling and quadrupling production over current farmer practices (Kihara et al., 2017). Evidence from *meta*-analysis and review studies shows that the use of agroforestry technologies also has the potential to increase crop yields and overall system productivity in SSA smallholder farming systems (Kaczan et al., 2013; Partey et al. 2017; Kuyah et al., 2019). However, improved soil health under CA is mostly concurrent with reduced yields especially in the first 2–5 years of establishment (Thierfelder et al., 2015a), although savings in labor often compensate for this. Where there is yield increase with either CA or ISFM, it is often accompanied by an increase in the crop residues biomass, which are useful for feeding animals (Mugwe et al., 2007; Mupangwa and Thierfelder, 2014). Feed provisioning varying from 7 to 21 t ha^{-1} yr^{-1} of above ground biomass under agroforestry using improved fallows, for example, is reported in an SSA-wide review (Partey et al., 2017). Improved soil health is also associated with enhanced microbial activities and enhanced plant access to different nutrients from soil (Smith et al., 2011; Coyne and Mikkelsen, 2015; Berruti et al., 2016) and subsequent nutrient transfer along the food chain (Grusak and DellaPenna, 1999). Therefore, improved soil health influences food and feed quality due to changes in mineral nutrition of crops (Sahrawat

Table 2
Quantities of nitrogen leached under different soil management practices in different locations of SSA.

Source	Country and years	Rainfall (mm)	Soil type	N leached (kg N ha^{-1})	Period and depth	Systems assessed
Nyamangara et al. (2003)	Zimbabwe (1996–1999)	840–1395	Luvisol	12–56	Seasonal (100 cm)	Manure and nitrogen fertilizer in combination
Poss and Saragoni (1992)	Togo (1985–1986)	308–377	Ferralsol	36–153	Annual (180 cm)	120 kg N ha^{-1} fertilizer treatments
Russo et al. (2017)	Kenya (March 2012–August 2013)	760–1162	Ferralsol	40–81	Annual (200 cm)	75 and 200 kg N ha^{-1} per season
Kamukondiwa et al. (1996)	Zimbabwe (1991–1992)	392	Lixisol	1.4–8.6	Seasonal (120 cm)	Manure and fertilizer
Mapanda et al. (2012)	Zimbabwe (2006–2009)	600–1040	Luvisol	3–26	Seasonal (110 cm)	Nitrogen fertilization
Kamukondiwa and Bergström (1994)	Zimbabwe (1989–1991)	435–929	n.d	0.3–39	Seasonal (120 m)	Manure and fertilizer
Wong et al. (1987)	Nigeria (1983–1984)	1250	Ultisol	82–144	Annual (135 cm)	92 and 138 kg N ha^{-1} fertilizer treatments
Omoti et al. (1983)	Nigeria (1981)	1369	Nitisol	3–42	Seasonal (150 cm)	31.2 kg N ha^{-1} fertilizer treatments
Sogbedji et al. (2006)	Togo (1997)	n.d	Ferralsol	0.2–6	Seasonal (100 cm)	60 and 120 kg N ha^{-1} fertilizer treatments
Wong et al. (1992)	Nigeria (2 seasons; Year unknown)	2030	Acrisol	15–236	Seasonal (135 cm)	92 and 138 kg N ha^{-1} fertilizer treatments
Van der Kruijs et al. (1988)	Nigeria (1983–1984)	2420	n.d	142–251	Annual (135 cm)	Nitrogen fertilization
Våje et al. (2000)	Tanzania (1995and 1996)	18–145	Andosol	167–242	Annual (89 cm)	200 and 100 kg N ha^{-1} fertilizer treatments
Munodawafa (2007)	Zimbambwe (1993–1996)	384–765	Arenosol	2–3	Annual	Mulch and Tide ridging

n.d refers to no data available.

and Wani, 2013).

Fuelwood provides 80% of energy supply in SSA, with estimated 692 kg per capita per annum of fuelwood consumed in rural South Africa (Dovie et al., 2004). It is an increasingly scarce resource among a large majority of smallholder farmers in SSA. Within agroforestry systems, use of green manure cover crops with woody stems, for instances pigeon pea (*Cajanus cajan*), sesbania (*Sesbania* spp.) and calliandra (*Calliandra* spp.) also provide fuelwood (Saxena, 2008; Saxena et al., 2010). The use of nitrogen-fixing agroforestry trees has the potential of increasing fuelwood production by 4–10 t ha^{-1} year^{-1}, as has been reported in Tanzania by Iiyama et al. (2014). This is an obvious alternative to deforestation, which opens doors for fast turnover of carbon sequestered over previous decades. A SSA-wide review of the potential of agroforestry in the provision of wood fuel is available from Iiyama et al. (2014).

Improving soil health is related to increased crop resilience to climate change (Grover et al., 2009) which is important for continued provisioning of food, fodder and fuelwood. The ability to reduce the impacts of the year-to-year or season-to-season weather variability on productivity is certainly a desirable attribute of improved soil health (Porter and Semenov, 2005). Based on long-term (13 yr) trials, growing maize (*Zea mays*) in association with legume trees increases production stability relative to conventional practices in southern Africa (Sileshi et al., 2012). In 30 season (15 yr) trials in western Kenya, systems that increase soil health are associated with improved yield stability across environments but are also associated with increasing yields over time and – especially those under CA – improved economics (own data). Yet globally, for some of the CA systems, real benefits, e.g. of rotations reported in Mozambique, are realized only after as much as 20 years (Rusinamhodzi et al., 2011). The benefits are derived from improved soil structure and regulation of water and nutrient flows (Ayuke et al., 2012). Besides having overall higher productivity, intercropping reduces crop failure compared to mono-cropping in farming systems in SSA (Mzezewa and Gwata, 2016; Kermah et al., 2017; Mthembu et al., 2018). While yield and yield stability can be argued for most soil health management practices, the use of some practices, such as fertilizer micro-dosing, induce nutrient mining resulting in overall decline in fertility in the long-run, as observed in Benin (Tovihoudji et al., 2017). Thus, while some soil health management practices result in quick provisioning benefits (yield), some systems require sufficient time of consistent implementation before benefits are realized. However, negative side-effects, such as nutrient mining, must also be considered.

3.1.2. Effects on freshwater

Up to 10–25% (Rockström, 2000) or even 50% of rainfall received may be found as runoff on eroded slopes (Rapp, 1977). This leads to heavy soil erosion, especially in conventional tillage systems with prolonged times of bare soil. In the humid tropics of SSA, annual soil loss rates had been estimated at about 50 t ha^{-1} (FAO, 1995). Lack of soil cover enhances crusting, inhibits rain water percolation, and increases top soil loss (Lal, 1987) often accompanied by nutrient transfers and deposition e.g., into water bodies (Zhou et al., 2014). In Eastern Africa for instance, total nitrogen (N) load of 152,000 t N year^{-1} is deposited into an already eutrophied Lake Victoria via riverine transport and atmospheric deposition (Zhou et al., 2014). Sediment loads in river water, which in Kenya have been observed to surpass 1000 t km^{-2} yr^{-1}, are associated with unsuitable management practices of agricultural land, and are several multiples over those associated with forest lands (Dunne, 1977). Although no data could be found for SSA, there is evidence from elsewhere that under such conditions of deteriorating water quality, degeneration of a multitude of sensitive wetland ecosystem functions occur (Dell'Anno et al., 2002; Chislock et al., 2013), including impaired and in extreme situations loss of aquatic life due to cyanobacteria toxins and decomposing organic matter (Yang et al., 2008). From experiences in Eastern Africa, the associated sedimentation of water reservoirs reduce their total economically viable live spans (period from dam construction to being filled-up with sediment) to not > 25–30 years (Rapp, 1977), costing countries huge investment to reverse the damage.

Nitrogen leaching into groundwater is not yet a problem in SSA as fertilizer use is still very low across the region (Alliance for a Green Revolution in Africa (AGRA), 2016). In paradox, soil infertility is in some cases blamed on leaching losses (Mugwe et al., 2011; Mucheru-Muna et al., 2014). In either case, potential for ground water contamination exists (Table 2). Although manure minimizes leaching relative to synthetic mineral nitrogen (Kamukondiwa et al., 1996), it is the combination of manure (12.5 t ha^{-1}) and mineral nitrogen (60 kg ha^{-1}) that had the biggest effect on maintaining productivity while minimizing leaching in Zimbabwe (Nyamangara et al., 2003). Whether under short or long-term trials, the leaching potential increases with nitrogen application and yet also varies widely from very low to sometimes > 100 kg N ha^{-1} yr^{-1} (Table 2). The extent of N leaching is dependent on rainfall intensity and amount, evaporation rate, soil structure, texture, tillage, cropping practices and the amount and form of N fertilizer applied (Russo et al., 2017).

The influence of management practices on nitrate-N leaching is however still unclear (Kimetu et al., 2007; Masso et al., 2017; Musyoka et al., 2019). Galvanizing higher nitrate losses – with rates that are significantly higher than the applied N e.g. in Nigeria, Tanzania and Togo – in some years are attributed to increased mineralization of N from organic matter and ammonium in clay minerals, and the possibility of the bulk of nitrates being derived from the soil (Våje et al., 2000; Wong et al., 1992; Poss and Saragoni, 1992). High leaching of nitrate (144 kg N ha^{-1} in Nigeria) is even observed in cases where there was no application of nitrogen (Wong et al., 1987). This points to uncertainties in the reported data and the need for evaluation of methods used for leaching assessments in the region (See Table 3).

What is clear is that a substantial quantity of N lost through leaching is affecting groundwater. In Nigeria, nitrate concentrations in groundwater under fertilized (100 kg N ha^{-1}) fields ranged between 12.8 and 24.6 mg/L compared to 2.8–5.2 mg/L under the unfertilized control (Adetunji, 1994). The proximity of the nitrate source (fields, etc.) to water bodies influence the ultimate water nitrate concentrations found in these water bodies. In South Africa, nitrate pollution from fertilized fields and pit latrines were higher where boreholes were situated less than 12 m from the sources, with nitrate concentrations ranging between 2.3 and 36.2 mg kg^{-1} and ammonium concentrations ranging between 0.003 and 8.30 mg/kg in different boreholes (Vinger et al., 2012). But these nitrogen values are below the 50 mg N/L commonly accepted threshold in drinking water beyond which human health (especially those of infants) is seriously affected under long-term exposure (Aslan and Türkman, 2004).

Nitrogen losses/inefficiencies increase with increase in time between application and crop uptake (Musyoka et al., 2019). Proper timing of nitrogen fertilizer application with crop growth requirements, alongside application of N at recommended rates, is critical in enhancing N use efficiency and reduction of losses such as through leaching. Nitrogen supply timed at the beginning of rapid crop growth of maize has been suggested to improve N uptake, increase N recovery efficiency and reduce leaching losses (Kitonyo et al., 2018). Although effects of N timing on crop growth and other parameters were independent of tillage systems, split application of nitrogen at 80 kg ha^{-1}, i.e., 1/3 at maize planting and 2/3 at four weeks later resulted to 62% more yields in the fertilized than unfertilized control treatment (Kitonyo et al., 2018), pointing to reduced losses and maximum utilization of the applied nitrogen by the crops.

Soil health management technologies provide opportunities to reduce, or even completely eliminate, runoff and resultant erosion, providing similar hydrological benefits as forest areas. CA systems with residue cover have high abundance of so-called ecosystem engineers, i.e. soil macro- fauna involved in tunneling and soil aggregation (Fig. 2; Ayuke et al., 2011; de Ferreira et al., 2016), which are important soil

Table 3
Greenhouse gas emissions under different soil health management practices in different locations of SSA.

Source	Country and years	GHG Emissions			Period	Systems assessed
		N_2O-N	CO_2	CH_4		
Masaka and Chivandi (2016)	Zimbabwe (2007–2009)	0.078–0.22 kg ha^{-1}month^{-1}	n.d	n.d	Monthly (60 days)	Manure application and N fertilizer application
Sommer et al. (2015)	Kenya (2013–2014 seasons)	12.0 kg ha^{-1}	n.d	n.d	Seasonal (2 seasons; approx. 238 days)	Maize-tephrosia rotation with manure, residue and nitrogen (30 kg N ha^{-1}) application
Chikowo et al. (2004)	Zimbabwe (Dec 2000-early Feb 2001)	0.1–0.3 kg ha^{-1}	n.d	n.d	Seasonal (56 days)	No-till and Sesbania sesban
Hickman et al. (2015)	Kenya (2011 and 2012)	0.012–0.25 kg ha^{-1}	n.d	n.d	Seasonal (114 and 102 days)	Unfertilized plots, 150 and 200 kg N ha^{-1}
Rosenstock et al. (2016)	Kenya and Tanzania (Jan-Dec 2013)	0.4–3.9 kg ha^{-1}yr^{-1}	3.5–15.9 t C ha^{-1}	−1.2–10.1 kg CH_4-C ha^{-1}	Yearly	
Dick et al. (2008)	Mali (Jan 2004-Feb 2005)	0.9–1.2 kg ha^{-1} yr^{-1}	n.d	n.d	Yearly	Application of organic manure, urea and phosphates
Predotova et al. (2010)	Niger (April 2006–Feb 2007; repeated March-Nov 2007)	48 kg ha^{-1} yr^{-1}	20–25 t C ha^{-1}yr^{-1}	n.d	Yearly	Fertilizer application and irrigation
Millar et al. (2004)	Kenya (Dec 1999; March-June 2000)	4.1 kg ha^{-1} (total after 84 days)	n.d	n.d	Seasonal (84 days)	*Sesbania* and *Macroptilium* residues
Masaka et al. (2014)	Zimbabwe (2007–2009)	0–21-0.74 kg ha^{-1}	n.d	n.d	Yearly	Manure fertilized plots
Baggs et al. (2006)	Kenya (Feb-June 2002)	0.1–0.57 kg N_2O-N ha^{-1}	1.75–2.25 t C ha^{-1}	0.06–0.29 kg CH_4-C ha^{-1}	Seasonal (99 days)	100 kg N ha^{-1}; tephrosia residue and no-till

n.d refers to no data available.

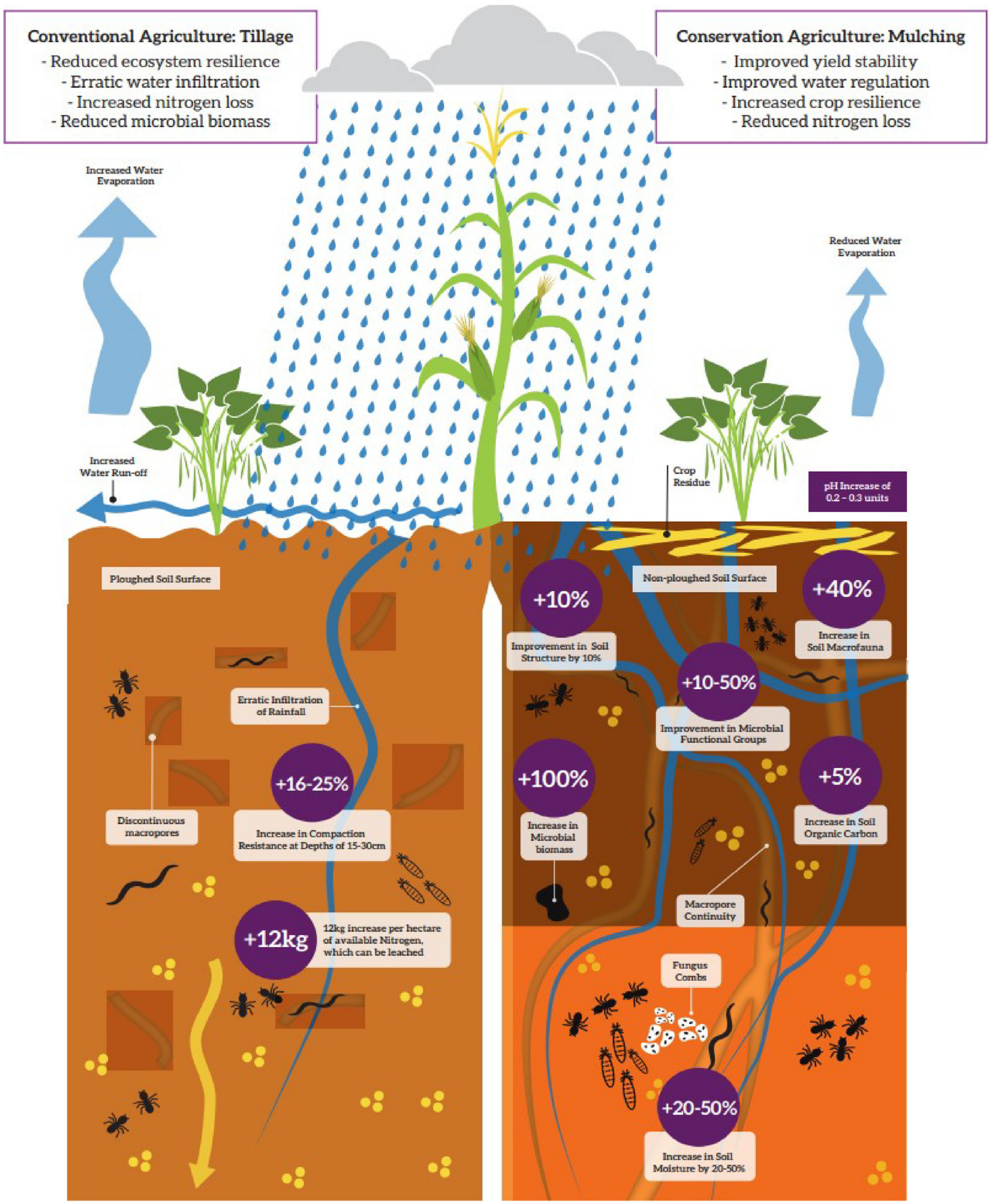

Fig. 2. A pictorial representation of some benefits of soil health management (i.e. in this particular case conservation agriculture) from data and information gathered in the context of the Sustainable Intensification of Maize-Legume Systems for Food Security in Eastern and Southern Africa project (SIMLESA; https://simlesa.cimmyt.org/). The data on soil macrofauna presented in this Figure are obtained from Ayuke et al. (2019).

physical properties regulating water movements. As such, CA systems reduce runoff and increase soil water infiltration rates compared to conventional tillage practices. Unfortunately, CA is practiced only to a limited extent in SSA – only about 1 million ha or 1% of arable land in Africa is under CA (Friedrich et al., 2017) – and is unlikely to yet confer widespread ecosystem service benefits. Besides CA, use of micro-catchments such as tied ridges increase soil water content, i.e., average of 27.5 mm per week, in Burkina Faso (Hulugalle, 1987) while use of mulch in Zimbabwe increased soil water content in two sites irrespective of tillage systems (Mupangwa et al., 2007). In the Ethiopian highlands, soil moisture improved by 10% in plots planted under Zai pit technology compared to flat planting (Amede et al., 2011). Zai pits are small water harvesting pits traditionally developed and used for rehabilitating eroded fields and increasing yields under water scarcity in Burkina Faso (Amede et al., 2011). In Tanzania, incorporation of mulch as a soil water conservation measure reduced soil erosion compared to where mulch was not used (Mwango et al., 2016). Increasing these types of soil health management practices across the landscape would enhance percolation of water thereby moderating base flows and controlling seasonal flooding and flash floods (Rapp, 1977; Adeboye et al., 2017) that put downstream communities at risk. Implementing soil health management practices in the highlands therefore benefits lowland communities but where direct benefits to the practicing farmers are delayed or not forthcoming, applying incentives such as green water credits, may boost adoption of these practices (Grieg-Gran et al., 2006; Droogers et al., 2006).

3.2. *Soil health and regulatory ecosystem services:*

3.2.1. *Effects on climate regulation*

The global soil C stock is at least three times the total atmospheric C (Gougoulias et al., 2014; FAO, 2016). Globally, inappropriate soil management practices i.e., use of inorganic fertilizers without organic inputs, crop residue burning and unsuitable cropping systems e.g. monoculture, have resulted in about 25–75% SOC losses in various agroecosystems (FAO, 2017). It is often assumed that the adoption of CA and ISFM results in SOC sequestration in agricultural systems of SSA. This is based on data that only compare differences between systems without a time perspective (Chivenge et al., 2007; Steward et al., 2018; Martinsen et al., 2019). However, data from long-term trials in Kenya, Nigeria and Togo varying from 10 to 40 years show a continuous loss of SOC in cropland systems under these management practices (Fig. 3). For example, in a 40-year experiment, Kintché et al. (2015) observed declining soil carbon i.e., 32–45% in continuous cropping systems and 46–52% in unfertilized fallows, from the initial conditions. Also, in several other experiments spanning 5–20 years, annual loss rates of soil organic carbon of between 0.5 and 7% are observed among treatments including tillage systems, fertilizer application regimes and dominant cropping systems across West Africa (Bationo et al., 2007). Thus, it appears that compared to conventional systems CA and ISFM only reduce the rates of decline of SOC relative to common land management practices but do not seem yet to be sequestering carbon (Sommer et al., 2018). A possible reason for the observed SOC loss could be the high temperatures and humid conditions that increase decomposition rates beyond what can be compensated for by carbon inputs (Andrén et al., 2007). Although CA and ISFM may in some regions not always results in carbon sequestration, these technologies do help in climate mitigation through avoiding enhanced SOC losses. Actual SOC loss mitigations are reported by different authors, e.g. 0.13 t C ha^{-1} and 0.78 t C ha^{-1} yr^{-1} in Kenya and Zimbabwe, respectively, due to retention of residues (Gwenzi et al., 2008; Sommer et al., 2018) and 0.26 t C ha^{-1} yr^{-1} with manure application in western Kenya (Sommer et al., 2018). As far as agroforestry systems are concerned, potential contributions to SOC are included in the review of Partey et al. (2017) where improved fallows (of varying duration from 1 to 5 yrs) sequestered on average 2.2 t C ha^{-1} yr^{-1} (minimum 0.7 and maximum 8.3 t C ha^{-1} yr^{-1}). Vågen et al. (2005) provides data for fallow systems, which have the potential to sequester between 0.1 and 5.3 t C ha^{-1} yr^{-1}. The temporal changes over time are likely to shift the functioning of ecosystems and delivery of their services (e.g., reducing provisioning of food; Kintché et al., 2015), and missing the goal of turning round agriculture to become a net sink of CO_2 with tough global target of achieving 4 per 1000 sequestration ambition (www.4p1000.org). Clearly, new strategies are needed, if SSA has to reverse the ongoing carbon losses, considering that even short fallows of less than 4 years are insufficient to bring a turnaround (Bostick et al., 2007).

Sub-Sahara Africa has a goal of increasing fertilizer use to 7.7 million Mt by 2050 (Drescher et al., 2011). The mere production but also the use of such amount of (additional) fertilizer has implications on greenhouse gas emissions. Thus, although the current contributions to greenhouse gases from the use of mineral fertilizers and manure in SSA is not nearly as high as in developing countries presently (van Loon et al., 2019), the expected growth in fertilizer applications requires an understanding of potential effects. In this region, the contribution of soil health management practices to greenhouse gases in SSA is often studied in the context of nitrogen fertilizer application with or without other nutrient sources. In western Kenya, and over a 3.5 months period,

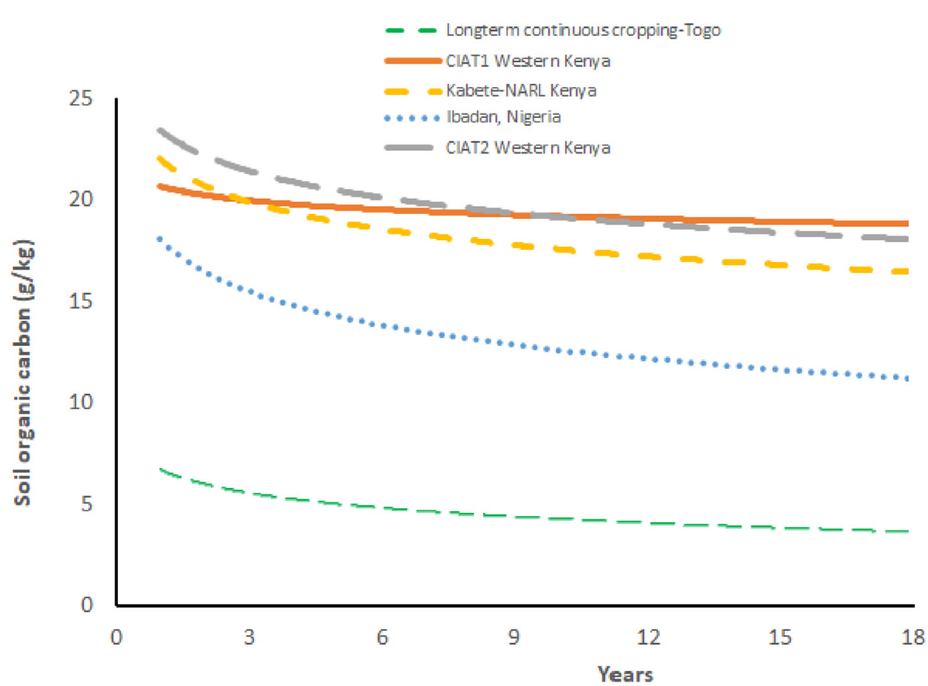

Fig. 3. Trends in SOC under long-term trials (minimum 10 years) in Kenya, Nigeria (Ibadan) and Togo. Derived from data extracted from Bationo et al. (2004), Sommer et al. (2018), Juo et al. (1995) and Kintché et al. (2015).

Hickman et al. (2015) observed N_2O emissions of 0.012–0.25 kg ha^{-1}, depending on whether plots where unfertilized or received between 150 and 200 kg N ha^{-1}. Almost similar values were observed in the subsequent year of the study. In the same region, addition of 30 kg N ha^{-1} in a maize- Tephrosia (*Tephrosia candida*) rotation with residue and manure applied significantly increased N_2O emissions (3.4 kg N_2O-N ha^{-1}) relative to no-fertilizer treatment (Sommer et al., 2015). In contrast, in Mali, combined application of urea and manure increase yields, yet reduced N_20 emissions over systems without manure but with urea (Dick et al., 2008). In central Kenya during the 4th week after planting, Kimetu et al. (2007) observed higher N_2O emissions (12.3 µg N_2O-N m^{-2} hr^{-1}) following incorporation of Tithonia (*Tithonia diversifolia*) than under application of urea (1.3 µg N_2O-N m^{-2} hr^{-1}), both targeting 60 kg N ha^{-1} although 9% of applied N in urea was observed at lower soil profile (higher leaching potential) unlike only 0.6% with Tithonia. Overall, most assessments are done in the year of fertilizer application and residual effect on emissions are rarely reported; only the study of Dick et al. (2008) reports residual effect of urea applied on both N_2O and CO_2 emissions.

Other studies with management practices, not necessarily linked to nitrogen application only, provide insights on how these practices influence greenhouse emissions. Although CA improves soil health, it often increases emissions of greenhouse gases such as N_2O (Birnholz et al., 2017; Kaye et al., 2005). The ability of CA systems to conserve soil moisture promotes N_2O release especially in areas receiving high rainfall (Flechard et al., 2007; Sommer et al., 2015). Tillage increases soil respiration and emissions in Mali (Dick et al., 2008). Besides tillage and residue incorporation increase emissions relative to surface residue applications (i.e., under CA) as observed in Kenya under a short-term study (Baggs et al., 2006), with the climate regime being an important factor especially in the long-term of the CA practice (Six et al., 2004). The contribution of tree/shrub legumes within cropping systems to greenhouse emissions is still unclear due to scarcity of data especially of a long-term perspective (Partey et al., 2017).

The increased greenhouse gas emission, e.g. with nitrogen use and ISFM, must be put into context to the increases gained in crop productivity, as discussed earlier. As such, the use of yield per emissions unit instead of just productivity on area basis is proposed. Besides, an increase in productivity of 60% over farmer practices due to NPK application across SSA as is often the case (Kihara et al., 2016) could mean, if put to scale, at least 30% in saving and restoration of the current crop lands and halt further encroachment into fragile lands and pristine ecosystems (Lal, 2000). Further land saving can be achieved through an additional 25% increase in crop yield due to application of secondary and micronutrients (beyond NPK fertilizers; Kihara et al., 2017). In the case of CA, reduced energy consumption e.g. for land preparation (no heavy machinery and tractors required) should be an important consideration (Benites, 2008). It is however not yet documented to what extent land saving can compensate for greenhouse gases evolved from increased soil health/productivity improving practices. Also, use of specialty fertilizers, such as controlled release types, could reduce emissions associated with use of current fertilizers. Since data on soil-based emissions are limited under the widely heterogeneous production environments in SSA, a call for further studies has been made (Rosenstock et al., 2016).

3.2.2. Effects on disease control and suppression of pathogens

Management practices for improving soil health influence pests and diseases in different ways. Implementing these practices, such as CA, is key strategy in promoting the proliferation of soil biota i.e., spiders (Mashavakure et al., 2019a) and beetles (Mashavakure et al., 2019b), that are beneficial to the ecosystem through pest predation, decreasing fungi and weed population as well as organic matter decomposition (Midega et al., 2008). Practicing crop rotation in CA can break the cycle of some prevalent crop pests and diseases, thus boosting food production (Thierfelder et al., 2015b; Pieri, 2002) as has been demonstrated for bacterial wilt in potatoes (*Ipomoea batatas*) and finger millet (*Eleusine coracana*) in Uganda (Lemaga et al., 2001; Kakuhenzire et al., 2013) and Ethiopia (Kassa, 2016). Besides, CA practices reduce prevalence of the parasitic plant striga (*Striga hermonthica*) i.e., using cover crops with allelophathic effect that lead to suicidal germination of striga (Rusinamhodzi et al., 2012; Thierfelder et al., 2013), responsible for approximately 15–95% of yield losses (Mloza-banda and Kabambe, 1997) especially in nutrient degraded soils (Khan et al., 2002). Push and Pull planting controls stem borer and Fall Armyworm (*Spodoptera frugiperda*) attack on cereal crops (Khan et al., 2011, 2018) and reduce physical injuries on cobs that often act as entry points of disease causing pathogenic fungi. Incorporating trees and shrubs in agricultural production helps in breaking winds which are associated with spread of pest and disease causing pathogens (Pasek, 1988). Soil health management i.e., residue application with reduced soil disturbance can promote growth of different bacterial groups like *Actinobacteria* and *Betaproteobacteria* (De la Cruz-Barrón et al., 2017) and fungal species like *Arbuscular mycorrhiza* and offer pathogenic protection to their host plants (Schouteden et al., 2015; Berruti et al., 2016). The prevalence of root rot nematodes is reduced under improved soil health (Riekert and Henshaw, 1998). Although there are overall net benefits, there are some cases of observed proliferation of some pests and parasites (e.g. nematodes) with some practices such as CA where surface residue application provides their suitable micro- environment (Thierfelder et al., 2015b; Mashavakure et al., 2018).

In very recent years, the use of bio-pesticides is increasing as part of the soil health management practices in response to societal concerns such as human health effects of mycotoxins. Despite very promising results, studies on effects of soil management practices on pests and diseases are overall scant in SSA. For example, soil health management practices, such as the use of atoxigenic strains of *Aspergillus flavus* is reducing aflatoxins that pose serious health effects to both humans and animals (Wu and Khlangwiset, 2010). With such biocontrol, the number of lives saved and quality of life gained by reducing aflatoxin- induced cancer far exceeds the cost of the biocontrol (Wu and Khlangwiset, 2010; Bandyopadhyay et al., 2016). The use of soil health management practices, such as biocontrol and push–pull, reduces the requirement for agro-chemicals (Midega et al., 2008) in controlling invasive pests and diseases and therefore reduce potential negative effects on consumers and the environment (Bandyopadhyay et al., 2016).

Improved soil health is associated with improved crop nutrition and quality of produce. For instance, based on a global assessments including SSA the prevalence of malnutrition has been shown to be tightly correlated with zinc deficiencies in soils (Wessells et al., 2012). Soil health management – in this case either the addition of zinc-containing mineral fertilizer or increasing activity of microbes that solubilize micronutrients– addresses these deficiencies.

3.3. Soil health and (processes) supporting ecosystem services

Supporting services of soils are those that enhance the function of the whole ecosystem including photosynthesis, nutrient and water cycling. Most of those related to nutrient cycling have been discussed in provisioning and regulating ecosystem services, i.e., supporting ecosystem services cut across all other ecosystem services (Millennium Ecosystem Assessment (MEA), 2005). The achievement of these ES is through the role of soil health improving abundance and functioning of specific functional groups such as P-solubilizing fungi and N- fixing bradyrhizobia (Ferreira et al., 2000). Increased richness and diversity of soil microbes has been observed due to specific management, e.g. the use of farm yard manure (FYM) and its combination with mineral fertilizers (Kibunja et al., 2010) and under CA systems of western Kenya (Kihara et al., 2012). Besides these, soil health influences other processes, such as photosynthesis through *Bradyrhizobium* strains controlling the opening and closing of stomata (Law and Strijdom, 1989) and other microbes including rhizobia stimulating plant growth such as

Table 4
Effects of management on indicators of ecosystem services reported in various medium and long-term agronomic trials in Kenya. +, - and 0 indicate positive, negative and no change, respectively relative to absence of that management practice.

Management practice	Supporting service		Regulating services		Provisioning service	
	Bacterial diversity	Fungal diversity	SOC	Aggregate stability	Food production	Nutrition
+Manure[≠]	+	+	+	+	+	0
+Rotation[£]	+	+	0	0	0	+
+intercropping[£]	+	+	0	+	+	+
+No-Till[£]	0	0	+	+	0	0
+No-Till[β]	0	0	+	+	–	0
+No-Till[€]	0	+	+	+	–	0
+No-Till[µ]	+	ND	+	+	–	0

[≠] 16-yr integrated soil fertility management trial in western Kenya (Siaya).
[£] 16-yr Conservation Agriculture trial in western Kenya (Siaya).
[β] 6-yr Conservation Agriculture trial in western Kenya (Kakamega).
[€] 6-yr conservation trial in eastern Kenya (Embu, all except regulating services from Micheni et al., 2016).
[µ] 3-yr conservation trial in eastern Kenya (Mbeere). ND = not determined. All are based on own data.

through production of phyto-hormones and other growth promoting molecules, or by acting as natural endophytes for agronomically important crops (Chaintreuil et al., 2000), for instance clover rhizobia in rice plants of North Africa (Yanni et al., 2001).

Improved soil health is associated with appropriate synchrony between nutrient supply and crop demand, avoiding problems of leaching and emissions. Besides, appropriate symbiosis between soil organisms (fungus, bacteria, archaea) and host plants benefit such plants to maximize their productivity (Johnson et al., 1997). Biological nitrogen fixing (BNF) for example can result in up to 400 kg N $ha^{-1}yr^{-1}$ fixed through symbiosis while variable quantities are fixed through associative and free-living associations (Barrios, 2007). Biological nitrogen fixation not only improves soil health with subsequent increase in crop yields but also provides relief towards the cost incurred in purchasing inorganic nitrogen fertilisers, not to mention the benefits of reduced energy use (and associated CO_2 emissions) for producing such synthetic fertilizer in the first place.

Overall, soil health improving practices may result in positive, negative or no change in different parameters of ecosystem services (Table 4) and period of implementation of a system is important in determining these effects.

3.4. Soil health and cultural ecosystem services:

When land use is changed, e.g. converted to cultivation, quick drops in important parameters across the different types of ecosystem services of supportive, regulative, provisioning and cultural services are observed (Tully et al., 2015). Poor soil health invites land expansion (habitat encroachment), poor recharge of groundwater and human–human and human-wildlife conflicts (Lamarque et al., 2009; Bob and Bronkhorst, 2010). Habitat encroachment affects the biodiversity – i.e. large mammals, birds and reptiles – important for tourism and takes over pristine and culturally-linked sites (Maude and Reading, 2010; Muhumuza and Balkwill, 2013). Conversion of large areas of indigenous forest communities in the Mau forest of Kenya for example has affected cultural ways of life of the hunting and gathering Ogiek community (Chabeda-Barthe and Haller, 2018). Practices that improve soil health avoid such problems and provide recreational benefits as reported in Ghana (Appiah-Opoku, 2011) and Kenya (Gathogo, 2013). Other benefits of soil health include agritourism, a growing industry where urban dwellers visit rural settings to experience farming activities such as farm restaurants, farm lodgings and farm walks (Rogerson and Rogerson, 2014). A study in Cameroon showed that soil health promoting practices, such as CA, also save labor time, which may occupy up to 60% of farmer's time (Biandoun, 2007). This potentially can afford hard-working farmers with more free time, especially women for own recreation and socializations.

4. Conclusions

A multi-dimensional assessment of soil health-promoting practices focusing on a wide range of ecosystem services is important to unravel the entire set of benefits of these practices across the SSA. This study provides an important framework to guide key considerations for such assessments. Clearly, soil health promoting practices in general result in positive changes on a majority of ecosystem services relative to lack of such practices. New indicators of performance of soil health practices should be considered including e.g., productivity per unit of greenhouse gases. Studies are required to provide data for some of the less studied dimensions such as leaching to not only cover more geographical and soil conditions but also understand the currently perceived uncertainties of measurements. Strategies are needed to ensure that ecosystem services resulting from investments in soil health practices are costed, e.g. through green water credits. Such credits would cover tradeoff experienced through reduced crop yield at commencement such as of conservation agriculture. We conclude that soil health practices are beneficial across a wide range of ecosystem services but investments are needed to scale these benefits and support livelihoods and economies in SSA.

Funding sources

This work was supported by CGIAR Water, Land and Ecosystems (WLE) under the restoring degraded lands (RDL) flagship through the CGIAR Fund Donors including: the Australian Center for International Agricultural Research (ACIAR); Netherlands Directorate- General for International Cooperation (DGIS); Swedish International Development Cooperation Agency (Sida); Swiss Agency for Development Cooperation (SDC); and the UK Aid.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We acknowledge participants of the Technical workshop of the International Nitrogen Management systems- East Africa Demonstration Site held in Kisumu in March 2019 this work was first presented. The resulting stimulating discussions, ideas and expressed demand by the participants motivated our progress to conclude the study. We also acknowledge Wilson Nguru, a student intern with Alliance for Bioversity International and CIAT, for developing the map

of the countries where data for this publication was retrieved.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2020.114342.

References

Adetunji, M.T., 1994. Nitrogen application and underground water contamination in some agricultural soils of South Western Nigeria. Fertilizer Res. 37 (2), 159–163.

Adeboye, O.B., Schultz, B., Adekalu, K.O., Prasad, K., 2017. Soil water storage, yield, water productivity and transpiration efficiency of soybeans (*Glyxine max L. Merr*) as affected by soil surface management in Ile-Ife, Nigeria. Int. Soil Water Conserv. Res. 5 (2), 141–150.

Adhikari, K., Hartemink, A.E., 2016. Linking soils to ecosystem services – A global review. Geoderma 262, 101–111.

Alliance for a Green Revolution in Africa (AGRA), 2016. Africa Agriculture Status Report 2016: Progress towards Agricultural Transformation in Sub-Saharan Africa. Retrieved from https://agra.org/wp-content/uploads/2017/09/aasr-report-2016-press0409201601.pdf.

Amede, T., Menza, M., Awlachew, S.B., 2011. Zai improves nutrient and water productivity in the Ethiopian highlands. Exp. Agric. 47 (S1), 7–20.

Andrén, O., Kihara, J., Bationo, A., Vanlauwe, B., Kätterer, T., 2007. Soil climate and decomposer activity in Sub-Saharan Africa estimated from standard weather station data: a simple climate index for soil carbon balance calculations. AMBIO: J. Hum. Environ. 36 (5), 379–387.

Appiah-Opoku, S., 2011. Using protected areas as a tool for biodiversity conservation and ecotourism: a case study of Kakum National Park in Ghana. Soc. Nat. Resour. 24 (5), 500–510.

Araya, T., Cornelis, W.M., Nyssen, J., Govaerts, B., Bauer, H., Gebreegziabher, T., Oicha, T., Raes, D., Sayre, K.D., Haile, M., Deckers, J., 2011. Effects of conservation agriculture on runoff, soil loss and crop yield under rainfed conditions in Tigray, Northern Ethiopia. Soil Use Manage. 27 (3), 404–414.

Aslan, S., Türkman, A., 2004. Biological denitrification of drinking water using various natural organic solid substrates. Water Sci. Technol. 48 (11–12), 489–495.

Ayuke, F.O., Brussaard, L., Vanlauwe, B., Six, J., Lelei, D.K., Kibunja, C.N., Pulleman, M.M., 2011. Soil fertility management: impacts on soil macrofauna, soil aggregation and soil organic matter allocation. Appl. Soil Ecol. 48 (1), 53–62.

Ayuke, F., Karanja, N., Okello, J., Wachira, P., Mutua, G., Lelei, D., Gachene, C., Hester, R., Harrison, R., 2012. Agrobiodiversity and potential use for enhancing soil health in Tropical soils of Africa. Soils Food Sec. 35, 94–134.

Ayuke, F.O., Kihara, J., Ayaga, G., Micheni, A.N., 2019. Conservation agriculture enhances soil fauna richness and abundance in low input systems: examples from Kenya. Front. Environ. Sci. 7, 97.

Baggs, E.M., Chebii, J., Ndufa, J.K., 2006. A short-term investigation of trace gas emissions following tillage and no-tillage of agroforestry residues in western Kenya. Soil Tillage Res. 90 (1–2), 69–76.

Bandyopadhyay, R., Ortega-Beltran, A., Akande, A., Mutegi, C., Atehnkeng, J., Kaptoge, L., Cotty, P.J., 2016. Biological control of aflatoxins in Africa: current status and potential challenges in the face of climate change. World Mycotoxin J. 9 (5), 771–789.

Bationo A., Nandwa S.M., Kimetu J.M., Kinyangi J.M., Bado B.V., Lompo F., Kimani S., Kihanda F. & Koala S., 2004. Sustainable intensification of crop-livestock systems through manure management in eastern and western Africa: lessons learned and emerging research opportunities. In Williams T.O., Tarawali S.A., Hiernaux P., Fernandez-Rivera S. (eds). Sustainable Crop - Livestock Production for Improved Livelihoods and Natural resource management in West Africa. Proceedings of an international conference held at IITA, Ibadan, Nigeria, 19-22 November 2001, 173-198.

Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., Kimetu, J., 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agric. Syst. 94 (1), 13–25.

Barrios, E., 2007. Soil biota, ecosystem services and land productivity. Ecol. Econ. 64 (2), 269–285.

Benites, J. R., 2008. Effect of no-till on conservation of the soil and soil fertility. In: Goddard, T., Zoebisch, MA, Gan, YT, Ellis, W., Watson, A. and S. Sombatpanit (eds.). No-Till Farming Systems. Special Publication No. 3, 59-72.

Berruti, A., Lumini, E., Balestrini, R., Bianciotto, V., 2016. Arbuscular mycorrhizal fungi as natural biofertilizers: let's benefit from past successes. Front. Microbiol. 6, 1559.

Biandoun, M.M' & Olinda-Bassala, J.P., 2007. Savoir paysan et fertilité des terres au Nord Cameroun, Cah. Agriculture. 16, 185–196.

Birnholz C., Braslow J., Koge J., Notenbaert A., Sommer R., Paul B., 2017. Rapid climate smartness assessment of GIZ soil protection and rehabilitation technologies in Benin, Burkina Faso, Ethiopia, Kenya, and India. Working Paper. CIAT Publication No. 431. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. 84 p.

Blum, W.H., 2005. Functions of soil for society and the environment. Rev. Environ. Sci. Bio-Technol. 4 (3), 75–79.

Bob, U., Bronkhorst, S., 2010. Environmental conflicts: Key issues and management implications. Afr. J. Conflict Resol. 10 (2).

Bostick, W.M., Bado, V.B., Bationo, A., Soler, C.T., Hoogenboom, G., Jones, J.W., 2007. Soil carbon dynamics and crop residue yields of cropping systems in the Northern Guinea Savanna of Burkina Faso. Soil Tillage Res. 93 (1), 138–151.

Chabeda-Barthe, J., Haller, T., 2018. Resilience of traditional livelihood approaches despite forest grabbing: ogiek to the west of mau forest, Uasin Gishu County. Land 7 (4), 140.

Chaintreuil, C., Giraud, E., Prin, Y., Lorquin, J., Bâ, A., Gillis, M., De Lajudie, P., Dreyfus, B., 2000. Photosynthetic bradyrhizobia are natural endophytes of the African wild rice *Oryza breviligulata*. Appl. Environ. Microbiol. 66 (12), 5437–5447.

Chikowo, R., Mapfumo, P., Nyamugafata, P., Giller, K.E., 2004. Mineral N dynamics, leaching and nitrous oxide losses under maize following two-year improved fallows on a sandy loam soil in Zimbabwe. Plant Soil 259 (1–2), 315–330.

Chislock, M.F., Doster, E., Zitomer, R.A., Wilson, A.E., 2013. Eutrophication: causes, consequences, and controls in aquatic ecosystems. Nat. Educ. Knowl. 4 (4), 10.

Chivenge, P.P., Murwira, H.K., Giller, K.E., Mapfumo, P., Six, J., 2007. Long-term impact of reduced tillage and residue management on soil carbon stabilization: implications for conservation agriculture on contrasting soils. Soil Tillage Res. 94 (2), 328–337.

Coyne, M.S., Mikkelsen, R., 2015. Soil microorganisms contribute to plant nutrition and root health. Better Crops 99, 18–20.

De Ferreira, O.A., de Moraes Sá, J.C., Lal, R., Tivet, F., Briedis, C., Inagaki, T.M., Romaniw, J., 2016. Macroaggregation and soil organic carbon restoration in a highly weathered Brazilian Oxisol after two decades under no-till. Sci. Total Environ. 621, 1559–1567.

De la Cruz-Barrón, M., Cruz-Mendoza, A., Navarro-Noya, Y.E., Ruiz-Valdiviezo, V.M., Ortíz-Gutiérrez, D., Ramírez-Villanueva, D.A., Luna-Guido, M., Thierfelder, C., Wall, P.C., Verhulst, N., Govaerts, B., 2017. The bacterial community structure and dynamics of carbon and nitrogen when maize (*Zea mays L.*) and its neutral detergent fibre were added to soil from Zimbabwe with contrasting management practices. Microb. Ecol. 73 (1), 135–152.

Dell'Anno, A., Mei, M.L., Pusceddu, A., Danovaro, R., 2002. Assessing the trophic state and eutrophication of coastal marine systems: a new approach based on the biochemical composition of sediment organic matter. Mar. Pollut. Bull. 44 (7), 611–622.

Dick, J., Kaya, B., Soutoura, M., Skiba, U., Smith, R., Niang, A., Tabo, R., 2008. The contribution of agricultural practices to nitrous oxide emissions in semi-arid Mali. Soil Use Manage. 24 (3), 292–301.

Doran, J.W., Zeiss, M.R., 2000. Soil health and sustainability: managing the biotic component of soil quality. Appl. Soil Ecol. 15, 3–11.

Dovie, D.B., Witkowski, E.T.F., Shackleton, C.M., 2004. The fuelwood crisis in southern Africa-relating fuelwood use to livelihoods in a rural village. Geo. J. 60 (2), 123–133.

Drescher, A., Glaser, R., Richert, C., & Nippes, K. R. 2011. Demand for key nutrients (NPK) in the year 2050. Draft Report. University of Freiburg, Department of Geography, pp. 77.

Droogers, P., Kauffman, J. H., Dijkshoorn, J. A., Immerzeel, W., & Huting, J. R. M. 2006. Green water credits: Basin identification (No. 1). ISRIC-World Soil Information.

Dunne, T. 1977. Studying patterns of soil erosion in Kenya. In FAO. Soil conservation and management in developing countries. Bulletin No. 33. FAO Forest Resources Division, Rome.

FAO, 1995. Land and Environmental Degradation and Desertification in Africa. FAO Corporate Document Repository.

FAO, 2002. The Comprehensive Africa Agriculture Development Programme (CAADP) of NEPAD.

FAO, 2016. Soils and climate change. Soils: key to unlocking the potential of mitigating and adapting to climate change. http://www.fao.org/3/a-i6478e.pdf.

FAO, 2017. Global Symposium on Soil Organic Carbon. GSOC17 http://www.fao.org/global-soil-partnership/resources/highlights/detail/en/c/461896.

FAO and ITPS, 2015. Status of the World's Soil Resources (SWSR)- Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy.

Ferreira, M.C., Andrade, D.D.S., Chueire, L.M.D.O., Takemura, S.M., Hungria, M., 2000. Tillage method and crop rotation effects on the population sizes and diversity of bradyrhizobia nodulating soybean. Soil Biol. Biochem. 32 (5), 627–637.

Flechard, C.R., Ambus, P., Skiba, U., Rees, R.M., Hensen, A., Van Amstel, A., Van Den Pol-Van Dasselaar, A., Soussana, J.F., Jones, M., Clifton-Brown, J., Raschi, A., 2007. Effects of climate and management intensity on nitrous oxide emissions in grassland systems across Europe. Agric. Ecosyst. Environ. 121 (1–2), 135–152.

Friedrich, T., Derpsch, R., Kassam, A., 2017. Overview of the global spread of conservation agriculture. In: Sustainable Development of Organic Agriculture. Apple Academic Press, pp. 75–90.

Gathogo, J., 2013. Historical developments of theological education in Eastern Africa–The example of Julius Krapf. Handbook of Theol. Educ. Afr. 28–46.

Giller, K.E., Andersson, J.A., Corbeels, M., Kirkegaard, J., Mortensen, D., Erenstein, O., Vanlauwe, B., 2015. Beyond conservation agriculture. Front. Plant Sci. 6, 870.

Gougoulias, C., Clark, J.M., Shaw, L.J., 2014. The role of soil microbes in the global carbon cycle: tracking the below-ground microbial processing of plant-derived carbon for manipulating carbon dynamics in agricultural systems. J. Sci. Food Agric. 94 (12), 2362–2371.

Grieg-Gran, M., Noel, S., Porras, I., & Dent, D. L., 2006. Green Water Credits: Lessons Learned from Payments for Environmental Services (No. 2). ISRIC-World Soil Information.

Grover, K.K., Karsten, H.D., Roth, G.W., 2009. Corn grain yields and yield stability in four long-term cropping systems. Agron. J. 101 (4), 940–946.

Grusak, M.A., DellaPenna, D., 1999. Improving the nutrient composition of plants to enhance human nutrition and health. Annu. Rev. Plant Biol. 50 (1), 133–161.

Gwenzi, W., Gotosa, J., Chakanetsa, S., Mutema, Z., 2008. Effects of tillage systems on soil organic carbon dynamics, structural stability and crop yields in irrigated wheat (*Triticum aestivum L.*)- cotton (*Gossypium hirsutum L.*) rotation in semi-arid Zimbabwe. Nutr. Cycl. Agroecosyst. 83 (3), 211.

Hickman, J.E., Tully, K.L., Groffman, P.M., Diru, W., Palm, C.A., 2015. A potential tipping point in tropical agriculture: avoiding rapid increases in nitrous oxide fluxes from

agricultural intensification in Kenya. J. Geophys. Res. Biogeosci. 120 (5), 938–951.
Hobbs, P.R., Sayre, K., Gupta, R., 2008. The role of conservation agriculture in sustainable agriculture. Philos. Trans. R. Soc. B Biol. Sci. 363 (1491), 543–555.
Hulugalle, N.R., 1987. Effect of tied ridges on soil water content, evapotranspiration, root growth and yield of cowpeas in the Sudan Savanna of Burkina Faso. Field Crops Res. 17 (3–4), 219–228.
Ichami, S.M., Shepherd, K.D., Sila, A.M., Stoorvogel, J.J., Hoffland, E., 2019. Fertilizer response and nitrogen use efficiency in African smallholder maize farms. Nutr. Cycl. Agroecosyst. 113 (1), 1–19.
Iiyama, M., Neufeldt, H., Dobie, P., Njenga, M., Ndegwa, G., Jamnadass, R., 2014. The potential of agroforestry in the provision of sustainable wood fuel in sub-Saharan Africa. Curr. Opin. Environ. Sustain. 6, 138–147.
Johnson, N.C., Graham, J.H., Smith, F.A., 1997. Functioning of mycorrhizal associations along the mutualism-parasitism continuum. New Phytol. 135 (4), 575–585.
Juo, A.S.R.; Franzluebbers, K.; Dabiri, A. Ikhile, B., 1995. Changes in soil properties during long-term fallow and continuous cultivation after forest clearing in Nigeria. Agriculture, Ecosystems and Environment. 56, 9–18.
Kaczan, D., Arslan, A., & Lipper, L., 2013. Climate-Smart Agriculture? A review of current practice of agroforestry and conservation agriculture in Malawi and Zambia. Working Paper No. 13-07.
Kakuhenzire, R.O., Lemaga, B.E., Kashaija, I.M., Ortiz, O.S., Mateeka, B.E., 2013. Effect of Crotalaria falcata in crop rotation and fallowing on potato bacterial wilt incidence, disease severity and latent infection in tubers and field soil. Biopest. Int. 9 (2), 182–194.
Kamukondiwa W., Bergström L., Campbell B.M., Frost P.G.H., Swift M.J., 1996. N Leaching in Manured and Ammonium Nitrate Fertilized Lysimeters in Zimbabwe. In: Van Cleemput O., Hofman G., Vermoesen A. (eds) Progress in Nitrogen Cycling Studies. Developments in Plant and Soil Sciences, vol. 68. Springer, Dordrecht.
Kamukondiwa, W., Bergström, L., 1994. Nitrate leaching in field lysimeters at an agricultural site in Zimbabwe. Soil Use Manag. 10 (3), 118–124.
Kassa, B., 2016. Potato bacterial wilt management in the Central Highlands of Ethiopia. Ethiopian J. Agric. Sci. 26 (2), 83–97.
Kaye, J.P., McCulley, R.L., Burke, I.C., 2005. Carbon fluxes, nitrogen cycling, and soil microbial communities in adjacent urban, native and agricultural ecosystems. Glob. Change Biol. 11 (4), 575–587.
Kermah, M., Franke, A.C., Adjei-Nsiah, S., Ahiabor, B.D., Abaidoo, R.C., Giller, K.E., 2017. Maize-grain legume intercropping for enhanced resource use efficiency and crop productivity in the Guinea savanna of northern Ghana. Field Crops Res. 213, 38–50.
Kibunja, C.N., Mwaura, F.B., Mugendi, D.N., 2010. Long-term land management effects on soil properties and microbial populations in a maize-bean rotation at Kabete, Kenya. Afr. J. Agric. Res. 5 (2), 108–113.
Kihara, J., Bationo, A., Waswa, B., Kimetu, J.M., Vanlauwe, B., Okeyo, J., Mukalama, J., Martius, C., 2012. Effect of reduced tillage and mineral fertilizer application on maize and soybean productivity. Exp. Agric. 48 (2), 159–175.
Kihara, J., Nziguheba, G., Zingore, S., Coulibaly, A., Esilaba, A., Kabambe, V., Njoroge, S., Palm, C., Huising, J., 2016. Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. Agric. Ecosyst. Environ. 229, 1–12.
Kihara, J., Sileshi, G.W., Nziguheba, G., Kinyua, M., Zingore, S., Sommer, R., 2017. Application of secondary nutrients and micronutrients increases crop yields in sub-Saharan Africa. Agron. Sustain. Dev. 37 (4), 25.
Kimetu, J. M., Mugendi, D. N., Bationo, A., Palm, C. A., Mutuo, P. K., Kihara, J., Nandwa, S. & Giller, K., 2007. Partial balance of nitrogen in a maize cropping system in humic nitisol of Central Kenya. In Advances in Integrated Soil Fertility Management in sub-Saharan Africa: Challenges and Opportunities (pp. 521-530). Springer, Dordrecht.
Kintché, K., Guibert, H., Bonfoh, B., Tittonell, P., 2015. Long-term decline in soil fertility and responsiveness to fertiliser as mitigated by short fallow periods in sub-Sahelian area of Togo. Nutr. Cycl. Agroecosyst. 101 (3), 333–350.
Kitonyo, O.M., Sadras, V.O., Zhou, Y., Denton, M.D., 2018. Nitrogen fertilization modifies maize yield response to tillage and stubble in a sub-humid tropical environment. Field Crops Res. 223, 113–124.
Khan, Z.R., Pittchar, J.O., Midega, C.A., Pickett, J.A., 2018. Push-pull farming system controls fall armyworm: lessons from Africa. Outlooks Pest Manage. 29 (5), 220–224.
Khan, Z., Midega, C., Pittchar, J., Pickett, J., Bruce, T., 2011. Push- pull technology: a conservation agriculture approach for integrated management of insect pests, weeds and soil health in Africa: UK government's Foresight Food and Farming Futures project. Int. J. Agric. Sustain. 9 (1), 162–170.
Khan, Z.R., Hassanali, A., Overholt, W., Khamis, T.M., Hooper, A.M., Pickett, J.A., Wadhams, L.J., Woodcock, C.M., 2002. Control of witchweed Striga hermonthica by intercropping with Desmodium spp., and the mechanism defined as allelopathic. J. Chem. Ecol. 28 (9), 1871–1885.
Kuyah, S., Whitney, C. W., Jonsson, M., Sileshi, G. W., öborn, I., Muthuri, C. W., & Luedeling, E., 2019. Agroforestry delivers a win-win solution for ecosystem services in sub-Sahara Africa. A meta-analysis. Agronomy for sustainable development, 39-47.
Lal, R., 2000. Soil Management in the developing countries. Soil Sci. 165 (1), 57–72.
Lal, R., 1987. Managing the soils of sub-Saharan Africa. Science 236 (4805), 1069–1076.
Lal, R., 1997. Mulching effects on runoff, soil erosion, and crop response on Alfisols in Western Nigeria. J. Sustain. Agric. 11 (2–3), 135–154.
Lamarque, F., Anderson, J., Fergusson, R., Lagrange, M., Osei-Owusu, Y., Bakker, L., 2009. Human-wildlife conflict in Africa: causes, consequences and management strategies (No. 157). Food and Agriculture Organization of the. United Nations (FAO).
Law, I.J., Strijdom, B.W., 1989. Inoculation of cowpea and wheat with strains of *Bradyrhizobium spp.* that differ in their production of indole acetic acid. S. Afr. J. Plant Soil 6 (3), 161–166.
Lemaga, B., Kanzikwera, R., Kakuhenzire, R., Hakiza, J.J., Manzi, G., 2001. The effect of crop rotation on bacterial wilt incidence and potato tuber yield. Afr. Crop Sci. J. 9 (1), 257–266.
Mapanda, F., Wuta, M., Nyamangara, J., Rees, R.M., 2012. Nitrogen leaching and indirect nitrous oxide emissions from fertilized croplands in Zimbabwe. Nutr. Cycl. Agroecosyst. 94 (1), 85–96.
Martinsen, V., Munera-Echeverri, J.L., Obia, A., Cornelissen, G., Mulder, J., 2019. Significant build-up of soil organic carbon under climate-smart conservation farming in Sub-Saharan Acrisols. Sci. Total Environ. 660, 97–104.
Masaka, J., Chivandi, E., 2016. Nitrogen leakages and vegetable dry matter yield in a subtropical wetland soil amended with cattle manure and mineral nitrogen fertiliser. S. Afr. J. Plant Soil 34 (2), 105–117.
Masaka, J., Nyamangara, J., Wuta, M., 2014. Nitrous oxide emissions from wetland soil amended with inorganic and organic fertilizers. Arch. Agron. Soil Sci. 60 (10), 1363–1387.
Mashavakure, N., Mashingaidze, A.B., Musundire, R., Nhamo, N., Gandiwa, E., Thierfelder, C., Muposhi, V.K., 2019a. Spider community shift in response to farming practices in a sub-humid agroecosystem of southern Africa. Agric. Ecosyst. Environ. 272, 237–245.
Mashavakure, N., Mashingaidze, A.B., Musundire, R., Nhamo, N., Gandiwa, E., Thierfelder, C., Muposhi, V.K., 2019b. Soil dwelling beetle community response to tillage, fertilizer and weeding intensity in a sub-Humid environment in Zimbabwe. Appl. Soil Ecol. 135, 120–128.
Mashavakure, N., Mashingaidze, A.B., Musundire, R., Gandiwa, E., Muposhi, V.K., Thierfelder, C., Nhamo, N., Bere, T., Akhtar, S.S., 2018. Short-term impacts of tillage and fertilizer treatments on soil and root borne nematodes and maize yield in a fine textured cambisol. J. Nematol. 50 (3).
Masso, C., Baijukya, F., Ebanyat, P., Bouaziz, S., Wendt, J., Bekunda, M., Vanlauwe, B., 2017. Dilemma of nitrogen management for future food security in sub-Saharan Africa–a review. Soil Res. 55 (6), 425–434.
Maude, G., Reading, R.P., 2010. The role of ecotourism in biodiversity and grassland conservation in Botswana. Great Plains Res. 109–119.
Micheni, A.N., Njeru, M.J., Kanampiu, F.K., Mburu, D.M., Mugai, E.N., Kitonyo, O.M., 2016. Response of soil microfauna to tillage methods and cropping systems in humic Nitosols of eastern Kenya. Afr. J. Hortic. Sci. 10, 21–23.
Midega, C.A.O., Khan, Z.R., Van den Berg, J., Ogol, C.K.P.O., Dippenaar-Schoeman, A.S., Pickett, J.A., Wadhams, L.J., 2008. Response of ground-dwelling arthropods to a 'push– pull' habitat management system: spiders as an indicator group. J. Appl. Entomol. 132 (3), 248–254.
Millar, N., Ndufa, J.K., Cadisch, G., Baggs, E.M., 2004. Nitrous oxide emissions following incorporation of improved-fallow residues in the humid tropics. Global Biogeochem. Cycles 18 (1).
Millennium Ecosystem Assessment (MEA), 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC. Also Available at https://www.millenniumassessment.org/documents/document. aspx.pdf [accessed 24 January 2019].
Mloza-Banda, H.R., Kabambe, V.H., 1997. Integrated management for striga control in Malawi. Afr. Crop Sci. J. 4 (2), 263–273.
Musyoka, M.W., Adamtey, N., Bünemann, E.K., Muriuki, A.W., Karanja, E.N., Mucheru-Muna, M., Cadisch, G., 2019. Nitrogen release and synchrony in organic and conventional farming systems of the Central Highlands of Kenya. Nutr. Cycl. Agroecosyst. 113 (3), 283–305.
Mthembu, B.E., Everson, T.M., Everson, C.S., 2018. Intercropping maize (*Zea mays L.*) with lablab (*Lablab purpureus L.*) for sustainable fodder production and quality in smallholder rural farming systems in South Africa. Agroecol. Sustain. Food Syst. 42 (4), 362–382.
Mucheru-Muna, M., Mugendi, D., Pypers, P., Mugwe, J., Kung'u, J., Vanlauwe, B., Merckx, R., 2014. Enhancing maize productivity and profitability using organic inputs and mineral fertilizer in central Kenya small-hold farms. Exp. Agric. 50 (2), 250–269.
Mugwe, J., Mugendi, D. N., Mucheru-Muna, M., & Kung'u, J. B., 2011. Soil inorganic N and N uptake by maize following application of legume biomass, tithonia, manure and mineral fertilizer in Central Kenya. In Innovations as Key to the Green Revolution in Africa (pp. 605-616). Springer, Dordrecht.
Muhumuza, M., Balkwill, K., 2013. Factors affecting the success of conserving biodiversity in national parks: a review of case studies from Africa. Int. J. Biodivers. 2013, 20.
Munodawafa, A., 2007. Assessing nutrient losses with soil erosion under different tillage systems and their implications on water quality. Phys. Chemi. Earth Parts A/B/C 32 (15–18), 1135–1140.
Mugwe, J., Mugendi, D., Kungu, J., Mucheru-Muna, M., 2007. Effect of plant biomass, manure and inorganic fertilizer on maize yield in the Central highlands of Kenya. Afr. Crop Sci. J. 15 (3).
Mupangwa, W., Twomlow, S., Walker, S., Hove, L., 2007. Effect of minimum tillage and mulching on maize (*Zea mays L.*) yield and water content of clayey and sandy soils. Phys. Chem. Earth Parts A/B/C 32 (15–18), 1127–1134.
Mupangwa, W., Thierfelder, C., 2014. Intensification of conservation agriculture systems for increased livestock feed and maize production in Zimbabwe. Int. J. Agric. Sustain. 12 (4), 425–439.
Mwango, S.B., Msanya, B.M., Mtakwa, P.W., Kimaro, D.N., Deckers, J., Poesen, J., 2016. Effectiveness of mulching under miraba in controlling soil erosion, fertility restoration and crop yield in the Usambara Mountains, Tanzania. Land Degrad. Dev. 27 (4), 1266–1275.
Mzezewa, J., & Gwata, E. T., 2016. Analysis of Soil Profile Water Storage under Sunflower× Cowpea Intercrop in the Limpopo Province of South Africa. In Alternative Crops and Cropping Systems. 131.
Njoroge, S., Schut, A.G., Giller, K.E., Zingore, S., 2017. Strong spatial-temporal patterns in maize yield response to nutrient additions in African smallholder farms. Field Crops

Res. 214, 321–330.
Nyamangara, J., Bergström, L.F., Piha, M.I., Giller, K.E., 2003. Fertilizer use efficiency and nitrate leaching in a tropical sandy soil. J. Environ. Qual. 32 (2), 599–606.
Obalum, S.E., Buri, M.M., Nwite, J.C., Watanabe, Y., Igwe, C.A., Wakatsuki, T., 2012. Soil degradation-induced decline in productivity of Sub-Saharan African soils: The prospects of looking downwards the lowlands with the sawah eco-technology. Appl. Environ. Soil Sci. 10.
Oldeman, L.R., Hakkeling, R.T.A., Sombroek, W.G., 1991. World Map of the Status of Human-induced Soil Degradation. An Explanatory Note. Global Assessment of Soil. Degradation (GLASOD). ISRIC–UNEP.
Omoti, U., Ataga, D.O., Isenmila, A.E., 1983. Leaching losses of nutrients in oil palm plantations determined by tension lysimeters. Plant Soil 73 (3), 365–376.
Palm, C., Blanco-Canqui, H., DeClerck, F., Gatere, L., Grace, P., 2014. Conservation agriculture and ecosystem services: an overview. Agric. Ecosyst. Environ. 187, 87–105.
Partey, S.T., Zougmoré, R.B., Ouédraogo, M., Thevathasan, N.V., 2017. Why promote improved fallows as a climate-smart agroforestry technology in sub-saharan africa? Sustainability 9 (11), 1887.
Pasek, J.E., 1988. Influence of wind and windbreaks on local dispersal of insects. Agric. Ecosyst. Environ. 22, 539–554.
Pieri, C., Evers, G., Landers, J., O'Connell, P., & Terry, E., 2002. No-till farming for sustainable rural development. International Bank for Reconstruction and Development, Rural Development Department.1818 H Street, N.W. Washington, DC 20433.
Porter, J.R., Semenov, M.A., 2005. Crop responses to climatic variation. Philos. Trans. R. Soc. B Biol. Sci. 360 (1463), 2021–2035.
Poss, R., Saragoni, H., 1992. Leaching of nitrate, calcium and magnesium under maize cultivation on an oxisol in Togo. Fertilizer Res. 33 (2), 123–133.
Predotova, M., Gebauer, J., Diogo, R.V., Schlecht, E., Buerkert, A., 2010. Emissions of ammonia, nitrous oxide and carbon dioxide from urban gardens in Niamey, Niger. Field Crops Res. 115 (1), 1–8.
Rapp A., 1977. Soil erosion and reservoir sedimentation case studies in Tanzania. In FAO. Soil conservation and management in developing countries. Bulletin No. 33. FAO Forest Resources Division, Rome.
Riekert, H.F., Henshaw, G.E., 1998. Effect of soybean, cowpea and groundnut rotations on root-knot nematode build-up and infestation of dryland maize. Afr. Crop Sci. J. 6, 377–383.
Rockström, J., 2000. Water resources management in smallholder farms in Eastern and Southern Africa: an overview. Phys. Chem. Earth Part B 25 (3), 275–283.
Rogerson, C.M., Rogerson, J.M., 2014. Agri-tourism and local economic development in South Africa. Bull. Geogr. Socio-Econ. Ser. 26 (26), 93–106.
Rosenstock, T.S., Mpanda, M., Pelster, D.E., Butterbach-Bahl, K., Rufino, M.C., Thiong'o, M., Mutuo, P., Abwanda, S., Rioux, J., Kimaro, A.A., Neufeldt, H., 2016. Greenhouse gas fluxes from agricultural soils of Kenya and Tanzania. J. Geophys. Res. Biogeosci. 121 (6), 1568–1580.
Rusinamhodzi, L., Corbeels, M., Nyamangara, J., Giller, K.E., 2012. Maize–grain legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique. Field Crops Res. 136, 12–22.
Rusinamhodzi, L., Corbeels, M., Van Wijk, M.T., Rufino, M.C., Nyamangara, J., Giller, K.E., 2011. A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. Agron. Sustain. Dev. 31 (4), 657.
Russo, T.A., Tully, K., Palm, C., Neill, C., 2017. Leaching losses from Kenyan maize cropland receiving different rates of nitrogen fertilizer. Nutr. Cycl. Agroecosyst. 108 (2), 195–209.
Sahrawat, K.L., Wani, S.P., 2013. Soil testing as a tool for on-farm fertility management: experience from the semi-arid zone of India. Commun. Soil Sci. Plant Anal. 44 (6), 1011–1032.
Saxena, K.B., 2008. World's first CMS pigeon pea hybrid commercialized. Patancheru 502, 324.
Saxena, K.B., Mula, M.G., Sugui, F.P., Layaoen, H.L., Domoguen, R.L., Pascua, M.E., Mula, R.P., Dar, W.D., Gowda, C.L.L., Kumar, R.V., & Eusebio, J.E., 2010. Pigeonpea: A Resilient Crop for the Philippine Drylands. Information Bulletin No. 85. Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. pp. 80.
Schouteden, N., De Waele, D., Panis, B., Vos, C.M., 2015. Arbuscular mycorrhizal fungi for the biocontrol of plant-parasitic nematodes: a review of the mechanisms involved. Front. Microbiol. 6, 1280.
Sileshi, G.W., Debusho, L.K., Akinnifesi, F.K., 2012. Can integration of legume trees increase yield stability in rainfed maize cropping systems in Southern Africa? Agron. J. 104 (5), 1392–1398.
Six, J., Ogle, S., Breidt, F., Conant, R., Mosier, A., Paustian, K., 2004. The potential to mitigate global warming with no-tillage management is only realized when practiced in the long term. Glob. Change Biol. 10, 155–160.
Smith, S.E., Jakobsen, I., Grønlund, M., Smith, F.A., 2011. Roles of arbuscular mycorrhizas in plant phosphorus nutrition: interactions between pathways of phosphorus uptake in arbuscular mycorrhizal roots have important implications for understanding and manipulating plant phosphorus acquisition. Plant Physiol. 156 (3), 1050–1057.
Sogbedji, J.M., van Es, H.M., Agbeko, K.L., 2006. Modeling nitrogen dynamics under maize on Ferralsols in Western Africa. Nutr. Cycl. Agroecosyst. 74 (2), 99–113.
Sommer, R., Mukalama, J., Kihara, J., Koala, S., Winowiecki, L., Bossio, D., 2015. Nitrogen dynamics and nitrous oxide emissions in a long-term trial on integrated soil fertility management in Western Kenya. Nutr. Cycl. Agroecosyst. 105 (3), 229–248.
Sommer, R., Paul, B.K., Mukalama, J., Kihara, J., 2018. Reducing losses but failing to sequester carbon in soils–the case of Conservation Agriculture and Integrated Soil Fertility Management in the humid tropical agro-ecosystem of Western Kenya. Agric. Ecosyst. Environ. 254, 82–91.
Steward, P.R., Dougill, A.J., Thierfelder, C., Pittelkow, C.M., Stringer, L.C., Kudzala, M., Shackelford, G.E., 2018. The adaptive capacity of maize-based conservation agriculture systems to climate stress in tropical and subtropical environments: a meta-regression of yields. Agric. Ecosyst. Environ. 251, 194–202.
Swift, M., Stroud, A., Shepherd, K., Albrecht, A., Batiano, A., Mafongoya, P., Place, F., Tomich, T., Vanlauwe, B., Verchot, L., & Walsh, M., 2006. "Confronting Land Degradation in Africa: Challenges for the Next Decade.", in World Agroforestry into the Future. Nairobi, Kenya: World Agroforestry Centre (ICRAF), 43-51.
Thierfelder, C., Wall, P.C., 2009. Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. Soil Tillage Res. 105 (2), 217–227.
Thierfelder, C., Chisui, J.L., Gama, M., Cheesman, S., Jere, Z.D., Bunderson, W.T., Rusinamhodzi, L., 2013. Maize-based conservation agriculture systems in Malawi: long-term trends in productivity. Field Crops Res. 142, 47–57.
Thierfelder, C., Matemba-Mutasa, R., Rusinamhodzi, L., 2015a. Yield response of maize (*Zea mays L.*) to conservation agriculture cropping system in Southern Africa. Soil Tillage Res. 146, 230–242.
Thierfelder, C., Rusinamhodzi, L., Ngwira, A.R., Mupangwa, W., Nyagumbo, I., Kassie, G.T., Cairns, J.E., 2015b. Conservation agriculture in Southern Africa: advances in knowledge. Renew. Agric. Food Syst. 30 (4), 328–348.
Tovihoudji, P.G., Akponikpè, P.I., Agbossou, E.K., Bertin, P., Bielders, C.L., 2017. Fertilizer microdosing enhances maize yields but may exacerbate nutrient mining in maize cropping systems in northern Benin. Field Crops Res. 213, 130–142.
Tully, K., Sullivan, C., Weil, R., Sanchez, P., 2015. The state of soil degradation in sub-saharan africa: baselines, trajectories, and solutions. Sustainability 7, 6523–6552.
van Loon, M.P., Hijbeek, R., Ten Berge, H.F., De Sy, V., Ten Broeke, G.A., Solomon, D., van Ittersum, M.K., 2019. Impacts of intensifying or expanding cereal cropping in sub-Saharan Africa on greenhouse gas emissions and food security. Glob. Change Biol. 25 (11), 3720–3730.
Vågen, T.G., Lal, R., Singh, B.R., 2005. Soil carbon sequestration in sub-Saharan Africa: a review. Land Degrad. Dev. 16 (1), 53–71.
Våje, P.I., Singh, B.R., Lal, R., 2000. Leaching and plant uptake of Nitrogen from a volcanic ash soil in Kilimanjaro region, Tanzania. J. Sustain. Agric. 16 (4), 95–113.
Van der Kruijs, A.C.B.M., Wong, M.T.F., Juo, A.S.R., Wild, A., 1988. Recovery of 15N-labelled fertilizer in crops, drainage water and soil using monolith lysimeters in south-east Nigeria. J. Soil Sci. 39 (4), 483–492.
Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Smaling, E.M.A., 2010. Integrated soil fertility management: operational definition and consequences for implementation and dissemination. Outlook Agric. 39 (1), 17–24.
Vanlauwe, B., Descheemaeker, K., Giller, K.E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J., Zingore, S., 2015. Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. Soil 1 (1), 491–508.
Vinger, B., Hlophe, M., Selvaratnam, M., 2012. Relationship between nitrogenous pollution of borehole waters and distances separating them from pit latrines and fertilized fields. Life Sci. J. 9 (1), 402–407.
Wessells, K.R., Singh, G.M., Brown, K.H., 2012. Estimating the global prevalence of inadequate zinc intake from national food balance sheets: effects of methodological assumptions. PLoS ONE 7 (11), e50565.
Wong, M.T.F., Van der Kruijs, A.C.B.M., Juo, A.S.R., 1992. Leaching loss of calcium, magnesium, potassium and nitrate derived from soil, lime and fertilizers as influenced by urea applied to undisturbed lysimeters in south-east Nigeria. Fertilizer Res. 31 (3), 281.
Wong, M.T.F., Wild, A., Juo, A.S.R., 1987. Retarded leaching of nitrate measured in monolith lysimeters in south-east Nigeria. J. Soil Sci. 38 (3), 511–518.
Wu, F., Khlangwiset, P., 2010. Health economic impacts and cost-effectiveness of aflatoxin- reduction strategies in Africa: case studies in biocontrol and post-harvest interventions. Food Addit. Contam. 27 (4), 496–509.
Yang, X.E., Wu, X., Hao, H.L., He, Z.L., 2008. Mechanisms and assessment of water eutrophication. J. Zhejiang Univers. Sci. B 9 (3), 197–209.
Yanni, Y.G., Rizk, R.Y., El-Fattah, F.K.A., Squartini, A., Corich, V., Giacomini, A., Vega-Hernandez, M., 2001. The beneficial plant growth-promoting association of Rhizobium leguminosarum bv trifolii with rice roots. Funct. Plant Biol. 28 (9), 845–870.
Zhou, M., Brandt, P., Pelster, D., Rufino, M.C., Robinson, T., Butterbach-Bahl, K., 2014. Regional nitrogen budget of the Lake Victoria Basin, East Africa: syntheses, uncertainties and perspectives. Environ. Res. Lett. 9 (10), 105009.
Zingore, S., Mutegi, J., Agesa, B., Tamene, L., Kihara, J., 2015. Soil degradation in sub-Saharan Africa and crop production options for soil rehabilitation. Better Crops 99 (1), 24–26.