

Review article

Aligning Conservation Agriculture among various disciplines in South Africa†

Pieter A Swanepoel 

Department of Agronomy, Stellenbosch University, Stellenbosch, South Africa

Author's email: pieterswanepoel@sun.ac.za

In South Africa, the term Conservation Agriculture (CA) is often used to describe any soil conservation action rather than a combination of the three management principles that CA encompasses, namely minimum soil disturbance, using a diversity of crops in rotation or association, and protecting the soil with an organic soil cover. A workshop was held with delegates from tertiary institutions, research institutions, government and private companies, in January 2019, to share and exchange CA research experiences and lessons, and to identify research gaps in the field of CA in South Africa. By collating the information from the workshop, this article aims to align CA approaches among various disciplines in South Africa and to identify the inevitable challenges with CA and (mis-)perceptions of CA in South Africa. It was clear that CA is applicable to most farming systems, but is context specific. No specific CA practice can be recommended as a panacea to solve issues experienced in all systems. Adaptation and application of CA within different South African farming systems needs to be dealt with sensibly and realistically, in ways that are based on practical rather than purely theoretical considerations. It is important that CA is not advocated without taking sustainable intensification into account. Dealing with CA sensibly requires a multidisciplinary approach.

Keywords: context-specific approach, interdisciplinary research, multidisciplinary approach, practical implementation, workshop

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Introduction

Conservation Agriculture (CA) is widely acknowledged as a set of management principles that support soil conservation (Govaerts et al. 2009; Smith et al. 2017; Kassam et al. 2019). The term CA is loosely used among South African farmers, industry experts and academia to refer to any action that has soil-conservation goals. However, this inaccurate reference causes confusion and may lead to misperceptions of CA as simply a sustainable crop-production system. The principles of CA include minimum soil disturbance, protecting the soil with an organic soil cover, and including a diversity of crops, either in crop rotation or association (Hobbs et al. 2008). Management principles can be broadly applicable to many farming systems and crops. In South Africa, CA is used successfully for field crops under rainfed conditions, particularly in smallholder systems but also in commercial and broadacre production systems. The term CA has been less frequently used in reference to systems involving crops grown under irrigation, permanent (i.e. orchards and vineyards) and semi-permanent crops (i.e. sugarcane) or to cultivated pastures. Yet, the management principles of CA are reported to be largely universal and could be applied in most production systems (Kassam et al. 2019).

To share and exchange CA research experiences and lessons, and to identify research gaps in the field of CA in South Africa, a workshop was facilitated with a wide range of representatives from across the CA community. The broad

objectives of the workshop were to: i) facilitate participants' sharing of information and experiences focusing on lessons learnt with regard to the contribution of CA to sustainable crop production and improved food security; ii) identify key issues in the development, promotion and adoption of CA in commercial and subsistence farming; iii) involve participants' in collective discussion of key challenges faced within CA practices; iv) link the challenges to underlying knowledge gaps and plan collaborative approaches to best address these gaps (in the form of concept notes that might be the basis of future research proposals); and v) promote networking to support the scaling-up of CA in South Africa. In accordance with information gathered from participants in the workshop, this article aims to align approaches to CA among various disciplines in South Africa and outlines a research agenda for CA in South Africa.

Methods

A workshop was held in Bloemfontein, South Africa, on 23 January 2019, and attended by approximately 200 delegates from universities and other tertiary educational institutions, research institutions, government, and private companies involved in CA in South Africa. The workshop was structured to have an opening session where the aim and objectives of the workshop were shared. This was followed by eight

Table 1: Structure of the Conservation Agriculture (CA) Workshop held in Bloemfontein, South Africa, 23 January 2019, showing the topics of the introductory sessions as well as the presenters of these invited presentations, and the facilitators and rapporteurs of five breakaway sessions related to those key topics in CA

Topic	Invited presenter	Breakaway session
1 Introduction to CA	JA Strauss	*
2 No-tillage CA in rainfed annual crop production	H Smith	Facilitator: PA Swanepoel Rapporteur: JA Strauss
3 CA systems other than no-tillage in rainfed annual crop production	R van Antwerpen	Facilitator: L Lindeque Rapporteur: C Botha
4 CA in orchards and vineyards	P Raath	Facilitator: N Cook Rapporteur: N Taylor
5 CA in irrigated agriculture	W de Clercq	Facilitator: J Annandale Rapporteur: M van der Laan
6 Soil fertility management in CA	G Nortjé	Facilitator: A Mostert Rapporteur: J van Biljon
7 Importance of detailed soil surveys in CA	E Verster	*
8 Responsible weed control in CA	E Hugo	*

* No breakaway session

introductory papers on specific production systems or key issues involving CA (Table 1). Five breakaway sessions related to topics 2 to 6 (see Table 1) were arranged, and delegates could choose any breakaway session. A facilitator and rapporteur were identified for each breakaway group; their main responsibility was to ensure that clear-cut conclusions and recommendations are made for submission to a final session of the workshop, facilitated by MC Laker (Department of Plant Production and Soil Science, University of Pretoria). In the final session, rapporteurs of each breakaway group reported back to all delegates. The overall rapporteur (PA Swanepoel) identified points of consensus and concern, which were presented as a conclusion to the workshop. Facilitators of the breakaway groups were encouraged to integrate discussion of topics 7 and 8 (Table 1). The entire meeting was audio-recorded to provide a comprehensive record of the presentations and subsequent breakaway discussions.

Results

CA in rainfed annual field crop production

The historical development of CA and an urge for change has been stressed by Strauss et al. (2021a). Multiple benefits of the three principles of CA have been described for field crop production in South Africa (Smith et al. 2017; Haarhoff et al. 2020; Strauss et al. 2021a). For instance, MacLaren et al. (2019a) showed that crop diversity in crop rotation systems in the Western Cape Province reduced weed abundance and maximised wheat yield. For the same production systems, Crookes et al. (2017) demonstrated that a more diverse crop rotation system resulted in higher profitability, particularly for cropping systems integrated with livestock. In addition, enhanced soil organic C sequestration as a result of no-tillage has been widely reported for South African crop production systems and is assumed to be

generally beneficial (Agenbag and Stander 1988; Kotze and du Preez 2007; Sosibo et al. 2017; Swanepoel et al. 2018). However, there are also examples of systems where no-tillage did not result in increased soil organic C contents (Sithole and Magwaza 2019). Higher maize grain yields have been observed for maize grain production under no-tillage compared with conventional tillage systems, despite an initial lag of aboveground biomass production (Berry et al. 1987; Sithole and Magwaza 2019). Moreover, Habig et al. (2018) found increased soil microbial richness and evenness for zero-tillage systems. This was likely due to the protection of the soil surface, either with cover crops or crop residue, which may result in increased soil fertility (Muzangwa et al. 2017), buffered soil pH (Kotze and du Preez 2007), increased microbial activity (Mukumbareza et al. 2015), reduced evaporation (Berry and Mallet 1988; Bennie and Hensley 2001) or better weed control (MacLaren et al. 2019b). In the Eastern Cape Province, Mcinga et al. (2020) also demonstrated similar effects of CA for meso-organisms through improved earthworm species richness and abundance.

Another beneficial management action that should be considered for CA is the integration of livestock into cropping systems and maintaining living roots all year round. However, these cannot be universally applied to all systems. For instance, it is not possible to maintain a living crop during summer under the Western Cape's Mediterranean-type climate, as the hot, dry summers are not conducive to crop production (MacLaren et al. 2019b). Many benefits of crop–livestock integration have been mentioned. For example, income diversification with mixed crop–livestock systems buffers the fluctuations in farm cash flow that stem from unstable markets and climate conditions (Crookes et al. 2017). Also, the benefits of integrating livestock into cropping systems to reduce weed pressure and reliance on herbicides have been demonstrated by MacLaren et al.

(2019a). Despite these benefits, some farmers in the Western Cape are reluctant to allow livestock on crop fields owing to perceived soil compaction and soil surface crusting caused by livestock trampling and the removal of crop residues – a similar concern experienced in Australian cropping systems (Kirkegaard et al. 2014). Competition for crop residues for covering the soil or for livestock feed was highlighted as a key issue in smallholder and communal systems where fences are lacking. More research on the effects of livestock in cropping systems is required. Theoretically, full and complete adoption of all three principles of CA should therefore result in the greatest benefits.

The complementarities or synergistic effects of adopting the bundled principles of CA were generally supported by the workshop delegates, although there is a paucity of South African research studies explicitly demonstrating the synergistic effects of bundled CA principles. Still, it was apparent that there are complementary biophysical or economic benefits when more than one principle is adopted simultaneously. The biophysical diversity of different farming regions and socioeconomic factors in South African farming systems vary substantially. It was acknowledged that the synergies of CA principles and its benefits are context specific. For instance, in dry areas crop yield improved with CA as a result of increased water infiltration (reduced runoff) and higher water-holding capacities of soils (Rockström et al. 2009). However, it can be expected that CA may intensify waterlogging in wet, humid regions, which may result in yield reductions (Pittlekow et al. 2015). The context-specificity of CA was further underscored by Swanepoel et al. (2018), demonstrating the differential impact of CA at sites with contrasting soil textures and seasonal weather. Another important aspect that was mentioned, is that communal farming systems, where CA is widely promoted, cannot be handled the same way as commercial, broadacre farming systems. This is because agroecological and socioeconomic conditions are substantially different between commercial and communal farming systems. Raaijmakers and Swanepoel (2020) demonstrated a substantial divide between commercial and emerging farmers' perceptions and adaptation choices. CA was an important adaptation measure to commercial farmers, whereas emerging farmers were not particularly enthusiastic adopters of CA. Therefore, CA cannot be promoted as a universal remedy that leads to multiple benefits in all cropping systems. The synergistic benefits of CA principles depend, to a large extent, on soil type, climate and the cropping system.

With regard to soil type, specific references were made to unpublished results showing that CA practices may be beneficial for the sandy areas of the Western Cape. Generally, there is a perception that CA cannot be executed successfully in deep sands – most importantly because of the high risk of soil compaction in sandy areas. A leading maize producer at the workshop mentioned that one should be willing to take drastic actions, such as strategic tillage, if a problem like soil compaction arises. It should be stressed, however, that negative effects of continuous tillage through time have been reported for sandy soils (Agenbag and Stander 1988; Haynes et al. 2003; Swanepoel et al. 2015a; Haarhoff et al. 2020). Although strategic actions to combat issues that arise from CA will be context-specific, more research in South

Africa is required to provide options to consider for combatting challenges that arise from CA. Although soil compaction is often framed as the reason for CA being of limited application with certain soils, Nebo et al. (2020) demonstrated that conversion from conventional tillage to no-tillage can reduce physical resistance in clay-loam soil, but that the crop rotation system also plays a role.

Herbicide resistance of weeds was highlighted as a key issue in CA systems in South Africa. Although the general idea of CA supports reducing herbicides in the long-term, as well as the use of other chemicals, in commercial CA systems it is not possible to produce crops without herbicides. Chemical control (and the costs thereof) increases with CA. It is only after CA has been firmly established that there can be a reduction expected in the use of herbicides. However, it depends on the weed spectrum in each situation. Herbicide resistance develops over time, and it was reported that 15 weed species in South Africa are resistant to herbicides in seven modes of action groups, a figure that is currently likely to be higher (Pieterse 2010). It is no longer possible to control weeds effectively by just using chemical herbicides. A more integrated, diverse approach is necessary, which might include, *inter alia*, integration with livestock (MacLaren et al. 2019a) or cover crops (MacLaren et al. 2019b; Smit et al. [In review]). Even so, a much better understanding of the interaction between cover crop type, diversity of mixtures, biomass production and weeds is required. Additionally, other challenges observed in CA systems that warrant more research included increased stubble-borne disease pressure (Taa et al. 2002; Lamprecht et al. 2006), increased insect pest pressure or a shift of insect communities (Thierfelder et al. 2015; Meyer 2018), and the effective incorporation of lime (Farina et al. 2000; Liebenberg et al. 2020).

CA systems other than no-tillage in rainfed annual crop production

An important aim of CA is to prevent soil erosion. To control soil erosion in South Africa, the Soil Conservation Act No. 76 of 1969 specifies that contour banks must be applied to fields with slopes greater than 2% unless adequately protected by perennial fodder crops. Width, depth, shape and slope norms for earth-bank contours have been developed to safely discharge surface water in conventional cropping system (Reinders et al. 2016). The Conservation of Agricultural Resources Act No. 43 of 1983 succeeded the previous Act, which *inter alia* involved government subsidies to conserve soil.

Furthermore, a fallow period preceding the growing season of summer-producing crops is a common practice across central South Africa (Bennie and Hensley 2001). A need for research on fallow periods was highlighted, to investigate whether it is necessary or to develop guidelines for effective management of a fallow period, so that it conforms to CA principles. Winter weeds need to be controlled in CA systems and cannot be considered as “cover crops” in annual row-crop productions. Most weed species are strong competitors for soil water and nutrients, which need to be preserved.

A lack of crop diversity for rainfed annual crop production systems was mentioned, both for the summer- and winter-producing regions. Alternative crops should be investigated that can be included in crop rotation systems. Another area

for investigation is *in situ* rainwater harvesting techniques that move water from a non-productive zone to a crop production zone, thereby enhancing the water infiltration rate and/or reducing the evaporation losses. Examples include ridging, mulching and various types of tillage operations that create furrows. Rainwater harvesting could be a particularly important part of CA for smallholder farming systems.

CA in orchards and vineyards

In South Africa, CA is traditionally linked to annual field-crop production systems. However, CA principles and practices are said to be universally applicable to all agricultural landscapes and land uses, and could therefore also be applicable for orchards and vineyards (Kassam et al. 2019). Since a permanent crop cannot be easily rotated, crop diversity is built into the system by using crops grown in association with the trees or vines, which are commonly referred to as the cover crops. In orchards and vineyards, the purpose of cover crops includes improving general soil health, soil moisture and temperature regulation (Fourie and Freitag 2010), weed and pest control (Fourie et al. 2016; MacLaren et al. 2019c), forage production (Fourie et al. 2015a), and other environmental or diversity benefits (MacLaren et al. 2019b). Cultivation of annual cover crops in the winter rainfall region is particularly important for deciduous crops. These cover crops can utilise rainfall in winter and can be killed by physical or chemical actions prior to the fruit production season (Fourie et al. 2015b; MacLaren et al. 2019b). In the sub-tropical summer rainfall regions, permanent perennial cover crops might be a better option. Also linked to the crop diversity principle in orchards and vineyards is protection of the soil with an organic mulch layer. When cover crops are not used, crop residues such as cereal straw or wood chips can be used to cover the soil (Fourie and Freitag 2010). One of the mostly universal goals of CA is to build soil organic matter, and producers also generally aim for sequestering carbon in the soils. However, for perennial, high-value crops, excessive nitrogen in soils, as a result of the increased mineralisation rate of soil organic matter, may lead to poor fruit quality.

Cover-cropping or mulching was generally accepted among delegates at the workshop as the way forward for orchards and vineyards, particularly to compensate for the more erratic rainfall and droughts being experienced in South Africa. The type of cover crop or mulch will be dependent on the climate, crop type and the needs or purpose of the producer. Again, context-specific practices are important, and no specific CA practice can be recommended as a panacea to issues experienced in orchards and vineyards.

Soil preparation, particularly ridging, has important implications for CA in orchards and vineyards. Ridging is a common practice in many fruit-tree orchards in South Africa. An undulating topography can complicate the design of ridges, which might lead to soil erosion, which conflicts with the goals of CA. Soil-surface crusting is also commonly observed on ridges, and the movement of machinery and the establishment of cover crops are challenging in ridged systems. Even though ridging is a preferred, but expensive land preparation technique, there is a serious paucity of research information on soil preparation and planting systems for fruit trees.

Moreover, the impact of CA practices on pest and disease pressure in South African orchards and vineyards is now well understood, although work has been done only recently on nematodes (Fourie et al. 2015b) and soilborne diseases (Langenhoven et al. 2019).

CA in irrigated systems

Irrigation systems are highly productive farming systems. From a CA perspective, the availability of crop residues to cover the soil is often not problematic because of the high biomass productivity associated with non-water-limiting production systems. However, the high input costs associated with irrigation systems need to be negated by a fast turnover or rotation of high-value crops. Planting into high stubble loads from the preceding crop can be challenging (Swanepoel et al. 2019). Excessive crop residue loads can lead to chemical or physical constraints for seedling emergence, for instance by reducing light quality, and a nitrogen-negative period or allelopathic effects, to name a few. Another issue that may arise from retaining crop residues is excessive moisture retention, which might impede the movement of tractors and other equipment. Since time for preparing the fields for the next crop is usually limited, there have been reports of producers that burn crop residues rather than remove biomass through raking, baling or grazing (Batidzira et al. 2016). Burning of crop residue is associated with numerous adverse effects, such as soil erosion (Thomas et al. 2018), air pollution and increased greenhouse gas emissions (Sun et al. 2016) and decreased soil quality (Turmel et al. 2015). More research is required to find the sustainable ways to remove or handle crop residues in irrigated agriculture.

Irrigation provides flexibility of the cropping system, and a diversity of crops can be cultivated over time. More than one crop can often be produced within a single year by making use of strategies such as double cropping, relay cropping, alley cropping or intercropping. Crop diversification is therefore often not as limiting in irrigated agriculture as it is in rainfed field cropping systems. However, many crops commonly produced under irrigation necessitate soil disturbance during the planting and/or harvesting process, such as for onions, groundnuts and potatoes. Even though producers are usually eager to build soil organic matter, reducing tillage is not an option for these crops. Furthermore, for South African potato production systems, producers might have numerous fields equipped with irrigation, but because of water restrictions and a build-up of nematodes and soilborne diseases not all fields can be irrigated every year, thereby reducing the capacity of the soil to build up organic matter (Swanepoel et al. 2021). The workshop delegates mentioned examples of land-use strategies that leading farmers follow. In the southern Cape, a producer successfully uses a crop rotation with potatoes for three years, followed by cultivated dairy pastures for four years, with or without a *Brassica* cover crop between the potato and pasture phases (Steyn et al. 2016). In the Northern Cape Province, some producers rotate cash crops and lucerne. During the lucerne phase, no soil disturbance occurs, which supports soil conservation goals. Similar to rainfed field-crop production systems, context-specificity of strategic land use or tactical agronomical decisions were stressed. Another

option to consider for reducing soil disturbance is strip tillage, which would be suitable option for growing onions, for instance. Strip tillage is not excluded from CA if less than 25% of the soil in the cropped area is disturbed (Kassam et al. 2019). However, it is possible to establish many crops under irrigation by means of no-tillage, for instance maize, wheat, barley and cultivated pastures. Soil compaction was, however, highlighted as a key issue for no-tillage systems under irrigation. An occasional deep ripping action is sometimes recommended, depending on the soil and system characteristics, at least before conversion to CA. However, since there is a movement towards precision agriculture techniques, particularly for irrigated systems, controlled traffic might mitigate the effects of soil compaction and so eliminate the need for ripping. McPhee et al. (2015) demonstrated that controlled-traffic farming can reduce the number of tillage passes for vegetable production systems. Controlled traffic and its interactions with other hardware, such as irrigation system characteristics or layout, might be complex and challenging to manage.

Since the application of CA practices provides a means for reducing soil water evaporation and thereby increasing water-use efficiency (Haarhoff and Swanepoel 2020), the implications in a water-scarce country like South Africa can be substantial. In South Africa, the irrigated agriculture sector uses approximately 60% of the country's runoff and contributes 30% of agricultural production by value (van der Laan et al. 2017). Hypothetically, if water use could be reduced by 20% by following CA in South Africa, the national water budget, water footprint of agricultural products and electricity use could be reduced significantly.

With CA, it can be expected that topsoils will be wetter for longer periods, which will, in turn, have implications for nitrogen cycling. Significant denitrification losses can occur when soils are wetter (Sexstone et al. 1985). Further losses of N through volatilisation could occur due to increased urease activity associated with crop residue degradation (Adetunji et al. 2017). As crop residues also buffer soil temperature fluctuations, slower crop development could be expected, contributing to a shift in the soil water balance, along with reduced runoff losses as expected, but increased deep drainage losses. It is therefore questionable whether irrigation scheduling tools used in the conventional systems will still be reliable as over-irrigation could be expected.

Soil fertility management in CA

Reports of CA's impact on soil fertility is mostly positive (Verhulst et al. 2010; Sithole et al. 2016), even though some aspects are contended (Giller et al. 2015). Stratification of nutrients towards the soil surface because of a lack of soil mixing was particularly emphasised by the workshop delegates. It is generally acknowledged that improved soil surface properties are beneficial for water uptake and gaseous exchange, and improved soil surface properties are commonly reported in the literature (Sithole et al. 2016). Conversely, Franzleubbers (2002) suggested that high stratification ratios could be a good universal indicator of soil quality as high ratios are uncommon for degraded soils; hence, it has been used as an indicator of soil quality for South African crop and pasture production systems (Dube et al. 2012; Swanepoel et al. 2015b). However, the effects

of stratification on plant production and root development are not well understood; it is unclear whether this is an actual or perceived issue, but an excessive build-up of nutrients (e.g. phosphorus) may be harmful to plant roots.

In consequence, it is crucial to optimise soil fertility before starting no-tillage to mitigate the nutrient stratification effects of CA and the immobility of certain fertilisers and ameliorants (Tshuma et al. 2021). According to delegates, limestone and phosphorus tend to receive more research attention for no-tillage systems – because the efficiency of long-time application of lime and phosphorus on the soil surface of no-tillage systems is questionable (Kirkegaard et al. 2014; Tshuma et al. 2021). Limestone should be applied and properly mixed to the recommended depth to ensure optimal pH levels before starting no-tillage to ensure that nutrient content is in the upper acceptable range throughout the soil profile.

The increase in organic-matter content brings about increases in the cation exchange capacity of soil as well as increased biological activity, which affects nutrient cycling, although it is not clear how big the contribution of nutrient recycling is. When possible, changes in soil nutrient dynamics and stratification are considered, and different fertiliser optima than for conventional tillage systems could be expected. For instance, producers in the Western Cape, where CA is well established, are still using nitrogen fertiliser guidelines that were developed under conventional tillage systems (Viljoen et al. 2020; Crous et al. 2021). These guidelines do not account for the potential supply of mineralised nitrogen from soil organic matter. In contrast, if sequestering soil C is one of the objectives of CA, the capacity of a range of soils to sequester carbon can be more than double if supplementary macronutrients are applied to crop residues as fertiliser (Kirkby et al. 2013). However, the optimum fertiliser rate will depend on the quality and quantity of the crop residues.

Norms and guidelines consequently need to be developed for different regions where CA is practiced. The first step would be to determine the most suitable nutrient extraction method. The possibility of different extraction methods for nutrients exists, but it is not certain how effective current extraction methods are for determining the nutrient contribution from the organic component. The second step would be to do calibration studies in the field across multiple locations, soil types and soil biology. The last step would be to determine the threshold values for different nutrients and different crops to develop a fertiliser guideline.

The stratification of nutrients, particularly soil organic matter, underscores the importance of interpreting data with caution, as samples taken at a shallow depth may falsely overestimate the benefits of soil nutrients and soil organic matter. There are confounding recommendations on how to take a soil sample for CA systems (Derpsch et al. 2014; Olson and Al-Kaisi 2015). For instance, in soils with a highly stratified pH, a soil acidity problem is often not picked up in soil tests if soil samples are taken to 200 mm or deeper, diluting the stratification effect. Erroneous soil fertility test results may lead to inappropriate soil amelioration and fertilisation recommendations and limit root development and plant productivity. Research is recommended to determine the most appropriate soil sampling strategy for CA.

Lastly, detailed soil surveys are critically important for CA. Well-executed soil-landform surveys, adapted to the requirements of CA, need to be developed. In-field spatial data and information on the physical properties of land are often lacking, yet are essential to form a solid knowledgebase for the implementation and expansion of CA.

A research agenda for CA in South Africa

There seem to be numerous barriers to the adoption of CA in various disciplines. The barriers are not necessarily identical for all contexts. More detail on reasons for non-adoption of CA, including natural physico-chemical and biological factors, are discussed by Nortje and Laker (2021). Regardless of the diverse factors contributing to the decision-making of farmers, research is necessary to understand why agricultural producers are deterred from adopting CA. In this regard, research is not required to advocate for CA, but rather to recognise factors that could contribute towards the sustainability of farming systems in South Africa. Even though CA mostly supports conservation and sustainability goals, CA can sometimes result in a farming system that entails challenges not experienced in conventional systems. Therefore, CA should not be advocated as a universal remedy to solve all the problems that producers experience. Furthermore, management recommendations should be based on robust, scientific data developed in multiple locations.

Soil conservation is one of the most important themes associated with the goals of CA as it is intertwined with many other key themes, such as food security, economics, water conservation and weed management (Table 2). However, since soil physical quality in South Africa is generally poor because of erosion, compaction, crusting and poor organic matter content, soil conservation should be a priority. Van Antwerpen et al. (2021) and Strauss et al. (2021b) stressed the importance of using CA to reduce the rate of soil loss and physical degradation in South Africa, and its role to ensure food security. There exist research opportunities to refine or develop technologies to prevent soil erosion (e.g. no-tillage, contour bunding, crop-residue management, mulching, cover crops), soil compaction (e.g. no-tillage, controlled traffic, strategic tillage or ripping, vertical mulching, deep trenching), soil surface crusting (e.g. mulching, cover crops, use of ameliorants). Since CA builds soil organic matter and stabilises soil structure, the relevance of the norms, and whether contour banks are necessary at all, has been questioned. Since contour banks impede movement of no-till equipment, many producers have removed the contours by physically levelling the soil. Therefore, research is required to evaluate the impact of such actions.

Context specificity was a point raised numerous times in the workshop. For instance, can CA goals be matched with crops that require soil disturbance, like groundnuts, potatoes, carrots, onions and even ridging in orchards?

A different approach to managing soil fertility is needed for CA as opposed to conventional systems, which stress the importance of developing integrated soil fertility management practices (Nortje and Laker 2021). Although no-tillage is associated with many benefits to combat soil degradation, improve soil fertility and control weeds, a pragmatic approach to tillage can be considered to facilitate nutrient distribution

across soil depths, particularly that of immobile nutrients like phosphorus (P) and lime, and to break up root growth-restricting layers in soil. The choice of crop (particularly legumes) and the design of crop sequences in rotation systems are important factors to consider for optimal soil nutrient management (Nortje and Laker 2021; Strauss et al. 2021b). There are significant gaps in our understanding of management of the soil biological component to facilitate effective nutrient uptake by plants, and for promoting soil resilience.

The pertinence of fertilisers, particularly N, P and K, as well as liming guidelines in CA systems, were identified as key concerns. Current fertiliser and lime guidelines were developed under conventional tillage practices (Liebenberg et al. 2020). Following CA for an extended period, changes occur in soil N mineralisation patterns, soil organic matter and the distribution of nutrients, which in turn changes the requirements of nutrient supplementation through fertilisation or liming. There have been reports of nutrient build-up (particularly P) and subsoil acidity or stratification of pH, which could be of particular concern in CA systems. The best extraction procedures for P, to inform us of plant-available P content in soil, was also identified as a key concern. There is a call for different fertiliser guidelines to be used in CA systems than those used in conventional systems.

Cover-cropping was mentioned as a possible solution to various issues in both orchards and vineyards and field-cropping systems, albeit little is understood about its management. A more integrated, diverse approach is needed to manage healthy soils, which might include cover crops. Even so, a much better understanding of the interaction between cover-crop type, diversity of mixtures, biomass production, weeds, pest and diseases and the specific goal or function of the cover crop is required. More research attention on cover crops is warranted.

Apart from soil conservation, conservation of water is another important goal of CA. The effects of CA are often more pronounced on production systems in semi-arid or dryland regions (Pittlekow et al. 2015). More research on how to manage CA principles in irrigated agricultural systems is needed so that the environmental impact of irrigated agriculture is minimised while plant health and productivity is maintained. Issues surrounding water quality, 'fertigation' farming and pollution should be addressed. A rigorous review of the effects of CA in irrigated agriculture is called for. For irrigated agriculture, the concept of CA overlaps heavily with that of precision agriculture.

Remote-sensing and precision agriculture technologies are emerging management tools with various applications in CA systems, including prediction of yield or stresses, as well as to assist with the control of weeds, pests and diseases. Remote-sensing and precision agriculture can contribute to bettering the management of CA systems, and thus needs more research attention. The combined approach of CA and precision agriculture fosters optimisation of CA.

Herbicide resistance, and perhaps also the resistance of pests and pathogenic fungi to chemical controls, are a major threat to the sustainability of CA systems. Judicious use of chemicals to control weeds is necessary (Hugo et al. 2021). An integrated weed management strategy is necessary to combine multiple ways of weed control, including ecological

Table 2: A research agenda around key themes in the domain of conservation agriculture in South Africa, the challenges or threats, as well as opportunities to address the challenges

Theme	Threats/Challenges	Opportunities
Soil conservation/ physical degradation	Soil erosion Soil compaction Poor soil structure and surface crusting	No-tillage Strategic tillage/ripping Controlled traffic Contour banking Deep tilling Crop residue management, mulching, and cover crops Intercropping Windbreaks
Soil fertility	Poor availability of nutrients Root development constraints (e.g. plough pans) Low soil organic matter content Stratification of nutrients Poor soil biological quality Soil acidity	Integrated soil fertility management Microbes (e.g. mycorrhizae) No-tillage Strategic tillage/ripping Crop residue management, mulching, and cover crops Crop rotations Lime choice (source; form; fineness; incorporation strategy)
Weeds and pests	Poor weed and pest control Herbicide resistance	Crop rotations Effectiveness and timeliness Tillage system x weed spectrum interaction Crop residue management, mulching, and cover crops Diversity of management
Water conservation and water-use efficiency	Low water-use efficiency Poor or inappropriate infrastructure Poor irrigation water quality Salinity and sodicity	Crop residue management, mulching, and cover crops Detailed soil surveys, land suitability evaluation for irrigation systems Rainwater harvesting Plant density Intercropping Water infrastructure and precision methods/technology Irrigation scheduling and water accounting
Economics	Increased input costs Lack of financial, natural human and physical capital	Alternative production practices Alternative crops (e.g. legumes) Diversity of management Mixed crop–livestock systems Long-term experiments
Climate change	Global warming Desertification Droughts	Strategies to reduce greenhouse gas emissions Integrated soil management/systems approach Livestock feeding strategies Soil carbon sequestration Mixed crop–livestock farming
Training and awareness	Lack of specialists/advisors equipped with theoretical knowledge Lack of practical experience Lack of high-level support services	Universities/training institutes/government should provide appropriate training opportunities Study groups; Farmers' Day events; workshops; symposia On-farm experimentation
Precision agriculture: better and more-precise soil surveying techniques	Inefficient water use Larger pumping costs Inefficient nutrient use Nutrient loss from soil Huge environmental impact Lower fruit/crop quality	Precision farming principles to be applied Upgrading of soils information Better farm planning More-even ripening/better quality Better quality control Better water management

management techniques (e.g. cover crops) and agronomic tactics (e.g. plant density). More research is required to understand changes in the weed spectrum because of CA in the long run, for appropriate management actions to be identified (Hugo et al. 2021).

Limited training and awareness constrain the utilisation of CA by farmers in South Africa. More specialists and advisors equipped with theoretical knowledge and practical experience, as well as high-level support services, are needed to make CA implementation a success (Van Antwerpen et al. 2021).

However, the impacts of CA on climate-change mitigation are context specific and the extent to which CA can mitigate climate-change effects is unknown. Enhancing soil quality through CA and by increasing soil organic C sequestration are essential to facilitate adaptation and climate-change mitigation (Lal 2021).

A common message in academia is the importance of working across disciplinary boundaries. Yet, even within the broader agricultural community, research is often executed in the realm of narrow disciplines. Interdisciplinary research

is essential to solve key issues or at least make progress towards food security and sustainability within the agricultural sector. Even so, interdisciplinary research should not be at the expense of discipline-specific research, as it will remain important to understand specific issues experienced within the agricultural sector. To align CA across disciplines in South Africa, an approach developed by Hoffman et al. (2018) was adapted to illustrate the relationships between the agricultural and socioeconomic sciences as well as between basic and applied sciences. Thus, Figure 1 depicts a theoretical framework using two axes that broadly capture the recommendations gleaned from the workshop among participants in various disciplines. The x-axis depicts a continuum between applied and basic research. The y-axis presents agricultural sciences, including CA in this context, on one end and agricultural economics and related social sciences on the other end. Discipline-specific sectors within agricultural sciences include studies of soil and water, climate science, agronomy, horticulture, plant pathology, entomology, animal breeding and pasture science, among others. In contrast are studies of the interactions between producers and environmental factors, and the relationships to broader society, which will include, *inter alia*, research concerned with agricultural economics especially, but also sociology, political science, and value and policy development. For instance, referring to Figure 1, a hypothetical study looking at various management practices that could change or develop a soil environment to become more suitable for root growth, as in a conventional farming system would fall within sector 1. Drawing on this same example, to understand

the complexities of the interaction between crops and the soil, an investigation of various pools of soil carbon and the effect of CA on the development of those pools would fall within sector 2, since such research would develop our understanding of agricultural problems. Sectors 3 and 4 mirror this example for the social sciences. Truly transdisciplinary research would be positioned at the centre of the axes; here, research into workable solutions for resolving agricultural and socioeconomic issues would be recognised.

Researchers involved in CA could use the overview illustrated in Figure 1 to reflect more deeply about their research activities and outcomes. Greater awareness of the different dimensions could inspire not only heightened interdisciplinarity within agricultural research but might also bring academics closer to the realities experienced by producers. Importantly, this could also stimulate awareness of the barriers that producers experience in adapting to external challenges (ranging from environmental ones like drought to socio-political issues) as well as the needs and aspirations of producers.

Conclusions

CA is applicable to most farming systems, and importantly it is context specific. The adaptation and application of CA principles within different South African farming systems need to be dealt with sensibly and realistically – hence, in ways that are based on practical rather than purely theoretical considerations. Therefore, this article outlines a research agenda (Table 2) for CA in South Africa. If CA does not

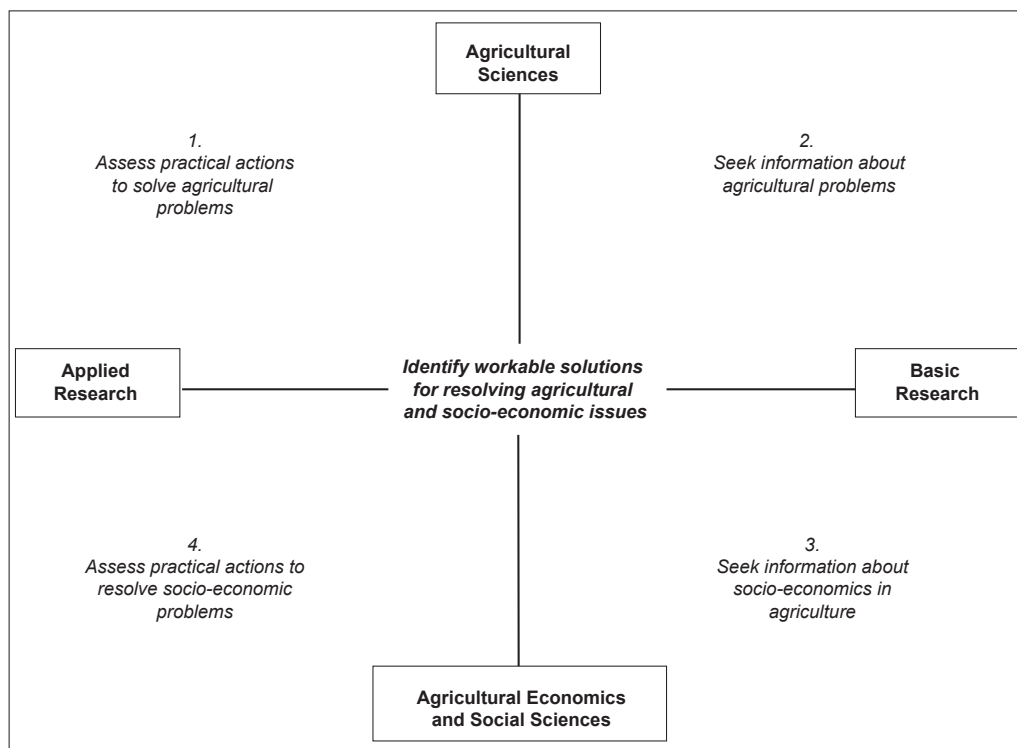


Figure 1: A schematic representation of relationships among various research activities in conservation agriculture, which can be used to align specific research projects within the broader scientific community (adapted from Hoffmann et al. [2018]).

support sustainable intensification, then a flexible, more pragmatic approach should be taken in its implementation. It is important that CA is not advocated without taking sustainable intensification into account. Dealing with CA sensibly requires a multidisciplinary approach.

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ORCID iD

Pieter Swanepoel — <https://orcid.org/0000-0002-6481-0673>

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