

Review and meta-analysis of organic matter in cultivated soils in southern Africa

C. M. Swanepoel · M. van der Laan · H. L. Weepener ·
C. C. du Preez · J. G. Annandale

Received: 10 July 2015 / Accepted: 18 January 2016 / Published online: 29 January 2016
© Springer Science+Business Media Dordrecht 2016

Abstract Soil organic matter (SOM) is tightly linked to soil quality, but cultivation generally causes a decline in SOM, reducing soil quality and releasing carbon dioxide into the atmosphere. Internationally, countries are expected to reduce their greenhouse gas (GHG) emissions, and compile and update GHG inventories. Many developing countries, such as those in southern Africa, do not have reliable information regarding SOM levels in cultivated soils, changes over time and best management practices to maintain or even restore SOM. A review was conducted to collate published research on SOM [or its indicator elements, carbon (C) and nitrogen (N)] in cultivated fields in southern Africa. A total of 84 publications were assessed, and information such as date, location, SOM/soil organic carbon (SOC) and clay content and key findings were recorded. Most of the publications (90 %) were published post-1990. The spatial distribution of these studies is very non-uniform. A

decline of 25–53 % in SOC due to cultivation was evident for cultivated fields in different precipitation zones in southern Africa, with SOC ranging from 0.7 to 2.5 %. These values correlate relatively well with existing SOC maps. A strong correlation between SOC and clay content in natural soil is weakened following cultivation. Carbon sequestration and GHG emission dynamics under various management systems and for different climatic regions, as well as how field crop production can play a role in mitigating climate change, are poorly understood. Intensified monitoring by multi-institutional collaboration is recommended to address this issue.

Keywords Agriculture · Carbon sequestration · Clay · Greenhouse gas emissions · Nitrogen · Nitrous oxide

Introduction

Soil quality can be defined as the ability of soil to perform or function according to its potential (Doran and Zeiss 2000), and the term is strongly linked to productive, stable soils that are resistant to erosion. Maintaining soil quality is essential to ensure sustainable agricultural production by optimising the natural characteristics of the system that are favourable for plant growth (Doran and Zeiss 2000; Lal 2004). Ecologically, soils provide a range of ecosystem

C. M. Swanepoel (✉) · H. L. Weepener
Agricultural Research Council (ARC)-Institute for Soil,
Climate and Water, Pretoria, South Africa
e-mail: SwanepoelC@arc.agric.za

C. M. Swanepoel · M. van der Laan · J. G. Annandale
Department of Plant Production and Soil Science,
University of Pretoria, Pretoria, South Africa

C. C. du Preez
Department of Soil, Crop and Climate Sciences,
University of the Free State, Bloemfontein, South Africa

services, such as nutrient cycling, carbon (C) sequestration, water filtration and storage, and are therefore considered an integral part of many natural systems (Doran and Zeiss 2000; Dominati et al. 2010). Soil organic matter (SOM), or its associated indicator elements, C and nitrogen (N), are often equated with soil quality (Mills and Fey 2003). Loss of SOM is a global concern as it not only leads to a deterioration of soil quality, but also releases greenhouse gases (GHG) to the atmosphere, resulting in accelerated climate change (Smith et al. 2007).

Soil is the largest terrestrial pool of organic C, storing more C than is found in all vegetation and the atmosphere combined (Schlesinger 1997), and representing more than 10 times the C stored in forests (Kindermann et al. 2008). Soil is recognised for having the potential to reduce atmospheric GHG concentrations via increased sequestration. Intensive cultivation, however, most often degrades soil organic C (SOC) and soil organic N (SON), and reduces crop production potential of the soil over the long term (Lal 2004).

A growing global population demands increased food production, placing an ever-increasing burden on limited natural resources. This is especially true for southern Africa, where soils are fragile and prone to degradation in the form of erosion, SOM depletion, salinisation, acidification and nutrient mining (Lal and Stewart 2010). The UN Food and Agriculture Organisation (FAO 1996) predicts that food insecurity will increase in Africa, whilst the rest of the world sees improved security. Food security is dependent on soil quality, and misuse of this agricultural resource may not only result in declining food production, but also contribute to climate change (Lal and Stewart 2010).

Many Southern African Development Community (SADC) countries are signatories to the United Nations Framework Convention on Climate Change (UNFCCC), and as developing countries under this Convention, they have an obligation to compile and periodically update an inventory of GHG emissions and sinks (DEAT 2009). Currently, however, there is very little reliable data for GHG inventories, or for identifying effective mitigation and adaptation options for the agricultural sector in this region. More specifically, there are (a) no reliable data on C sequestration potential in various agro-ecological

zones or for different cultivation practices; (b) limited data on actual changes or losses of SOC in different agro-ecological zones, or for different land-uses, and (c) very little data on the release of carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) for different production systems. In addition to indicating climate change potential, such information is also useful to evaluate the state of soil as a resource to support functional ecosystems and sustainable crop production.

The objective of this study is to establish the current state of knowledge for cultivated land in southern Africa by reviewing published research on SOM and its indicator elements C and N—including GHG emissions. The focus is on the spatial and temporal distribution of C and N studies, and collating and analysing the main results regarding the status of SOM/SOC. Finally, possible mitigation options and future research needs are discussed.

Materials and methods

Selection of studies

Countries included in the study were based on SADC membership (<http://www.sadc.int/member-states/> accessed 12 September 2014), up to the equator as a northern boundary. This included Angola, Botswana, the Democratic Republic of Congo (DRC) (section south of the equator), Lesotho, Malawi, Mozambique, Namibia, Republic of South Africa (RSA), Swaziland, United Republic of Tanzania, Zambia and Zimbabwe. Search engines used included Web of Science, SA ePublications, Scielo and African Journals On-line. Keywords were adjusted according to search engines and databases, and consisted of a combination of ‘soil organic matter’ or ‘soil carbon’ or ‘carbon dynamics’, ‘carbon dioxide’, ‘nitrous oxide’, ‘soil respiration’ or ‘respiration’ and ‘Africa’. The search did not specifically include the keyword ‘nitrogen’, as most studies on N are about fertilizer application or efficacy, while studies on organic N were picked up under ‘soil organic matter’ or ‘soil organic carbon’ due to the tight link between C and N.

A list of all the publications was compiled and evaluated based on title, keywords and abstract, to

select only studies from southern Africa focussing directly on agriculture, or indirectly on aspects influencing agricultural production (for example, effect of burning of natural woodlands on soil fertility, where burning is not directly related to agriculture but is done to clear land for crop cultivation). Studies that were representative of natural conditions only, rehabilitation of mines or dedicated landfill sites were not included. We did not focus on specific crops, as many sites were subject to mixed cropping, with complex cropping histories, while other studies did not focus on specific cropping systems but rather on cultivation practices.

Publications were categorised according to the International Union of Soil Sciences' (IUSS) scientific structure. The IUSS identified four major soil science divisions (soil in time and space; soil properties and processes; soil use and management; and the role of soils in sustaining society and the environment), with a number of commissions listed in each division (<http://www.colostate.edu/programs/IUSS/>; accessed 22 July 2015). Publications were further categorised as reviews, trials or surveys (Brouder and Gomez-Macpherson 2014). Reviews are publications that summarise existing research; trials include statistically designed studies with various treatments at one or more sites; while surveys include studies where samples were taken across a wide area, or comparisons of contrasting land-uses in a smaller area (Table 1).

For each publication, the date, location, SOC values (from cultivated as well as adjacent natural fields, when available), clay content, treatments or management practices, and main outcomes were recorded. The publication date was used to represent the temporal distribution of the studies. Some publications listed several locations, while others listed several values for one location (e.g. research trial) and some were not linked to any specific locations (e.g. reviews). Comparisons were complicated by differences in sampling procedure and reporting of SOC, which included different soil depths and different measurement units (e.g. % SOC, % SOM, Mg ha⁻¹ or g kg⁻¹). Some publications did not explicitly give SOC results, and some only reported changes in SOC. Soil organic matter was converted to SOC by using a conversion factor of 1.724 (Stevenson and Cole 1999). We standardised all the collated results from various publications on topsoil SOC in percentage for further analysis and comparisons.

Spatial distribution analysis

Soil organic matter study location points were plotted on a total annual precipitation map (New et al. 2002), as well as a SOC map (AfsIS 2014), in order to evaluate how representative the distribution of SOM studies are in terms of these two variables. There is a strong link between SOC and climatic properties, especially precipitation, which is linked to distribution of vegetation, soil formation, rate of mineralisation, as well as SOC, making it an appropriate parameter to evaluate degree of representation of current studies (Weil and Magdoff 2004). The precipitation map was prepared using data from the Climatic Research Unit (CRU), University of East Anglia (New et al. 2002). We summarised monthly precipitation grids into annual total precipitation, using six classes: desert (0–200), arid (200–400), semi-arid (400–600), sub-humid (600–800), humid (800–1000) and super-humid (>1000 mm year⁻¹). Soil organic carbon maps (SoilsGrid1km) were obtained from AfsIS (2014), and SOC was classified into five classes (0–5, 5–10, 10–20, 20–30 and >30 g kg⁻¹ in the 0–50 mm top layer). Soil maps for Africa (SoilsGrid1 km) have been produced at 30" resolution using an automated spatial prediction framework. Spatial prediction models were fitted per soil variable (such as SOC, pH, texture, coarse fragments, bulk density, depth to bedrock and cation exchange capacity), using a compilation of major international soil profile databases (ca. 12,000 soil profiles) (ISRIC 2013; AfsIS 2014; Hengl et al. 2014).

Results

A total of 84 publications met the criteria of being suitably focussed on agricultural SOM related research and were used in the meta-analysis. Survey publications were most common, comprising 54 % of the total, followed by trials (27 %) and review publications (19 %) (Table 1). The majority (90 %) of the publications were published after 1990. Review publications only became common from the year 2000 onwards, made possible by the increased number of surveys and trials and easier access to publications (Fig. 1). This corresponds with the worldwide interest in C and global warming/climate change as a research topic, which gained momentum in the 1990s as

Table 1 Publication list (n = 84) on C and N dynamics in cultivated fields in southern Africa, divided into IUSS divisions and commissions

Commissions	Publications
Division: soil properties and processes	
Biology	Amelung et al. (2002) ^S , Brodowski et al. (2004) ^S , Graham and Haynes (2005) ^T , Graham and Haynes (2006) ^T , Pardo et al. (2010) ^S , Pardo et al. (2014) ^S , Swanepoel et al. (2014) ^T
Mineralogy	Wattel-Koekkoek et al. (2001) ^S , Wattel-Koekkoek and Buurman (2004) ^S , Nciizah and Wakindiki (2014) ^S
Soil chemistry	Meyer et al. (1983) ^S , Du Preez and Burger (1986) ^S , Meyer (1989) ^S , Greyling et al. (1990) ^S , Laubscher and Du Preez (1991) ^S , Tagwira et al. (1992) ^S , Van der Mey et al. (1994) ^S , Barrios et al. (1997) ^S , Materechera et al. (1998) ^T , Keutgen and Huysamer (1998) ^T , Lobe et al. (2002) ^S , Rowell and Coetzee (2002) ^S , Lobe et al. (2005) ^S , Matlou and Haynes (2006) ^S , Verge et al. (2007) ^R , Eustice et al. (2011) ^R , Hickman et al. (2011) ^R , Mapanda et al. (2011) ^T , Kim (2012) ^S , Mapanda et al. (2012) ^T , Nyamadzawo et al. (2013) ^T
Soil physics	Mrabet (2002) ^R , Lobe et al. (2011) ^S
Division: soil use and management	
Conservation	Fourie et al. (2007a) ^T , Fourie et al. (2007b) ^T , Dube et al. (2012) ^T
Degradation and remediation	Nhantumbo et al. (2009b) ^S , Lauer et al. (2011) ^S , Kusters et al. (2013) ^S
Engineering and technology	Snapp et al. (1998) ^R
Fertility and nutrition	Prinsloo et al. (1990) ^S , Wiltshire and Du Preez (1993) ^T , Du Preez and Du Toit (1995) ^S , Du Toit and Du Preez (1995) ^S , Almendros et al. (2001) ^S , Du Preez et al. (2001) ^T , Dominy et al. (2002) ^S , Graham et al. (2002) ^T , Pardo et al. (2003) ^S , Mills and Fey (2003) ^R , Haynes et al. (2003) ^T , Barnard and Du Preez (2004) ^R , Mtambanengwe and Mapfumo (2005) ^S , Buhmann et al. (2006) ^S , Kotze and Du Preez (2007) ^T , Kotze and Du Preez (2008) ^T , Meyer and Van Antwerpen (2010) ^R , Loke et al. (2012) ^T , Fourie (2012) ^T , Ando et al. (2014) ^T
Soil evaluation and land-use planning	Pearson (1952) ^R , Watson (1954) ^R , Van der Watt (1987) ^S , Du Toit et al. (1994) ^S , Du Preez and Wiltshire (1997) ^S , Lobe et al. (2001) ^S , Dominy and Haynes (2002) ^S , Du Preez (2003) ^R , Milne and Haynes (2004) ^S , Zingore et al. (2005) ^S , Hensley et al. (2006) ^R , Mapfumo et al. (2007) ^T , Du Preez et al. (2010) ^R , Du Preez et al. (2011a) ^R , Du Preez et al. (2011b) ^R , Shoko and Moyo (2011) ^S , Mujuru et al. (2013) ^T
Division: Sustaining society and environments	
Land-use change	Gillson et al. (2012) ^R
Soils and the environment	Schmidt and Schmidt (1963) ^S , King and Campbell (1994) ^S , Du Toit and Du Preez (1993) ^S , Mills and Fey (2004) ^S , Mills et al. (2005) ^S , Nhantumbo et al. (2009a) ^S

Superscripts: R = review publication (n = 16), S = surveys (n = 45) and T = trials (n = 23)

marked with the establishment of the Intergovernmental Panel on Climate Change (IPCC). Most of the research topics focused on soil chemistry as well as fertility and nutrition (Table 1). Data on N levels, C:N ratios and GHG emissions was surprisingly limited in the papers reviewed.

The spatial distribution of research in our sample, was biased toward RSA (70 %), followed by Zimbabwe (15 %) and Mozambique (4 %). Studies that summarised results for Africa as a continent, comprised 2 % of the publications. Malawi, Tanzania and

Zambia produced 2 % each. Botswana and Namibia produced 1 % each, while Angola, DRC, Lesotho and Swaziland yielded no outputs (Fig. 2) (note that not every study can be linked to a location point on the map in Figs. 2 and 3, as some were review studies, some reported values for a region or continent and some studies (e.g. laboratory studies) were not linked to a specific site).

According to the precipitation zone-SOM study location map (Fig. 3), the areas in the semi-arid and sub-humid areas are best represented, while desert and

Fig. 1 Temporal distribution of 84 peer-reviewed articles on SOM in southern Africa

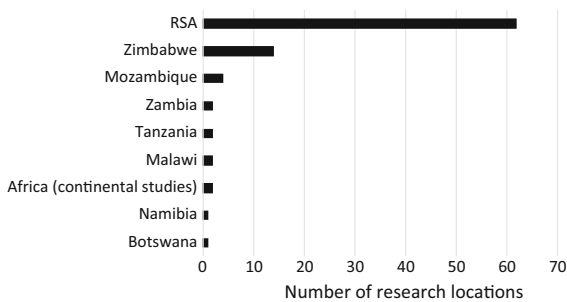
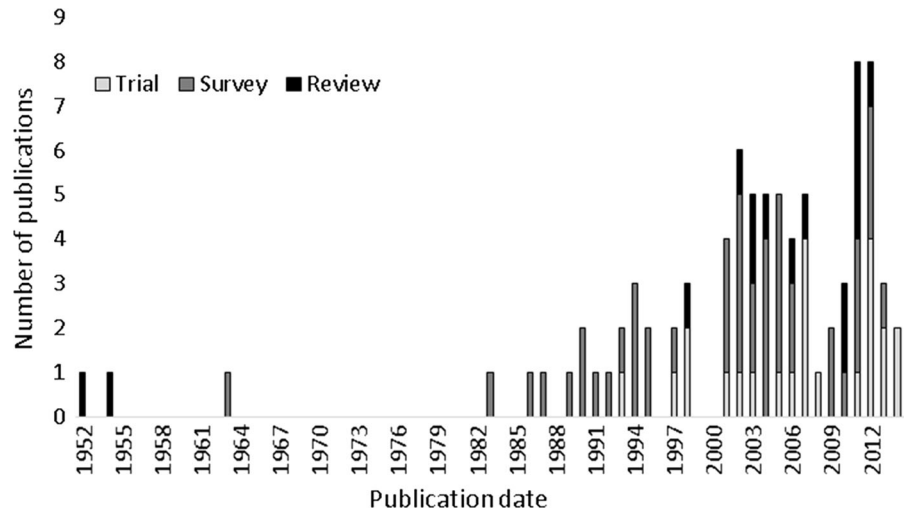


Fig. 2 Number of research locations in various countries in southern Africa

super-humid areas are poorly represented. Desert areas do not cover a large part of the study area (6 % of total), and agricultural activities are much lower in these regions. Super-humid areas represent the greatest fraction of the study area (44 %), yet only 3 % of studies fall into this category. Furthermore, a total of 34 SOC values were reported in conjunction with clay content. Correlating SOM with clay content gave an R^2 value of 0.61.

The interpolated SOC map, ‘SoilGrid1Km’ (Fig. 4) for southern Africa indicates that most of the region is characterised by low SOC contents, with the exception of the northern and eastern areas. Our results show that 50 % of all the study locations ($n = 266$) occur in the 5–10 g kg^{-1} SOC zone, followed by 38 % in the 10–20 g kg^{-1} SOC zone, 10 % in the 0–5 g kg^{-1} zone, 2 % in the 20–30 g kg^{-1} zone and 0 in the >30 g kg^{-1} SOC zone.

A total of 294 SOC values were reported in the publications for varying topsoil depth, the majority (23 %) of which was reported for the 0–200 mm depth. These values were categorised per rainfall class and topsoil depth (Table 2). The overall average SOC value reported for southern Africa was 1.4 % (± 1.36), however, categorised according to precipitation zones, this value can range from 0.7 % (arid zone) to 2.5 % (humid zone).

A further 79 data pairs were collected (representing 48 different locations) reporting on SOC in cultivated soils compared to adjacent undisturbed fields. After assigning the data pairs into precipitation zones, we used a simple linear regression to compare these values (Fig. 5). The slope of the regression lines represents the extent of decline, suggesting that over a wide range of SOC levels, and a range of production practices over varying time intervals, cultivation leads to an average overall loss of 46 % SOC in southern African croplands (slope of combined data for southern Africa is 0.54). More specifically, the SOC decline in the various precipitation zones is 25 % ($n = 27$) for semi-arid areas, 53 % ($n = 42$) for sub-humid areas and 46 % ($n = 10$) for humid areas (Fig. 5).

Discussion

Reporting SOM or SOC for varying depths and across different rainfall regions complicates comparison of this variable across different studies. SOM is strongly

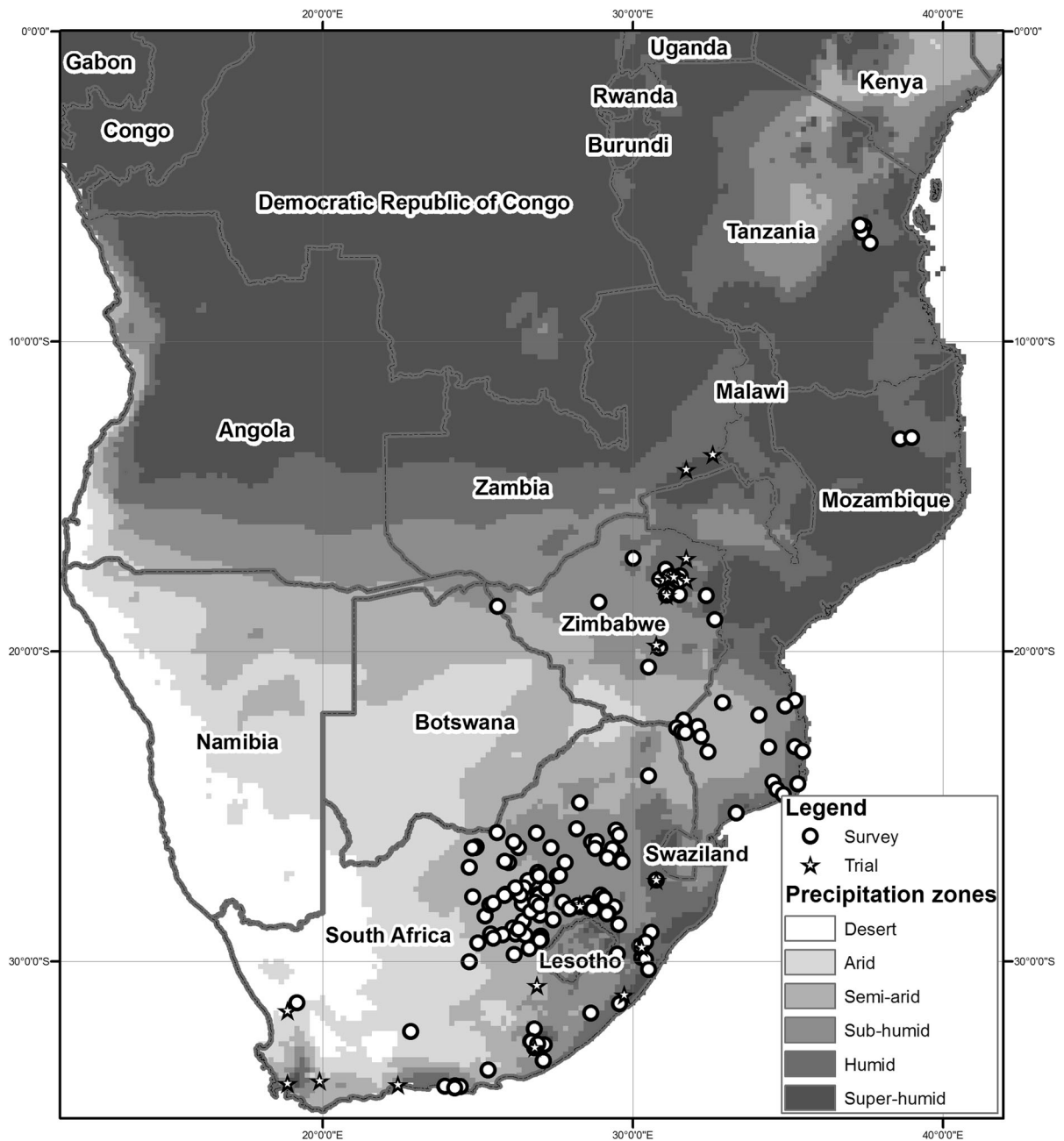


Fig. 3 Distribution of research locations, as extracted from peer-reviewed publications, relative to precipitation zones of southern Africa

correlated with soil depth (Jobbagy and Jackson 2000), and as a result, Van der Watt (1987) suggested that studies focusing on SOM (or SOC and SON) should use small sampling intervals, such as 50 or 75 mm. Despite this, only 3 % of all reported SOC

levels were collected from the top 50 mm. Common research themes in the selected publications included a decline of SOM associated with cultivation, and subsequently a range of possible options to retain or restore the lost C and N.

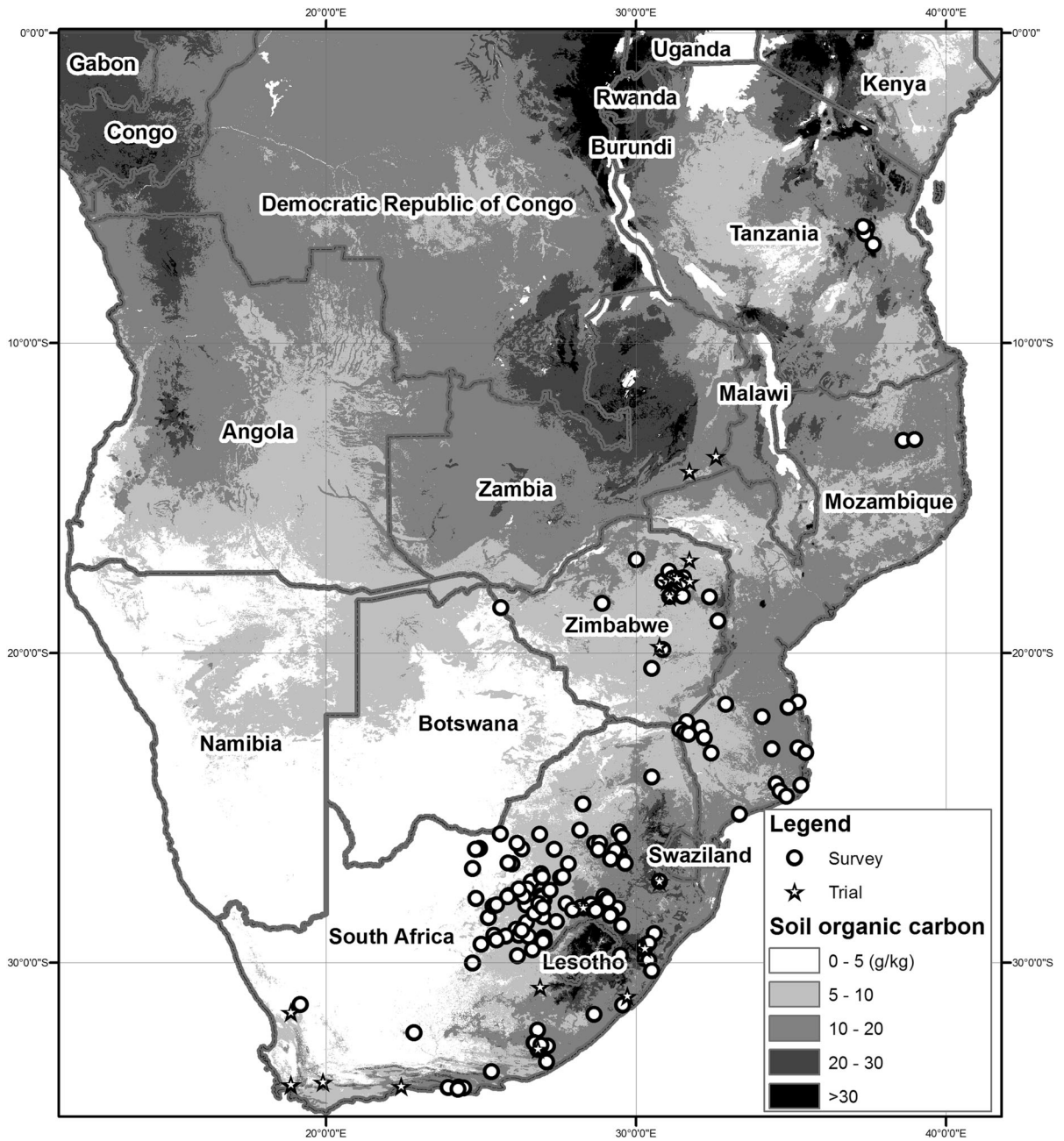


Fig. 4 Distribution of research locations, as extracted from peer-reviewed publications, relative to the SoilGrid1km map (AfSIS 2014) of soil organic carbon zones of southern Africa

Driving forces behind soil organic matter change

The organic matter content of a mature natural soil is determined by a specific combination of soil forming factors which includes climate, topography, vegetation and organisms, parent material and time (Stevenson

and Cole 1999). This equilibrium is disturbed by human intervention such as land-use change (Pardo et al. 2012) or cultivation (Du Preez and Wiltshire 1997; Pardo et al. 2010; Loke et al. 2012). During cultivation, crop residues are either incorporated into or left on the soil, burnt or physically removed for other

Table 2 Average soil organic carbon (SOC) (%) and number of values reported in different precipitation categories for various soil depths in cultivated fields

Soil Depth (mm)	Precipitation classes (mm)						Total
	0–200	200–400	400–600	600–800	800–1000	>1000	
Number of studies							
0–50			1	5		3	9
0–100		7	3	11	46	2	69
0–140					2		2
0–150			5	11			16
0–200			55	92	22		169
0–300		5	8		7		20
0–500		3	2		4		9
Total	0	15	74	119	81	5	294
Soil organic carbon (%)							
0–50		0	1.12	1	0	1.63	1.22 (± 1.28)
0–100		1.03	3.07	1.86	2.66	1.47	2.35 (± 1.76)
0–140		0	0	0	1.87	0	1.87 (± 0.54)
0–150		0	0.91	0.67	0	0	0.74 (± 0.3)
0–200		0	0.63	1.19	2.04	0	1.12 (± 0.94)
0–300		0.15	0.47	0	2.03	0	0.94 (± 1.33)
0–500		0.97	3.86	0	3.81	0	2.87 (± 1.4)
Total	0	0.73	0.83	1.2	2.47	1.56	1.44 (± 1.36)

use, such as animal feed. Any tillage, or other soil disturbance, will increase oxidation of residues and previously occluded SOM, resulting in the release of CO₂ and decline of SOM. These are key drivers for the loss of SOM in southern Africa (Materchera et al. 1998; Mills and Fey 2004; Loke et al. 2012).

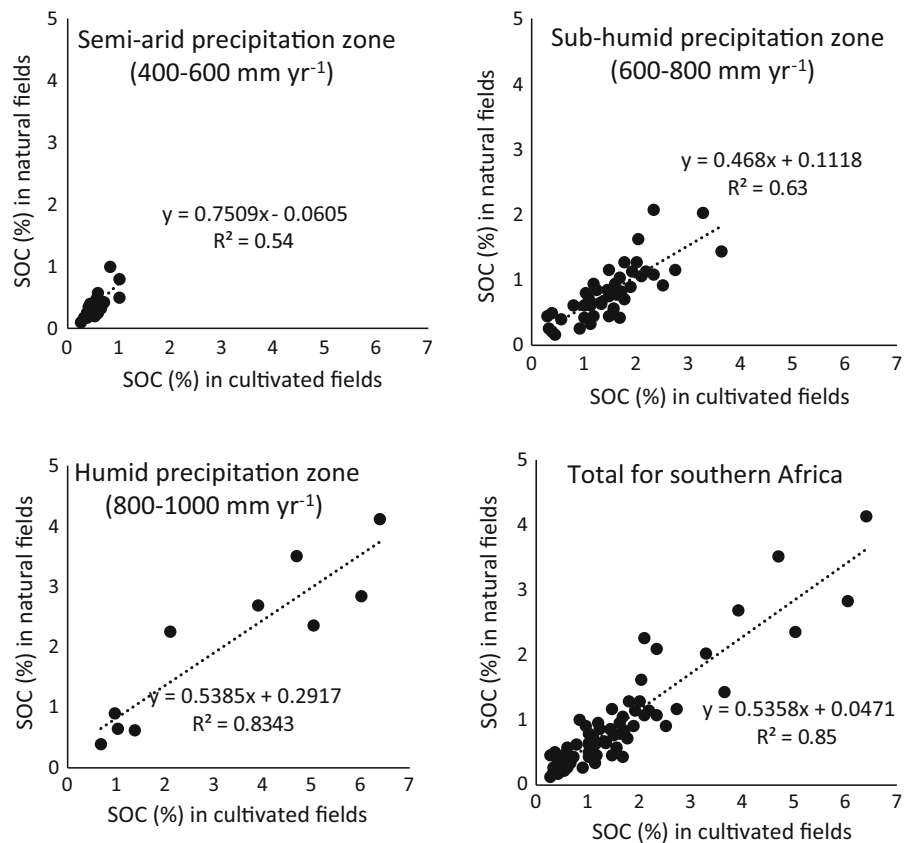
We therefore identified major driving forces that result in SOM decline, and these include tilling (Du Toit et al. 1994; Mills and Fey 2003), crop removal through grazing or burning (Mills and Fey 2003; Kotze and Du Preez 2007) and duration of cultivation (Du Toit et al. 1994; Lobe et al. 2001; Dominy et al. 2002; Dube et al. 2012). Inferior driving forces were regarded as those aspects that correlated (positive or negative) with SOM content. Some soil properties, such as clay content (Wattel-Koekkoek and Buurman 2004), or management strategies, such as conservation practices (Van der Watt 1987; Mills and Fey 2003; Fourie et al. 2007a, b; Kotze and Du Preez 2007; Loke et al. 2012), can protect or buffer the SOM loss.

Inferior driving forces included the following: soil structure or aggregation (Kosters et al. 2013) soil water content and temperature (Schmidt and Schmidt 1963; Du Toit et al. 1994; Du Toit and Du Preez 1995;

Nhantumbo et al. 2009a, b; Nyamadzawo et al. 2013), soil texture (Dominy et al. 2002; Wattel-Koekkoek and Buurman 2004; Zingore et al. 2005; Mapfumo et al. 2007; Nciizah and Wakindiki 2014), microbial populations and functional diversity (Amelung et al. 2002; Swanepoel et al. 2014), biogeochemical activity (Amendros et al. 2001), soil mineral composition (Wattel-Koekkoek et al. 2001), soil chemical environment (Tagwira et al. 1992), N fertilizer application or fertilizer management (Graham et al. 2002; Mills and Fey 2003; Dube et al. 2012), type of cropping system, management (Graham and Haynes 2005; Dube et al. 2012) or type of crop residue (Tagwira et al. 1995; Lobe et al. 2005) and erosion (Lobe et al. 2002).

Comparing percentage of SOM change per site (cultivated versus adjacent natural fields), shows that the majority (94 %) of the data points resulted in a net SOM loss after cultivation. But perhaps more interesting is the five studies sites where a build-up of SOM occurred. Two of these sites occurred in the central maize producing areas of RSA (Greyling et al. 1990), and was part of a survey study that included seven location sites. This paper focussed on N mineralisation, and did not provide any supporting information

Fig. 5 Relationship between soil organic carbon (SOC, %) in natural fields and corresponding cultivated fields for the semi-arid precipitation zone (n = 27), sub-humid precipitation zone (n = 42) and humid precipitation zone (n = 10)



(for example on irrigation) or an explanation why SOC was increased in cultivated soils. Another two sites were part of a survey study by Mills and Fey (2004), who suggested the increase was not significant, and the overall trend when all the data was taken into account, indicated a decline in SOC. The fifth study site was collected from Swanepoel et al. (2014), and the increase in SOC was associated with permanent grazing.

Cultivation as the primary driver in soil organic matter decline

In all the publications, the most important driver in SOM decline was cultivation. Our results indicate a SOC decline of between 25 and 53 % in various precipitation zones of southern Africa (Fig. 5). These values will change with, for instance, the duration of cultivation or type of cultivation practice. Other studies have reported similar results: 10 % SOC decline after Miombo woodland was converted to maize fields in Zimbabwe (King and Campbell 1994), 10–75 % loss after 5–90 years of cultivation in the

Free State Province, RSA (Du Toit et al. 1994), 35–50 % SOC loss after cultivation in Botswana (Pardo et al. 2012), 50 % loss after 50 years of cultivation in a long-term trial in Pretoria, RSA (Nel et al. 1996); 65 % of SOC loss in semi-arid savannah in South Africa (Lobe et al. 2001), and a 60 % loss of SOC in temperate, and 75 % in tropical regions has been reported by Lal (2004). One exception was reported by Du Preez and Wiltshire (1997) for central RSA, where SOC in some fields under irrigation declined by 12–49 %, while in other areas it increased by 19–33 %. This is most likely due to irrigation enabling more plant and microbial biomass growth than would have been possible under natural rainfall conditions, resulting in larger biomass contributions to SOC.

Temporal aspects of SOM decline were also studied. Rapid decline in SOM was reported to occur in the first five years of cultivation (Du Toit et al. 1994), 10–20 years after cultivation (Dominy et al. 2002), and up to 30 years after cultivation (Lobe et al. 2011). A new equilibrium of SOC was reached for

each of these studies after 35, 30–40 and 34 years, respectively.

Varying results on management effect on SOM build-up or retention are reported. Limited success was achieved in restoring N fertility under a wheat trial in central RSA using stubble mulch practices in lieu of straw burning (Wiltshire and Du Preez 1993). Some cultivation efforts do appear to reduce the rapid decline of SOC, and these include reduced tillage (Van der Watt 1987; Mrabet 2002; Kotze and Du Preez 2007), trash retention for sugarcane instead of burning (Graham and Haynes 2006; Eustice et al. 2011), cover crop and green manure use (Fourie et al. 2007a, b; Fourie 2012) and pastures (Haynes et al. 2003; Swanepoel et al. 2014).

Soil organic carbon and clay content

The correlation of $R^2 = 0.61$ ($n = 34$) between SOC and clay content for cultivated topsoils (Fig. 6) is not as strong as SOC-clay relations in undisturbed soils. Du Toit and Du Preez (1993) found a strong correlation ($R^2 = 0.91$, $n = 41$) between SOC and the clay plus fine silt fraction of undisturbed soils in central summer rainfall areas of South Africa. Similarly, Stronkhorst and Venter (2008) reported a strong correlation between the SOC and the clay plus fine silt fraction ($R^2 = 0.85$), closely followed by SOC versus clay only fraction ($R^2 = 0.85$) when comparing 4837 soil samples across South Africa. Miles et al. (2008) found a correlation of $R^2 = 0.88$ ($n = 42$) comparing SOC and clay content for KwaZulu–Natal topsoils under sugarcane cultivation. A possible reason for the weaker correlation of SOC with clay content observed in our review for cultivated soils is

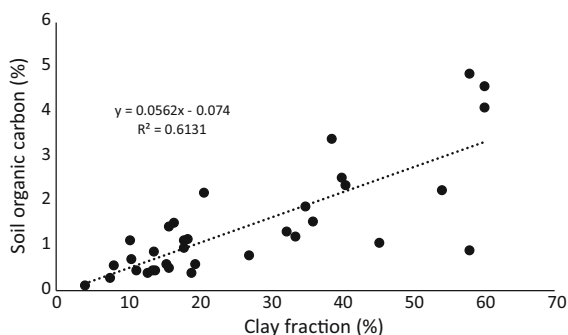


Fig. 6 Correlation between reported clay content and SOC from selected publications for southern Africa

the wide range of data and drastically modified conditions for these soils. In general, a decline of SOC was reported in most studies, regardless of clay content, but some fields have relatively high organic matter levels, especially pastures or conservation agriculture fields where retention of SOM is a priority. There is most often no indication of duration of cultivation, where recently cultivated soils would be expected to have lost less SOC than long-term cultivated soils. This relatively poor correlation of SOC versus clay fraction could, at least partly, explain the poor correlation between SOC values in our sample compared to SOC values in the SoilGrid1km SOC map (Figs. 4, 7). Clay (or soil texture) is one of the soil properties used to derive the maps (AfsIS 2014), but the SOC versus clay relationship changes under cultivated conditions.

Using simple linear regression to compare our review's measured data with corresponding values from the SoilGrid1km map gives a correlation of $R^2 = 0.5$ ($n = 202$) (Fig. 7). Even though there is a similarity between the map units and the corresponding published data, the large local variation in SOC content, land-use impacts, and decline of SOC in cultivated fields can cause significant variation from the predicted map values. The compromised correlation between SOM and clay in cultivated soils indicates that these maps should be used with caution.

Soil nitrogen

Nitrogen and C dynamics are closely linked to SOM dynamics in the soil, although N and C are not mineralised at the same rate (Du Toit et al. 1994; Mills

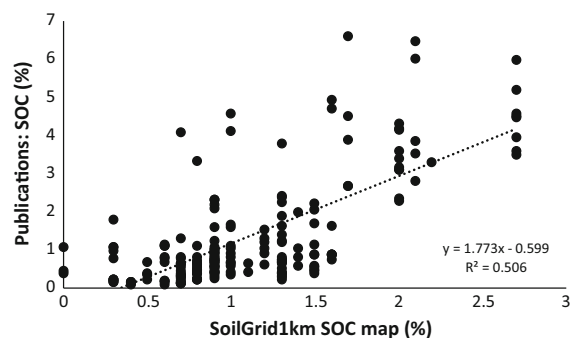


Fig. 7 Comparing predicted SOC values ($n = 202$) from the SoilGrid1km SOC map (AfsIS 2014) to reported values in publications for the same location points

and Fey 2004). There are a plethora of studies published on N in agriculture, but the vast majority of these publications are fertilizer related. The studies in our publication sample focusing on N dynamics for cultivated fields include characterisation of N status (Mills and Fey 2004), N mineralisation (Meyer et al. 1983; Greyling et al. 1990; Prinsloo et al. 1990; Van der Mey et al. 1994; Brodowski et al. 2004), nitrification rates (Laubscher and Du Preez 1991), N fertility (Du Toit and Du Preez 1995), N and agroforestry (Kim 2012; Barrios et al. 1997), N leaching (Matlou and Haynes 2006; Mapanda et al. 2012), gaseous emissions (Mapanda et al. 2012) and improved analytical methods (Meyer 1989). Very few studies have been conducted on multiple components of the N balance in cultivated soils.

As with SOM, cultivation was observed to negatively affect SON levels. The loss of N fertility is mainly attributed to a reduction in the organic N pool. Nitrogen decline was unique for each agro-ecological zone, where in warmer, drier areas N declines at a quicker rate than in cooler wetter agro-ecological zones (Du Toit and Du Preez 1995). In some studies, relatively more C than N was lost under cultivation, possibly due to removal of residues with a higher C:N ratio during harvesting, or a higher N mineralisation rate in the soil. This results in slightly reduced C:N ratios in cultivated topsoils (Prinsloo et al. 1990; Du Toit et al. 1994; Mills and Fey 2004). Other studies measured an increase in C:N ratio following fertilizer treatment and SOM return under sugarcane production (Graham et al. 2002). Up to 70 % of amino acid content was irretrievably lost from the soil organic N pool after 20–30 years of cultivation in semi-arid areas (Brodowski et al. 2004). Depletion of soil N fertility has significant implications for sustainable crop production (Du Toit and Du Preez 1995), especially in Africa where access to fertilizers is often limited. Worldwide, N fertilizer use efficiencies range from 35 to 65 % (Smil 1999), indicating that much of the N taken up by crops is from biofixation and newly mineralised N, which correlates with these data showing loss of organic N from the soil.

Carbon and nitrogen losses and greenhouse gas emissions

Only eight of the 84 publications reported on GHG emissions. These include review articles (Verge et al.

2007; Eustice et al. 2011; Hickman et al. 2011), modelling (Eustice et al. 2011) and direct measurement (Keutgen and Huysamer 1998; Mapanda et al. 2011; Kim 2012; Mapanda et al. 2012; Nyamadzawo et al. 2013). The main results reported in these publications are listed in Table 3. The results vary widely as the various publications focused on different aspects.

The review articles reported GHG emissions for the continent (Verge et al. 2007; Hickman et al. 2011), or for a sub-region under production of a specific crop (Eustice et al. 2011). Both Verge et al. (2007) and Hickman et al. (2011) used IPCC Tier 1 methodology to calculate GHG emissions, while Eustice et al. (2011) compared GHG emissions from trashed and burnt sugarcane cropping systems in South Africa, using the DSSAT (Decision Support System for Agrotechnology Transfer) model. All three publications highlighted the lack of studies measuring direct GHG emissions from cultivated African (local) soils. Eustice et al. (2011), for instance, were unable to verify the modelling data, due to a lack of existing data for GHG emissions. According to Hickman et al. (2011), even the data used by IPCC to produce the default emission factors/coefficients for Africa, has been based on very few African studies. Sub-Saharan Africa is especially poorly represented, with all the available studies conducted in South Africa and Zimbabwe, and only one (a study on nitrogen oxide emissions) was done on an agricultural site, rendering the IPCC Tier 1 estimates extremely coarse (Hickman et al. 2011).

More recently, a few studies were published on direct emissions, and were picked up in our search. Mapanda et al. (2011) measured direct emissions (CO₂, CH₄ and N₂O) from soils under maize cropping, as well as indirect N₂O emissions (Mapanda et al. 2012) from the same site in Zimbabwe. Also in Zimbabwe, Nyamadzawo et al. (2013) measured direct GHGs from flooded rice paddies, while in South Africa, Keutgen and Huysamer (1998) investigated soil respiration in apple orchards. Mapanda et al. (2011, 2012) and Nyamadzawo et al. (2013) acknowledged that the variation in emissions data is large, and consequently the confidence in fluxes is low. This was ascribed to the sporadic measurement and limited number of observations in southern Africa as a region.

It is reported that application of composted manure-N instead of mineral fertilizer (Mapanda et al. 2011) and intercropping in combination with

Table 3 Reference, context and reported greenhouse gas emissions (GHG) from peer-reviewed publications

References	Description	Result ^a		
		CO ₂	N ₂ O	CH ₄
Keutgen and Huysamer (1998)	Direct measurement (static chamber) of soil respiration from citrus orchard, RSA	0.1–0.4 g CO ₂ m ⁻² h ⁻¹		
Verge et al. (2007)	IPCC 2000 and UNFCCC online GHG database to determine CO ₂ and N ₂ O emissions from agricultural soils in Africa (2000)	626 Tg total GHG CO ₂ equivalent (eq)	345 Tg CO ₂ eq	
Eustice et al. (2011)	Modelling was used to determine CO ₂ and N ₂ O emissions under sugarcane production (burned vs trashed) for RSA	2522–3443 kg CO ₂ eq ha ⁻¹ season ⁻¹	1.7–11.3 kg N ha ⁻¹ season ⁻¹ (mean N ₂ O loss through denitrification)	
Hickman et al. (2011)	IPCC 2006 and EDGAR database was used to determine direct and indirect N ₂ O emissions for southern Africa	9–28 Gg yr ⁻¹		
Mapanda et al. (2011)	Direct measurement (static chamber) was used to determine GHG emissions from soils fertilized with cattle manure and NH ₄ NO ₃	0.1–90.3 mg CO ₂ -C m ⁻² h ⁻¹	0–32 µg N ₂ O-N m ⁻² h ⁻¹	Emissions: 1.7–1130 µg CH ₄ -C m ⁻² h ⁻¹ Consumption: –0.1 to –773 µg CH ₄ -C m ⁻² h ⁻¹
Kim (2012)	IPCC 2006 and linear interpolation methods to determine CO ₂ and N ₂ O emissions from soils associated with N fixing trees in Malawi	4.05–10.5 Mg C ha ⁻¹ yr ⁻¹	0.14 Mg CO ₂ eq ha ⁻¹ yr ⁻¹ (mitigation potential of N ₂ O)	
Mapanda et al. (2012)	IPCC 2006 to determine indirect N ₂ O for different soil types in Zimbabwe	0–197 g N ₂ O-N ha ⁻¹ season ⁻¹		
Nyamadzawo et al. (2013)	Direct measurement (static chamber) was used to determine GHG emissions from rice paddies in Zimbabwe	2680 kg ha ⁻¹ season ⁻¹ (average value for treatments)	0.12 kg ha ⁻¹ season ⁻¹ (average value)	12.54 kg ha ⁻¹ season ⁻¹ (average value)

^a Ranges of GHG emission are listed for relative comparison reasons, and are not sensitive to treatment effects

N-fixing trees (Kim 2012) may be a potential mitigation option against N₂O emissions. Nyamadzawo et al. (2013) found that intermittently saturated rice paddies are a potential source of significant GHGs and should receive more attention. It was also found that soil water content as

influenced by rainfall amount and distribution (Mapanda et al. 2012), degree of saturation (Nyamadzawo et al. 2013), clay content, fertilizer use (Mapanda et al. 2012) and ambient temperature (Keutgen and Huysamer 1998) influenced gas emissions from agricultural soils in varying degrees.

One of the possible reasons for the limited research on C sequestration and GHG emissions in southern Africa could be the lack of funding and analytical facilities, and a greater emphasis on production to alleviate food insecurity. While routine analysis for organic C or N can be handled by most laboratories, facilities to analyse gas samples, especially N₂O, at common atmospheric levels are not readily available. From the studies published on direct emissions, Mapanda et al. (2011, 2012) and Nyamadzawo et al. (2013) all had either European or American collaborators, stressing the fact that the facilities to do this research locally are severely limited.

Conclusions and recommendations

Research studies on SOM and its indicator elements C and N in agricultural soils have only recently (post-1990) gained momentum in southern Africa. Some of these studies give insight into C and N dynamics in cultivated fields, while others—or the lack thereof—clearly highlight gaps and research needs. The result of the 84 publications reviewed can be summarised as follows:

- Soil organic matter in agricultural fields in southern Africa has declined by 25 % in semi-arid areas, 53 % in sub-humid areas and 46 % in humid areas; with an average decline of 46 % due to cultivation. This figure may be more representative of the central maize-producing region of South Africa than of the entire sub-continent, due to very limited research studies done elsewhere. This is a huge concern, as it results in both elevated levels of GHGs in the atmosphere, and loss of soil quality which influences the production potential of soils in a region that is already food insecure.
- There is large variation in SOC levels in the sub-region, ranging from 0.7 % SOC in semi-desert areas to 2.5 % SOC in humid areas, with an overall average of 1.4 % SOC for cultivated fields.
- Cultivation reduces the relatively strong correlation between clay and SOM that is found in undisturbed soils. Care should thus be taken when applying certain modelling assumptions or predictions to cultivated agricultural soils.
- Duration of cultivation influences decline of SOM, and while initially this rate is rapid, it stabilises

after 30–40 years when a new equilibrium is reached.

The poor representation of certain topics highlights key research needs:

- There is a knowledge gap regarding how much C can realistically be restored in degraded agricultural soils in southern Africa. The limited scientific publications and unequal distribution of studies, combined with poor baseline data for most southern African countries (e.g. agro-ecological maps, detailed land-use maps, or GHG inventories) should be addressed.
- Gaseous losses from agricultural soils are grossly understudied. Limited research on topics such as C and N gaseous losses from agricultural soils, best management practices to reduce losses, and GHG emission factors are virtually lacking for southern Africa.
- Modelling will become more important as a way of estimating C sequestration, GHG emissions, and effect of management practices on C and N dynamics, but cannot be done in the absence of reliable measured data.

Acknowledgments The authors would like to acknowledge the ARC and the Water Research Commission (Project K5/2501, Quantifying and managing agricultural nitrogen and phosphorus pollution from field to catchment scale) for financial support and thank Dr. Thomas Fyfield (ARC-ISCW) for editorial comments.

References

- AfSIS (2014) The Africa soil information service: overview. <http://africasoils.net/data/overview>. Accessed 11 Dec 2014
- Almendros G, Giampaolo S, Pardo MT (2001) Laboratory appraisal of carbon sequestration and nutrient availability after different organic matter inputs in virgin and cultivated Zimbabwean soils. *Commun Soil Sci Plant Anal* 32(5, 6):877–894
- Amelung W, Lobe I, Du Preez CC (2002) Fate of microbial residues in sandy soils of South African Highveld as influenced by prolonged arable cropping. *Eur J Soil Sci* 53:29–35
- Ando K, Shinjo H, Noro Y, Takenaka S, Miura R, Sokotela SB, Funakawa S (2014) Short-term effects of fire intensity on soil organic matter and nutrient release after slash-and-burn in Eastern Province, Zambia. *Soil Sci Plant Nutr* 60(2):173–182
- Barnard RO, Du Preez CC (2004) Soil fertility in South Africa: the last twenty five years. *S Afr J Plant Soil* 21(5):301–315

- Barrios E, Kwesiga F, Buresh RJ, Sprent JI (1997) Light fraction soil organic matter and available nitrogen following trees and maize. *Soil Sci Soc Am J* 61:826–831
- Brodowski S, Amelung W, Lobe I, Du Preez CC (2004) Losses and biogeochemical cycling of soil organic nitrogen with prolonged arable cropping in the South African Highveld: evidence from D- and L-amino acids. *Biogeochemistry* 71:17–42
- Brouder SM, Gomez-Macpherson H (2014) The impact of conservation agriculture on smallholder agricultural yields: a scoping review of the evidence. *Agric Ecosyst Environ* 187:11–32
- Buhmann C, Beukes DJ, Turner DP (2006) Plant nutrient status of soils of the Lusikisiki area, Eastern Cape Province. *S Afr J Plant Soil* 23(2):93–98
- DEAT (Department of Environmental Affairs and Tourism) (2009). Greenhouse gas inventory of South Africa 1990–2000. National inventory report. Compilation under the United Nations framework convention on climate changes (UNFCCC). DEAT, RSA
- Dominati E, Patterson M, Mackay A (2010) A framework for classifying and quantifying the natural capital and ecosystem services of soils. *Ecol Econ* 69(9):1858–1868
- Dominy CS, Haynes RJ (2002) Influence of agricultural land management on organic matter content, microbial activity and aggregate stability in the profiles of two Oxisols. *Biol Fertil Soils* 36:298–305
- Dominy CS, Haynes RJ, Van Antwerpen R (2002) Loss of soil organic matter and related soil properties under long-term sugarcane production on two contrasting soils. *Biol Fertil Soils* 36:350–356
- Doran JW, Zeiss MR (2000) Soil health and sustainability: managing the biotic component of soil quality. *Appl Soil Ecol* 15:3–11
- Du Preez CC (2003) Volhoubare lanagebruik en grondkwaliteit: organiese materiaal as indikator. *S Afr Tydskr Natuurwetenskap Technol* 22(4):106–112
- Du Preez CC, Burger RT (1986) Anorganiese stikstof in miliegronde van die Oranje-Vrystaat en Transvaal met planttyd. *S Afr J Plant Soil* 3(3):148–150
- Du Preez CC, Du Toit ME (1995) Effect of cultivation on the nitrogen fertility of selected agro-ecosystems in South Africa. *Fertil Res* 42:27–32
- Du Preez CC, Wiltshire GH (1997) Changes in the organic matter and nutrient contents of some South African irrigated soils. *S Afr J Plant Soil* 14(2):49–53
- Du Preez CC, Steyn JT, Kotze E (2001) Long-term effects of wheat residue management on some fertility indicators of a semi-arid Plinthosol. *Soil Tillage Res* 63:25–33
- Du Preez CC, Mkeni P, Van Huyssteen C (2010) Knowledge review on land use and soil organic matter in South Africa. In: Proceedings of the 19th world congress of soil science, soil solutions for a changing world. 1–6 Aug, Brisbane, Australia
- Du Preez CC, Van Huyssteen CW, Mkeni PNS (2011a) Land use and soil organic matter in South Africa 1: a review on spatial variability and the influence of rangeland stock production. *S Afr J Sci* 107(5, 6):27–34
- Du Preez CC, Van Huyssteen CW, Mkeni PNS (2011b) Land use and soil organic matter in South Africa 2: a review on the influence of arable crop production. *S Afr J Sci* 107(5, 6):35–42
- Du Toit ME, Du Preez CC (1993) Verwantskap tussen organiese materiaalinhoud van sekere onversteurde ortiese bogronde, grondeienskappe en klimaatsdata in Suid-Afrika. *S Afr J Plant Soil* 10(4):168–173
- Du Toit ME, Du Preez CC (1995) Effect of cultivation on the nitrogen fertility of selected dryland soils in South Africa. *S Afr J Plant Soil* 12:73–81
- Du Toit ME, Du Preez CC, Hensley M, Bennie ATP (1994) Effect of cultivation on the organic matter content of selected dryland soils in South Africa. *S Afr J Plant Soil* 11(2):71–79
- Dube E, Chiduzza C, Muchanonyerwa P (2012) Conservation agriculture effects on soil organic matter on a Haplic Cambisol after four years of maize-oat and maize-grazing vetch rotations in South Africa. *Soil Tillage Res* 123:21–28
- Eustice T, Van Der Laan M, Van Antwerpen R (2011) Comparison of greenhouse gas emissions from trashed and burnt sugarcane cropping systems in South Africa. *Proc S Afr Sugar Technol Assoc* 84:326–339
- FAO (1996) Food, agriculture, and food security: developments since the world food conference and prospects, world food summit technical background doc 1. Food and Agriculture Organisation, Rome
- Fourie JC (2012) Soil management in the Breede River Valley Wine Grape Region, South Africa. 4. Organic matter and macro-nutrient content of a medium-textured soil. *S Afr J Enol Vitic* 33(1):105–114
- Fourie JC, Agenbag GA, Louw PJE (2007a) Cover crop management in a chardonnay/99 Richter vineyard in the coastal region, South Africa. 3. Effect of different cover crops and cover crop management practices on organic matter and macro-nutrient content of a medium-textured soil. *S Afr J Enol Vitic* 28(1):61–68
- Fourie JC, Agenbag GA, Louw PJE (2007b) Cover crop management in a Sauvignon Blanc/Ramsey vineyard in the semi-arid Olifants River Valley, South Africa. 3. Effect of different cover crops and cover crop management practices on the organic matter and macro-nutrient contents of a sandy soil. *S Afr J Enol Vitic* 28(2):92–100
- Gillson L, Midgley GF, Wakeling JL (2012) Exploring the significance of land-cover change in South Africa. *S Afr J Sci* 108(5–6):1–3
- Graham MH, Haynes RJ (2005) Organic matter accumulation and fertilizer-induced acidification interact to affect soil microbial and enzyme activity on a long-term sugarcane management experiment. *Biol Fertil Soils* 41:249–256
- Graham MH, Haynes RJ (2006) Organic matter status and the size, activity and metabolic diversity of the soil microbial community in the row and inter-row of sugarcane under burning and trash retention. *Soil Biol Biochem* 38:21–31
- Graham MH, Haynes RJ, Meyer JH (2002) Soil organic matter content and quality: effects of fertilizer applications, burning and trash retention on a long-term sugarcane experiment in South Africa. *Soil Biol Biochem* 34(1):93–102
- Greyling NB, Du Preez CC, Human JJ (1990) Net nitrogen mineralization in cultivated and uncultivated soils of the maize producing areas in South Africa. *S Afr J Plant Soil* 7(1):26–31

- Haynes RJ, Dominy CS, Graham MH (2003) Effect of agricultural land use on soil organic matter status and the composition of earthworm communities in KwaZulu-Natal, South Africa. *Agric Ecosyst Environ* 95:453–464
- Hengl T, De Jesus JM, MacMillan RA, Batjes NH, Heuvelink GBM, Ribeiro E et al (2014) SoilGrids1 km—global soil information based on automated mapping. *PLoS ONE* 9(8):e105992. doi:10.1371/journal.pone.0105992
- Hensley M, Le Roux P, Du Preez CC, Van Huyssteen C, Kotze E, Van Rensburg L (2006) Soils: the Free State's agricultural base. *S Afr Geogr J* 88(1):11–21
- Hickman JE, Mavlikova M, Kroeze C, Palm CA (2011) Current and future nitrous oxide emissions from African agriculture. *Curr Opin Environ Sustain* 3:370–378
- ISRIC—World Soil Information (2013) Soil property maps of Africa at 1 km. <http://www.isric.org/data/soil-property-maps-africa-1-km>. Accessed 11 Dec 2014
- Jobbagy EG, Jackson RB (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecol Appl* 10(2):423–436
- Keutgen N, Huysamer M (1998) Rootstock-dependent soil respiration in a citrus orchard. *S Afr J Plant Soil* 15(3):93–98
- Kim D (2012) Estimation of net gain of soil carbon in a nitrogen-fixing tree and crop intercropping system in sub-Saharan Africa: results from re-examining a study. *Agrofor Syst* 86:175–184
- Kindermann GE, McCallum I, Fritz S, Obersteiner M (2008) A global forest growing stock, biomass and carbon map based on FAO statistics. *Silva Fenn* 42(3):387
- King JA, Campbell BM (1994) Soil organic matter relations in five land cover types in the miombo region (Zimbabwe). *For Ecol Manag* 67:225–239
- Kosters R, Preger AC, Du Preez CC, Amelung W (2013) Re-aggregation dynamics of degraded cropland soils with prolonged secondary pasture management in the South African Highveld. *Geoderma* 192:173–181
- Kotze E, Du Preez CC (2007) Influence of long-term wheat residue management on organic matter in an Avalon soil. *S Afr J Plant Soil* 24(2):114–119
- Kotze E, Du Preez CC (2008) Influence of long-term wheat residue management on acidity and some macronutrients in an Avalon soil. *S Afr J Plant Soil* 25(1):14–21
- Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. *Science* 304:1623–1627
- Lal R, Stewart BA (eds) (2010) Food security and soil quality. CRC Press, Taylor and Francis Group, New York
- Laubscher DJ, Du Preez CC (1991) The relationship between maximum nitrification rate and relevant properties of soils from the central irrigation areas in South Africa. *S Afr J Plant Soil* 8(1):22–26
- Lauer F, Kosters R, Du Preez CC, Amelung W (2011) Microbial residues as indicators of soil restoration in South African secondary pastures. *Soil Biol Biochem* 43:787–794
- Lobe I, Amelung W, Du Preez CC (2001) Losses of carbon and nitrogen with prolonged arable cropping from sandy soils of the South African Highveld. *Eur J Soil Sci* 52:93–101
- Lobe I, Du Preez CC, Amelung W (2002) Influence of prolonged arable cropping on lignin compounds in sandy soils of the South African Highveld. *Eur J Soil Sci* 53:553–562
- Lobe I, Bol R, Ludwig B, Du Preez CC, Amelung W (2005) Savanna-derived organic matter remaining in arable soils of the South African Highveld long-term mixed cropping: evidence from C-13 and N-15 natural abundance. *Soil Biol Biochem* 37:189–1909
- Lobe I, Sandhage-Hofmann A, Brodowski S, Du Preez CC, Amelung W (2011) Aggregate dynamics and associated soil organic matter contents as influenced by prolonged arable cropping in the South African Highveld. *Geoderma* 162:251–259
- Loke PF, Kotze E, Du Preez CC (2012) Changes in soil organic matter indices following 32 years of different wheat production management practices in semi-arid South Africa. *Nutr Cycl Agroecosyst* 94:97–109
- Mapanda F, Wuta M, Nyamangara J, Rees RM (2011) Effects of organic and mineral fertilizer nitrogen on greenhouse gas emissions and plant-captured carbon under maize cropping in Zimbabwe. *Plant Soil* 343:67–81
- Mapanda F, Wuta M, Nyamangara J, Rees RM (2012) Nitrogen leaching and indirect nitrous oxide emissions from fertilized croplands in Zimbabwe. *Nutr Cycl Agroecosyst* 94:85–96
- Mapfumo P, Mtambanengwe F, Vanlauwe B (2007) Organic matter quality and management effects on enrichment of soil organic matter fractions in contrasting soils in Zimbabwe. *Plant Soil* 296:137–150
- Materechera SA, Mandiringana OT, Mbokodi PM, Nyamapfene K (1998) Organic matter, pH and nutrient distribution in soil layers of a savanna Thornveld subjected to different burning frequencies at Alice in the Eastern Cape. *S Afr J Plant Soil* 15(3):109–115
- Matlou MC, Haynes RJ (2006) Soluble organic matter and microbial biomass C and N in soils under pastures and arable management and the leaching of organic C, N and nitrate in a lysimeter study. *Appl Soil Ecol* 34:160–167
- Meyer JH (1989) Rapid simultaneous rating of soil texture, organic matter, total nitrogen and nitrogen mineralization potential by near infra-red reflectance. *S Afr J Plant Soil* 6(1):59–63
- Meyer JH, Van Antwerpen R (2010) Advances in sugarcane soil fertility research in Southern Africa. *S Afr J Plant Soil* 27(1):19–31
- Meyer JH, Wood RA, McIntyre RK, Leibbrandt NB (1983) Classifying soils of the South African sugar industry on the basis of their nitrogen mineralizing capacities and organic matter contents. *Proc S Afri Sugar Technol Assoc* 57:151–158
- Miles N, Meyer JH, Van Antwerpen R (2008) Soil organic matter: what do they mean? *Proc S Afr Sugar Technol Assoc* 81:324–332
- Mills AJ, Fey MV (2003) Declining soil quality in South Africa: effects of land use on soil organic matter and surface crusting. *S Afr J Sci* 99:429–436
- Mills AJ, Fey MV (2004) Soil carbon and nitrogen in five contrasting biomes of South Africa exposed to different land uses. *S Afr J Plant Soil* 21(2):94–103
- Mills AJ, O'Connor TG, Donaldson JS, Fey MV, Skowno AL, Sigwela AM, Lechmere-Oerel RG, Bosenberg JD (2005) Ecosystem carbon storage under different land uses in three semi-arid shrublands and a mesic grassland in South Africa. *S Afr J Plant Soil* 22(3):183–190

- Milne RM, Haynes RJ (2004) Soil organic matter, microbial properties, and aggregate stability under annual and perennial pastures. *Biol Fertil Soils* 39:172–178
- Mrabet R (2002) Stratification of soil aggregation and organic matter under conservation tillage systems in Africa. *Soil Tillage Res* 66:119–128
- Mtambanengwe F, Mapfumo P (2005) Organic matter management as an underlying cause for soil fertility gradients on smallholder farms in Zimbabwe. *Nutr Cycl Agroecosyst* 73:227–243
- Mujuru L, Mureva A, Velthorst EJ, Hoosbeek MR (2013) Land use and management effects on soil organic matter fractions in Rhodic Ferralsols and Haplic Arenosols in Bindura and Shamva districts of Zimbabwe. *Geoderma* 209–210:262–272
- Nciizah AD, Wakindiki IIC (2014) Particulate organic matter, soil texture and mineralogy relations in some Eastern Cape ecotopes in South Africa. *S Afr J Plant Soil* 29(1):39–46
- Nel PC, Barnard RO, Steynberg RE, De Beer JM, Groenwald HT (1996) Trends in maize grain yields in a long-term fertilizer trial. *Field Crop Res* 47:53–64
- New M, Lister D, Hulme M, Makin I (2002) A high-resolution data set of surface climate over global land areas. *Clim Res* 21(1):1–25
- Nhantumbo ABJ, Katterer T, Ledin S, Du Preez CC (2009a) Carbon loss from *Brachystecia spiciformis* leaf litter in the sandy soils of southern Mozambique. *Nutr Cycl Agroecosyst* 83:13–26
- Nhantumbo ABJC, Ledin S, Du Preez CC (2009b) Organic matter recovery in sandy soils under bush fallow in southern Mozambique. *Nutr Cycl Agroecosyst* 83:153–161
- Nyamadzawo G, Wuta M, Chirinda N, Mujuru L, Smith JL (2013) Greenhouse gas emissions from intermittently flooded (dambo) rice under different tillage practices in Chiota smallholder farming area of Zimbabwe. *Atmos Clim Sci* 3:13–20
- Pardo MT, Ristori G, D'Acqui LP, Almendros G (2003) An assessment of soil fertility and agronomic constraints in Southern African savannahs: a case study of the Pandamatenga area, Botswana. *S Afr Geogr J* 85(1):35–41
- Pardo MT, Almendros G, Zancada MC, Lopez-Fando C (2010) Biofertilization of degraded southern African soils with cyanobacteria affects organic matter content and quality. *Arid Land Res Manag* 24(4):328–343
- Pardo MT, Almendros G, Zancada MC, Lopez-Fando C, Gonzalez-Vila FJ (2012) Cultivation-induced effects on the organic matter in degraded Southern African soils. *Commun Soil Sci Plant Anal* 43:541–555
- Pardo MT, Almendros G, Zancada MC, Lopez-Fando C, Gonzalez-Vila FJ (2014) Cultivation-induced effects on the organic matter in degraded southern African soils. *Comm Soil Sci Plant Anal* 43(3):541–555
- Pearson CHO (1952) The maintenance of organic matter in the soils of the Natal Coast Belt. *S Afr Sugar J* 36:17–23
- Prinsloo MA, Wiltshire GH, Du Preez CC (1990) Loss of nitrogen fertility and its restoration in some Orange Free State Soils. *S Afr J Plant Soil* 7(1):55–61
- Rowell MJ, Coetzee ME (2002) The measurement of low organic matter contents in soils. *S Afr J Plant Soil* 20(2):49–53
- Schlesinger WH (1997) Biogeochemistry and analysis of global change. Academic Press, San Diego
- Schmidt G, Schmidt U (1963) Soil organic matter and nitrogen contents of veld and cultivated soils in the central Orange Free State. *Plant Soil* 19(3):315–323
- Shoko MD, Moyo S (2011) Soil characterization in contrasting cropping systems under the fast track land reform programme in Zimbabwe. *Afr J Food Agric Nutr Dev* 11(3)
- Smil V (1999) Nitrogen in crop production: an account of global flows. *Glob Biogeochem Cycles* 13(2):647–662
- Smith P, Martino Z, Cai D, Gwary H, Janzen P, Kumar B, McCarl S, Ogle F O'mare, Rice C, Scholes B, Sirotenko O (2007) Agriculture. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Climate change 2007: mitigation. Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
- Snapp SS, Mafongoya PL, Waddington S (1998) Organic matter technologies for integrated nutrient management in smallholder cropping systems of southern Africa. *Agric Ecosyst Environ* 71:185–200
- Stevenson FJ, Cole MA (1999) Cycles of soil. Carbon, nitrogen, phosphorus, sulphur, micronutrients, 2nd edn. Wiley, New York, pp 46–47
- Stronkhorst L, Venter A (2008) Investigating the soil organic carbon status in South African soils and the relationship between soil organic carbon and other soil chemical properties. ARC-Institute for Soil Climate and Water, Report Nr GW/A/2008/24. Pretoria, South Africa
- Swanepoel PA, Habig J, Du Preez CC, Botha PR, Snyman HA (2014) Biological quality of a podzolic soil after 19 years of irrigated minimum-till kikuyu-ryegrass pasture. *Soil Res* 52:64–75
- Tagwira F, Piha M, Mugwira L (1992) Effect of pH, and phosphorus and organic matter contents on zinc availability and distribution in two Zimbabwean soils. *Commun Soil Sci Plant Anal* 23(13, 14):1485–1500
- Van der Mey GA, Combrink HM, Du Preez CC (1994) Nitrogen mineralization in selected soils from the maize producing areas of South Africa. *S Afr J Plant Soil* 11(2):64–70
- Van der Watt HH (1987) The effect of reduced tillage on soil organic carbon. *S Afr J Plant Soil* 4(3):147–149
- Verge XPC, De Kimpe C, Desjardins RL (2007) Agricultural production, greenhouse gas emissions and mitigation potential. *Agric For Meteorol* 142(2–4):255–269
- Watson RGT (1954) Organic matter and sugar cane agronomy. Improving the level under field conditions. *S Afr Sugar J* 38:319–327
- Wattel-Koekkoek EJW, Buurman P (2004) Mean residence time of kaolinite and smectite-bound organic matter in Mozambiquan soils. *Soil Sci Soc Am J* 68:154–161
- Wattel-Koekkoek EJW, Van Genuchten PPL, Buurman P, Van Lagen B (2001) Amount and composition of clay-associated soil organic matter in a range of kaolinitic and smectitic soils. *Geoderma* 99:27–49
- Weil RR, Magdoff F (2004) Significance of soil organic matter to soil quality and health. In: Magdoff F, Weil RR (eds) Soil organic matter in sustainable agriculture. CRC Press, New York, pp 1–43

Wiltshire GH, Du Preez CC (1993) Long-term effects of conservation practices on the nitrogen fertility of soil cropped annually to wheat. *S Afr J Plant Soil* 10(2):70–76

Zingore S, Manyame C, Nyamugafata P, Giller KE (2005) Long-term changes in organic matter of woodland soils cleared for arable cropping in Zimbabwe. *Eur J Soil Sci* 56:727–736