Review article

Conservation Agriculture farming systems in rainfed annual crop production in South Africa†

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South Africa is, relative to the rest of the world, a water scarce country with a limited amount of arable land, especially land with a long-term sustainable agricultural production potential. Agriculture should therefore focus on the implementation of soil and water conservation systems. Soil conservation is administered in the South African legislation under the Conservation of Agricultural Resources Act 43 of 1983. The objective of this paper is to summarise Conservation Agriculture (CA) systems practiced in South Africa. These include measures to control wind and water erosion as well as soil compaction through implementation of rip on the row, vertical mulching, controlled traffic, crusting control, mulching, water harvesting and crop rotation. No-tillage is not in the scope of this paper, although aspects of reduced and minimum tillage are covered. Integrating these with existing farming systems could be complex and should be considered with great care. It is proposed that CA specialists should be trained to assist farmers in the selection, adoption and implementation of appropriate CA systems.

Keywords: conservation agriculture, rainfed, farming systems, South Africa

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Introduction

Context of the paper

This paper is an elaboration on a paper that was presented at a workshop on conservation agriculture, which formed part of the Combined Congress of the South African Societies of Soil, Crop, Horticultural and Weed science held in Bloemfontein in January 2019. It covers conservation farming systems, except for no tillage, which was covered in a separate paper that was also presented at the workshop (Strauss et al. 2021). It further does not address aspects related to soil fertility matters, since those were also addressed in a separate presentation at the workshop (Nortjé and Laker 2021). Soil fertility, including soil acidity, situations in South Africa have also been reviewed comprehensively by Barnard et al. (2001) and van der Merwe et al. (2001).

Since this paper is the result of a workshop that formed part of a congress of soil and crop related societies, its focus is on Conservation Agriculture in crop farming, including annual grain crops as well as perennial fruit, nut orchards, vineyards and sugarcane. Extensive grazing on natural rangelands and eco-tourism areas will only receive cursory mentions.

Definition of conservation agriculture and its objectives

The European Conservation Agriculture Federation (ECAF) gives a balanced definition of conservation agriculture and the objectives associated with it (Gonzalez-Sanchez et al. 2015):

> Conservation Agriculture (CA) is defined as a sustainable agriculture production system comprising a set of farming practices adapted to the requirements of crops and local conditions of each region, whose farming and soil management techniques protect the soil from erosion and degradation, improve its quality and biodiversity, and contribute to the preservation of the natural resources water and air, while optimizing yields.

This definition has two very important components, namely:

1. Adaptation of CA to local conditions, including both natural resources (for example soil and climate) as well as socio-economic conditions.
2. Inclusion of all kinds of soil and water conservation techniques i.e. contour bunding, traditional soil and water conservation techniques, water harvesting, windbreaks, cover crops, stubble mulching, minimum tillage and no tillage.

After the definition, ECAF added a paragraph that largely defeats the above core aspects of their definition by narrowing it down to:

Agronomic practices included in CA are based on three core principles, which must be fulfilled concomitantly:

- Minimum soil disturbance.
- Maintenance of permanent soil covers.
- Cropping system diversity, crop rotations.

It seems that most present-day proponents of CA embrace the FAO's definition of CA (FAO, 2018), namely:

Conservation Agriculture is a farming system that promotes maintenance of a permanent soil cover, minimum soil disturbance (i.e. no tillage), and diversification of plant species. It enhances biodiversity and natural biological processes above and below the ground surface, which contribute to increased water and nutrient use efficiency and to improved and sustained crop production.

The FAO then states the three principles of CA as follows:

1. Minimum mechanical soil disturbance (i.e. no tillage) through direct seed and/or fertilizer placement.
2. Permanent soil cover (at least 30 percent) with crop residues and/or cover crops.
3. Species diversification through varied crop sequences and associations involving at least three different crops.

These three CA principles should all be adopted for this system to be successfully implemented (Pittelkow et al. 2015). Although minimum soil disturbance is an important component of CA there are also other conservation practices available to the producer. This paper will list a number of practices/systems available to farmers who have soil sustainability as an objective.

Why is Conservation Agriculture important for South Africa?

Good soil and water are essential to produce food for a growing population but South Africa is very poorly endowed with regard to both resources. About 13% of South Africa's land is considered to be arable (i.e. fit for cultivation) of which only 3% is considered to have a high potential for crop production (Laker 2005). Much of this high-potential land has to date either been lost due to fragmentation or transformation to non-agricultural land uses, or been affected by degrading impacts from adjacent incompatible land uses. In addition, a large proportion of the arable land has only marginal potential for cropping. This situation is due to the fact that the country is dominated by low and erratic rainfall and poor-quality soils. It is therefore evident that the country cannot afford for these resources to become degraded and conservation measures by means of implementing CA systems are essential.

It is estimated that there are currently 34 861 commercial farming units in SA and that each unit supports 1 520 people. However, it is predicted that by 2035 farming units will have decreased to 20 182 whilst those depending on each farming unit will have increased to 3 472 (Statistics SA quoted by Theunissen 2019). This is a result of the expected exponential population growth with a much slower growth in food production (Strydom and Struweg 2016). Between 1969 and 2013 cereal production in SA decreased by 30%, and by 24% in the Southern African Development Community (SADC) countries, whilst during the same period production has increased by 30% in the developed economies of the world (Strydom and Struweg 2016). In order to accommodate this increased dependence on our farming land, the production capacity per hectare must be improved or the area used for production must be increased. The latter may not be possible due to limited resources for production, as well as urbanisation and global warming, whilst the former will require substantial capital and research, including government support (Strydom and Struweg 2016). In addition, increased production could result in the exploitation of existing natural resources that will ultimately lead to the degradation and possible loss of those resources. According to Le Roux et al. (2008) the most limiting constraint to improved production capacity is soil erosion. Le Roux et al. (2008) estimated that the annual rate of soil loss in South Africa is 12.3 t ha^{-1} yr^{-1}, which is in sharp contrast to the rate of soil formation of 0.25 to 0.38 t ha^{-1} yr^{-1} (Matthee and Van Schalkwyk 1984). The comparative soil loss rate in Australia is only 4.1 t ha^{-1} yr^{-1} (Le Roux et al. 2008). Although conditions between Australia and South Africa differ substantially, it nevertheless indicates that South Africa must attempt to lower its rate of soil loss as it will ultimately impact on the country's ability to be food-secure.

Conservation Agriculture (CA) is a farming system that can prevent loss of arable land, whilst regenerating degraded lands. It promotes the maintenance of a permanent soil cover, diversification of plant species, and minimum soil disturbance (FAO 2018). Conservation Agriculture encompasses a selection of systems which offer options for farmers in every ecological zone. These include systems such as no-tillage, minimum soil disturbance from cultivation, sowing or broadcasting of crop seeds, direct placing (drilling) of planting material in the soil, harvesting operation, infield traffic and surface water control.

Methodology

Information for this review was mostly obtained from published literature, including articles in journals and research reports. Since the objective with the paper is to give an overview of the CA situation in South Africa the main focus was on South African publications and reports. Important information was also obtained from unpublished South African reports. Insightful unpublished information was obtained from personal contact with a number of knowledgeable individuals with vast experience in the field of various soil conservation technologies in South Africa. In addition, the authors drew on the wide experience and meaningful field observations of the authors themselves. It should be kept in mind that good observation is good science, sometimes generating more useful information than statistical experiments.

The three major forms of physical degradation of soil that necessitate the implementation of effective conservation technologies

The three major forms of physical degradation of soil that make the implementation of effective and efficient conservation technologies in South Africa absolutely imperative are: soil erosion, soil crusting (surface sealing, Figure 1) and subsurface soil compaction (Figure 2). All three are very serious and extremely widespread in the country. They are closely related in the sense that the inherent vulnerability of different soils to each of these forms of degradation is largely due to the same soil properties.

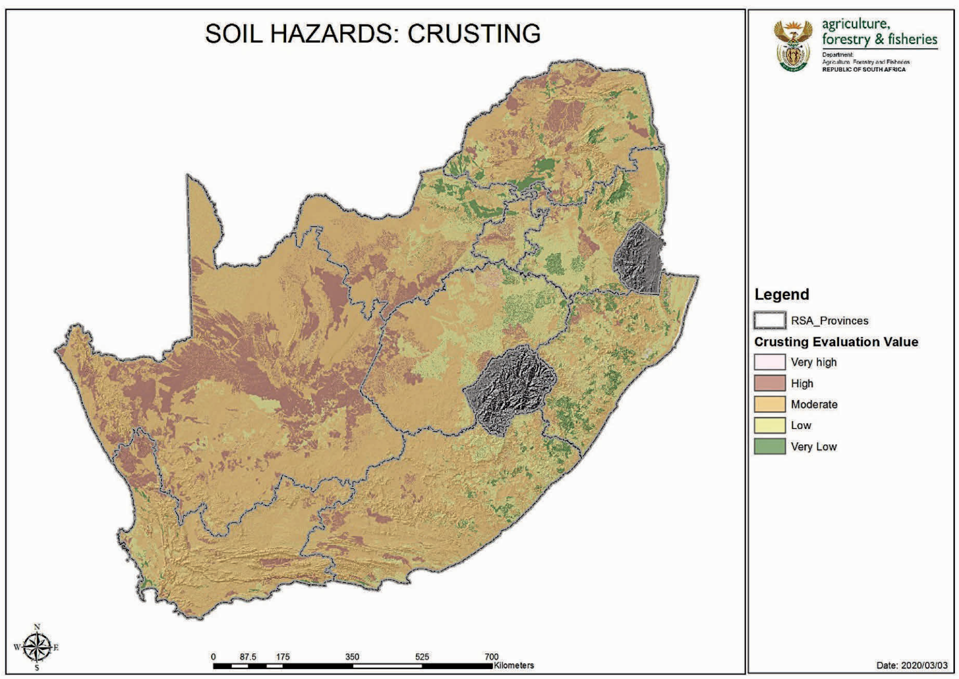

Figure 1: A soil surface crusting hazard classification for South Africa (DAFF, 2017).

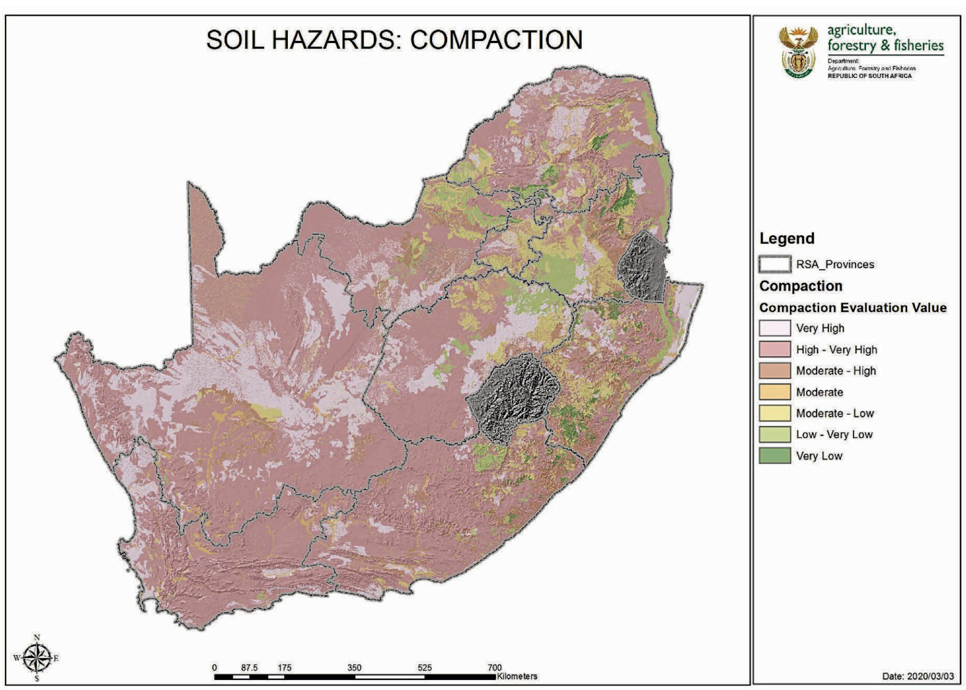

Figure 2: Soil compaction hazardous areas in South Africa (DAFF, 2017).

Laker (2004) published a comprehensive review of the existing knowledge with regard to soil erosion in South Africa. Although this article was published 15 years ago, the basic aspects such as the soil properties affecting the vulnerability of soils to erosion and the impacts of environmental factors and soil management remain the same. Laker and Nortjé (2019) published a comprehensive review of the existing knowledge of soil crusting in South Africa, and in 2020 wrote a comprehensive review of the existing knowledge of subsurface soil compaction in South Africa (Laker and Nortjé 2020).

Since all these reviews are available from prominent journals and are easily accessible no major review thereon will be given here. Only a few of the most salient points relevant to this paper are highlighted. The review papers further include numerous references from the original results that can be followed up.

Soil erosion

Soil erosion is a serious problem globally, where, according to the Global Assessment of Human Induced Soil Degradation (GLASOD) project of UNEP, soil erosion accounts for 84% of the total of global degraded areas (Oldeman 1992). Water erosion contributed 56% and wind erosion 28% to this erosion. In South Africa, more than 70% of the land surface has been affected by varying intensities of soil erosion (Le Roux et al. 2007). When MC Laker contributed the data for South Africa, Lesotho and Namibia for the GLASOD project, Oldeman, the project leader, questioned whether the situation could in fact be as bad as depicted. In contrast Mr. Vosloo, then Director: Soil Conservation, of the Department of Agriculture commented that the situation in some areas was actually under-estimated.

Gully erosion is the most conspicuous form of water erosion, with dongas (huge gullies) in some areas dominating the scenery of landscapes. Although some areas are devastated by gully erosion, the aerial extent and impact of gully erosion is relatively insignificant compared with the aerial extent and impact of sheet erosion (also called inter-rill erosion). The difference in impact between the two is due to the fact that gully erosion removes less fertile topsoil but much more infertile subsoil. In contrast, sheet erosion removes almost exclusively only fertile topsoil over large areas. It is easy to observe the impact of sheet erosion in rangelands where all the topsoil between the vegetation has been washed away, leaving each shrub to stand on a pedestal with large bare patches in between. In cultivated areas it could be called the “silent death”, because only an expert would be able to identify the removal of fertile topsoil.

The reason for the South African situation is that large parts of the country are covered by soils that are inherently extremely vulnerable to water erosion (Laker, 2004). Parent material and low rainfall are major factors contributing thereto. The worst affected are soils in semi-arid areas that have developed from mudstones and shales of the Beaufort geological group. Due to the relatively low rainfall, pedogenesis is limited and unfavourable soil properties are inherited from these parent materials. Cultivation of these soils has been disastrous, even with good contouring and other soil management practices. The ultimate extreme examples are the areas covered by red duplex soils that have developed from the purple mudstones and shales of the Tarkastad subgroup over a large area in the Eastern Cape with Queenstown as the centre, as well as those developed from the red mudstones and shales of the Elliott formation (the former infamous “Red Beds”) in the Sterkspruit-Herschel area in the far north of the Eastern Cape province as well as the adjoining south eastern corner of the Free State. The red colour of the soils misled planners to believe that they were good, stable soils. Keep in mind that these are just examples of a much wider problem situation.

About 25% of SA is highly susceptible to wind erosion (Hoffman and Todd 2000). It occurs in all the areas covered by sandy soils and where strong winds prevail during the driest part of the year (Laker 2004). The western Free State and the areas to the west and northwest constitute the largest cultivated area in the country which is subjected to very severe wind erosion. This is due to the fact that it is dominated by sandy soils and is affected by very strong westerly winds during spring. As there is little rainfall in winter the soils are then at their driest and thus most vulnerable to wind erosion. The biggest hazard from a crop production point is sandblasting of the small maize plants. Smaller important crop production areas are the sandy coastal areas of the Western Cape province, which are lashed by howling south-easterly winds during the non-rainy summer season. All of the mentioned areas fit in more or less with the “wind erosion day” concept of Virmani (1988) on the prediction of a wind erosion hazard, namely a combination of a dry season, strong winds and high temperatures.

To minimise wind and water erosion, the use of combinations or all of the land management options are often required. Each option can be regarded as a system and the integration of several systems is often complex but nevertheless worthwhile. A combination often found in the sugarcane industry is the use of contours, surface cover (green manuring and cover crops), minimum tillage and strip cropping. This combination is very effective in minimising water erosion during the 3–6 month fallow period before the field is replanted to sugarcane.

Subsurface soil compaction

Soil compaction is a global problem in modern intensive mechanised agriculture and South Africa is no exception (Laker 2001; Laker and Nortjé 2020). Laker (2005) and Laker and Nortjé (2020) point out that most soils in South Africa are inherently extremely vulnerable to subsurface compaction and that the problem is much more wide-spread and serious than the global norm depicted in the findings of the GLASOD project (Oldeman 1992). Vast amounts of research on soil compaction in South Africa have been published and were recently summarised in review paper by Laker and Nortjé (2020). It was determined after the introduction of intensive mechanised cropping systems in the 1960s that the fine sandy soils of the northwest Free State are extremely vulnerable to soil compaction. Laker (2005) commented that about 80% of this important region, which produces a major proportion of the white maize that is South Africa’s main staple food crop, is susceptible to serious soil compaction. Research at the then University of the Orange Free State and Free State Region of the Department of Agriculture, reviewed by Laker and Nortjé (2021), revealed serious soil compaction at the irrigation schemes of Vaalharts and the Lower Orange river. Serious soil compaction was subsequently found in many other areas and irrigation schemes (Laker and Nortjé, 2020). Mitchell and Berry (2001) concluded that soils with less than 15% clay in the plough layer are especially susceptible to compaction. Van Antwerpen and Tweddle (2014), Laker and Nortjé, (2020) and Tweddle et al. (2021) concluded that subsurface soil compaction is caused mainly by infield wheel traffic.

The negative impacts of soil compaction on crop production are numerous and the most observable are reduced water use efficiency, stunted crop development and poor yields (Chan et al. 2005; Laker 2005; Tweddle 2016; du Plessis 2019; Laker and Nortjé 2020). According to Smith (1992) soil compaction results in an increase in bulk density, decreased infiltration, a decrease in available water capacity, and lower oxygen diffusion rates. Several South African researchers have also found that it leads to poor nutrient uptake and nutrient imbalances in crops, as well as predisposing fruit crops including citrus and avocado to root rot diseases such as *Phytophthora* (Plate 1), as reviewed by Laker and Nortjé (2020).

Due to the nature of sugarcane farming, soil compaction is mainly located at the surface. Compaction of a moist Longlands soil in year one resulted in a sugarcane stalk yield loss of about 30% in the first crop and nearly 50% in the second crop (Swinford and Boevey 1984). The alleviation and prevention of soil compaction is therefore an important production management consideration. Although soil disturbance might be the only practical option to alleviate compaction quickly, it should be executed with careful consideration for the depth of occurrence (van Antwerpen 2019) and the accompanying production system(s) (i.e. rip on the row, controlled traffic, water harvesting, mulching and irrigation).

Soil compaction is also one of the major yield-limiting factors in the sandy and sandy loam soils of the North-Western province (du Plessis 2019). To combat this, two systems are combined. First, the ground is treated with subsoilers that have three tines spaced between 300 mm and 500 mm apart and fitted with hammer head tips to loosen the soil to a depth of 500 mm and an overall width of 1200 mm (du Plessis 2011). In addition to this, a controlled traffic system guided by GPS is recommended to keep the wheels of equipment away from the production zone and in permanent traffic zones (du Plessis 2014).

Plate 1: *Phytophthora* infestation of the thick horizontal citrus root in a compacted soil.

Soil crusting

Soil crusting is a widespread and serious problem in South Africa. It has various negative implications including reduced water infiltration which results in dry soil, excessive water loss due to increased runoff, and increased evaporation losses leading to poor crop growth and reduced water use efficiency (Laker and Nortjé 2019). Increased runoff also aggravates water erosion. A soil crust leads to poor gas exchange, germination and root efficiency due to a lack of oxygen. Poor root efficiency results in poor uptake of plant nutrients and water, and thus poor plant production. Due to its high mechanical resistance, a soil crust also leads to reduced seedling emergence, especially of small-seeded crops such as wheat, and dicotyledons (all kinds of beans). In some parts of South Africa wheat farmers consider poor emergence as the most serious effect of soil crusting. Soil crusting is a widespread and serious problem in both rainfed and irrigated cropping areas in South Africa (Laker and Nortjé 2019), affecting both annual field crop systems and perennial orchards and vineyards.

Management practices, technologies and systems aimed at counteracting the three major forms of soil degradation and bringing about conservation of soil and water, in order to achieve sustainable crop production

The emphasis of this paper will be on what should be done and what can be done. It is, however, in some cases equally important to emphasise what should not be done. Many of the practices, technologies and systems will be aimed at counteracting one of the forms of soil degradation, whilst others will counteract more than one form of degradation simultaneously.

When studying what is presented in this section and the following section it should be kept in mind that South Africa is part of what Laker (2003) calls "the relatively unknown Third Major Soil Region of the World" at the mid-latitudes, which is dominated by soils and climatic conditions that differ widely from those in the two better known soil regions of the world, namely (i) the predominantly fertile soils of the developed countries at high latitudes in the northern hemisphere and (ii) the soils of the humid tropics. It should be noted that major portions of the grain producing areas of Argentina are covered by soils that are quite similar to those of the high latitude areas in the northern hemisphere. The third major soil region is dominated by poor quality soils and hot, dry climates. In this respect there are some similarities between southern Africa and the Sahel, which is notorious for its extreme soil degradation (Maisharou et al. 2015). The most important point is that one cannot expect CA measures that are implemented successfully in Europe, North America (USA and Canada) and Argentina to be implemented as such without adjustments, if at all, to take into account South African conditions.

Contour bunding

Contour bunding has been the mainstay of soil conservation in undulating croplands for probably close to a century and in many areas this is still the case. Since its implementation, photos of neatly contoured fields have become a symbol of soil conservation. In the 1930s, fencing of rangeland into grazing camps and the construction of contours in cultivated areas were two methods that were encouraged to conserve soil. The purpose of contour bunding is to curb water erosion by controlling runoff from cultivated fields. Correctly aligned contour bunds coupled with well-planned runoff water ways are effective at achieving this. Less conspicuous is that it also helps to retain more water in the cultivated areas by slowing down water flow and increasing infiltration. It is thus also a water conservation technology. Ploughing between the contour bunds perforce had to follow the shape of the bunds, thus further enhancing water retention. During a soil survey on farms in the Clocolan district in the 1970s it was observed that some farmers used mouldboard ploughs with mouldboards that were shaped such that they did not turn the sods over, but turned them just on their sides, creating spaces in which basically all rain was captured. It led to such little runoff that too little water reached the town's water storage dam, resulting in a water crisis.

The Soil Conservation Act No.76 of 1969 specified that contours must be used in fields with slopes greater than 2% unless adequately protected by perennial fodder crops. To encourage the adoption of soil conservation methods, government subsidised the cost associated with construction of contours (Cooper 1996). It is imperative that contour bunds be aligned and constructed correctly. Incorrectly aligned and/or constructed contour bunds are worse than having no contours as they result in large volumes of water breaking through in places, leading to severe erosion. To ensure that contour bunds were constructed correctly, the Department of Agriculture deployed specially trained soil conservation technicians to assist with this activity. Field extension officers were also involved.

The success of contour bunding has also been marred by it leading to some of the worst examples of gully erosion, which developed in correctly contoured fields (Laker 2004), as depicted in Plate 2. This happened because initially cultivation was permitted on slopes of up to 12%, without taking the inherent vulnerabilities of different soils into consideration. Research in South Africa, especially since the 1980s, has shown that the safe permissible upper limits to prevent erosion from different soils vary from slopes of more than 12% to as low as just over 1% (Laker 2004). To be able to decide upon a permissible upper limit for a specific field, a detailed soil map is absolutely essential.

Some large-scale commercial farmers have over the decades been concerned by the significant areas lost to production where the contour bunds are constructed. In contrast it has been found that small-scale farmers in some areas make beneficial use of the bunds by planting fruit trees on them, with other crops in the areas in between. IFAD (1992) reported planting of apple trees on contour bunds in Lesotho, whilst one of the authors (MC Laker) found peach trees being planted on contour bunds in the secluded Amatola basin in the central Eastern Cape province and bananas near Piggs Peak in Eswatini.

Ripping

The identification of widespread severe subsurface soil compaction, especially in the sandy soils of the north-western

Plate 2: Gully erosion due to crusting in contoured cropland following cultivation of poor-quality soil on a slope too steep for this soil. Due to crusting the establishment of natural vegetation was poor.

Free State, led to the realisation that the compacted layers had to be broken up by means of tined implements. The tines had to be just long enough to get in under the compacted layer. This practice is known as ripping of the soil or subsoiling.

Compacted soils are commonly ripped to a depth of 45 cm which is sufficient to reach and disrupt the compacted layer (Laker 2001). However general ripping gave variable results and often lead to short-lived alleviation of compaction. In the early 1970s C.D. Koch observed in experiments that maize plants performed poorly where a tractor wheel, after ripping, had run between the rip line and the row where the crop was planted. This then led to the highly successful practice of "rip on row" (ROR), i.e. ensuring that the crop rows are planted directly on top of the rip line (Beukes and Koch 2017a). Compared to ploughing and cultivation it has been shown that ROR is more effective in alleviating compaction of the production zone leading to improved yields (Table 1).

Under near-normal rainfall conditions, results from three locations in the North-Western Free State were variable but all showed favourable yield responses for mono-culture maize (Beukes and Koch 2017a) as well as for rotations of maize, soybeans and forage sorghum (Beukes and Koch 2017b) to ROR compared to minimum soil disturbance (only light surface disturbance and planting on the row from the previous crop).

According to Laker and Nortjé (2020), very little ROR is presently explicitly done by farmers in the Free State and North West provinces. 'Complete' ripping is widely implemented, but it effectively amounts to ROR due to the combination of ripping with controlled traffic. With the advent of GPS and self-steering tractors this is easy to implement. It is estimated that in the predominantly sandy soils of the central and western Free State this system is applied to approximately 80% of the area. In North West province, with a smaller proportion of sandy soils, it is estimated that ROR is applied to 50-60% of the area. Professor Alan Bennie (personal communication) points out that with this system there is minimal disturbance of the surface soil layer and stubble is left on the ground 'thus qualifying it to be recognised as conservation agriculture'. Bennie (2001) summarised research results obtained by him and his team which showed that conventional tillage gave the best yields and was most economic on the sandy soils, with results from ROR being somewhat inferior. However, because of the serious wind erosion under conventional tillage, they recommended that the ROR system should be applied. Thus, it combats two types of soil degradation simultaneously on these soils, namely (i) soil compaction, for which it was originally introduced, and (ii) wind erosion. The latter was also stressed by Beukes and Koch (2017a).

Table 1: Rainfed maize yields under different cultivation systems on apedal sandy soils in the North-Western Free State which are prone to compaction (Laker (2001) reporting on work by Astrid Hattingh).

Cultivation system	Grain yield (t ha^{-1})
Rip on the row	5.2
Plough – 25 cm	1.5
Cultivator – 15 cm	1.2

Table 2: Suggested maximum number of seasons of no-tillage before tillage may be required (Mitchell and Berry 2001).

Clay content of the tilled layer (%)	Number of seasons		
	Dryland grain crops	Irrigated grain crops	Silage crops
1–8	1	1	1
9–16	2	2	2
17–24	4	3	2
25–32	8	5	3
33–40	16	8	5
>40	32	11	7

Controlled traffic

Due to observations and studies by Koch and others in the 1970s that the position of the wheel tracks of tractors relative to crop rows and rip lines was of paramount importance and that most (up to 90%) compaction occurs during the first pass of a vehicle, it was realised that random traversing of the soil caused major general compaction of cultivated fields (Laker and Nortjé, 2020). In response, the system of controlled traffic was introduced, i.e. travelling in the same tracks during all operations in a season. The use of GPS and self-steering tractors are presently making this much easier (Figure 3). Van Antwerpen and Tweddle (2014) and Tweddle et al. (2021) supported by Prof Bennie and Martiens du Plessis (personal communication) stressed strongly that controlled traffic is an absolute requirement for sustainable crop production. Du Plessis (2019) stressed that without controlled traffic even no-tillage is not sustainable. Du Plessis (2019) also indicated that permanent controlled traffic, i.e. driving in the same tracks in all years and not only per season, is gaining attention in the North West province and that some farmers rip only once every two, three or four years, resulting in cost savings. The interval probably depends on the soil texture in line with the findings reported by Mitchell and Berry (2001) (Table 2).

In the sugarcane industry vehicles are often driven over the cane stools (crop row) after harvest during the collection and transport of cane stalks out of the field, thus leading to compaction. Problems with soil compaction, and the realisation / acknowledgement that equipment causing compaction cannot be kept out of fields, has led to the development and adoption of controlled traffic for continual infield operations (Braunack et al. 1995). The objective with the controlled traffic system was to divide fields into a production zone and a traffic zone. The intention for the traffic zone was never to disturb it again. The principle applied in the development of this system was to keep wheels of all infield equipment away from the production zone. A controlled traffic system, therefore, creates zones in fields with low (the crop row) and high (the interrow) bulk densities (Figure 4). Bulk density of the production zone is therefore kept favourable for root development and crop growth whilst the compacted interrow provides good traction and low rolling resistance and therefore favours wheel traffic. The impact of the latter on yield ranged from no yield loss for light equipment staying in the interrow to 48% yield loss for heavy equipment driving over the stools (Table 3). The damaging effect of driving over cane stools is permanent, which means that the yield potential of affected stools is permanently lowered. Since sugarcane fields are replanted after approximately 10 years, there are great financial incentives to adopt controlled traffic systems.

Vertical mulching

About 65% of soils in the SA sugarcane industry have a grey topsoil, which implies that the clay content is in the range 10% to 25%, soil organic matter is low, nematodes are a problem and water and nutrient holding capacities are low. They further compact and crust easily and are extremely vulnerable to runoff and erosion. These soils are also often shallow, with a duplex character, and when ripped the benefits do not last long. One solution is to incorporate an ameliorant into the soil during subsoiling, a process termed 'vertical mulching'. The best ameliorant from the results of several field trials was filter cake (or milo, a fine cake of organic matter obtained from sugarcane mills with a peat-like appearance), applied at 100 tonnes ha^{-1} in the ripped slot (performed only once). After harvesting the fourth crop (four years after plant) of a field trial that lasted 13 years, water infiltration rates were still four times higher compared to other treatments (no vertical mulching and vertical mulching with no ameliorant). Mean yield response in the longest running trial was a significant 9.8 tonnes cane stalks per hectare per annum over 10 crops (Figure 5). The results from the first five crops harvested from this trial and others were described by Meyer et al. (1992).

Table 3: Mean (median in brackets) yield response of sugarcane as a % of an un-trafficked control to interrow and row traffic distinguishing between equipment with a low, medium and high impact on crop yield and under high soil moisture conditions (Tweddle et al. 2021)

Traffic position	Impact of equipment on stalk yield (%)		
	Low	Medium	High
Interrow	100.3 (97.9)	92.8 (95.5)	86.9 (85.0)
Crop row	97.4 (97.4)	72.8 (73.9)	51.8 (53.0)

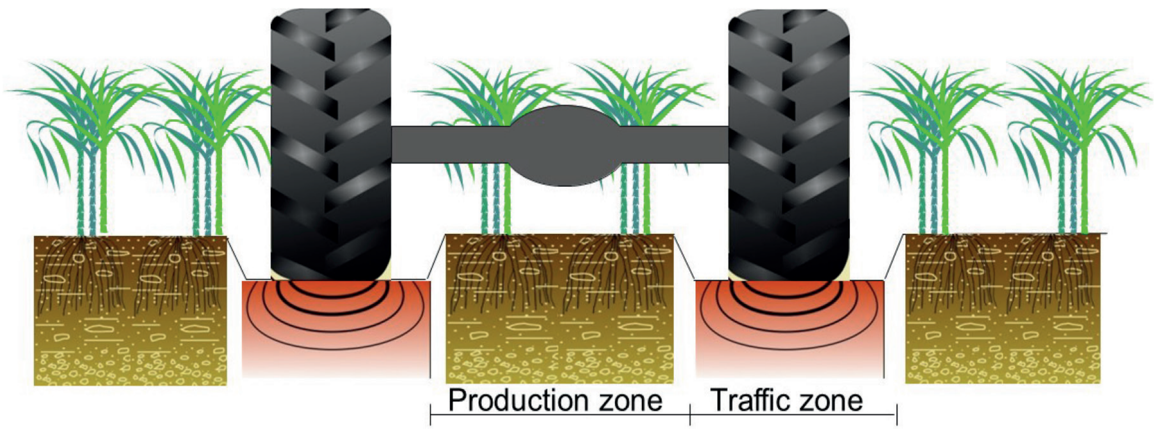

Figure 3: Field layout managed with a controlled traffic system. Distances are determined by factors such as the available equipment, the crop and water regime (rainfed vs irrigation).

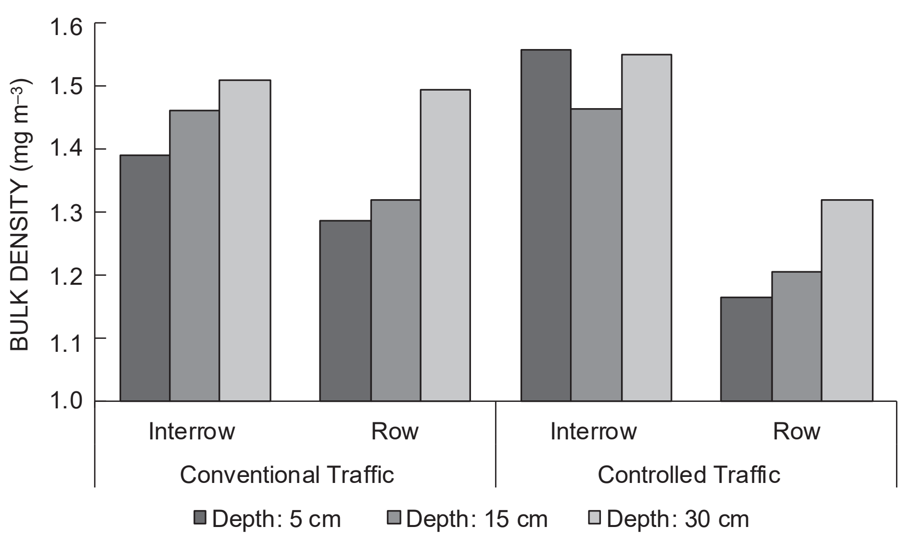

Figure 4: Soil bulk densities measured in the interrow and crop row zones at depths 5, 15 and 30 cm after sugarcane was extracted from the field following harvesting and comparing conventional and controlled traffic systems (van Antwerpen unpublished data).

Deep trenching

Deep trenching (to about 1 m depth) is an effective way to combat the effects of subsurface soil compaction in perennial crops, such as orchards and vineyards. In the late 1960s Laker (1981; 1986) was tasked to search for the cause of a serious incidence of growth stunting disease (*groeistilstandsiekte*) in sultanas (Thompson seedless grapes) at the Lower Orange River irrigation area, resulting in major financial losses to farmers. He identified serious subsurface soil compaction leading to induced K deficiencies in the vineyard crop as the cause of this problem.

Laker (1981; 1986) compared three systems of deep trenching (all to 1 m depth) in the middle of the inter-rows with the farmer's normal shallow cultivation in a vineyard with extremely severe growth stunting disease. The one-time only treatments were implemented too late to give results in the first season. In the second season trenching increased yields by between 45 and 98% over the control, reaching yields similar to those in healthy vineyards, in the third season yield increased by 42 to 64% and in the fourth season by 30 to 47%. There were no significant differences between the three trenching methods, namely no organic matter (OM) incorporated, shallow incorporation of OM and deep (throughout the whole depth of the trench) incorporation of OM. In the fourth season only one of the 24 tested vines in the control plots did not have growth stunting disease. In contrast none of the 72 tested vines in the trenched plots showed the condition. The question remains as to how often the treatments need to be repeated. These data are also summarised in Laker and Nortjé (2020).

In 1959, Laker followed an introductory course in Viticultural Science as part of his BSc Agric curriculum at Stellenbosch University. In the course, Prof. C.J. Theron advocated making deep trenches in every fourth vineyard interrow during pruning time and incorporating the pruned material from four rows into the trench, shifting the trench every year, so that every interrow is trenched once every four years. This is similar to vertical mulching.

Mulching

One solution to prevent the formation of crusts is to keep the soil surface covered with biomass – whether dead (as a mulch) or alive (as a cover crop). Biomass is available in ample quantities in the Eastern and Southern coastal regions and the relatively high rainfall areas in the north eastern parts of the central plateau, namely the Highveld of Mpumalanga and the north eastern Free State. However, further towards the west of the latter areas finding biomass is a huge challenge as rainfall is too low for the production of sufficient material to keep the soil adequately covered, keeping in mind that CA by definition requires a minimum of only 30% cover (FAO 2018). There is an even bigger problem in South Africa's main wheat producing areas in the Western Cape, namely the Swartland and the Rûens, where biomass production is low due to poor quality soils and low rainfall (400-420 mm per annum). In unpublished papers presented at SSSSA congresses during the 1970s L.L. Eksteen reported that experiments at Langgewens Experiment Station between Malmesbury and Moorreesburg in the Swartland showed that the amount of wheat stubble produced was too little to make any difference whether it was left on the fields or not. As a result, in the 1950s and 1960s the stubble was utilized beneficially by grazing it with Merino wool sheep. At the time Malmesbury, known as a major wheat producing district, was also the district with the highest sheep numbers in South Africa.

South African research has shown the high effectiveness of applying a mulch in alleviating soil crusting and creating a stable structure at the soil surface, e.g. Stern et al. (1991; 1992). Mulching decreases runoff and increases water use efficiencies and yield. Some deciduous fruit farmers in the Western Cape overcome crusting problems associated with the ground below the canopies of trees under drip or micro-irrigation effectively by mulching. Mulching ranges from applying wood chips to allowing weeds to grow during the winter rain period and killing them with a suitable weedicide during spring. Unfortunately, mulching is practiced by a

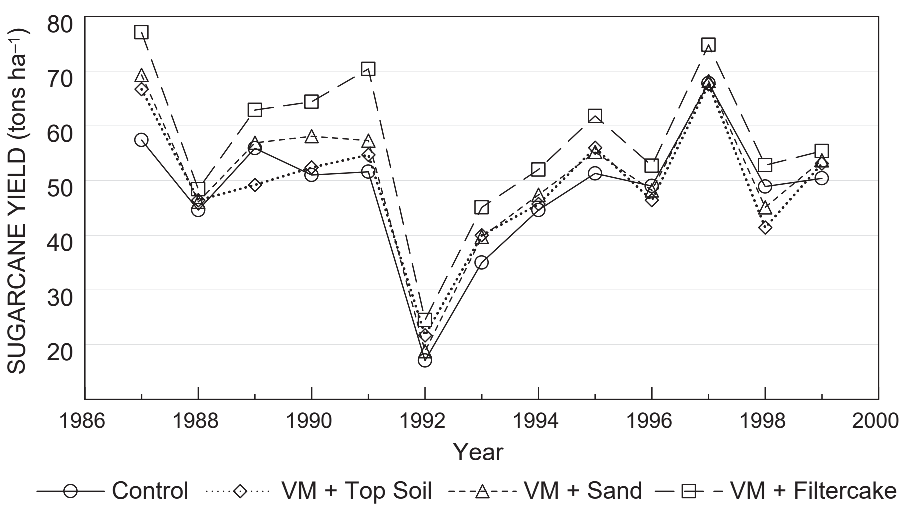

Figure 5: Yield results from the vertical mulching (VM) trial conducted in the Mtunzini region on a Longlands soil using three ameliorants. With the exception of 1988 VM + Filter cake treatment yields were continuously significantly higher compared to the control till 1996 (van Antwerpen unpublished data).

minority of farmers as most believe that mulching is too expensive.

Despite the apparent abundance of biomass available as a mulch in the KwaZulu-Natal region, crusting is still a factor limiting water infiltration and leading to significant amounts of runoff and erosion. Studies conducted at 19 sites in the Limpopo, Mpumalanga, KwaZulu-Natal and Eastern Cape provinces showed that the site with the lowest infiltration rate, ascribed to crusting, was in KwaZulu-Natal where it would be least expected (Mills and Fey 2004).

About 90% of all sugarcane fields are burnt in preparation for harvesting but nevertheless yield at least 7 tonnes ha^{-1} of unburnt leaf material which, if spread, can cover about 70% of the available soil surface area. Other than the prevention of crusting, mulches have shown to benefit sugarcane production in a number of ways. When a farmer switches from burning at harvest to no burning, the first observation is that the weed pressure is suppressed and less is spent on herbicides (Thompson 1966). In dryland areas evaporation is reduced by about 90 mm (Thompson 1966) and stalk yield is increased by 9 tonnes ha^{-1} (Thompson 1976). In irrigated areas the average reduction in water required for irrigation (and therefore electricity use) is 15% (Olivier and Singles 2015). Soil carbon is enhanced (Thompson 1965; Mthimkhulu et al. 2018), microbial activity is higher (Graham et al. 2002), soil aggregates are more stable (Mthimkhulu et al. 2016), the mulch is a source of nutrients (van Antwerpen et al. 2001), water holding capacity is improved (van Antwerpen 2001) and the soil temperature is mediated, being warmer by 4 ºC in winter and cooler in summer (Thompson 1966).

In the drier North-Western parts of South Africa organic material that can be used as a mulch is mainly residue left after harvesting and varies from no residue from peanuts, 1.2 tonnes ha^{-1} for sunflower seeds and 2.5 to 4.0 tonnes ha^{-1} for maize (Martiens du Plessis, personal communication). These amounts are not sufficient to cover the soil surface to prevent crusting, but when left rooted are sufficient to significantly reduce wind erosion (Bilbro and Fryrear 1994).

Cover crops

Cover crops are used effectively in perennial crops such as orchards and vineyards. In the European Conservation Agriculture Federation (ECAF) document by Gonzalez-Sanchez et al. (2015) it is stated:

> Groundcovers (GC) is the most widely used CA agronomic practice for perennial crops, whereby the soil surface between the rows of trees remains protected against erosion. With this technique, at least 30% of the soil not covered by the canopy is protected either by sown cover crops, spontaneous vegetation or inert covers, such as pruning residues or tree leaves.

However, in South Africa the problem is not the area between the trees, which is usually well protected by ground covers, but the bare areas under the canopies of the trees.

By its nature, the production of sugarcane is a monocropping system with a replant event approximately every 10 years. To break the monocropping pattern it is important for several reasons that farmers grow a cover crop in the period before replanting. Popular crops are oats in winter and sunn hemp or several bean species (velvet beans, dolichos beans and cowpeas) in summer. The use of cover crops has always benefitted the following sugarcane crop with regard to stalk yield, an effect that lasts between one and three successive crops (Rhodes et al. 2010). In Eswatini the response to fallowing and green manuring was approximately 50% in the first crop after planting and 25% in the second and third crops, with no response thereafter (Nixon 1992).Typical stalk yield responses are 5–20% after a bare fallow and 10–40% after a cover crop when compared with continuous sugarcane cultivation (SASRI 2010).

Use of ameliorants to overcome soil crusting

Research in South Africa has shown that apart from mulching, surface application of different ameliorants can also be used effectively to overcome soil crusting (Stern et al. 1991; 1992). Ameliorants include large organic molecules, such as the highly effective anionic polyacrylamide (PAM), or an inorganic ameliorant such as gypsum (or phosphogypsum) The latter is less effective than organic ameliorants and sometimes has no effect (Stern et al. 1991; 1992; Laker and Vanassche 2001). Because a very thin surface layer (only a few mm) has to be ameliorated, only small amounts are required, making it cost effective.

In the Sundays River valley, crusting of the soils in orchards was so extreme that oranges could float in water applied to the trees with micro-irrigation (Laker and Vanassche 2001). The latter authors solved the problem by surface application of a coal-derived humic material which led to increased water infiltration, deeper finely branched roots and improved yields (Table 4).

Crop rotation

Practising crop rotation is one of the three principles in the FAO's definition of CA (FAO 2018). This is however the one principle against which there appears to be quite a large amount of resistance to adoption. In regions where annual crops are produced it is common to rotate at least two crops although three is not uncommon. Examples are a summer crop followed by a winter crop and where possible the following summer crop is different from the initial one. Crop rotation is often included in trials used for research (e.g. Garside and Bell 2001; Beukes 2018). The advantages of crop rotation include improved soil health and higher yields (Pearson 1958; Garside and Bell 2001; Nixon 2005). In this sense improved soil health often means higher levels of labile carbon (McDaniel et al. 2014) and nitrogen (Garside and Bell 2001), increased microbial species richness and numbers (Haynes and Graham 2004), improved soil structure (Chan and Heenan 1996) and breaking disease cycles (Bieske 1965), to name a few effects. Each of the above-mentioned impacts is expressed in various strengths following crop rotation, and can result in sugarcane stalk yield responses of between 14% and 84% (Garside et al. 2000). The species of crops used for rotation does not seem to be the important factor, but literature favours the inclusion of a legume crop at times (Garside and Berthelsen 2004; Magdoff and Van Es 2009).

It is understood that farmers will not adopt a system that they cannot economically afford. Thus, a crop rotation must have the incentive of a larger gross margin, e.g. by reducing the amount of fertiliser or pesticide that must be applied Grain

SA researchers provided data from recent studies towards promoting no tillage in the drier parts of North West province to Nortjé and Laker (2021). From these data the researchers were surprised to find out how effective monoculture of maize still is in these areas after a very long time of practising it. Thus, there does not seem to be a logical reason for farmers to give it up as yet.

In some cases, crop rotations used in the distant past were abandoned and researchers are now trying to re-introduce crop rotations into those areas. An example is the Swartland wheat producing area in the Western Cape. In the 1950s and 1960s the farmers in that area practised a three-year rotation involving wheat, lupins (legume) and a fallow season, with the additional sheep grazing factor mentioned earlier. Somehow this changed to wheat monoculture at some point. In 1996 a new long-term experiment involving a large number of different crop rotations was started. The results after 20 years of research showed that most (89.4%) farmers benefitted, but that some (2.4%) performed worse with crop rotations than with monoculture (Strauss 2015).

Wind breaks

Windbreaks are an effective way to curb wind erosion. According to Funk and Reuter (2006) they can be expensive to establish and may take a long time to become effective. However, these authors are referring to the use of trees as windbreaks, which are often established around orchards to curb wind damage to trees and fruit and not so much to curb wind erosion.

On the Joostenberg Flats near Cape Town in the late 1940s and early 1950s highly sophisticated small-scale farmers produced excellent vegetables, such as carrots, and crops (e.g. watermelons). This was done despite the fact that the area is characterised by almost pure sands and experiences gale force winds in summer. On one farm in 1945 it was noticed that the farmer planted oats in winter, and in summer he cultivated narrow strips between strips of oats that he left standing as wind breaks. At a soil conservation congress in Bangkok, Morgan et al. (1988) presented results of highly sophisticated experiments, including wind tunnels. They stated that:

> Strip cropping is a recommended practice for wind erosion control. In England, live barley strips and planted straw strips are used for this purpose and to provide shelter to wind-sensitive crops such as onions, sugar beet and carrots.

Their wind-tunnel studies found that the ideal crop for in-field shelter has bladed leaves to minimize streamlining and leaves aligned full-face to the wind to minimise ‘wall’ effects. Planted straw strips and live barley strips meet these requirements.

Thus, the wind tunnel studies confirmed what farmers on the Joostenberg Flats already knew and had implemented successfully 40 years earlier (MC Laker, personal experience).

Rainwater harvesting

South Africa is generally considered to be a water-scarce country with an average rainfall of 450 mm year^{-1} compared to the global average of about 860 mm year^{-1} (DEA 2019) and ranked 39th driest out of 182 countries in the world (FAO 2016). In the arid and semi-arid regions of Southern Africa resource-poor farmers produce household crops and every year face the risk of crop failure due to a shortage of water. Options to conserve water and to allow for optimum use of available rainfall are therefore important to South Africans. An in-field rainwater harvesting (IRWH) technique (Figure 6) for rural farmers of the Thaba Nchu region was proposed by Hensley et al. (2000). The system requires an area of runoff to collect (harvest) rainwater and to channel it to the crop rows (production zone) which are divided by a ridge. On the “up-side” the ridge is subdivided with smaller ridges running perpendicular to the main ridge. The purpose is to create basins to capture the rainwater and to prevent water from running along the ridge and out of the field. The IRWH system incorporates a number of soil conservation practices. These include: contours to control surface water flow; a mulch applied on the upside of the ridge to reduce evaporation, thus preventing crust formation where mulches are applied and improving water infiltration; reduced tillage as only soils in the production zone are disturbed in preparation for planting; and controlled traffic as the wheels of equipment are limited to the rainwater harvesting zone which is a no-tillage area where a crust is formed to promote runoff towards the production zone. In a manually operated IRWH system the width of the production zone is 1 m and that of the runoff zone 2 m (Hensley 2000). In a mechanical operation the production zone is widened to 1.1 m and the runoff zone to 2.4 m. With good demonstration plots and marketing, adoption of IRWH increased from 6 households in 2001 to 1033 households in 2004. This system was tested with 16 crop types and approximately 66% of households selected to plant maize or dry beans. Yield benefits in favour of IRWH were at least 42% for homestead gardens where all operations are manual. Where mechanical equipment was used to prepare fields, yield benefits averaged at 16% (Botha et al. 2016).

Indigenous soil and water conservation technologies in South Africa

It is well known that there are highly successful indigenous soil and water conservation technologies in Africa. The best known for cultivated areas are those found in the western Sahel

Table 4: Results of fresh orange yield from field experiments with coal-derived humic products (HP) (Adapted from Laker and Vanassche 2001)

Treatment	Fresh orange yield (kg/tree)		Yield increase (kg/tree)
	1991 Control	1993	
Control: Soil surface loosened by scratching under tree canopies	34.3	49.9	15.6[b]
0.25% Humic product surface application under canopies, soil loosened by scratching	23.9	61.9	38.0[a]
Gypsum 5 tonnes ha^{-1} equivalent under canopies, surface loosened by scratching	26.5	38.2	11.7[b]
Surface loosened by scratching under canopies + 1 m deep trench along row under drip line	24.2	37.5	13.3[b]

Figures with the same symbol are not statistically different ($p < 0.05$).

(Burkina Faso, Niger, Mali), namely planting pits (zai, tassa), demi-lunes (half-moon structures to concentrate runoff water and planted to crops) and stone bunds (IFAD 1992; Maisharou et al. 2015; Saidou and Ichaou 2015). It appears that there was a perception that such systems are not really found in South Africa. However, in the early 1990s a post-graduate student from the Venda area in Northern Limpopo brought co-author M.C. Laker a photo of a stone bund in Venda. It was then overgrown by weeds and shrubs but was still in use when the student was a child. At about the same time Van Averbeke and others became aware of the brilliant *Gelesha* system that was used in the Transkei area of the Eastern Cape up to the 1960s. With this system the soil was ripped with ox-drawn rippers immediately after harvest in July. One of the reasons was that the oxen were still strong at that time of the year, but at the end of winter they would be too weak to pull the ripper through the hard soil. Most importantly it opened up the soil to effectively capture the all-important spring rains. The effective use of these rains is enormously important, as the eastern coastal areas do not have normal summer rainfall patterns, but rainfall peaks in spring and autumn. This is the case all along the eastern plateau of Africa right up into Ethiopia. Introduction of government tractor schemes meant the end of the *Gelesha* system. In the end the most important benefit of *Gelesha* was lost, because cultivation is now typically done, like everywhere else, after the rains have started. Most indigenous systems that had been used effectively fell away under the pressure of modern systems which are often not adapted to the circumstances. Denison and Wotshela (2009) have subsequently made a major survey of indigenous water harvesting and conservation practices in South Africa and documented an amazing array of such practices and their practical implications.

Adoption of CA

The estimated global adoption of CA was 100 million hectares in 2007 (FAO 2008) which has increased to about 157 million hectares in 2013. This amounts to an increase of 55%, but still only represents 11% of global cultivated[1] land (Kassam et al. 2015). However, if this trend is analysed it shows that large scale adoption of CA is mainly in the Americas and Australia (FAO 2008; Kassam et al. 2015). These figures are, however, heavily skewed towards no tillage. In the literature no tillage areas are often accounted for as the adoption of CA (Giller et al. 2015) which could be as high as 61% of the total area under CA (calculated from data by Derpsch 2001).

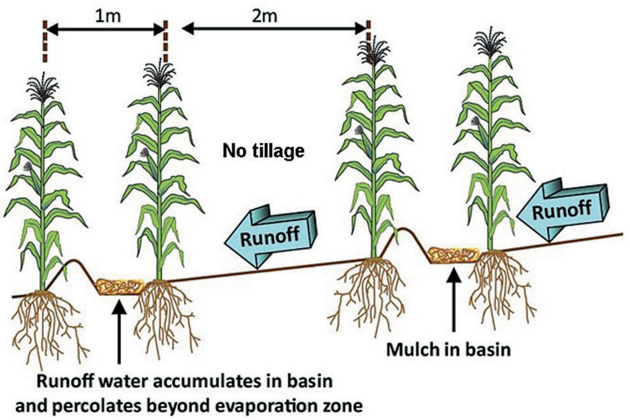

Figure 6: An illustration of the in-field rainwater harvesting system (Hensley 2000).

On a global scale Africa contributes only about 0.3% of the area under CA. Nevertheless, adoption of CA (as defined by the FAO (2018)) in Africa has increased from zero hectares in 1988 to approximately 300 000 hectares in 2007 (FAO 2008). Kassam et al. (2015) estimated that the area under CA in Africa was 480 000 hectares in 2008, and increased to 1.2 million hectares by 2013, shared among only 15 countries. The estimated area of cultivated land under CA in South Africa was 368 000 hectares in 2008 with no increase in the area under CA in the 2013 census (Kassam et al. 2015). The reasons for this apparent lack of adoption should be clear from the discussions thus far: Practices can and will be adopted only if they are relevant or adapted to specific conditions and situations. The 80% adoption of the CA system of ripping, controlled traffic and consequential stubble mulching on the sandy soils of the central and western Free State is a prime example of major adoption of a system that suits the area. On the other hand, there are practically no cases of successful no tillage in the area and it was found that no tillage is a failure on the sandy soils of the central and western Free State (Bennie 2001).

In a study on the adoption of the promoted three-component CA package (reduced tillage plus mulch plus intercropping) by small-scale farmers in the highlands of Tanzania, Rioux and San Juan (2015) found that the level of adoption was low: 45% for practising one CA sub-practice only, 6% for practising two sub-practices at a time, and no one practising the full package of all three sub-practices. This confirmed what has been well-known since the 1960s, namely that whereas scientists see and advocate a package, farmers see the individual components of a package and choose individually. A key conclusion by Rioux and San Juan (2015) with regard to the adoption of CA by small-scale farmers is: '*The main factors determining adoption were wealth and food security status, land tenure, land availability, labour, perceived payoffs and access to information and training.'*

Conservation agriculture interventions generally have a positive effect on soil properties, soil health and crop yield if applied correctly. Local research involving farmers is needed to support best-management practices for different agro-ecological zones (Swanepoel et al. 2018). In a recent CA review article Swanepoel et al. (2018) showed an exponential

[1] The authors wish to highlight here the confusion that is caused by the incorrect use of the term 'arable land' instead of 'cultivated land', i.e. for land that is under cultivation, by numerous authors. 'Arable land' is not a synonym for 'cultivated land'. There is an enormous basic difference between the two concepts. Cultivated land is land that is currently under cultivation. According to the Oxford dictionary 'arable' is defined as 'fit for cultivation'. In *A Glossary of Soil Science* van der Watt & van Rooyen (1995) define 'arable land' as 'land so located that production of cultivated crops is economical and practical' and 'arable soil' as 'soil that can produce crops requiring tillage'. Not all arable land is presently being cultivated. In some areas there are significant areas of arable land that are not or have never been cultivated. There are also areas that have been cultivated that should never have been cultivated due to limit production potential resulting in the degradation of the soil resource. A major proportion of the worst soil degradation, especially soil erosion, is where non-arable land, i.e. land that is not fit for cultivation, has been or is being cultivated.

increase in the literature output for South Africa (Figure 7) which is similar to the international trend (Baveye 2020) and is regarded as a positive development. This should be seen as just the beginning in the development and distribution of knowledge of CA systems, and scientists and extension officers (agricultural advisors) should be encouraged to increase their outputs and contacts with farmers.

Conclusions

Conservation agriculture (CA) is well established and is strongly supported by literature worldwide. In an effort to protect and retain our soils CA is also described and promulgated in our national legislation (e.g. CARA 1983; DAFF 2017) with the aim of maintaining the agricultural sustainability of South Africa. After reading this article it is hoped that the reader has been convinced that CA is much more than no tillage or zero tillage and that many systems are available to the concerned farmer to select from for implementation to protect his soils and their production potential. The benefits to CA are numerous and aim to sustain the production and profits on farms in the long term. This paper lists a number of CA practices that are practiced in South Africa. It is, however, by no means a complete list but serves as a reminder of practices commonly found in South Africa. Several of these practices can be seen as systems in their own right and require careful consideration during the adoption phase. Failing to do so could lead to disappointing results, often due to following incorrect procedures and/or incompatibility with existing practices / systems on the farm. This highlights the need for knowledgeable individuals to assist with the adoption and implementation of CA practices. This requires the training of CA specialists who are not only equipped with theoretical knowledge, but also possessing applied practical experience. This is a tall order and agriculture institutions and universities are requested to become involved in the development of courses and training of CA specialists to assist farmers with the adoption and incorporation of CA into existing practices on the farm.

In addition, a proper knowledge management system of CA is required. Such a system should not only have a record of the extent to which CA is being practiced in South Africa but should further include the relevant CA practices (or systems) being used, in order to have a better understanding of applied CA practices in relation to localised conditions. This will enable the compilation of a "Best CA practices manual" approach to be applied per geographic locality (based on actual infield applications under relevant conditions) aligned with the capability, suitability and potential of the natural agricultural resource and the impact of CA on the larger agro-ecosystem.

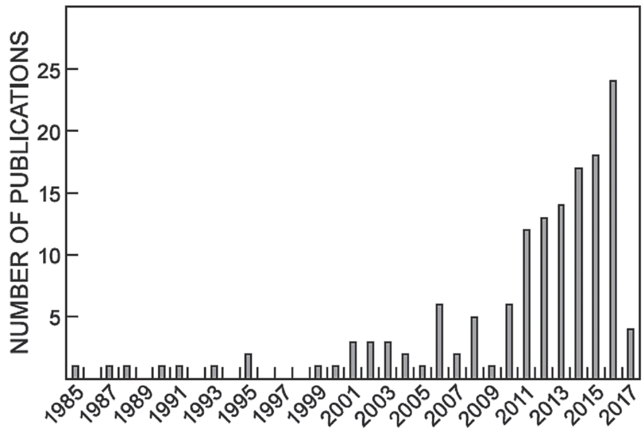

Figure 7: Trends in the number of conservation agriculture research outputs from 1985 to 2017 (Swanepoel et al. 2018).

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