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

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ABSTRACT

Soil organic matter (SOM) is tightly linked to soil quality, but cultivation generally causes a rundown of 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] in cultivated fields in southern Africa. A total of 84 publications were assessed, and information such as date, location, SOM/soil organic carbon (SOC) content, clay and key findings were recorded. The spatial distribution of these studies is very unequal, and focused on the central maize producing areas of South Africa. Analysis of the data shows an average SOC of 0.7 % in low rainfall areas, and up to 2.5% in higher rainfall areas. A rundown of 46% of SOC due to cultivation was representative for all cultivated fields in southern Africa (R^2 = 0.84). Research gaps include understanding C sequestration and GHG emission dynamics under various management systems and for different climatic regions, which are important from a soil quality perspective as well as for inventory purposes; to help understand how field crop production can play a role in mitigating climate change; as well as a lack of multi-institutional collaboration and facilities.

Keywords: agriculture, carbon sequestration, cultivated soil, greenhouse gas emissions, soil organic matter, southern Africa

INTRODUCTION

Soil quality can be defined as the ability of soil to preform or function according to its potential (Doran & 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 et al. 2004). Ecologically, soils provide a range of ecosystem 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, salinization, acidification and nutrient mining (Lal and Stewart 2010). The 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 methane (CH_4) and nitrous oxide (N_2O) 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 by reviewing published research on SOM and its indicator elements C and N – including GHG emissions – for cultivated land in southern Africa. 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 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 were 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 it 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. A total of 84 publications met the criteria of being suitably focussed on agricultural SOM related research and were used as a representative sample in the meta-analysis. 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 & 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).

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 Merwe 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]; Kosters 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 1993[S]; Du Toit and Du Preez 1993[S]; Mills and Fey 2004[S]; Mills et al. 2005[S]; Nhantumbo et al. 2009a[S].

Superscript: R= Review publication (n=16), S = Surveys (n=45) and T= Trials (n=23)

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 other listed several values for one location (e.g. research trial) while still others 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 (Schmidt and Schmidt 1963). We standardized all the collated results from various publications on topsoil SOC in percentage for further analysis and comparisons.

Map preparation

Precipitation zone map

Soil organic matter study location points were plotted on a total annual precipitation map (New et al. 2002), in order to evaluate how representative the distribution of SOM studies are in terms of precipitation variation. There is a strong link between SOC and climatic properties, especially precipitation, which is linked to distribution of vegetation, soil formation, rate of mineralization, as well as SOC, making it an appropriate parameter to evaluate degree of representation of current studies (Weil and Magdoff 2004).

The Climatic Research Unit (CRU), University of East Anglia, have prepared a 10' latitude/longitude dataset of mean monthly surface climate, which includes precipitation (New et al. 2014). The gridded data was interpolated by the CRU from a data set of weather station means for the period from 1961 to 1990. 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 map

Soil maps for Africa (SoilsGrid1km) have been produced at 30" resolution using an automated spatial prediction framework (ISRIC, 2013; AfSIS 2014; Hengl et al. 2014). Spatial prediction models were fitted per soil variable (such as SOC, pH, texture, course fragments, bulk density, depth to bedrock and cation exchange capacity), using a compilation of major international soil profile databases (ca. 12 000 soil profiles), and a selection of ca. 75 global environmental covariates representing soil forming factors. The environmental covariate layers include products derived from remote sensing imagery such as MODIS (Moderate Resolution Imaging Spectroradiometer) and SRTM (Shuttle Radar Topography Mission) terrain models. Soil organic carbon is classified into six classes (0-5, 5-10, 10-20 and 20-30 g kg^{-1} in the 0-50 mm top layer).

RESULTS AND DISCUSSION

I Temporal and spatial characteristics of research studies

Survey publications were most common, consisting of 54% of the total, followed by trials (27%) and review publications (19%) (Table 1). 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 to the worldwide interest in C

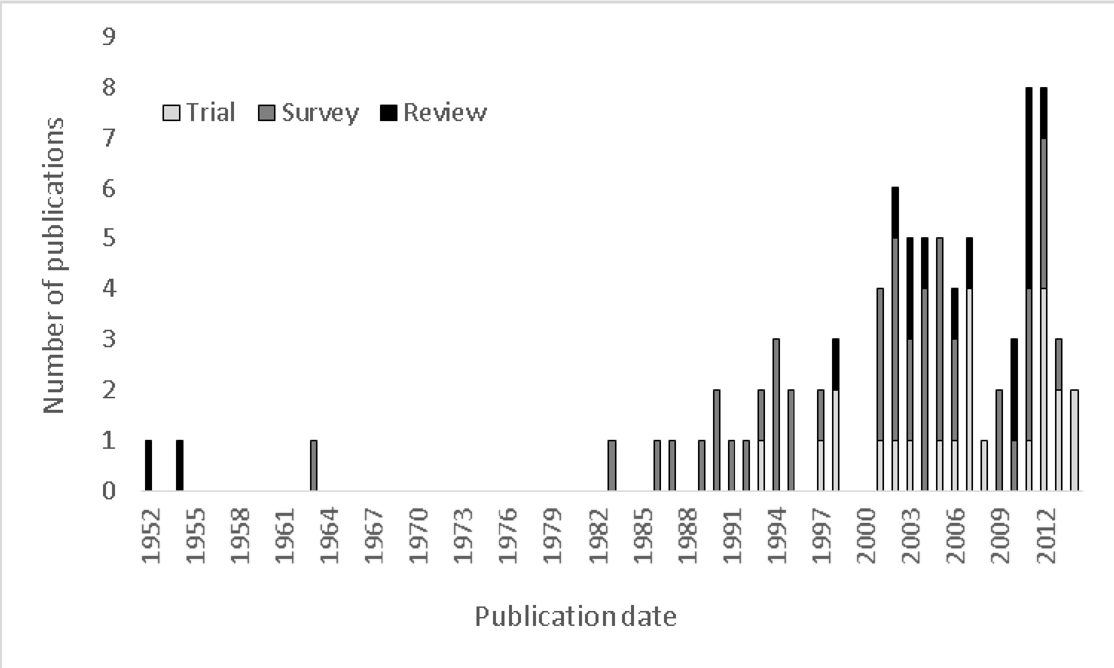

Fig. 1 Temporal distribution of 84 peer reviewed articles on SOM in southern Africa

and global warming /climate change as a research topic, which gained momentum in the 1990's as marked with the establishment of the Intergovernmental Panel on Climate Change (IPCC). The number of peer reviewed publications on SOM has increased in the last decade (Fig. 1). Most of the research topics focused on soil chemistry as well as fertility and nutrition (Table 1).

Analysing the publication sample, the distribution of research (in terms of locations studied) in countries of southern Africa is biased toward RSA (70%), followed by Zimbabwe (15%) and Mozambique (4%). Studies that summarised results for Africa as a continent, consisted of 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).

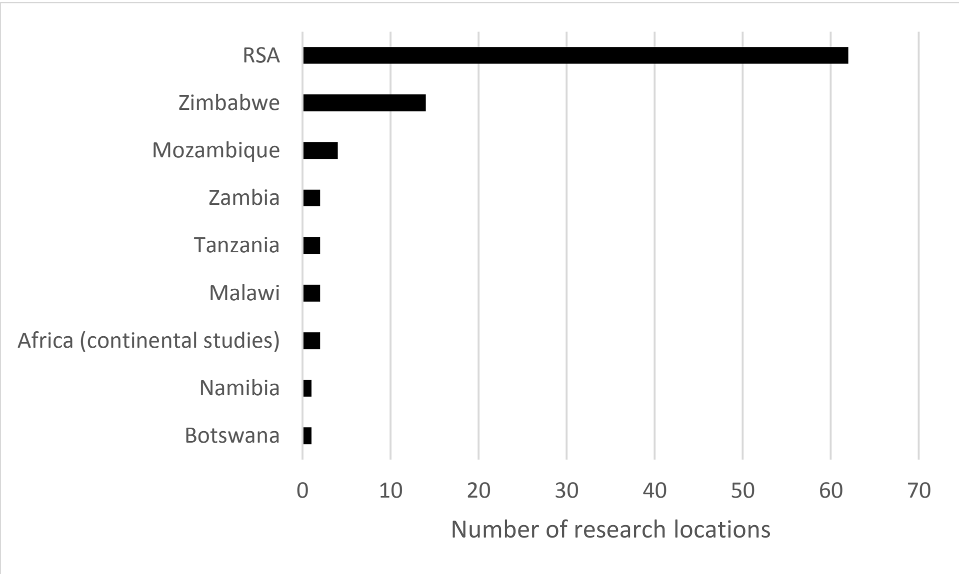

Fig. 2 Number of research locations in various countries in southern Africa

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

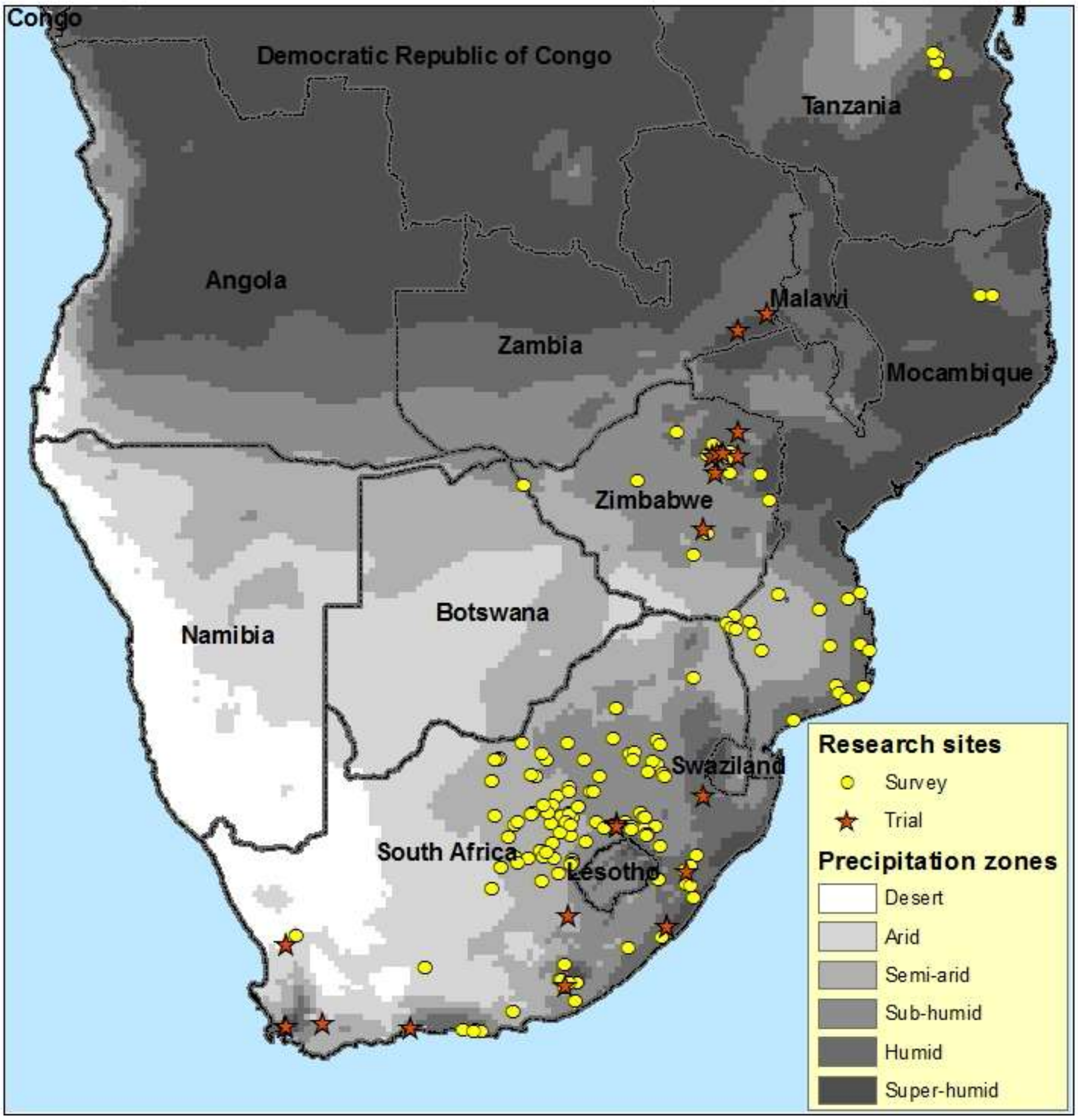

Fig. 3 Distribution of research locations, as extracted from peer reviewed publications, relative to precipitation zones of southern Africa

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 in this category. This is most likely as a result of high levels of SOM occurring in these regions and therefore not being perceived to be a limiting factor for crop production, but also because of extensive civil unrest in the region, such as the Angolan War of Independence (1961-1974), the

Angolan Civil War (1975-2002), Mozambique's Civil War (1977-1992), and the ongoing conflict in the Congolese region (since 1960) (www.wikipedia.org).

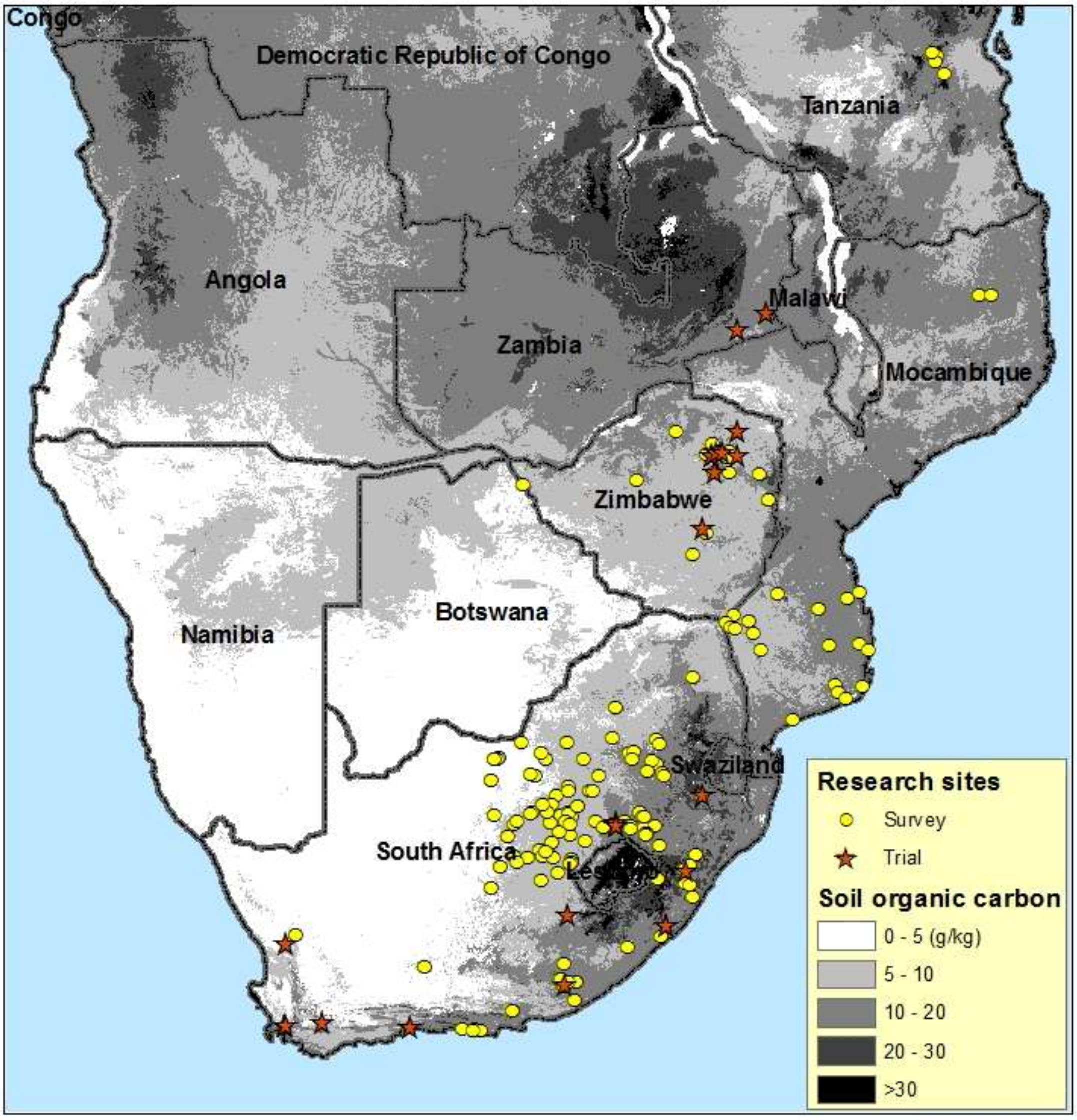

Fig. 4 Distribution of research locations, as extracted from peer reviewed publications, relative to the SoilGrid1km map (AfSIS 2014) of soil organic carbon zones of southern Africa

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. Other studies have confirmed that South Africa, for instance, is characterized by low SOC content with 58% of the soils containing less than 5 g kg^{-1} SOC and only 4% of the soils containing more than 20 g kg^{-1} SOC (Barnard 2000). 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 5-10 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 >30 g kg^{-1} in the SOC zone.

The SoilGrid1km map of SOC can be a useful tool for basin scale studies and estimates, but should be used with caution. Using simple linear regression to compare our sample's measured data with corresponding values from the map gives a relatively poor correlation (R^2=0.5) (Fig. 5). The reason for this poor correlation can be ascribed to inadequate models, large local variation in SOC content, different topsoil depths reported, land-use effects, and rundown of SOC in cultivated fields.

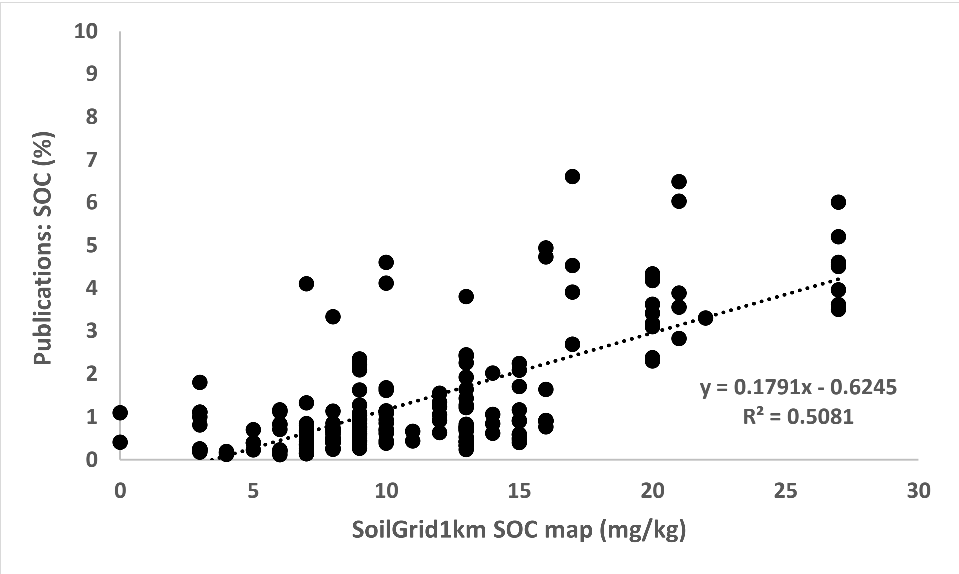

Fig. 5 Comparing predicted SOC values from SoilGrid1km SOC map (AfSIS 2014), to reported values in publications for same location points

II Carbon and N dynamics

Common research themes in the selected publications included a rundown of SOM associated with cultivation, and subsequently a range of possible options to retain or restore the lost C and N. These approaches include conservation agriculture practices such as minimum/reduced tillage, crop rotation or intercropping, or crop diversification, and inclusion of legume crops and cover crops. Some topics also centred on the *status quo* of SOM, or fertility, of certain areas. Other publications explored the various primary factors that have an effect on SOM and SON. A limited number of studies investigated the associated GHG emissions from agricultural soils.

Soil organic matter content in cultivated soils

Reporting SOM or SOC for varying depths and across different rainfall regions complicates comparison of this variable across different studies. SOM is strongly correlated to 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 intervals, such as 50 or 75 mm. Despite this, only 3% of all reported SOC levels were collected from the top 50 mm. Most studies (23%) reported SOC for the 0-200 mm soil depth. We categorised the 294 reported values per rainfall class and depth (Table 2). The large standard deviations for the reported values could be partly due to small sample size, but also due to other factors influencing SOC, such as treatment effects and clay content as well as soil heterogeneity.

Soil organic matter rundown due to cultivation

Rundown of SOM is a common theme in the reviewed publications. We collated all the reported data where SOC from natural or undisturbed soils and adjacent cultivated fields

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

Soil Depth (mm)	Rainfall 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)**

were reported (n=74, locations=48), and used a simple linear regression to compare these values (Fig. 6). The slope (0.54) of the regression line represents the degree of rundown, suggesting that over a wide range of SOC levels, and a range of production practices over

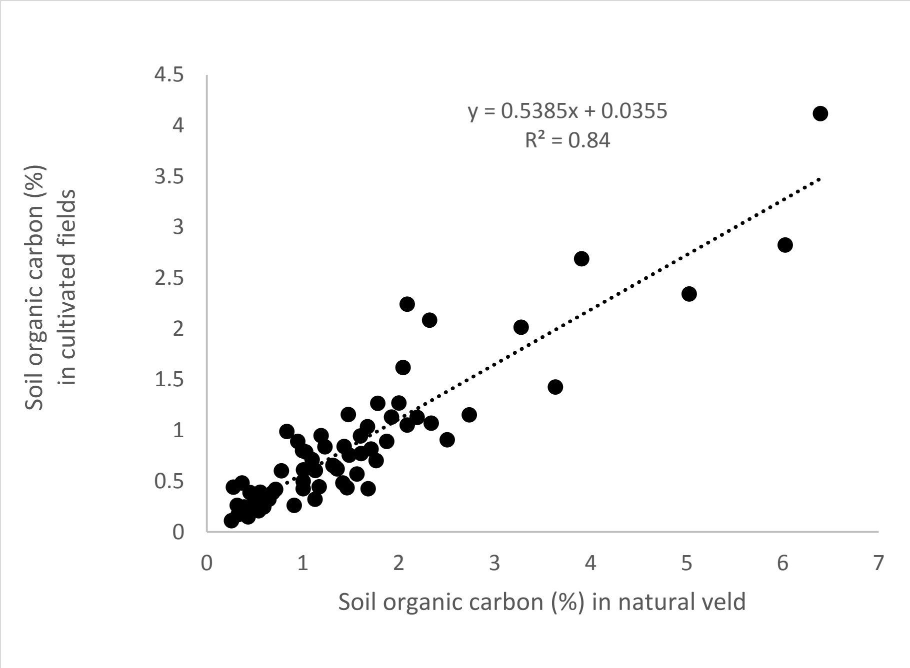

Fig. 6 Relationship between soil organic carbon in undisturbed areas and corresponding cultivated fields (n =74, locations = 48)

varying time intervals, cultivation leads to an average overall loss of 46% SOC in southern African croplands. This value will change with, for instance, the duration of cultivation or type of cultivation practice, but the good fit (R^2=0.84) indicates that cultivation leads to almost half SOC rundown.

Researchers reported varying degrees of SOC rundown: 10% SOC rundown after Miombo woodland was converted to maize fields in Zimbabwe (King & Campbell 1994); 10-75% loss after 5-90 years of cultivation in the Free State Province, South Africa (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 (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 South Africa where SOC in some fields under irrigation declined with 12-49%, while in other areas *increased* by 19-33%. This is probably 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.

The mechanisms of SOM rundown dynamics has been studied in terms of duration of cultivation. Rapid decline in SOC 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 years, 30-40 years and 34 years, respectively. Differences in the rate at which SOC was lost, can be attributed to climatic conditions, type and quality of organic matter, management practices and clay content (Mills and Fey 2004; Wattel-Koekkoek and Buurman 2004; Du Preez et al. 2011a; Loke et al. 2012). Interestingly, Wattel-Koekkoek and Buurman (2004) observed that the type of clay did not significantly influence the residence time of organic matter and C in the soil.

Varying results on management effect on SOM build-up or retention are reported. Limited success was achieve in restoring N fertility under a wheat trial in central RSA (Wiltshire and Du Preez 1993). Some cultivation efforts do appear to reduce the rapid decline of SOC. Few studies reported positive SOC retention which 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 crops, green manure (Fourie et al. 2007; Fourie 2012) and pastures (Haynes et al. 2003).

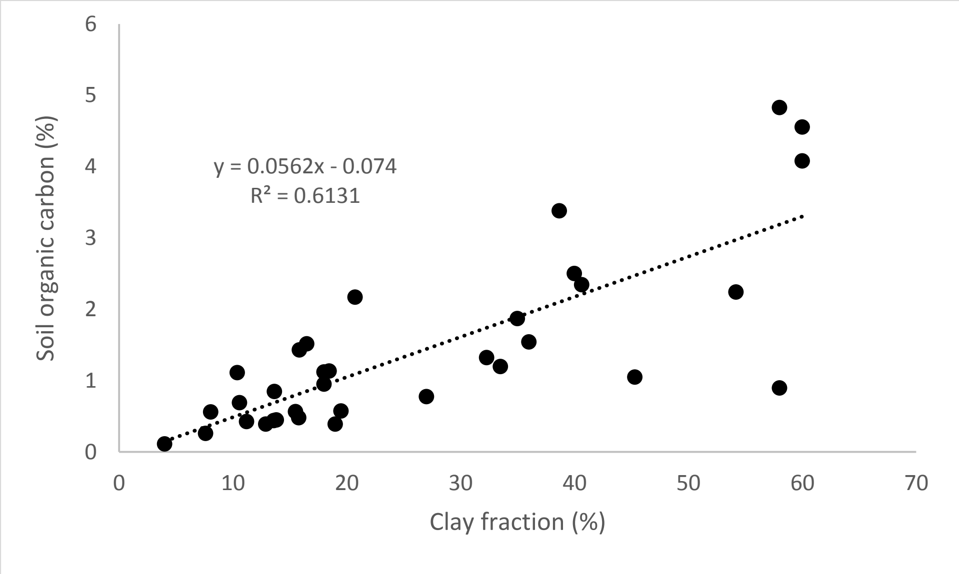

Fig. 7 Correlation between reported clay content and SOC from selected publications for southern Africa

Soil organic carbon and clay content

The correlation of R^2=0.61 (n=34) between SOC and clay content for cultivated topsoils (Fig. 7) is not as strong as SOC/clay relations in undisturbed soils. Du Toit & 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 & 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 comparing SOC and clay content for KwaZula 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 the 'mixed bag' of data and drastically modified conditions for these soils: in general a rundown of SOC is 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 also no representation of duration of cultivation, where recently cultivated soils would be expected to have lost less SOC than long term cultivated soils. This relative poor correlation of SOC versus clay fraction could partly explain the poor correlation between SOC values in our sample compared to SOC values in the SoilGrid1km SOC map (Figs. 4 and 5). Clay (or soil texture) is one of the soil properties used to derive the maps (AfSIS, 2014, Hengl et al. 2014), but the SOC vs clay relationship changes under cultivated conditions.

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 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 characterization of N status (Mills and Fey 2004), N mineralization (Meyer et al. 1983; Geyling 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 soil N levels. The loss of N fertility is mainly attributed to a reduction in the organic N pool. Nitrogen decline was unique for each ecotope, where in warmer, drier areas N declines at a quicker rate compared to in cooler wetter ecotopes (Du Toit and Du Preez 1995). In some studies, relatively more C than N was lost under cultivation, possibly due to removal of organic matter with a higher C:N ratio during harvesting, or a higher N mineralization 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 35-65% (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.

Greenhouse gas emissions from cultivated soil

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 & Huysamer 1998; Mapanda et al. 2011; Kim 2012, Mapanda et al. 2012; Nyamadzawo 2013).

The review articles reported GHG emissions for the continent (Verge et al. 2007; Hickman et al. 2011), or for a sub-region under specific crop production (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 system 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), and in a more recent publication, Van der Laan et al. (2015), 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 (study on nitrogen oxide emissions) was done on an agricultural site, rendering the IPCC Tier 1 estimates very 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 (carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)) from soils under maize cropping, as well as indirect N_2O 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. Kim (2012) re-calculated emission data from a previous publication. Mapanda et al. (2011, 2012) and Nyamadzawo et al. (2013) acknowledged that the variation in emission data is large, and subsequently the confidence in fluxes are 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 N-fixing trees (Kim 2012) may be a potential mitigation option against N_2O emissions. Nyamadzawo et al. (2013) found that intermittently saturated rice paddies are a potential source of significant GHGs and need to 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 emission in southern Africa could be the lack of funding and 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 N_2O, at common atmospheric levels are not readily available. From the studies published on direct emissions, Mapanda et al. (2011), Mapanda et al. (2012) and Nyamadzawo et al. (2013) all had either European or American collaborators, stressing the fact that the facilities to do this research locally is severely limited.

CONCLUSIONS AND RECOMMENDATIONS

Cultivation is usually associated with SOM loss, and these data indicate that in southern Africa 46% of organic matter has been lost from cultivated soils. This figure is 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. 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. Duration of cultivation also influences rundown of SOM, and while initially the rate rundown is rapid, it stabilizes after 30 to 40 years when a new equilibrium is reached. Having lost almost half the SOC in cultivated fields is a huge concern, as it results in both elevated levels of GHG in the atmosphere, but perhaps more importantly the loss of soil quality which influences the production potential of soils in a region that is already food insecure. There is clearly a knowledge gap regarding how much C can realistically be restored in rundown 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. detailed land-use maps, or GHG inventories) are a concern highlighting the need for more research funding on this serious topic. 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. Increasing sequestration of C in soils must be recognised as a win-win situation as it not only remove C from the atmosphere, but also improves soil quality.

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