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# The benefits of conservation agriculture on soil organic carbon and yield in southern Africa are site-specific

C.M. Swanepoel[a,b,*], R.P. Rötter[c,d], M. van der Laan[b], J.G. Annandale[b], D.J. Beukes[a], C.C. du Preez[e], L.H. Swanepoel[f], A. van der Merwe[g], M.P. Hoffmann[c]

[a] Agricultural Research Council (ARC)-Institute for Soil, Climate and Water, Belvedere Street 600, Pretoria 0001, South Africa
[b] University of Pretoria, Department of Plant and Soil Sciences, Hatfield, Pretoria 0028, South Africa
[c] University of Goettingen, Tropical Plant Production and Agricultural System Modelling (TROPAGS), Grisebachstraße 6, 37077 Goettingen, Germany
[d] University of Goettingen, Centre of Biodiversity and Sustainable Land Use (CBL), Buesgenweg 1, 37077 Goettingen, Germany
[e] Department of Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein 9300, South Africa
[f] Department of Zoology, University of Venda, Thohoyandou 0950, South Africa
[g] Department of Development Economics and Cooperation, Swiss Federal Institute of Technology (ETH), Zurich 8093, Switzerland

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ABSTRACT

Conservation agriculture (CA), with reduced tillage, permanent soil cover and diversified cropping systems, is advocated in southern Africa to improve soil quality, reduce input costs and mitigate climate-induced risks. However, improvements in terms of yield and soil organic carbon (SOC) under CA are slow and variable and many small-scale farmers are unable to buffer themselves against potential short-term financial losses. In this study we examined the effects of CA-related management practices on SOC sequestration and productivity at two medium-term sites on a sandy soil (eight year trial) and clay soil (six years) in maize producing areas of South Africa. Using field data, current input costs and market prices for crops, we calculated the gross margin for each system. Treatments compared conventional ploughing under maize monoculture with reduced tillage, intercropping and crop rotation. On the clay soil, SOC was increased under reduced tillage (57.6 t C $ha^{-1}$) compared to conventional tillage (54.9 t C $ha^{-1}$) while there was no difference for the sandy soil (19.7 t C $ha^{-1}$ average across treatments). Profitability was most strongly influenced by seasonal rainfall, but was higher on the sandy soil than the clay soil, with an average gross margin of R11,344 $ha^{-1}$ and R5,686 $ha^{-1}$, respectively. This study has demonstrated that while certain CA practices can create site-specific benefits for farmers, it is highly dependent on local weather and soil conditions. For the clay soil an additional payment scheme would be required to reward farmers in southern Africa for C-sequestration to make CA profitable and achieve increased C-mitigation through soil sequestration.

## 1. Introduction

Loss of soil organic carbon (SOC) can be attributed to soil degradation, that often coincides with distinct land use changes due to cultivation (Lal, 2004; Bot and Benites, 2005; Swanepoel et al., 2016). Most of the carbon (C) lost from the soil is emitted to the atmosphere in the form of carbon dioxide ($CO_2$), contributing to global warming (Lal, 2004; Smith, 2016). Loss of SOC often results in a loss of soil quality, which reduces crop yield (Feller and Beare, 1997; Lal, 2004; Bot and Benites, 2005). The recent '4 per 1000 Initiative', launched under the framework of the Lima-Paris Action Agenda (LPAA), aims to demonstrate that agricultural soils can play a crucial role for both food security and climate protection (Van Groeningen et al., 2017).

South African soils have relatively low SOC levels, largely due to the warm, humid to semi-arid climate, which plays a dominant role in determining the biomass production of native vegetation (Du Preez et al., 2011). For example, it is estimated that 58% of the topsoils in South Africa contain less than 0.5% organic C (Du Preez et al., 2011). In addition, it is estimated that a total of 46% of SOC has been lost from agricultural soils in southern African, due to continuous conventional cultivation (e.g. ploughing, removal of crop residues, mono-crops) (Swanepoel et al., 2016).

To combat the loss of SOC and enhance or maintain soil quality, alternative agricultural practices, such as conservation agriculture (CA), are advocated (Bot and Benites, 2005; Hobbs et al., 2008; Van der Laan et al., 2017). CA aims to reduce environmental impact, improve

* Corresponding author at: ARC-Institute for Soil, Climate and Water, Private Bag X79, Pretoria, 0001, South Africa.
*E-mail address:* SwanepoelC@arc.agric.za (C.M. Swanepoel).

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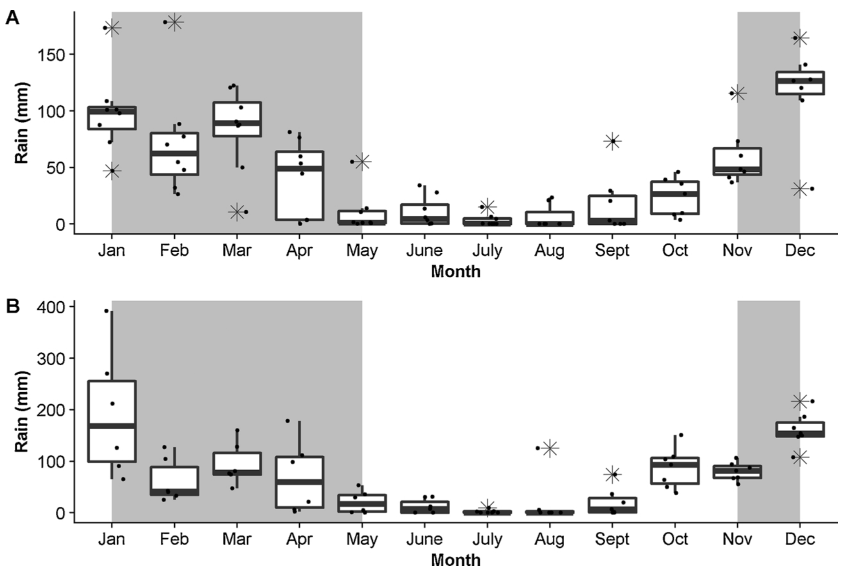


**Fig. 1.** Monthly rainfall for A) Buffelsvlei (eight-year average) and B) Zeekoegat (six-year average). The lines represent the median monthly rainfall, and the dots the monthly rainfall values during the trial seasons.

soil quality, optimize crop yields and reduce input costs. These benefits are accrued by adopting three basic management principles, namely minimal soil disturbance, permanent soil cover and crop rotation (Bot and Benites, 2005; Hobbs et al., 2008; Wall, 2008). The increase in SOC is often directly credited as the underlying driver for positive changes in CA systems (Hobbs et al., 2008; Wall, 2008). Some researchers, however, suggest that SOC is not the key driver, as the distribution of SOC within the soil profile changes under CA, and not necessarily the total SOC stock, resulting in higher levels of SOC on the surface and in top layers and less in deeper soil layers (Baker et al., 2007). Alternative underlying drivers for improving soil quality and yields associated with CA systems could also be soil nutrient ratios (Kirkby et al., 2016), or improved soil physical conditions, resulting in improvements in water infiltration, reduced evaporation, soil water-holding capacity and more favourable thermal conditions (Baker et al., 2007; Kirkegaard and Hunt, 2010).

Conservation agriculture practices have been globally promoted (Hobbs et al., 2008), and indeed been widely adopted in the Brazilian and Australian commercial farming sector (Llewellyn et al., 2012; Kirkegaard et al., 2014). However, the adoption in South Africa is still limited. In 2008/09 approximately 5.2 million hectares was under cultivation (DAFF, 2016), of which only 368 000 ha (7% of total cultivated land) was under no-till cultivation (Derpsch et al., 2014). Such low adoption in SA seems to stem from several reasons. There is increasing evidence that CA cannot be promoted as a blanket solution for management, but instead has to be tailored to the site-specific biophysical conditions (Giller et al., 2009; Kirkegaard et al., 2014; Giller et al., 2015). For example, lower yields in CA have been attributed to increased waterlogging in clay soils, soil compaction and nutrient immobilization (Rusinamhodzi et al., 2011). Van der Laan et al. (2017) reported that CA could increase the reliance on agrochemicals, such as herbicides. The emergence of herbicide resistant weeds could increase reliance on chemicals even more, with associated environmental impacts.

Site-specific CA practices that are in line with local soil and climate conditions are even more important in the semi-arid rainfall areas of South Africa than in the more humid areas, as the previous face considerably higher climate-induced risk (Sithole et al., 2016; Thierfelder et al., 2014). A major challenge is that effective build-up of soil organic matter and subsequent soil quality improvement often take several years, even decades, to take effect (Govaerts et al., 2009). Hence, medium- to long-term trials are needed to assess drivers behind CA that result in improvements in soil quality and crop productivity for a given agro-ecological region. While several CA trials have been conducted in South Africa, they are usually of short duration (one to two seasons), limiting their usefulness for untangling long term effects of CA (e.g. Murungu et al., 2010; Dube et al., 2012; Myburg, 2013).

In this study we aim to address this particular shortcoming in CA research by explicitly studying the effect of management practices on SOC and profitability in two medium-term field trials: one eight-year field trial on a sandy loam soil and one six-year trial on a clay soil. These represent unique longer running trials in South Africa, for which SOC and yield data were annually measured, enabling evaluation of CA under sub-Saharan African conditions.

We specifically evaluated the impact of conventional practices (maize monoculture and conventional ploughing) and CA treatments (reduced tillage, crop rotation and intercropping systems) on SOC and profitability. We hypothesized that more complex cropping systems with reduced tillage would: (i) lead to higher SOC content over time and (ii) show higher productivity, which in turn would result in (iii) overall higher economic profitability for these systems.

## 2. Materials and methods

### 2.1. Study sites

Two field trials were conducted (Buffelsvlei and Zeekoegat) with contrasting soils (sandy loam versus clay), both representative of the summer rainfall maize regions of South Africa. Buffelsvlei (26°29′42″S, 26°36′07″E, altitude: 1390 m asl) was an on-farm trial, situated in the North West Province. According to Köppen-Geiger climate zones, this area occurs in the arid, steppe, cold arid region (Bsk) (Engelbrecht and Engelbrecht, 2016) and receives an annual rainfall of 570 mm year$^{-1}$ (Fig. 1) (average over eight seasons), with an average maximum temperature of 26.2 °C and minimum temperature of 9.6 °C (supplementary data Table A1 presents monthly rainfall, minimum and maximum temperature during the growing seasons). Zeekoegat (25°36′55″S, 28°18′56″ E, altitude: 1168 m asl) was an on-station trial at Zeekoegat Experimental Farm situated in Gauteng Province, in the warm temperate, dry winter, hot summer region (Cwa). The site received an annual rainfall of 871 mm year$^{-1}$ (Fig. 1) (average over 6 trial years) with average maximum annual temperature of 27.0 °C and minimum temperature of 10.7 °C. For both sites, most of the precipitation (on average > 80% of annual amount) occurred during the summer