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

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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.

Key words: crop rotation, intercropping, profitability, maize, reduced tillage, soil conditions

Highlights

- Presentation of unique results from 6 and 8 year CA field trials in South Africa.
- In clay soils, SOC increased from 54.9 to 57.6 t ha^{-1} under reduced tillage.

- In sandy soils, SOC changes were mostly influenced by climatic conditions.
- The profitability of CA depended on soil conditions.
- Seasonal weather variation was the main determinant of profitability, irrespective of management.

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 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^{o}C and minimum temperature of 9.6^{o}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^{o}C and minimum temperature of 10.7^{o}C. For both sites, most of the precipitation (on average >80% of annual amount) occurred during the summer cropping season (November to April; Fig. 1). Rainfall is highly variable between and within seasons (Fig 1), and consequently greatly affects dryland crop production (for details, see Supplementary data, Table A2).

The soil from Buffelsvlei is a Chromic Lixisol (IUSS Working Group WRB, 2014), sandy loam (16% clay) on underlying granite (Table 1). Soil samples taken prior to the commencement of the field trials show that the Buffelsvlei site had a high topsoil phosphorus (P) (Bray-1) of 35 mg kg^{-1}, due to previous fertilization, that decreased with depth. The soil was slightly acidic. The soil at Zeekoegat is a Rhodic Nitisol (IUSS Working Group WRB, 2014) with clay (44.5% clay) texture, red, moderately fine to medium blocky structure on underlying gabbro. The soil

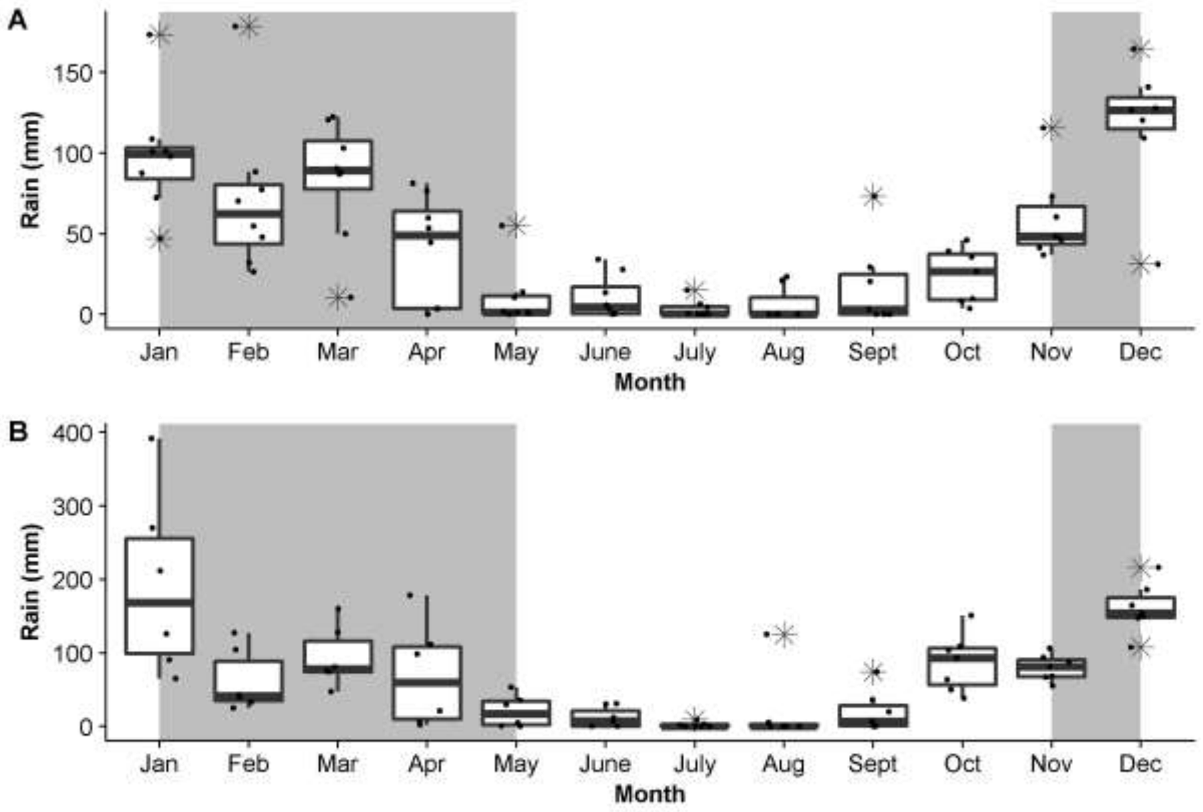

Fig. 1: Monthly rainfall for A) Buffelsvlei (eight-year average) and B) Zeekoegat (six-year average). The lines represent the average monthly rainfall, and the dots the monthly rainfall values during the trial seasons.

was slightly acidic and had relatively low topsoil P content. Table 1 summarizes selected soil physical and chemical properties of the two sites at the start of the trials.

Table 1: Buffelsvlei and Zeekoegat initial topsoil properties

Soil Depth (mm)	Soil texture (% clay)	Bulk density*(g cm^{-3})	pH (H_2O)	SOC (%^{1})	P (Bray-I) (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})
				Buffelsvlei				
0-150	Sandy loam (17%)	1.6	5.4	0.45	35	152	392	74
150-300	Sandy clay loam (22%)	1.6	4.9	0.41	17	123	297	90
				Zeekoegat				
0-100	Clay (44%)	1.5	6.1	1.25	5	485	1189	265
100-300	Clay (45%)	1.4	5.9	1.24	4	536	1219	272

*Bulk density for Buffelsvlei was estimated, using general bulk density values for sandy soil (Hillel, 1982)

2.2 Field trial management

2.2.1 Buffelsvlei

This trial was initiated in 2008 and continued for eight cropping seasons. The experimental design was a randomized complete block design, comparing the standard maize monoculture system under conventional tillage (CT), serving as the control, with five reduced tillage (RT) cropping systems. The RT cropping systems were: i) maize monoculture, ii) maize/sunflower rotation, iii) maize/cowpea rotation, iv) maize/sunflower/millet rotation and v) maize/cowpea/millet rotation. Additional plots were added in order to have each crop represented every year. For the purpose of the analysis, each combination was treated as a separate treatment. The treatment combinations were numbered *a* to *l* (supplementary data, Table A3), with the name of the first crop in the sequence indicating the crop with which the sequence starts in 2008: a = maize monoculture, CT; b = maize monoculture RT; c = cowpea/ maize rotation; d = maize/ cowpea rotation; e = maize/ sunflower rotation; f = sunflower/ maize rotation; g = millet/ sunflower/ maize rotation; h = sunflower/ maize/ millet rotation; i = maize/ millet/ sunflower rotation; j = cowpea/ maize/ millet rotation; k = maize/ millet/ cowpea rotation; l = millet/ cowpea/ maize rotation. Each treatment was replicated four times, resulting in 48 plots. Plot size was 25 m x 20 m.

Crop management followed standard agronomic practices in the area: Planting of main crops took place in November or December, followed by legumes a few weeks later, depending on soil water. However, management practices were adopted yearly according to needs: fertilizer was applied according to annual soil analysis (for example N application for maize ranged between 55-115 kg ha^{-1}, see Table 2); herbicide or pesticide was applied according to specific needs. The same cultivar was planted each year, however, in a few cases a particular cultivar was no longer available and a similar cultivar was used instead. The details of these farming activities are summarized in Table 2.

Table 2: Details of farming activities at Buffelsvlei trial for each season

	2008/09	**2009/10**	**2010/11**	**2011/12**	**2012/13**	**2013/14**	**2014/15**	**2015/16**
Conventional tillage (300 mm depth)	Chisel plough + disk harrow	Chisel plough + disk harrow	Mouldboard plough + disk harrow	Mouldboard plough + disk harrow	Mouldboard plough + disk harrow	Mouldboard plough + disk harrow	Mouldboard plough + disk harrow	Mouldboard plough + disk harrow
Reduced tillage	No-till planter	No-till planter	No-till planter	No-till planter	No-till planter	No-till planter	No-till planter	No-till planter
Fertilizer for maize (kg ha^{-1})	N=55 P=12 K=8	N=17+34** P=11 K=6	N=27+70 P=18 K=9	N=25+76 P=17 K=8	N=13+67 P=8 K=4	N=19+56 P=13 K=6	N=46+54 P=23 K=12	N=32+83 P=21 K=11
Fertilizer for cowpea/soybean (kg ha^{-1})	N=10 P=20 K=9	N=17 P=11 K=6	N=17 P=11 K=6	N=25 P=17 K=8	N=13 P=9 K=4	N=13 P=8 K=4	N=16 P=8 K=4	N=17 P=11 K=6
Fertilizer for sunflower (kg ha^{-1})	N=35 P=8 K=0	N=17+28 P=11 K=6	N=27+70 P=18 K=9	N=38 P=25 K=13	N=13+28 P=9 K=4	N=13+28 P=8 K=4	N=16+18 P=8 K=4	N=17 P=11 K=4
Fertilizer for millet (kg ha^{-1})		N=17 P=11 K=6	N=27+70 P=18 K=9	N=25+76 P=17 K=8	N=13+69 P=8 K=4	N=13 P=8 K=4	N=16+27 P=8 K=4	N=32 P=21 K=11
Target densities *Mz, Sun, Cp: (plants ha-^{1}) Millet = kg seed ha^{-1}	Mz: 20 000 ha^{-1} Sun: 44 000 ha-^{1} Soy: 330 000 ha^{-1} Millet: 10 kg ha^{-1}	Mz: 20 000 ha^{-1} Sun: 40 000 ha^{-1} Soy: 330 000 ha^{-1} Millet: 10 kg ha^{-1}	Mz 24 500 ha^{-1} Sun: 40 000 ha^{-1} Cp: 110 000 ha^{-1} Millet: 10 kg ha^{-1}	Mz: 24 000 ha^{-1} Sun: 40 000 ha^{-1} Cp: 110 000ha^{-1} Millet: 10 kg ha^{-1}	Mz: 24 000 ha^{-1} Sun: 40 000 ha^{-1} Cp: 110 000 ha^{-1} Millet: 10 kg ha^{-1}	Mz 27 000 ha^{-1} Sun: 38 000 ha^{-1} Cp: 129 000 ha^{-1} Millet: 10 kg ha^{-1}	Mz: 25 000 ha^{-1} Sun: 38 000 ha^{-1} Cp: 78 000 ha^{-1} Millet: 10 kg ha^{-1}	Mz 25 000 ha^{-1} Sun: 80 000 ha^{-1} Cp:100 000 ha^{-1} Millet: 10 kg ha^{-1}
Planting date	Mz: 26 Nov ‘08 Sun: 4 Dec ‘08 Soy: 4 Dec ‘08 Millet:4 Dec ‘08	Mz:16 Nov ‘09 Sun: 5 Jan ‘10 Soy: 5 Jan ‘10 Millet: 14 Dec	Mz: 19 Nov ‘09 Sun: 4 Jan ‘11 Cp: 19 Nov ‘10 Millet: 23 Nov	Mz: 25 Nov ‘12 Sun 12 Jan ‘12 Cp: 25 Nov’12 Millet: 25 Nov	Mz: 5 Dec ‘12 Sun: 4 Dec ‘12 Cp: 4 Dec ‘12 Millet: 4 Dec ‘12	Mz: 28 Nov ‘13 Sun:28 Nov ‘13 Cp: 28 Nov ‘13 Millet: 28 Nov ‘13	Mz: 26 Nov ‘14 Sun: 8 Dec ‘14 Cp: 17 Nov ‘14 Millet: 8 Dec ‘14	Mz:24 Nov ‘15 Sun: 23 Nov ‘15 Cp:23 Nov ‘15 Millet: 23 Nov ‘15
Herbicide and pesticide (at planting and in season)	Dual Gold / Roundup	Dual Gold / Roundup	Gramozone, Dual Gold/ Roundup Kombat	Roundup/ Dual/ Karate/ Bulldock	Assist/ Cipla/ Tronic/ Gramozone/ Roundup	Dual/Karate/ Gramozone/ Roundup/ Assist	Gramoxone/ Dual/ Mamba/ Herbiboost/	Grammoxone / Roundup/ Dual Gold/ Assist
Cultivar maize	PAN 6Q-521R	PAN 6Q-521R	PAN 6P-563R	PAN 5Q 649R	PAN 5Q 649R	PAN 5Q 649R	BG 5685R	BG5785 BR
Cultivar sunflower	PAN 7049	AGSUN 8251	PAN 7050	PAN 7049	PAN 7049	PAN 7095 CL	PAN 7095 CL	PAN 7031 CL
Cultivar soybean	LS 616R	Egret	-	-	-	-	-	-
Cultivar cowpea	-	-	Bechuana White	Bechuana White	Bechuana White	Bechuana White	Bechuana White	Bechuana White
Cultivar millet	Common	Common	Common	Common	Common	Common	Okoshana	Okoshana

*Mz= Maize, Sun=Sunflower; Soy=Soybean, Cp=Cowpea, ** ‘+’ indicates splitting of fertilizer: at planting + top-up

2.2.2 Zeekoegat

The Zeekoegat trial was initiated in November 2007 and continued for six cropping seasons. A split plot randomized complete block design was used, with three replicates. Each replicate was split into two tillage systems (CT and RT) and then further subdivided into twelve treatments (six cropping systems × two fertilizer levels), resulting in a total of 72 (3 x 2 x 12) experimental plots. Plot dimensions were 7.2 m x 8.0 m. The cropping systems tested included: maize monoculture, maize/cowpea rotation, maize/soybean rotation, maize/cowpea intercropping, maize/oats intercropping and maize/vetch intercropping. For the rotation systems, crops were alternated each season. Consequently, unlike the Buffelsvlei trial, maize yields in the crop rotation treatments are only available for every second year, while maize yields in the monoculture and the intercropping systems were available annually (see supplementary data, Table A4). Maize was planted in standard 0.9 m rows, and initially the intercrops were planted in-between. However, this was changed in the third cropping season, to tramlines of 1.8 m to better accommodate the intercrops. Cowpea and soybean were planted in 0.3 m rows.

Management followed standard agronomic practices for the region: planting took place in November or December, following the first significant rain of at least 20 mm within 3-6 days. Conventional plots were cultivated up to 300 mm depth with a mouldboard plough, followed by a disk harrow or four-tine implement to create furrows for planting. In the RT plots, only a four-tine implement was used to create furrows for planting. Management details, such as tillage, planting densities, fertilizer application, herbicide and pesticide, planting dates etc., are summarized in Table 3.

Table 3: Details of farming activities at Zeekoegat trial for each season

	2007/08	**2008/09**	**2009/10**	**2010/11**	**2011/12**	**2012/13**
Conventional tillage (300 mm deep)	Mouldboard plough/	Slasher/ Mouldboard plough/ disk harrow	Slasher/ Mouldboard plough/ four tine cultivator frame	Slasher/ Mouldboard plough/ four tine cultivator frame	Slasher/ Mouldboard plough/ four tine cultivator frame	Slasher/ Mouldboard plough/ four tine cultivator frame
Reduced tillage (200 mm deep)	Slasher/ Hand hoes	Slasher / Hand hoes	Slasher / four tine cultivator frame	Slasher / four tine cultivator frame	Slasher / four tine cultivator frame	Slasher / four tine cultivator frame
Fertilizer, maize (optimal)* kg ha^{-1}	N=48+24*** P=13+7 K=12	N=46+21 P=20+2 K=0 **	N=42+28 P=13+2 K=0	N=42+28 P=13+2 K=0	N=42+30 P=8+5 K=0	N=42+30 P=6+6 K=0
Fertilizer for legumes (optimal)	N=0 P=5 K=12	N=0 P=26 K=0	N=0 P=11 K=0	N=0 P=8 K=0	N=0 P=9 K=0	N=0 P=8 K=0
Fertilizer for oats (optimal)	N=28 P=13 K=8	N=46 P=20 K=0	N=42 P=13 K=0	N=42 P=13 K=0	N=42 P=13 K=0	N=42 P=6 K=0
Target densities	Maize: 37,000 plants ha^{-1} Legume: 60,000 plants ha^{-1} Intercrop: 30,000 ha^{-1} Oats: 50 kg seed ha^{-1} Vetch: 30 kg seed ha^{-1}	Maize: 37,000 plants ha^{-1} Intercrop: 30,000 ha^{-1} Oats: 50 kg seed ha^{-1} Vetch: 30 kg seed ha^{-1}	Maize mono: 37,000 ha^{-1} Maize + intercrop: 18,500 Legume: 150,000 ha^{-1} Intercrop: 100,000 ha^{-1} Oats: 50 kg seed ha^{-1} Vetch: 30 kg seed ha^{-1}	Maize: 37,000 plants ha^{-1} Maize + intercrop: 18500 Intercrop: 100,000 ha^{-1} Oats: 50 kg seed ha^{-1} Vetch: 30 kg seed ha^{-1}	Maize mono: 37,000 ha^{-1} Maize + intercrop: 18,500 Legume: 150,000 ha^{-1} Intercrop: 100,000 ha^{-1} Oats: 50 kg seed ha^{-1} Vetch: 30 kg seed ha^{-}	Maize: 37,000 plants ha^{-1} Maize + intercrop: 18,500 Intercrop: 100,000 ha^{-1} Oats: 50 kg seed ha^{-1} Vetch: 30 kg seed ha^{-1}
Planting date	Maize:27 Nov '07 Legume: 27 Nov '07 Intercrop: 17 Dec '07 Oats, vetch: 26 Feb '08	Maize: 17 Nov '08 Intercrop: 17 Dec '08 Oats, vetch: 25 Feb '09	Maize: 19 Nov '09 Legume: 19 Nov '09 Intercrop:17 Dec '09 Oats, vetch:7 Mar 10	Maize: 29 Nov '10 Intercrop:21 Dec '10 Oats,vetch:18 Mar '11	Maize: 29 Nov '11 Legume: 29 Nov '11 Intercrop:19 Dec '11 Oats, vetch:13 Mar '12	Maize: 19 Nov '12 Intercrop: 12 Dec '12 Oats,Vetch:24 April '13
Herbicide and pesticide (before planting + follow-up)	Roundup/ Dual gold/ Cyperin + manual weeding	Roundup/ Dual gold/ Cyperin + manual weeding	Roundup/ Springbok/ Dual Gold/ Cyperin + manual weeding	Roundup/ Dual Gold/ Cyperin + manual weeding	Cleanup/ Cypermetrial / Dual Gold/ Cypermetian + manual weeding	Cleanup/ Cypermetrian/ Dual Gold + manual weeding
Cultivar maize	Pannar 6P/110	Pannar 6P/110	Pannar 6P/110	Pannar 6P/110	Pannar 6P/110	Pannar 6P/110
Cultivar cowpea	Mixed variety	Mixed variety	Mixed variety	Mixed variety	Mixed variety	Mixed variety
Cultivar soybean	Glenda	Glenda	Glenda	Glenda	Glenda	Glenda
Cultivar oats	SSH 491	SSH 491	SSH 491	SSH 491	SSH 491	SSH 491

*Fertilizer application for 'Low' treatments, were 50% of that reported for optimal

**From the second year, no K was applied, due to the high natural K content of the soil

*** '+' indicates splitting of fertilizer: at planting + top-up

2.3 Soil and plant sampling

Data collected from the two sites included SOC, grain yield and biomass.

Soil organic C: Composite soil samples were taken annually in June at Buffelsvlei at 0-150 and 150-300 mm, and in October at Zeegoekat at 0-100 and 100-300 mm, and analyzed for organic C using the Walkley-Black method (Allison 1965). We calculated C stocks for both sites and each layer by multiplying SOC (%) with bulk density (g cm^{-3}) and depth (mm). Bulk density for the sandy soil was assumed to be 1.6 g cm^{-3} (Hillel, 1982), while bulk density for clay soil was measured as 1.47 g cm^{-3} for topsoil (0-100 mm layer) and 1.43 g cm^{-3} for the 100-300 mm layer.

Grain yield: Maize was left in the field to let grains dry to about 12.5% moisture content before harvesting. A representative sample per plot, consisting of 15-30% of the total maize plants per plot (avoiding maize plants in plot borders) was collected, and grain weights converted to t ha^{-1}. Sunflower was harvested between 30 and 45 days after bloom, when the heads turn brown and the seed moisture reached about 35% moisture content.

Aboveground biomass: Biomass was determined by removing above-ground vegetation (both main crops and intercrops) in fixed grids. Stems and leaves were dried in an oven at 40°C to constant weight and converted to kg ha^{-1}. Only a sample of the crop residues was removed to determine above-ground biomass. The remainder were left on the surface, as per CA methodology, and not removed to be sold, even though it was assigned a monetary value. The conversion of biomass to monetary value is to account for the overall contribution to a particular farming system, as provided by surface cover from crop residues.

2.4 Profitability analysis

Profitability is used as a proxy to compare the performance of various systems across seasons, since it encompasses all the components in the system and allows for comparing yields and biomass from different crops as well as input costs. To determine the relative profitability of the different systems, gross margins (total income minus total variable costs) were calculated and standardized to South African Rand per hectare (R ha^{-1}). To allow for the effect of yearly inflation, we used the average yearly Consumer Price Index (CPI) (StatsSA, 2017), to express all values in current prices. The average exchange rate of the South African Rand to the United States Dollar, as based on monthly average was R14.71 : $1 in 2016 (World Bank Data, 2017). To simplify the profitability analysis we followed Rötter and Van Keulen (1997) and only used actual, direct costs and expenses that directly related to the specific farming systems. We omitted general expenses, such as land rental, investments or maintenance, which will add to farming cost, but would not be affected by the type of farming practiced. Labour costs were also excluded, since there are no reliable data on labour differences between CA and conventional farming on commercial farms in South Africa. This analysis is reflecting the actual measured differences in income and expenses as a result of conventional farming versus CA, for the two case studies.

The total income included both grain and fodder crops. For grain crops, income was calculated by multiplying grain yield (maize and sunflower grain (t ha^{-1})) with average market price (R t^{-1}), and similarly for biomass production as fodder (above ground biomass (t ha^{-1} multiplied with fodder price [R t^{-1}]). Costs included were: seed, fertilizer herbicide, pesticide costs and land preparation (fuel). The data used in the calculations were obtained from various sources (supplementary data, Table A5). The grain yield and biomass data were obtained from the trials. For medium-term multi-treatment trials, usually some gaps occur in the datasets. In this case, a total of 6% of grain yield data, and 48% of biomass data were missing. Gaps in the data were filled using average values from the particular year and treatment.

Direct costs such as land preparation, were obtained from production models developed by GrainSA Ltd (2017). The average diesel price for each year was used to calculate the costs for the different tillage systems. Retail prices for seed and fertilizer were obtained from fertilizer and seed companies, and the target planting density of each system was used to calculate seed cost (Tables 2 and 3). Potential income from biomass was determined by consulting farmers' magazines dating back to 2008 (supplementary data, Table A5). The average selling prices for various fodder types, such as maize residues, soybean, cowpea and oats were recorded and in the absence of vetch hay prices, we used data for lucerne. All values are expressed per hectare and in constant prices.

2.5 Statistical analyses

We used repeated measures analysis of variance (ANOVA) at 5% significance level, to test the effect of the independent factors affecting SOC, and added plot as the repeat variable. At Buffelsvlei we used SOC data at the 0-150 and 150-300 mm depths and treated each possible cropping combination as a treatment (the 12 cropping systems described previously). At Zeekoegat we used SOC data from 0-100 and 100-300 mm depths tested against tillage system × cropping system × fertilizer level × year. Similarly, to assess the effect of treatments on profitability, we also applied repeated measures ANOVA with the gross margin as dependent variable and the various cropping treatments as the independent variables (Field et al., 2012). Analysis was done using R software (R Core Team, 2016).

3. Results

3.1 Productivity

In this section we focus on maize, as it is the most important crop for the region. Productivity of the different systems, expressed in grain and biomass yield (supplementary data, Tables A6, A7, A8 and A9), highly determined the profitability.

At Buffelsvlei, average maize grain yield ranged from 2.48 t ha^{-1} in 2011/12 season to a maximum of 8.88 ton ha^{-1} in 2013/14 (supplementary data, Table A6). Average biomass for the various crops in the rotation systems were 7.52 t ha^{-1} for maize, 4.78 t ha^{-1} for millet, 5.41 ton ha^{-1} for cowpea and 5.64 t ha^{-1} for sunflower (Table A7).

At Zeekoegat the maize grain yield was high in the first two seasons with an average maize yield of 6.32 t ha^{-1} in the first year (2007/08), but this decreased in the third season to 1.26 t ha^{-1}, and remained low until the end of the trial (supplementary data, Table A8), likely due to low rainfall, or poor rainfall distribution and/or soil compaction. Biomass followed a similar trend across years (supplementary data, Table A9), with high biomass in the first two seasons and lower biomass production in the last four seasons. The average biomasses for the main crops were as follows: 4.28 t ha^{-1} for maize, 1.9 t ha^{-1} for cowpea and 0.8 t ha^{-1} for soybean. Biomasses of intercrops were 0.55 t ha^{-1} for cowpea, 0.95 t ha^{-1} for oats, and 1.71 t ha^{-1} for grazing vetch.

3.2 Soil organic carbon

In the sandy soils at Buffelsvlei, SOC was not significantly altered by any of the treatments. The only significant results were between years of planting season ($p=0.015$), with the 2010/11 season resulting in the highest SOC content of 0.51% (± 0.1) and 0.49% (± 0.08) for the top- and subsoil, respectively (Fig. 2, Table 4). The lowest SOC content was in the 2012/13 season with 0.31% (±0.06) and 0.29% (± 0.05) SOC in the topsoil and subsoil, respectively. Buffelsvlei had in average C stocks for the 0-300 mm layer of 19.3 t ha^{-1}. The SOC content in the various treatments in the final trial season are presented in Fig 3.

In the clay soil at Zeekoegat, a significant increase in SOC under RT ($p<0.001$) was observed (Fig 4, Table 4). A gradual increase in topsoil (0-100 mm) SOC of 1.28% (±0.01) in 2007/08 to 1.51% (±0.16) in 2012/13 was measured under RT. While, over the same period, the SOC levels in CT systems were 1.21% (±0.05) and 1.3% (±0.08) for the first and last trial years,

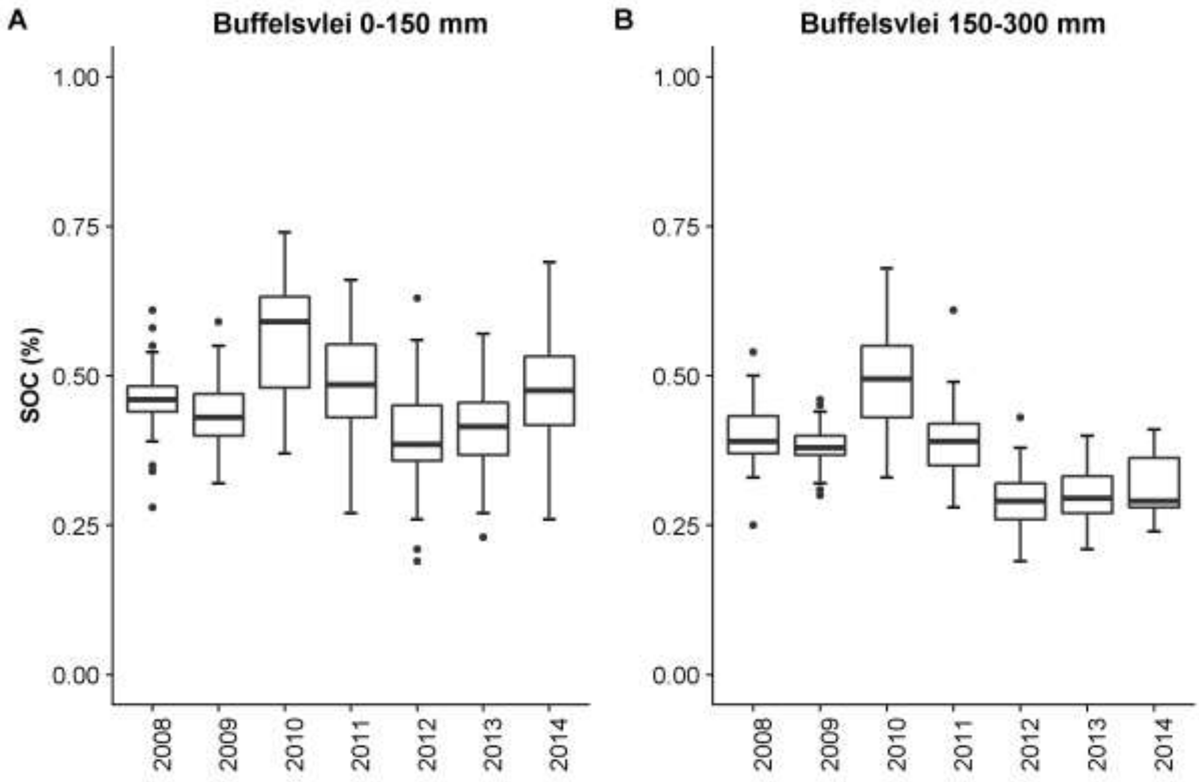

Fig. 2: Comparing average soil organic carbon (SOC) levels for eight seasons at Buffelsvlei in A) topsoil and B) subsoil, as affected by crop rotation.

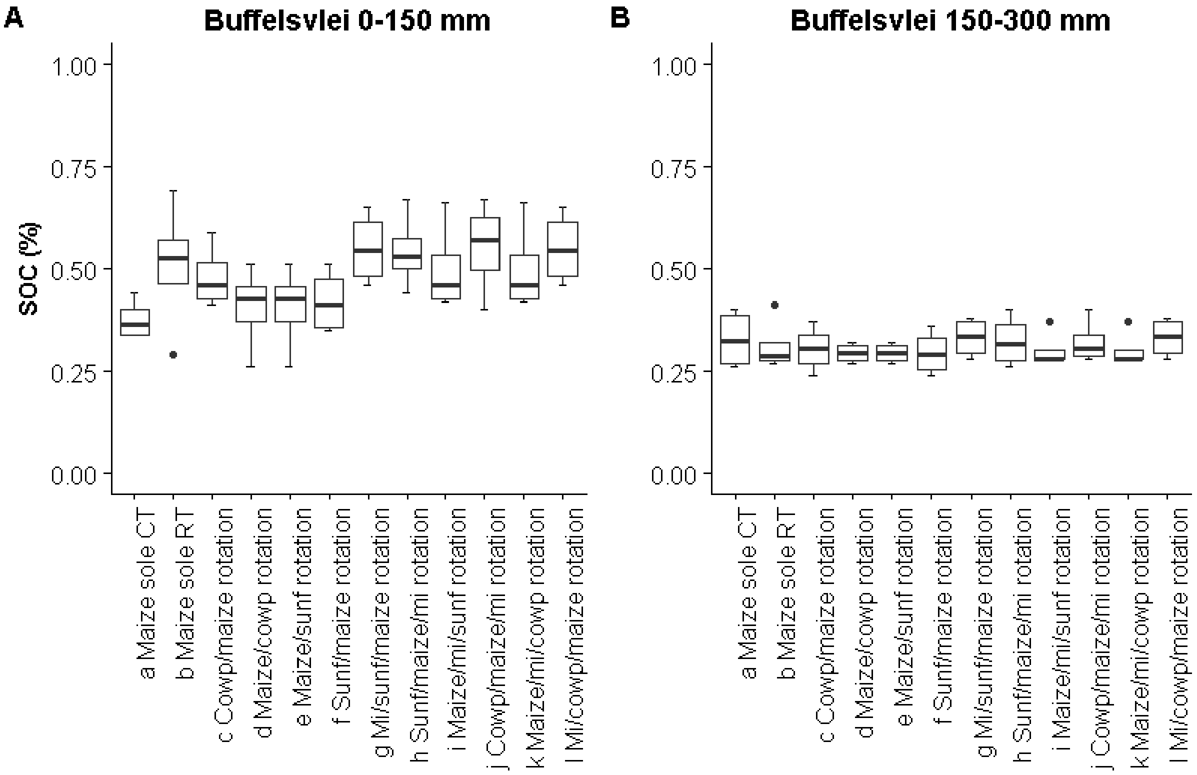

Fig 3: Soil organic carbon (%) content in A) topsoil and B)subsoil in the different treatments after 7 trial seasons (2014) at Buffelsvlei.

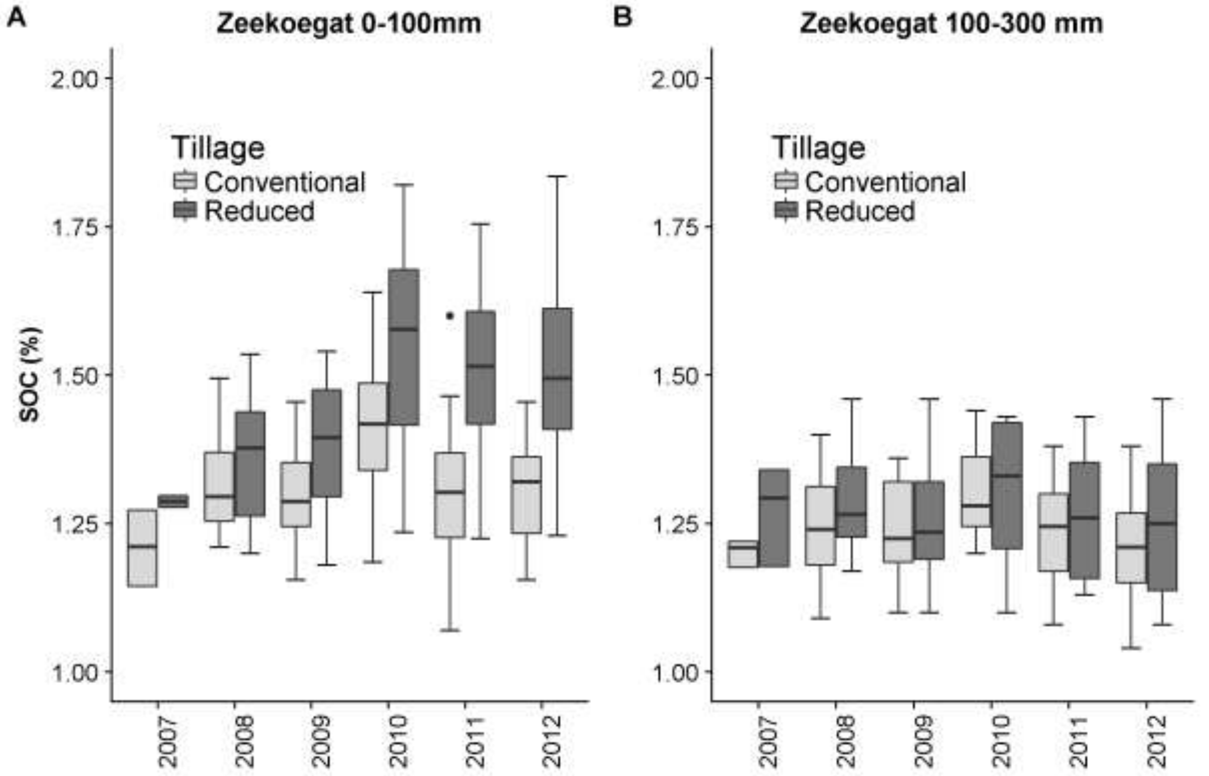

Fig 4: Comparing average soil organic carbon (SOC) levels for six seasons at Zeekoegat in A) topsoil and B) subsoil, as affected by crop systems and tillage.

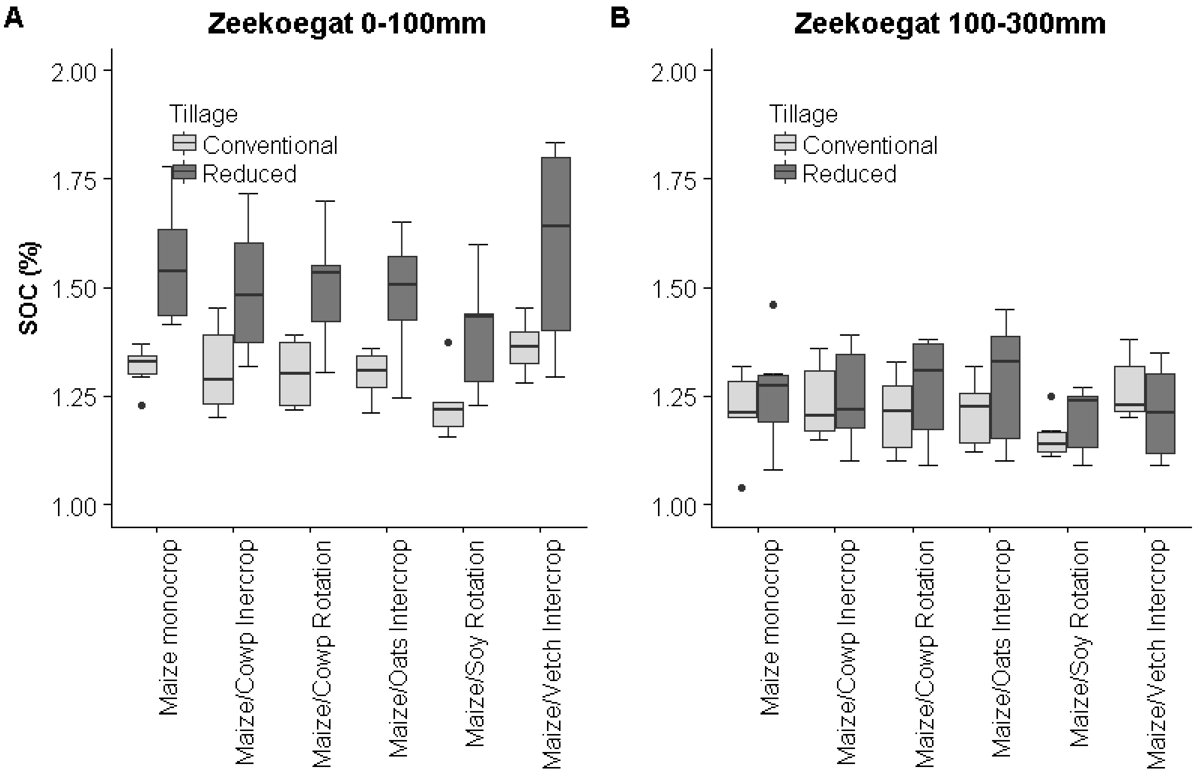

Fig 5: Soil organic carbon (%) content in A) topsoil and B)subsoil in the different treatments after 6 trial seasons (2013) at Zeekoegat.

respectively. There was also a significant effect across years or growing season ($p<0.001$) for both soil depths, with the highest SOC of 1.48% (±0.15) in the 2010/11 season. Due to a higher SOC percentage, the average C that these soils contain is 56.3 t ha^{-1}.The SOC stocks were built-up from 54.9 t ha^{-1} under CT to 57.9 t ha^{-1} under RT. The SOC content in the various treatments in the final trial season are presented in Fig 5.

Table 4: ANOVA table for soil organic carbon for Buffelsvlei and Zeekoegat as affected by year, cropping system, and year, tillage, crop, fertilizer respectively

Source of variation	df	*p*-value	df	*p*-value
	Buffelsvlei trial			
	0-150 m soil layer		**150-300 mm soil layer**	
Year	1	**0.015***	1	**<0.001****
Cropping system	9	0.987	9	0.990
Year: Cropping system	13	0.410	13	0.994
	Zeekoegat trial			
	0-100 mm soil layer		**100-300 mm soil layer**	
Year	5	**<0.001****	5	**<0.001****
Year: Tillage	5	**<0.001****	5	**0.002***
Year: Crop	5	0.808	5	0.713
Year: Fertilizer	5	0.087	5	0.637
Year: Tillage: Crop	5	0.759	5	0.513
Year: Tillage: Fertilizer	5	0.254	5	0.803
Year: Crop: Fertilizer	5	0.841	5	0.845
Year: Tillage: Crop: Fertilizer	5	0.797	5	0.731

**Highly significant ($p<0.001$), *Significant ($p<0.05$)

3.3 Profitability

Cropping at Buffelsvlei was more profitable than at Zeekoegat, with an average gross margin of R11,344 ha^{-1} compared to R5,686 ha^{-1} (Figs 6 and 7). At Buffelsvlei, the cropping system

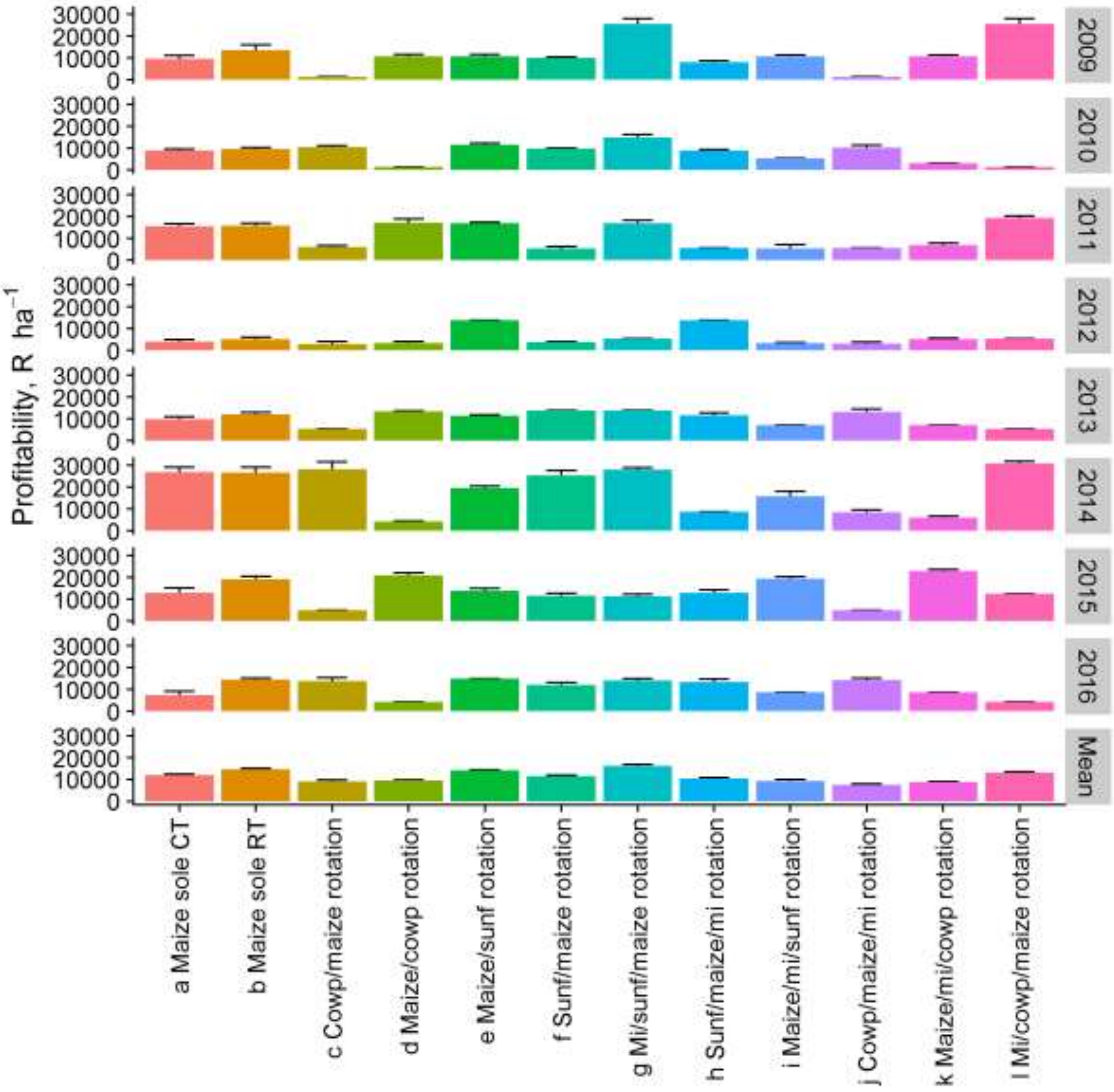

Fig. 6: Gross margins for 12 treatments over eight cropping seasons at Buffelsvlei expressed in South African Rand ha^{-1}.. Each treatment (a-l) is indicated on x-axis, (CT=conventional tillage, RT=reduced tillage, cowp = cowpea, sunf =sunflower, mi=millet). The actual crop planted per season can be seen in Table A1.

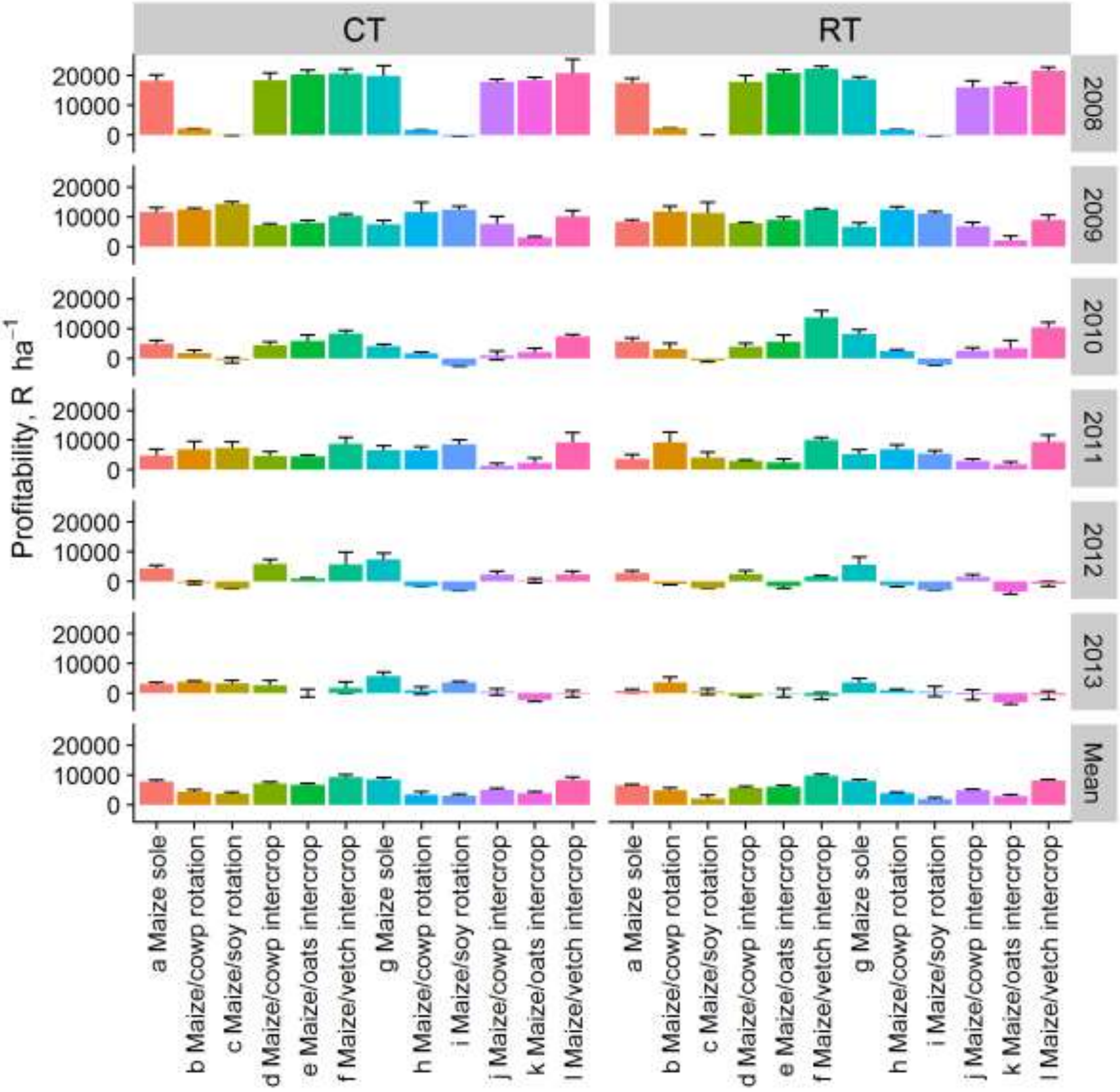

Fig. 7: Profitability for 12 farming systems at Zeekoegat expressed in South African Rand ha^{-1}: A combination of six cropping systems and two fertilizer levels (system a-f = low fertilizer; system g^{-l} = high fertilizer, see Table 3 for fertilizer levels) and two tillage systems (RT = reduced tillage and CT = conventional tillage, cowp = cowpea, soy = soybean) .

millet/sunflower/maize sequence was the most profitable with an eight-year average of R16,276 ha^{-1}, while the cowpea/maize/millet cropping sequence performed worst with R7,641 ha^{-1}. The 2013/14 season was the most profitable with an overall profitability of R19,078 ha^{-1}, while the lowest profitability was two years prior (2011/12) at R5,770 ha^{-1}. Due to high financial return on maize grain compared to income from other crops, the years in which maize was planted were most profitable: on average, maize-years resulted in a profit of R14,011 ha^{-1}, followed by sunflower (R12,472 ha^{-1}), millet (R9,615 ha^{-1}) and cowpea (R4,872 ha^{-1}) (Fig 6). The average eight-year profitability of the different treatments at Buffelsvlei, showed relatively high variation between treatments.

At Zeekoegat there were a number of factors that had a significant impact on profitability, including season, tillage and cropping system (Table 5). The cropping system that was most profitable was maize/vetch intercropping with R8,890 ha^{-1}, while the maize/soybean rotation performed worst at R2,725 ha^{-1}. At R5,960 ha^{-1}, the CT system was slightly more profitable than RT (R5,413 ha^{-1}). However, the most profitable systems, were the maize/vetch cropping systems under RT and low fertilizer inputs (R9,885 ha^{-1}) (Fig 7).

Table 5 ANOVA results for gross margins of different systems for Buffelsvlei and Zeekoegat

Source of variation	**df**	***p*-value**
	Buffelsvlei trial	
Year	7	**<0.001****
Cropping system	20	**<0.001****
Year x Cropping system	57	**<0.001****
	Zeekoegat trial	
Year	5	**<0.001****
Year: Tillage	5	**0.001***
Year: Fertilizer	5	**0.284**

Year: Cropping system	50	**<0.001****
Year: Tillage :Fertilizer	5	**0.907**
Year: Tillage: Cropping system	50	**0.977**

**Highly significant (p<0.001), *Significant (p<0.05)

4. Discussion

At Buffelsvlei management did not have a significant effect on SOC. At Zeekoegat, only tillage practices had a significant effect on SOC, and RT positively impacted on SOC by 57.6 t C ha^{-1} stored in the top soil (0-100 mm) compared to ploughing that resulted in 54.9 t C ha^{-1}, but this was not the case for other treatments (cropping systems or fertilizer). At both sites, ‘year’ or ‘season’ influenced SOC, indicating that weather conditions such as rainfall, rainfall distribution or temperature, and the associated biomass growth, had a significant effect on SOC. Similarly, profitability was mostly influenced by seasonal variation and not by treatments. This indicates that environmental conditions overruled management practices.

4.1 Productivity

The sandy, aeolian soils in the North West Province can be highly productive under good management practices. These soils are deep and freely drained with stable water tables that can support crops, even in low annual rainfall areas (Bennie et al., 1995). Buffelsvlei, a site representative of these conditions, was therefore able to support high yields, despite relatively low rainfall (average rainfall 570 mm yr^{-1}) and low SOC content. It was interesting to compare the treatments at Buffelsvlei where the same cropping combinations were planted in different sequences (supplementary data, Table A1). For example, the maize, millet, sunflower cropping combination resulted in large maize yield differences depending on the specific sequence: during the eight-year trial, maize was planted twice in the millet/maize/sunflower sequence and the average grain yield was 7.62 t ha^{-1}; while in the sunflower/maize/millet sequence, maize was planted three times, with an average yield of 3.73 t ha^{-1}. It is clear that the climatic conditions, such as rainfall and available soil water, more strongly influenced the yields compared to the CA practice of intercropping. Rusinamhodzi et al. (2011) found that yield increases under CA in low rainfall areas are associated with high agrochemical inputs, such as fertilizer, rather than crop rotation, as was the case at Buffelsvlei. Crop modelling techniques could be useful to help disentangle and quantify the influence of climatic variation as compared to management practices.

Productivity in the clay soils of Zeekoegat was above the 4 ton ha^{-1} target maize yield for the area (supplementary data, Table A4) during the first two seasons, with an average of 6.32 and 5.02 t ha^{-1} for 2007/08 and 2008/09, respectively. This could be ascribed to adequate and well-distributed rainfall during the first two seasons, and/or to the release of nutrients from decomposition of natural organic matter and absence of pathogens in the soil, following cultivation of natural soil (Jordan, 2013). From the third season, productivity decreased for all systems to an average maize grain yield of 1.26 (2009/10), 1.64 (2010/11), 1.44 (2011/12) and 1.14 (2012/13) t ha^{-1}. One aspect that contributed to lower yields was the change in planting densities that was adopted during these seasons, where tramline maize (1.8 row spacing) was implemented for intercropping systems (Table A4). Finally, we noted compaction in the RT plots (data not shown). The reduction in yield was more severe under the RT plots, and thus concurs with results from other researchers that found that topsoil compaction is often associated with reduced- or no-till actions (Steyn et al., 1995; Taylor et al., 2012). Topsoil compaction might have resulted in reduced root elongation as well as reduced water infiltration and storage, and subsequently lower biomass production and yields (Bengough and Mullins, 1991).

4.2 Soil organic carbon

In the sandy soils at Buffelsvlei, the lack of physical and structural protection of organic matter resulted in strong dependence on seasonal SOC on organic matter input and residue management, as reported by Feller and Beare (1997) and Steward et al. (2007) for similar conditions. Buffelsvlei is located in an area with naturally low SOC content with an original SOC content of 0.5%. The 2010/11 season did present a significantly higher average SOC, but this coincided with a productive season in which all treatments produced high biomass. The temporary SOC increase is likely due to high crop organic material input for that year (supplementary data, Table A5), and not due to treatment effects (Feller and Beare, 1997). Our results correspond with model estimates by Farage et al. (2007), who found that only small increases in SOC are expected in sandy soil in semi-arid areas in Africa. The high productivity associated with the Buffelsvlei treatments was unrelated to SOC content.

In the clay soil at Zeekoegat, the CA treatments had a measurable effect on SOC. Clay has a higher capacity to retain SOC, due to higher specific surface area that carries a charge, enabling it to bind and chemically stabilize organic matter (Wattel-Koekkoek et al., 2001). Under RT the SOC gradually increased, while the same trend was not observed in CT treatments. The potential of C sequestration by reduced tillage has recently been questioned by Powlson et al. (2014) from a global perspective. In a review, Cheesman et al. (2016) drew similar conclusions for southern Africa. However, other similar site-specific studies found that RT could effectively increase SOM (Kotze and Du Preez, 2007; Govaerts et al., 2009; Sosibo et al., 2017). Our study confirms this but concurrently points to the fact that this depends strongly on the particular soil (and weather) conditions.

4.3 Profitability

The Buffelsvlei site, having deep, well-drained sandy soils supported higher maize yields, which resulted in higher profitability, despite the lower SOC content and the area receiving less rainfall than Zeekoegat. However, none of the CA treatments emerged as significantly more profitable compared to conventional treatments such as monoculture or CT systems over time. Maize grain yields and prices were the most important drivers contributing to profitability – as found in previous studies in Eastern Africa (e.g. Rötter and Van Keulen, 1997). In a meta-analysis done by Rusinamhodzi et al. (2011), a strong correlation was found between maize yield in dryland agricultural and rainfall, and the variability in yield was better explained by total rainfall and rainfall distribution, rather than the specific CA treatments.

The reduced maize grain yields and biomass production at Zeekoegat subsequently reduced the profitability on this site. However, comparative analysis between treatments at Zeekoegat indicates that the most productive system was the CA treatment maize/vetch intercropping. This was despite the fact that maize in this system was planted in tramlines (18,500 plants ha^{-1}) from the third season, compared to full stands in monoculture treatments (37,000 plants ha^{-1}). Grazing vetch is a creeping or ranking leguminous plant that forms a thick and effective cover, and as such, other researchers also reported highly positive effects when associating grazing vetch with cereal crops (Murungu et al., 2010; Dube et al., 2012). It is important to note that other CA treatments did not perform equally well, indicating that the effects of specific CA practices on yield are highly specific to regions (Giller et al., 2009; Govaerts et al., 2009). The successful implementation of CA will depend on the site-specific agro-ecological characteristics, including soil type and climate. Govaerts et al. (2009) pointed out that profitability under CA systems is highly variable and will depend on the type of farming implemented, climatic conditions and annual market prices. In the current business model, there is no payment scheme for additional sequestrated C in the soil. Such schemes would improve the profitability of CA at least in our case on the clay soil and could potentially compensate for the observed reduction in yield. For example, the ‘4 per 1000’ initiative (Van Groenigen et al., 2017) motivates increases in SOC to reduce indirect impacts of global warming, even though it is not linked directly to monetary rewards.

As pointed out by other researchers (e.g. Kirkegaard et al., 2014; Giller et al., 2015; Thierfelder et al., 2015; Mafongoya et al., 2016), further tailoring of CA to site-specific conditions as the basis for increasing profitability and sustainability of the systems necessitates robust knowledge which can only be derived from longer-term trials, rather than more conventional trials such as used those for cultivar assessment or to determine fertilizer requirements. We have made an attempt to move towards this direction with our medium-term field experiments. Complementary crop simulation modelling may help to better disentangle yield and SOC determining factors and to identify optimal site-specific management components to define best management practices of CA (Corbeels et al., 2016; Ngwira et al., 2014; Sommer et al., 2007).

5. Conclusions

In this study we presented rare medium-term field trial data from two contrasting sites, and demonstrate that CA cannot be promoted as the panacea that in all cases leads to SOC build-up and significantly improved yields. The potential benefits of CA systems depend highly on environmental conditions, especially seasonal weather and soil type. For our conditions, changes in SOC and other soil properties due to management practices simply occurred too slowly to reflect in yields or profitability in the short- or medium-term, and profitability linked more closely to year-specific practices such as crop rotation choice.

Possible increases in SOC in the topsoil are not well captured in the current profitability model, neither is improved ecological and social sustainability of such systems. Thus, the current profitability model can only capture a fraction of the potential advantages of CA, and future research should address both climate change mitigation and adaptation in CA systems. Longer-term sustained funding initiatives and mechanisms are essential to gather the data needed to better understand the issues addressed in this paper.

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Supplementary data

Table A1: Monthly rainfall, maximum temperature and minimum temperature for the trial duration at Buffelsvlei

Table A2: Monthly rainfall, maximum temperature and minimum temperature for the trial duration at Zeekoegat

Table A3: Cropping sequence for treatments across years at Buffelsvlei

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Table A5: Average input cost and income (R ha^{-1}) used for profitability calculations for different years

Table A6: Grain yield (t ha^{-1}) for maize and sunflower in various cropping systems over seasons for Buffelsvlei

Table A7: Biomass (t ha^{-1}) for each cropping system over seasons for Buffelsvlei

Table A8: Maize grain yield (t ha^{-1}) for cropping system, tillage and fertilizer levels over seasons for Zeekoegat.

Table A9: Total aboveground biomass (t ha^{-1}) for cropping system, tillage and fertilizer levels over seasons for Zeekoegat

Table A1: Monthly rainfall, maximum temperature and minimum temperature for the trial duration at Buffelsvlei

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ave Trial**
						Rainfall (mm)							
2009	72.4	70.3	10.7	0.0	1.0	27.9	6.3	23.4	20.3	35.5	60.4	109.2	
2010	108.7	88.4	122.4	76.5	13.7	0.0	0.3	0.0	0.0	9.6	73.2	126.5	
2011	97.8	77.5	90.4	81.3	10.7	34.0	0.3	0.0	0.0	46.0	36.8	141.0	
2012	47.0	26.4	86.9	3.8	0.3	13.5	0.5	0.0	29.5	39.1	46.2	164.3	
2013	100.8	32.0	87.9	44.5	1.3	0.0	0.0	0.0	0.0	26.7	41.2	120.4	
2014	101.3	178.6	103.1	3.5	1.5	3.3	0.0	21.1	3.1	8.6	115.6	127.8	
2015	173.5	54.6	120.7	59.7	0.8	5.8	4.6	0.0	73.2	3.8	48.5	31.0	
2016	87.6	47.7	50.0	53.6	55.1	0.5	15.0						
Average	*98.6*	*71.9*	*84.0*	*40.3*	*10.5*	*10.6*	*3.4*	*6.4*	*18.0*	*24.2*	*60.3*	*117.2*	***545.4***
						Temperature maximum (^{o}C)							
2009	24.7	26.9	27.1	26.7	22.5	19.2	17.3	21.3	27.3	27.4	27.1	30.6	
2010	26.9	29.6	28.3	25.5	21.5	19.1	18.3	23.7	28.5	29.8	28.8	28.6	
2011	27.2	28.2	27.9	23.2	21.9	19.1	17.8	22.1	27.5	28.9	30.0	29.0	
2012	30.6	29.7	28.7	25.0	24.9	19.4	20.8	22.7	24.7	29.4	30.3	27.2	
2013	30.2	31.6	28.9	25.6	23.7	21.8	21.4	22.1	27.6	29.3	31.3	27.3	
2014	30.8	28.7	25.9	24.7	24.4	21.2	20.0	23.1	28.4	30.8	27.6	29.4	
2015	30.1	31.0	28.4	26.9	27.8	20.3	21.9	26.2	26.5	31.8	30.6	33.8	
2016	31.2	32.4	29.4	27.6	22.6	20.9	20.0						
Average	*29.0*	*29.8*	*28.1*	*25.6*	*23.7*	*20.1*	*19.7*	*23.0*	*27.2*	*29.6*	*29.4*	*29.4*	***26.2***
						Temperature minimum (^{o}C)							

2009	16.8	15.6	12.8	8.6	5.1	3.3	-1.1	3.7	9.3	12.7	13.0	16.4	
2010	16.8	15.4	14.4	12.3	7.6	-0.6	2.3	1.0	8.2	12.0	14.4	15.7	
2011	16.6	15.2	14.6	10.8	5.7	0.8	-1.0	2.1	7.5	10.5	13.4	15.4	
2012	16.0	15.6	12.8	7.7	4.6	1.1	1.0	4.9	7.1	12.6	14.7	15.5	
2013	16.4	15.0	13.9	8.4	4.2	1.0	3.0	2.6	8.1	11.3	14.3	15.5	
2014	16.6	15.7	13.9	7.0	4.1	0.3	-0.6	3.5	7.6	12.3	13.6	16.6	
2015	15.9	13.7	13.4	9.6	5.0	1.4	3.4	4.8	10.3	13.6	13.0	17.5	
2016	17.5	16.9	13.7	10.6	5.7	2.7	0.3						
Average	*16.6*	*15.4*	*13.7*	*9.4*	*5.3*	*1.2*	*0.9*	*3.2*	*8.3*	*12.1*	*13.8*	*16.1*	***9.7***

Table A2: Monthly rainfall, maximum temperature and minimum temperature for the trial duration at Zeekoegat

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ave for trial**
							Total monthly rainfall (mm)						
2007	-	-	-	-	-	30.1	9.4	0	36.3	150.9	55.1	149.3	
2008	270	42.8	159.9	21.4	35.5	7.5	3	0	0	38.2	106.5	107.8	
2009	211.8	127.5	74	2.5	29.6	31	2.2	125	386	93.3	94	147.3	
2010	125.7	33.1	47.5	178.3	53.3	0.1	0.3	0	0	49.7	68.1	216.1	
2011	392.1	40.1	127.6	111.6	5.1	11.9	0.3	5.4	1.3	63.7	67.2	164.3	
2012	64.9	104.1	81	6.5	0.9	0.2	0	0	74.3	108.7	81.2	154	
2013	90.3	25.4	75.9	98.2	0.55	0	0	0	6.6	103.63	87.62	186.15	
Average	*192.5*	*62.2*	*94.3*	*69.8*	*20.8*	*11.5*	*2.2*	*18.6*	*72.1*	*86.9*	*80.0*	*160.7*	***871.5***
							Temperature maximum (^{0}C)						
2007						21.44	21.42	24.83	30.20	25.74	28.52	27.91	
2008	27.27	30.28	25.70	23.95	23.71	22.14	21.63	25.93	28.84	31.40	29.28	30.73	
2009	29.57	28.51	28.17	27.35	23.92	21.80	20.05	23.35	29.02	28.63	27.65	29.42	
2010	28.92	30.89	30.15	24.41	23.91	20.96	21.33	24.92	29.61	31.59	29.79	29.11	
2011	28.19	29.40	30.08	24.52	23.72	21.03	20.21	23.71	28.86	29.49	30.44	28.91	
2012	30.68	31.20	29.94	26.26	26.24	21.72	22.93	25.09	26.16	27.80	29.42	28.67	
2013	30.73	32.06	29.53	26.15	24.83	23.31	22.44	23.78	29.10	28.88	30.32	27.88	
Average	*29.2*	*30.4*	*28.9*	*25.4*	*24.4*	*21.8*	*21.4*	*24.5*	*28.8*	*29.1*	*29.3*	*28.9*	***26.9***
							Temperature minimum (^{0}C)						
2007						3.35	2.24	4.52	11.34	13.32	15.00	15.47	
2008	16.61	15.60	13.78	8.78	7.17	3.70	2.72	5.58	7.90	13.50	15.99	16.52	
2009	17.96	16.47	13.68	9.15	5.86	4.32	0.68	3.92	9.61	14.42	14.07	15.82	
2010	17.69	16.16	15.44	12.83	7.74	1.76	3.81	4.36	8.89	13.58	15.73	16.25	
2011	17.27	15.84	14.97	11.77	6.09	0.67	0.84	3.47	8.20	11.92	14.43	16.51	
2012	16.81	16.79	14.12	8.88	6.06	1.72	2.73	4.63	8.95	12.16	13.57	16.13	
2013	16.85	15.77	14.43	9.13	4.98	2.20	3.04	4.19	10.50	11.94	14.60	16.26	
Average	*17.2*	*16.1*	*14.4*	*10.1*	*6.3*	*2.5*	*2.3*	*4.4*	*9.3*	*13.0*	*14.8*	*16.1*	***10.5***

Table A3: Cropping sequence for treatments across years at Buffelsvlei

Cropping system	Sequence	2008/09	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16
i	a	Maize, CT	Maize, CT	Maize, CT	Maize, CT	Maize, CT	Maize, CT	Maize, CT	Maize, CT
	b	Maize, RT	Maize, RT	Maize, RT	Maize, RT	Maize, RT	Maize, RT	Maize, RT	Maize, RT
ii	c	Cowpea	Maize	Cowpea	Maize	Cowpea	Maize	Cowpea	Maize
	d	Maize	Cowpea	Maize	Cowpea	Maize	Cowpea	Maize	Cowpea
iii	e	Maize	Sunflower	Maize	Sunflower	Maize	Sunflower	Maize	Sunflower
	f	Sunflower	Maize	Sunflower	Maize	Sunflower	Maize	Sunflower	Maize
iv	g	Millet	Sunflower	Maize	Millet	Sunflower	Maize	Millet	Sunflower
	h	Sunflower	Maize	Millet	Sunflower	Maize	Millet	Sunflower	Maize
	i	Maize	Millet	Sunflower	Maize	Millet	Sunflower	Maize	Millet
v	j	Cowpea	Maize	Millet	Cowpea	Maize	Millet	Cowpea	Maize
	k	Maize	Millet	Cowpea	Maize	Millet	Cowpea	Maize	Millet
	l	Millet	Cowpea	Maize	Millet	Cowpea	Maize	Millet	Cowpea

Table A4: Cropping sequence for treatments across years at Zeekoegat

Cropping system	**2007/08**	**2008/09**	**2009/10**	**2010/11**	**2011/12**	**2012/13**
Maize monocrop	Maize	Maize	Maize	Maize	Maize	Maize
Maize / cowpea rotation	Cowpea	Maize	Cowpea	Maize	Cowpea	Maize
Maize / soybean rotation	Soybean	Maize	Soybean	Maize	Soybean	Maize
Maize / *cowpea intercrop*	Maize *Cowpea*	Maize *Cowpea*	Maize *Cowpea*	Maize *Cowpea*	Maize *Cowpea*	Maize *Cowpea*
Maize / *oats intercrop*	Maize *Oats*	Maize *Oats*	Maize *Oats*	Maize *Oats*	Maize *Oats*	Maize *Oats*
Maize /*vetch intercrop*	Maize *Vetch*	Maize *Vetch*	Maize *Vetch*	Maize *Vetch*	Maize *Vetch*	Maize *Vetch*

Table A5: Average input cost and income (R ha^{-1}) used for profitability calculations for different years

Cropping seasons		2007/08	2008/09	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16	Reference / Data sourced
						INPUT COST					
Fertilizer (R kg^{-1})	**N**	10	18	13	12	16	17	19	19	20	GrainSA monthly fertilizer prices (www.grainsa.co.za)
	P	17	50	19	23	25	26	26	27	34	
	K	6	18	19	12	12	14	14	14	15	
Seed (R ha^{-1})	**Maize (3.7 plants m^{-2})**	604	669	733	797	862	926	990	1055	1119	Seed companies, including Pannar (www.pannar.co.za), Agricol (www.agricol.co.za)
	Cowpea (15 plants m^{-2})	233	300	368	435	503	570	638	705	773	
	Soybean (15 plants m^{-2})	350	397	444	491	538	585				
	Vetch (30 kg seed ha^{-1})	700	750	800	850	900	1000				
	Oats (50 kg seed ha^{-1})	300	350	380	410	430	500				
	Sunflower (15 plants m^{-2})	424	397	409	421	433	423	434	469		
	Millet (10 kg seed ha^{-1})	309	361	412	463	515	566	618	669		
Land preparation (R ha^{-1})	**CT**	268	354	274	299	402	456	501	492	435	GrainSA production model (www.grainsa.co.za); average diesel prices (www.aa.co.za)
	RT	134	177	137	150	201	228	251	246	217	
Herbicide, pesticide (R ha^{-1})	**Maize, CT**	344	455	566	678	789	900	1011	1123	1234	Production models from agricultural economists from GrainSA (www.grainsa.co.za)
	Maize, RT	378	501	623	745	868	990	1113	1235	1357	
	Legume, RT	265	350	436	522	607	693	779	864	950	
	Legume, CT	241	319	396	474	552	630	708	786	864	
	Sunflower	213	282	351	420	489	558	627	696	765	
						INCOME					

Grain (R kg^{-1})	**Maize**	1700	1400	1150	1850	2100	2200	2200	2600	3350	www.grainsa.co.za www.daff.gov.za www.fao.org www.sagis.org www.nda.agric.za
	Sunflower		3000	3500	4100	5000	5200	4900	5100	6900	
Biomass (fodder) (R kg^{-1})	**Maize**	550	550	600	550	675	750	750	800	800	Classifieds in Farmers Weekly (www.farmersweekly.co.za) and Landbouweekblad (www.landbou.com) (2007-2013)
	Vetch	1500	1500	1500	1500	1550	1600	1600	1650	1650	
	Sunflower	550	550	600	550	675	750	750	800	800	
	Millet	2000	1650	1300	1400	1400	1400	1500	1550	1600	
	Cowpea	900	1100	1300	1000	1100	1200	1200	1250	1250	
	Soybean	600	600	550	600	630	750	760	820	850	
	Oats	2000	1650	1300	1400	1400	1400	1500	1550	1600	

Table A6 Grain yield (ton ha^{-1}) for maize and sunflower in various cropping systems over seasons for Buffelsvlei

Cropping system	**2008_09**	**2009_10**	**2010_11**	**2011_12**	**2012_13**	**2013_14**	**2014_15**	**2015_16**
1. Maize monocrop CT	4.354	4.049	5.791	2.417	2.992	8.686	4.083	1.827
2. Maize monocrop RT	6.213	4.417	5.799	2.92	3.789	8.535	6.277	3.867
3. Cowp/Maize	NA	5.036	NA	1.957	NA	9.031	NA	3.701
4. Maize/Cowp	4.847	NA	6.379	NA	4.280	NA	6.934	NA
5. Maize/**Sun**	4.847	***1.948****	6.246	***1.9***	3.543	***2.859***	4.337	NA
6. **Sun**/Maize	***2.068***	4.570	***1.053***	2.369	***1.9***	8.270	***1.731***	3.184
7. Millet/**Sun**/Maize	NA	***2.476***	6.297	NA	***1.9***	8.944	NA	***1.9***
8. **Sun**/Maize/Millet	***1.609***	4.011	NA	***1.9***	3.612	NA	***1.944***	3.563
9. Maize/Millet/**Sun**	4.793	NA	1.082	2.291	NA	***2.324***	6.322	NA
10. Cowp/Maize/Millet	NA	4.840	NA	NA	4.212	NA	NA	3.829
11. Maize/Millet/Cowp	4.793	NA	NA	2.896	NA	NA	7.624	NA
12. Millet/Cowp/Maize	NA	NA	7.279	NA	NA	9.779	NA	NA

***Sunflower grain yield in bold italic**

Table A7: Biomass (ton ha^{-1}) for each cropping system over seasons for Buffelsvlei

Cropping systems	**2008/09**	**2009/10**	**2010/11**	**2011/12**	**2012/13**	**2013/14**	**2014/15**	**2015/16**
1 Maize monocrop CT	*7.52*	*7.52*	*7.52*	2.62	*7.52*	12.53	*7.52*	*7.52*
2 Maize monocrop RT	*7.52*	*7.52*	*7.52*	2.24	*7.52*	12.55	*7.52*	*7.52*
3 Cowpea/maize rotation	*5.64*	*7.52*	6.08	2.36	*5.41*	12.98	*5.41*	*7.52*
4 Maize/cowpea rotation	*7.52*	*5.64*	*7.52*	4.17	*7.52*	5.06	*7.52*	*5.41*
5 Maize/sunflower rotation	*7.52*	5.76	*7.52*	*5.64*	*7.52*	8.16	*7.52*	*5.64*
6 Sunflower/maize rotation	*5.64*	*7.52*	3.00	2.17	*5.64*	11.80	5.78	*7.52*
7 Millet/sunflower/maize rotation	12.41	6.66	*7.52*	*5.03*	*5.64*	12.91	9.28	*5.64*
8 Sunflower/maize/millet rotation	*5.64*	*7.52*	*4.74*	*5.64*	*7.52*	*7.45*	5.94	*7.52*
9 Maize/millet/sunflower rotation	*7.52*	*4.70*	2.81	1.85	*6.50*	7.04	*7.52*	*7.78*
10 Cowpea/maize/millet rotation	*5.64*	*7.52*	*4.74*	3.94	*7.52*	7.39	*5.41*	*7.52*
11 Maize/millet/cowpea rotation	*7.52*	*7.52*	6.86	2.16	*6.50*	6.33	*7.52*	*7.78*
12 Millet/cowpea/maize rotation	12.41	*5.64*	*7.52*	*5.03*	*5.41*	14.05	9.83	*5.41*

***** Due to incomplete datasets, default values were used extensively. Estimated data are in *italics*

**Refer to Table 2 for details of specific crops planted in different years. The rotation crops would be maize with sunflower or cowpea or soybean or millet, and this influenced the biomass produced

Table A8: Maize grain yield (t ha^{-1}) for cropping system, tillage and fertilizer levels over seasons for Zeekoegat.

Cropping system	Till	Fertilizer	2007/08	2008/09	2009/10*	2010/11	2011/12	2012/13
1. Maize monocrop	**CT**	**Low fert**	6.11	5.51	1.43	1.53	1.89	1.56
2. Maize/Cowpea Rotation	**CT**	**Low fert**	NA**	5.91	NA	2.32	NA	1.92
3. Maize/Soybean Rotation	**CT**	**Low fert**	NA	6.87	NA	2.21	NA	1.19
4. Maize/Cowpea Intercrop	**CT**	**Low fert**	6.07	3.45	1.16	1.43	1.99	1.18
5. Maize/Oats Intercrop	**CT**	**Low fert**	6.46	4.14	0.97	1.16	1.34	0.87
6. Maize/Vetch Intercrop	**CT**	**Low fert**	6.10	4.04	1.48	1.95	2.11	1.25
7. Maize monocrop	**CT**	**High fert**	7.10	4.55	1.16	2.21	2.46	2.39
8. Maize/Cowpea Rotation	**CT**	**High fert**	NA	6.60	NA	1.95	NA	1.21
9. Maize/Soybean Rotation	**CT**	**High fert**	NA	6.96	NA	2.77	NA	1.92
10. Maize/Cowpea Intercrop	**CT**	**High fert**	6.39	5.19	0.99	1.07	1.31	1.09
11. Maize/Oats Intercrop	**CT**	**High fert**	6.49	4.06	0.93	1.14	1.18	0.84
12. Maize/Vetch Intercrop	**CT**	**High fert**	6.66	5.46	1.06	2.28	1.62	0.88
1. Maize sole	**RT**	**Low fert**	5.82	3.78	1.61	1.07	1.43	0.83
2. Maize/Cowpea Rotation	**RT**	**Low fert**	NA	5.54	NA	2.46	NA	1.32
3. Maize/Soybean Rotation	**RT**	**Low fert**	NA	5.24	NA	1.41	NA	0.77
4. Maize/Cowpea Intercrop	**RT**	**Low fert**	5.85	3.69	1.12	0.89	1.28	0.48
5. Maize/Oats Intercrop	**RT**	**Low fert**	6.55	4.54	1.26	0.98	0.63	0.80
6. Maize/Vetch Intercrop	**RT**	**Low fert**	6.66	5.11	1.08	1.60	0.89	0.63
7. Maize sole	**RT**	**High fert**	6.60	3.77	1.72	1.55	2.08	1.82
8. Maize/Cowpea Rotation	**RT**	**High fert**	NA	6.89	NA	1.84	NA	1.18
9. Maize/Soybean Rotation	**RT**	**High fert**	NA	6.24	NA	2.13	NA	1.09
10. Maize/Cowpea Inercrop	**RT**	**High fert**	5.65	4.71	1.23	1.27	1.08	0.61
11. Maize/Oats Intercrop	**RT**	**High fert**	5.75	3.46	1.43	0.85	0.68	0.73
12. Maize/Vetch Intercrop	**RT**	**High fert**	6.88	4.78	1.55	1.37	0.99	0.78

*From 2009/10 season, the maize in all intercropping treatments was changed from full stands (0.9 m row width) to tramlines (1.8 m rows)

**NA: Not applicable – the years in which rotation crops (legumes) were planted and no maize yield was available

Table A9: Total aboveground biomass (ton ha^{-1}) for cropping system, tillage and fertilizer levels over seasons for Zeekoegat

Cropping system	Till	Fert	2007/08	2008/09	2009/10	2010/11	2011/12	2012/13
1. Maize monocrop	CT	Low fert	6.00	6.00	7.22	6.23	3.90	3.49
2. Maize/Cowp Rotation*	CT	Low fert	2.60	6.00	2.16	6.49	1.49	3.19
3. Maize/Soy Rotation	CT	Low fert	1.50	6.00	2.36	7.70	0.06	4.64
4. Maize/Cowp Inercrop	CT	Low fert	6.55	6.55	6.31	5.77	4.28	3.51
5. Maize/Oats Intercrop	CT	Low fert	6.95	6.95	6.36	5.35	2.44	2.61
6. Maize/Vetch Intercrop	CT	Low fert	7.71	7.71	7.68	7.30	4.68	3.35
7. Maize monocrop	CT	High fert	6.00	6.00	8.08	8.10	7.19	5.36
8. Maize/Cowp Rotation	CT	High fert	2.60	6.00	2.56	8.80	1.08	3.40
9. Maize/Soy Rotation	CT	High fert	1.50	6.00	0.91	8.86	0.03	4.31
10. Maize/Cowp Inercrop	CT	High fert	6.55	6.55	4.17	3.96	4.06	2.89
11. Maize/Oats Intercrop	CT	High fert	6.95	6.95	5.11	5.34	4.13	2.30
12. Maize/Vetch Intercrop	CT	High fert	7.71	7.71	7.62	7.83	3.77	3.27
1. Maize monocrop	RT	Low fert	6.00	6.00	7.59	6.00	3.30	2.71
2. Maize/Cowp Rotation	RT	Low fert	2.60	6.00	2.87	9.06	1.05	4.41
3. Maize/Soy Rotation	RT	Low fert	1.50	6.00	1.93	5.73	0.12	2.55
4. Maize/Cowp Inercrop	RT	Low fert	6.55	6.55	5.52	5.16	2.58	1.46
5. Maize/Oats Intercrop	RT	Low fert	6.95	6.95	6.80	4.43	1.32	2.85
6. Maize/Vetch Intercrop	RT	Low fert	7.71	7.71	12.38	9.07	3.63	1.76
7. Maize monocrop	RT	High fert	6.00	6.00	11.92	8.32	6.10	4.55
8. Maize/Cowp Rotation	RT	High fert	2.60	6.00	2.89	9.15	1.12	3.32
9. Maize/Soy Rotation	RT	High fert	1.50	6.00	1.14	6.63	0.14	3.17
10. Maize/Cowp Inercrop	RT	High fert	6.55	6.55	5.39	4.92	3.28	2.60
11. Maize/Oats Intercrop	RT	High fert	6.95	6.95	6.40	6.35	1.33	1.59
12. Maize/Vetch Intercrop	RT	High fert	7.71	7.71	9.33	7.92	1.91	2.73

*The total biomass in the rotation plots represent maize biomass in one year, and intercrop biomass the next. Refer to table A4 for year specific crops