Conservation agriculture in rainfed annual crop production in South Africa

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Abstract

The pressures from population growth, changing diets and climate change are driving the need to transform global food production to ensure efficiency, improved reliability and more sustainable production methods. The arable land for crop production and permanent pastures in South Africa account for 10 to 12 percent of the total land surface. South Africa is classified as semi-arid, with the average rainfall below the world average. Dryland agriculture thus has to identify and promote management systems with high water-use efficiency; this is crucial in a country with a debilitating water deficit. Climate change is expected to exacerbate climate variability in South Africa and thus exert even more pressure on rain-fed dryland production. Conservation Agriculture is a holistic set of principles aimed as a guide to sustainable, reliable and climate smart farming practices. Although initially set as a guide for grain farmers the principles are also applicable, through adaptation of the three basic principles, to other agricultural commodities. The three principal system have been extensively promoted with successful adoption and adaptation in many countries. This paper aims to highlight the research results and challenges of rain-fed Conservation Agriculture in South Africa.

Keywords: dryland agriculture, grain farming, on-farm research, rainfed agriculture, recommendations, summer rainfall

Introduction

The pressures from population growth, changing diets and climate change are driving the need to transform global food production to ensure efficiency, improved reliability and more sustainable production methods (Garnett et al. 2013; Poppy et al. 2014). One of the transformations that was put forward as one of the possible solutions is Conservation Agriculture (CA), as promoted by the Food and Agriculture Organization (FAO) of the United Nations. CA is a holistic set of principles aimed as a guide to sustainable, reliable and climate smart farming practices (Jat et al. 2014; Lal 2020). CA comprises three principles: (1) advanced crop rotations for natural fertilisation and to control pests, weeds and diseases (Hobbs et al. 2008; Kassam et al. 2019); (2) the minimisation of soil disturbance in order to improve soil structure, infiltration and water-holding capacity; and (3) permanent organic soil cover to conserve soil moisture and to moderate soil surface temperatures (FAO, 2013). Although initially set as a guide for grain farmers the principles are also applicable, through adaptation of the three basic principles, to other agricultural commodities. The CA system has been extensively promoted by a range of key stakeholders with successful adoption and adaptation in many countries (Derpsch et al. 2010; Kassam et al. 2019) and with significant adoption in some regions in South Africa (Findlater et al. 2019).

The arable land for crop production and permanent pastures in South Africa account for 10 to 12 percent of the total land surface. "Of the potentially available rain water, agriculture and forestry utilise approximately 74% for the production of crops, trees and livestock on pastures and natural vegetation. Dryland crop production on 11 million ha, with an average annual rainfall of 600 mm, utilises 12% of the rainfall; irrigated crop production from stored surface and underground resources 2%; 60% are used to maintain the growth of forests and the natural vegetation that is used as grazing for livestock and game and the remaining runoff to the sea or is used for domestic, industrial and other purposes.", as elegantly put by Bennie & Hensley (2001). Dryland agriculture thus have to identify and promote management systems with high water-use efficiency, which is crucial in a country with a debilitating water deficit (De Witt et al. 2015). Climate change is projected to impact rain-fed farming by increasing climate variability in most areas, and to reduce mean rainfall in some of the areas (IPCC, 2019). These farmers operate in a highly variable and largely semi-arid climate that is expected to become even more variable with climate change (RSA 2011; Niang et al. 2014; Engelbrecht et al. 2015). South Africa has two major rainfall regions that correspond with the production of different crops. Wheat (*Triticum aestivum*) is the most valuable cash crop in the south-western winter rainfall region, while maize (*Zea mays*) is most valuable in the eastern summer rainfall region and in the rest of the country (RSA 2013). Climate change is expected to exacerbate climate variability in South Africa, and to reduce mean rainfall in the winter rainfall region (RSA 2011; Midgely et al. 2016).

The importance of CA for rain-fed production

According to Fey (2010) the landscapes and agroecology of South Africa are highly complex and diverse. There is large variation in soil properties and this plays an important role in the implementation of any agricultural production system. Only three percent of the South African agricultural land has a high potential, while 91 percent is classified as either sub-, semi-arid or dry-humid. This underlines the importance of implementing water–use efficient agricultural production systems. The country is divided into two halves by an imaginary line, running north-south. The two halves roughly translate to below 500 mm of annual precipitation on the western side and above 500 mm on the eastern side, with the average annual rainfall half of the world average (Smith 1998). With erratic and poorly distributed rainfall over seasons, moisture stress often occurs in the most important crop developmental stages, combined with high transpiration rates, often higher than the rainfall, pressure on food production is high (De Villiers et al. 2004). This scenario is even worse when water loss through runoff, evaporation and deep drainage occur on unproductive soils. According to Bennie and Hensley (2004) high-energy rainstorms combined with soil crusting, floods, hail, frost and varying intensity of droughts are commonplace in South African dryland production. Le Roux et al. (2008) reported an annual topsoil loss of 13 metric ton per hectare in South Africa due to water erosion alone. These constraints endanger sustainable production and food security if South Africa continues on the business-as-usual dogma (Blignaut and Van Heerden 2009; Turton 2015).

Soil is seen as the heart of CA and is influenced by various soil properties and their functions (Lal 2015a). There is no one single definition of soil functions; however, the summary from the World Soil Information network (Ribeiro et al. 2018) as "Soil is our life support system. Soils provide anchorage for roots, hold water and nutrients. Soils are home to myriad microorganisms that fix nitrogen and decompose organic matter, and armies of microscopic animals as well as earthworms and termites. We build on soil as well as with it and in it" provides a very useful summary of the importance of soils to humankind.

The key soil functions are food production, biological diversity, carbon sequestration, source of raw materials, availability of nutrients and water, support for plants and infrastructure (Baveye et al. 2016;

Pereira et al. 2018). The soil properties that influence them are: soil organic carbon (SOC), soil pH, bulk density, soil biology, cation exchange capacity, available water capacity, soil texture, soil porosity, soil aggregate stability and hydraulic conductivity. The ability of the soil to provide these functions will, however, depend upon the state of the soil properties, which will determine the level of ecosystem services (provisioning, regulating, cultural, supporting) leading to food, energy and water security (or insecurity) (Hatfield et al., 2018).

Soil degradation (e.g. due to tillage) threatens soil's ability to perform all of these functions (Hatfield, 2014; Bender et al. 2016), hence a key part of this awareness on soil health and -security is understanding the linkage among soil and ecosystem services and sustainable agriculture (Bouma, 2014). To fully understand the interface of soils with ecosystem services in the food, energy, water nexus (e.g. CA), will require a more holistic approach than has been considered previously. From a soil health point of view, this will primarily require us to study and monitor all the soil properties and functions, including their state and modification.

According to Hatfield et al. (2018a), the soil biological system plays a crucial role in soil property modification, or soil restoration, hence preserving and/or enhancing soil biology is a key to soil biological processes. This is certainly one of the key outcomes of CA, as the restoration of soil should be seen as the premise for the success of CA in South Africa and globally. According to Derpsch et al. (2014), CA will not be successful on degraded soils. In the light of the degraded state of South African soils under cultivation (Swanepoel et al. 2016), one of the primary goals of CA, which is in fact a moral responsibility of the grain industry, is soil restoration, at least during a transformation period of five to ten years.

Soil is a living ecosystem and not just a growing medium for plants. The soil's biological function is to supply uninterrupted metabolic energy to the biological processes in the soil. Plants are responsible for the transformation of atmospheric carbon (CO_2) into sugars, or liquid carbon (Jones 2015), via photosynthesis, which provides the energy for the biological processes. These sugars are then converted into more complex molecules in the plant. About 30 to 40 percent of these sugars are leaked by the roots to feed the microbial life in the soil (the soil food web through different trophic levels) and later decomposition of the plant residues will go through the same process; in return these microbes provide the plant with essential nutrients through plant-microbial mutualistic relationships (Detheridge et al. 2016; Zhang et al. 2016). A portion of the liquid carbon are used to build stable SOC. SOC will cycle and accumulate only if the carbon produced through this process surpasses the carbon lost through respiration, decomposition and leaching (Esmaraldo 2017). It is not only a larger diversity and large active populations, but also the ratios of the soil microbes that play a role in SOC building processes (Six et al. 2006; De Vries et al. 2013).

The importance of organic matter in soil cannot be stressed enough. It impacts all three major properties of the soil, namely the physical, chemical and biological components. Soil organic matter (SOM) promotes aggregate stability, which in turn affects the infiltration rate, filtration and the water holding capacity of the soil. It increases the cation exchange capacity, soil buffer capacity and nutrient supply, all chemical functions. It supports the bustle, assortment and functions of organisms in soil, the area of the soil that is the least understood (Verstraete and Mertens 2004; Du Preez et al. 2011; Nimmo et al. 2013; Hontoria et al. 2016). Due to its significant influence on all the soil properties, SOC has been identified as the parameter with the most significant influence on all soil properties and is therefore seen as the leading indicator of the health and quality of soils (Van Antwerpen 2005).

The stability of soil aggregates, or soil structure, refers to the resistance to structural rearrangement of particles and pores when exposed to different stresses, for example trampling, runoff, infiltration, cultivation practices, raindrop impact and irrigation (Krull et al. 2004; Hakeem et al. 2016). Soil disturbance though tillage practices lead to the devastation of aggregates and accelerate decomposition of SOC (FAO 1993; Esmaraldo 2017; Silva et al. 2019). The stability is linked to microbial activity that produces the humic glues that make aggregation possible (Hillel 1982). The less soil is disturbed the lower the rate of organic matter decomposition and the healthier the soil. The Australian adoption of minimum tillage, stubble retention and no-till sowing systems increased the cropping intensity and is linked to a reduced risk of soil degradation (Chan and Pratley 1998; McTainsh et al. 2001). In South Africa the continuation of tillage is still placing further strain on an already low SOC and will lead to even further soil degradation and food insecurity. According to Swanepoel et al. (2016) the average SOC loss due to tillage is around 46 percent and the improvement of SOC is critical for the restoration and increase in productivity of soils (Mills and Fey 2003; Du Preez et al. 2011), thus underlining the base philosophy and goal of CA (Lal 2015b).

According to Bustamante et al. (2014) the task that lies in front of agriculture is to ensure the increase in the production of crops, but to integrate the conservation agenda at the same time. The focus of which is regenerating the functioning and protection of natural resources and increasing climate smart agricultural production. The integrated (system) approach of CA is key to sustainable production. Results from a study done by Dos Santos Soares et al. (2019) underlined the positive effect of the long-term soil management practices of introducing a varied plant residue, not only in quantity, but in chemical composition as well. This practice has a positive effect on the chemical and microbial characteristics over the longterm.

In general, CA is associated with positive outcomes, however, there are research reports on unintentional drawbacks, such as soil compaction layers (Steyn et al. 1995; Bennie and Hensley 2001; Taylor et al. 2012), changing aspects of weed populations and dynamics (Murungu et al. 2010; Dube et al. 2012; Swanepoel et al. 2015), herbicide resistance (Kirkegaard et al. 2014) and increased input costs (Giller et al. 2009). Other research showed that not reaching minimum soil cover levels had a negative effect on the uptake of CA and questions still remain what the critical levels of residue should be in different regions, especially where livestock is included in the system (Giller et al. 2009; Baudron et al. 2012; Thierfelder et al. 2015). Piggin et al. (2015) and Govaerts et al. (2005) indicated no yield loss when there was a limited removal of residues. However, the positive impacts and returns of CA far exceed the negative experiences in almost every context around the world (Flower et al., 2017; Pittelkow et al, 2015; Kassam et al., 2019). For all of these negative results strong positive results have also been obtained. According to Flower et al. (2017) the paybacks of crop rotation are well recognised and the use of alternative crops in cereal systems under Mediterranean climatic conditions has been proven. They however also evaluated the inclusion of cover crops as a means to increase the diversity of cereal systems, but did not show an economic benefit from this inclusion. This is in contrast to the findings of Smit (2019) while evaluating the utilisation of cover crops in existing cereal rotation systems. Grazing two different cover crop mixtures showed positive results on soil mineral content and subsequent wheat quality.

There is a perception that CA production systems are solely dependent on the application of copious amounts of herbicide and insecticide, however, according to McLaren et al. (2019a) insecticide use has declined to the point that it is hardly ever necessary to spray in many cases. Long–term CA trial data in the Western Cape also showed that the crop and pasture systems were more effective in weed control than the pure cash-crop systems. Diversity in the systems, including crop types and livestock resulted in low weed numbers and the systems used lower inputs in terms of fertiliser and herbicides (McLaren et al. 2019b). LaCanne and Lundgren (2018) showed that farming systems using no insecticide had fewer problems with pests than the alternative where insecticides were used extensively. These studies also underline the fact that problem insects can adapt to insecticide input if the diversity of insects are reduced.

Although the CA concept initially did not include the integration of livestock, the inclusion of annual and perennial pastures, in particular mixed grass-legume pastures, has led to further improvements of the system, including increased diversification, quicker SOC building, increased financial and income stability and increased profits (Basson 2017). Robust and diversified crop–livestock systems can and should be integrated with CA systems to control environmental quality and improve resistance of crops to drought (Franzluebbers and Stuedemann 2013; Lal 2020). Another benefit of legumes and legume pasture in crop rotation is the nitrogen that is fixed and made available to the following crop. Smith and Chalk (2020) indicated that nitrogen fixation was greater under no-till compared to conventional cultivation. The benefits of CA lie not only in better yields and gross margins but, also, reduced inputs. The CA system is not only environmentally friendly, but also makes economic sense (De Wit et al. 2015; Hardy et al. 2010; Knott et al. 2016; Nell 2019).

In a review of CA research in South Africa, Swanepoel et al. (2017) highlighted the lack of a substantial results library (archive) and placed emphasis on the need to step up research done on soil cover, cover crops, soil biology, soil water, livestock integration, economics, greenhouse gas emissions and carbon fractions across a range of agro-ecosystems. They recommended a systems research approach where farmers are key participants in adapting CA in different agro-ecosystem regions across the country.

Findlater et al. (2019) assessed CA adoption among grain farmers in South Africa in 2015. He found that only 14 percent of farmers adopted the complete CA system, compared to the perception of farmers indicating an adoption rate of between 40 and 80 percent. This implies that the farmers' definition of CA differs substantially from the official FAO definition. This is a major source of concern since erroneous adoption of CA principles is by far the biggest factor why it doesn't work in specific cases, which jeopardises its quicker out-scaling and its potential to solve the various problems associated with grain production, such as soil degradation, loss of biodiversity, poor resource use efficiency, high input costs and dwindling sustainability and economic viability. Ultimately the proper implementation of all the CA principles in a specific context are the only way CA will be able to meet the goals as a climate change adaptation and mitigation strategy and foster true agricultural sustainability and climate resilience.

Crop production in the rainfed summer rainfall crop production areas

South Africa's summer rainfall rainfed crop production areas include a relatively small area in south-central Limpopo province, small area in the western highlands of KwaZulu-Natal, the north-eastern part of the Eastern Cape Province and the so-called "Maize quadrangle" on the central plateau. The latter covers the Highveld of Mpumalanga, Gauteng, Northwest province (except the far western part) and the northern Free State.

The summer rainfall rainfed crop producing areas are key to food security in South Africa. Except for wheat, all major grain and oilseed crops are almost exclusively grown in these areas. For most crops the bulk (80-90%) is produced in the maize quadrangle. White maize make up 89% of the total (National Yield Estimates Committee 2019). The relative contributions of different provinces differ markedly between different crops, depending on the climatic (particularly rainfall) and soil requirements of different crops. Of most critical importance is that the very marginal areas (in terms of soils and rainfall) produce on average 74% (in some seasons nearly 80%) of South Africa's white maize, the primary staple food for a major proportion of South Africa's population, as opposed to 61% of the total maize.

A surprising scenario from all the statistics for all summer crops is that the Free State is actually the main food basket of the country and not areas like the Mpumalanga Highveld and KwaZulu-Natal province, which have better natural resources in terms of a combination of higher rainfall and better quality soils.

Climate and soil resources of the summer rainfall areas of South Africa

Climate

Rainfall is the primary climatic factor of interest to rainfed crop production in a dry country like South Africa. The summer rainfall area is in the subtropics and has a semi-arid climate. The rainfall is erratic with a large seasonal variation and these facts also have impacts on CA practices and their adoption. Most importantly, the east-west decrease in average annual rainfall over the main summer rainfed cropping area from the eastern escarpment to the western limit of the area, from about 1 000 mm per annum on the eastern side of the Mpumalanga Highveld to 400 mm per annum in the west (Schulze 1997). Smith (1998) classified all parts of the summer rainfall areas that receive less than 550 mm rain per annum as not suitable for rainfed crop production. Yet, a very large proportion of especially white maize is produced in areas with lower rainfall than this in the north western Free State and Northwest province. These areas with between 550 and 400 mm annual rainfall are “high drought risk” areas (Soil Science Society of South Africa, 1984) that require special soil management and risk reduction approaches. These areas also pose special challenges to CA. Secondly, a peculiarity of the rainfall in the coastal plateau of the Eastern Cape Province is that it has a bimodal distribution, with spring and autumn rainfall peaks, posing special challenges to rainfed cropping, including CA.

A characteristic of the rainfall of South Africa’s summer rainfall areas, especially in the maize quadrangle, is that prolonged droughts, with several successive years with far below normal rainfall, followed by several years with far above normal rainfall, are common (Laker, 2008). A characteristic of these rainfall cycles is that they are not oscillating, but always basically “all or nothing” sequences. Therefore there is no pre-warning that could assist farmers to adapt their practices.

The high average potential evapotranspiration over the summer rainfall areas, which far exceeds the average annual rainfall, causing huge water deficits, aggravates the water scarce situation and increases the rain water management challenges. Across Mpumalanga, Gauteng and Northwest and across the Free State the mean annual “A-pan Equivalent” increases from 1 800-2 200 mm in the east to 2 800-3 000 mm in the west (Schulze, 1997). Very high mid-summer Potential Evapotranspiration values lead to high water deficits in mid-summer – the crop growing season.

A third climatic factor is the strong westerly winds that prevail in the sandy soil dominated western Free State in August and also into September. This is at the end of winter, when the topsoils are at their driest after the rainless winters and the structureless sandy soils are at their most vulnerable to wind erosion. This is important in regard to the introduction of sustainable CA management systems.

Soils

There are major differences between the dominant soils that are found in different zones of the summer rainfall region. The higher the average annual rainfall the more highly weathered, leached and more stable against water erosion, crusting and subsurface compaction the arable soils are (Laker, 2004; Laker & Nortjé, 2019, 2020). The outcome is a variety of soils that have various properties and characteristics with different requirements and different challenges in regard to sustainable crop/soil management. It requires site specific solutions, also under CA. This emphasises the idea that farmers are ultimately the key innovators to adapt CA in their unique on-farm contexts.

Smith (1998) gave comprehensive discussions of the soils of the areas in the maize quadrangle with average annual rainfall of higher than 600 mm, the grain production area of KwaZulu-Natal and a narrow strip in the far north-eastern corner of the Eastern Cape. Though the soils with orthic (normal) A horizons over red or yellow-brown apedal B horizons (uniformly red or yellow-brown subsoils without moderate to strong macro-structure) are by far the most important soils that are used for rainfed crop production, especially maize. These subsoils are favourable for root development unless they have been compacted through in-field wheel traffic or cultivation practices. Of these soils, the soils of the Hutton and Avalon forms (Soil Classification Working Group, 1991) are by far the most widely used.

The high drought-prone western parts of the maize quadrangle in the north-western Free State and Northwest province have important soil scenarios that enable successful rainfed cropping, but pose serious challenges to achieving this. The north western Free State is dominated by aeolian sandy soils on which rainfed crop production is practised. These are mainly soils of the Hutton form, some several metres deep, and the Avalon form. All the soils are eutrophic. The sandy nature of these soils enable effective capturing of rain water due to their very high infiltration rates. The soils are almost exclusively fine sandy soils, as defined in the South African soil classification system (Soil Classification Working Group, 1991). This substantial water storage capacity, provided the soil is deep enough, and in the case of Avalon soils together with the additional water storage in the soft plinthic horizon (Laker 2008), enables ample water storage in the soil with appropriate soil water management. The fine sandy soils of the area have two very negative characteristics, namely their extreme susceptibility to wind erosion and their extreme vulnerability to subsurface soil compaction by in-field vehicular traffic. Laker & Nortjé (2020) gave a comprehensive review of existing knowledge on subsurface soil compaction in South Africa, including extensive discussions on these areas.

The North West Province has significant areas with sandy red and yellow-brown apedal soils, but less so than in the north-western Free State. All the red and yellow-brown apedal soils of the area are eutrophic. Whereas in the past the deep sandy soils were believed to be the best for crop production soil ratings for cultivation have changed dramatically due to experience that soils with additional water storage capacities are actually superior.

The soils of the grain producing areas of KwaZulu-Natal are almost exclusively dystrophic red and yellow apedal soils with orthic or humic topsoils, being infertile and very strongly acidic. The same is true for the far north eastern corner of the Eastern Cape. A characteristic of the soil of the Eastern Cape towards the more marginal areas is that they are extremely susceptible to crusting (Laker and Nortjé 2019).

The main rainfed crop production area in Limpopo province, namely the Springbok Flats, has major areas of fertile soils that are clayey from the surface. These are soils with strong swell-shrink properties (soils with vertic A horizons) and non-vertic soils, i.e. with melanic A horizons. The former is more abundant. These soils are not suitable for the production of crops like maize, soybeans or groundnuts. Where the rainfall is adequate, sorghum can be grown successfully on such soils as well as sunflower and wheat.

Challenges imposed by the nature of the physical-biological resources of different areas

Because of the great importance of food security in South Africa it is critically important to manage these limitations sustainably. Limitations on sandy soils such as extreme susceptibility to wind erosion, subsurface compaction and high drought risk and limitations in other soil types and areas like crusting soils, mid-summer droughts, extreme soil infertility, high soil acidity and rain water use efficiency, are furthermore all underlain by low SOC and soil health levels across all arable soils. To address these issues effectively, it requires the adaptation of suitable crop-livestock CA systems through an on-site, context–specific systems research process (Swanepoel et al. 2017).

Past sustainable agriculture research initiatives in rainfed annual crop production in the summer rainfall areas

Period before 2000

During this period, a portion of the formal research done through research institutions, in most cases working with farmers, was on pure no-till systems (i.e. without adequate incorporation of the other CA principles, especially crop diversity, which requires at least three rotation crops and/or cover crops). In KwaZulu-Natal, the main area where no-till is practised in the summer rainfall area of South Africa, some useful research comparing it with other crop/soil management systems that farmers in the different areas implement has been done. In the maize quadrangle, extremely little such formal research on no-till has been done during this period (Goddard et al. 2020).

In the 1960s severe wind erosion and the identification of extremely severe soil compaction in the sandy soils of the western Free State made it clear that excessive cultivation was no longer feasible. By about 1970 it was realised that the severe subsurface soil compaction was not plough pans, but traffic pans caused by the impact of the wheels of tractors and other vehicles and implements traversing the cultivated fields (Laker & Nortjé, 2020). This brought about a change to cultivation with tined implements (ripping) together with minimal secondary cultivations and adoption of the principles of "rip-on-row" and "controlled traffic", leading to much less soil disturbance and retention of some stubble.

Increased worldwide interest in no-till led to the belief that this could possibly become the best solution to alleviate both the wind erosion and subsurface soil compaction in this area. This led to research by Bennie et al. (1994) and a summary by Bennie (2001) comparing no-till with other systems in the western Free State, such as "conventional" clean cultivation, stubble mulching on the soil surface and a 10 month fallow system which was originally designed by Ten Cate (Hensley and Laker 1978). All other systems out-performed no-till as far as yield and soil water management concerned. Although the conventional cultivation out-yielded the stubble mulch cultivation by some margin on the two sandy soils, Bennie et al. (1994) recommended the use of the latter due to the wind erosion hazard associated with the former. They could not recommend no-till because it performed too poorly, which effectively stopped the further development of no-till systems in the sandy soil areas of South Africa during this period. Furthermore, the poor results of no-till systems under certain conditions were confirmed by other local and international studies and experiences (Beukes et al., 2016; Fagioli, 2019; Smith et al., 2018, 2019) stating that this system is not sustainable, especially over the medium to long term, even if it performs better on clay soils than on sandy soils (Bennie, 2001), and will either be dependent on frequent tillage practices and increasing levels of agro-chemicals to correct the ever increasing problems (e.g. soil compaction or weeds) in order to sustain production. However, in the North West Province it did improve yields due to better infiltration and less runoff (Smith et al., 2018). The more sustainable long-term alternative is to transform these pure no-till practices to a more holistic CA system that includes all the CA principles, building SOC and relying on a range of eco-system functions and services to address these problems (Pittelkow et al. 2015; Lal 2020)

The research and development regarding crop/soil management on the sandy soils in this period led to the following situation, which Bennie (2020) described as follows: "The general practice is deep rip combined with controlled traffic, giving the same effect as rip on row. Self-steering tractors make this practice easy. It is estimated that 80% of the approximately 1.5 million ha of deep sandy soils are cropped like this using the 'rip-on-row' system, where at least 30% plant material is left on the soil surface, technically qualifying for one of the CA principles of permanent organic soil cover." From this description it can be argued that a no-till system with controlled traffic could be a feasible option for the sandy soils in marginal rainfall areas. According to Bennie (2020) up to 60% of the farmers in the western Free State adopted the long fallow-maize system.

The third principle in the CA system, which is crop diversification including three different crops (combined with minimum soil disturbance and a retention of a soil organic cover), have not received adequate research investigations during this period. In both the drier, sandy parts of the maize quadrangle, as well as the eastern production areas, the challenge is to find suitable profitable cash crops in rotation with maize. The most common choices in the west are sunflower, soya bean and groundnuts and in the east in it predominantly soya beans, but even if three of them are used in a rotation (which seldom happens), they all produce too little residues to effectively protect the soil against wind erosion (Bennie (2019/20). On top of this, the soil disturbance practices associated with groundnut harvesting is another problem. Around 2000 no reliable and sustainable solution to crop diversification, complimenting no-till within a more holistic CA system, emerged.

CA crop/soil management systems research, 2000 to 2020

Background

Before the start of and during this period a significant percentage of farmers (between 10 and 20%) have started to adopt the complete CA system in the summer rainfall area (Findlater et al. 2019), while the rest were in some stage of transformation towards CA (De Wit et al. 2015). Very few farmers were still doing full conventional tillage systems as environmental and socio-economic factors were continuously pushing them towards more sustainable practices. Hence farmers are continuously testing and adapting their systems, which culminates in a myriad of different systems found at any given moment, ranging from some form of reduced tillage right up to a holistic CA system. From this perspective, this paper supports the view that 'every farmer is doing the best they can to adapt within his/her unique biophysical and socio-economic conditions or context' and their progress is firstly determined by awareness, knowledge and understanding of CA principles and critical technical fields, such as soil health, weed management, livestock integration and access/adaptation of implements, followed by socio-economic challenges (values, goals, cash flow) and lastly by biophysical constraints (such as soil types and climate).

Almost all the pioneer commercial farmers in the summer rainfall area of South Africa who started their transformation journey to adapt to a CA system in this period, have converted their farming systems without the support or influence of formal research studies in their regions (Van Coller, CA farmer, Viljoenskroon, Free State, personal communication 2019). Their conviction to change mostly came from an intense awareness of soil erosion on their farms due to tillage-based cropping, as well as their deteriorating economic situation. Their search for guidance and inspiration to effectively adapt their systems were mainly sourced from farmers in other countries (such as Argentina, USA, Australia and Brazil), in other provinces (especially KwaZulu-Natal and the Western Cape), and pioneer/leader farmers in other regions or in their own regions. Later on, the internet and social media have also played a huge role in general awareness raising, influenced by international icons such as Gabe Brown, Ray Archuleta and Christine Jones. Other major local awareness events, such as farmers' days and conferences, have had a significant influence right through this period. All of these influences have inspired farmers to start their own transformation journey on their farms, in some cases working with farmer groups and technical advisors, through an on-farm testing, experimentation and adaptation process. CA systems are now found in all conditions – from higher rainfall regions with clay soils to hot and dry regions with very sandy soils. Obviously, the latter situation is more challenging to adapt CA successfully leading to a much lower adoption in those regions.

A few key initiatives have been launched from around 2000 to improve the adaptation of CA in the summer rainfall area. Regional initiatives, such as the KZN No-Till Club (which started before 2000), have consistently made positive impacts through awareness events, on-farm research and publications. The CA Farmer Innovation Programme (FIP), funded by The Maize Trust and implemented through Grain SA, was launched in 2013 with the aim to formalise and coordinate CA research under commercial, semi-commercial and smallholder farmers in different summer rainfall regions. A key initiative in the sandy soil area of the north-west Free State was the Sandy Soils Development Committee (Beukes et al., 2018, 2019). The key agency for implementing CA FIP smallholder projects in the KZN and Eastern Cape Provinces has been Mahlathini Development Foundation (MDF), while various independent and official researchers from the Agricultural Research Council (ARC) and universities with the right experience, were involved in their other CA projects. In the earlier part of this period, a range of LandCare-related CA projects were implemented among smallholders, mostly by the ARC and their provincial and local counterparts, which were funded by the National and Provincial governments (Goddard et al., 2020).

These initiatives' aims have been to engage with, support and strengthen the farmer-driven process, which were quite active and is briefly mentioned above. They employed a family of approaches, methodologies and tools, which are all grouped under a farmer-centred Innovation Systems approach (Smith and Visser 2014), which have literally been part of the CA development and expansion across the world that effectively started in the 1950's (Coughenour and Chamla 2000) and were later formalised by the likes of Freire (1973) and Chambers and Jiggins (1987) and adapted in local contexts by Smith (2006) and described by Smith et al. (2017). The evolvement of these approaches were mainly motivated by the poor impact that linear approaches had on the transformation of complex whole farming systems. Their key elements (methodologies) are awareness, on-farm experimentation, participatory monitoring and evaluation (PM&E) and the facilitation of social learning (sharing and learning in groups), and they are underpinned by sound philosophies, such as communicative action (Habermas 1981), experiential- (Kolb 1984), discovery- and action learning and action research (Lewin 1946; Fell 1996; Argyris 1983). What proved these approaches to be good choices for CA research and development, was their consistency in achieving the following key desired outcomes, namely: improved awareness, knowledge and skills, better interaction and communication, better adaptation and adoption of new technologies and quicker restoration of natural resources. The South African LandCare programme and CA policy have also included these approaches to drive CA mainstreaming in South Africa from a government perspective (Goddard et al. 2020).

On-farm research

Swanepoel et al. (2017) reviewed all accessible CA research literature in South Africa published prior to March 2017. Seventy percent (70%) of all local CA research was published after 2010 and most data generated was from peer-reviewed articles (45%) and researcher-managed field trials (61%) collected from on-station research facilities linked to universities, provincial government departments or research institutions such as the ARC, as opposed to 5% from farmer-led or collaboratively-managed on-farm trials and 10% from technical project reports. Less than 20% (16% in Free State and 3% in North West) of the research output was produced in the summer rainfall areas where 70% of the grain is produced (the “Maize quadrangle”). Clearly, this is where the big data gap lied under commercial and semi-commercial farmers, as well as a gap under smallholder farmers in the eastern seaboard areas (especially the KwaZulu-Natal and Eastern Cape Provinces). Hence, the initiation of the CA FIP in these areas aiming to increase the amount and impact of CA research. This section aims to provide a better insight into the results obtained and lessons learned from this initiative, which are captured in their annual technical progress reports currently accessible from the Grain SA website (www.grainsa.co.za).

On-farm experimentation, as described by Selener (1998) and Smith (2006), was employed as a key methodology in the CA FIP. Collaboratively-managed (farmer-researcher) trials were found to be the most suitable to address key research questions and were used extensively in all commercial CA FIP projects; the Ottosdal project has seen the peak of this effort with 80 collaboratively-managed trials done between 2013 and 2020. Farmer-managed trials have been rigorously used by all the categories of farmers in this area as an “inherent, intuitive part of a farmers’ innovativeness and resilience to adapt their practices to CA, which happens spontaneously, every day, rather than as the result of some external motivation” (Hansson 2019); however, very little data have yet been collected from these trials at commercial farms. In the Vrede and Reitz projects in the northeastern Free State, the use of long term monitoring of benchmark sites on farmer-managed trials were employed as complementary research tool to fill this gap (Smith et al. 2018). According to Kruger et al. (2019) farmer-managed trials were the main choice among smallholders with 550 smallholders implementing CA experiments and 3 000 smallholder farmers involved through learning groups across 19 villages in KZN and the Eastern Cape between 2013 and 2019. A quite extensive monitoring process was implemented around these experiments and useful data was collected. Kruger et al. (2019) identified the need for a few researcher-managed trials to investigate some research questions in the smallholder projects.

The following CA treatments and topics were prioritised by the multi-disciplinary CA FIP project teams working with commercial farmer groups: cover crops and livestock integration, crop rotations, green fallow systems, higher crop density (higher plant population x narrower row width), intercropping, tine vs disc no-till planters, soil fertility and fertiliser rates, weed management, conventional vs CA crop systems and maize cultivar evaluation under high density CA systems. In the smallholder projects the following treatments and topics were prioritised in their experimentation: crop rotation compared with intercropping, inclusion of summer cover crops in the crop rotation trials, winter cover crops, late season beans, introduction of lab-lab beans, fodder production and supplementation, different hand-, animal- and tractor-operated no-till planters and knapsack sprayers. Various measurements were made such as: soil health (Haney test, Solvita), production (grain, biomass and meat), biodiversity, economy (profit), soil cover, weed suppression, soil temperature and soil water balance (including runoff, infiltration, erosion and soil water content).

Major findings about commercial farmers in the CA FIP projects implemented in the summer rainfall area:

Diverse annual and/or perennial cover crop systems in rotation with cash crops and/or as a green fallow system, provided a valuable tool to integrate livestock in a sustainable manner. The livestock factor provided an extra, stable income stream and served as an effective risk reduction strategy. Ninety percent (90%) of commercial crop farmers have livestock, but the current practice of utilising cash crop residues as winter fodder is unsustainable.

These diverse CA crop-livestock systems facilitated the successful recovery of some critical soil ecosystem functions and the restoration of degraded soils in a fairly short period, while steadily increasing cash crop yields, reducing production inputs and increasing overall profitability. This provided an ideal or preferred start for a transformation phase into CA of between 5 and 10 years, depending on the soil and climatic conditions. This phase could be quite difficult and challenging to farmers, but starting with a good diversity and quantity of biomass (provided by multi-specie cover crops) for soil cover makes this transformation much easier.

The diverse CA crop-livestock systems, but livestock in particular, have a huge positive effect on soil biology, or the soil food web, improving key soil properties to critical threshold levels (Lal 2015 a of b), resulting in the restoration of essential soil functions and services, such as soil carbon sequestration, soil nutrient cycling, above- and below-ground biodiversity, the water infiltration rate, water runoff and erosion, weed management and the reduction of soil borne diseases (Smith et al. 2018, 2019, 2020). Beukes et al (2019) found sharp increases in %SOC (from 0.48% to 0.64%) within 3 years on the hot, sandy soil conditions in the north west Free State using summer and winter multi-species cover crops systems (without livestock), showing the potential of CA for soil carbon sequestration even in those conditions. Successful crop production with no-till on these sandy soils with their compaction susceptibility is problematic. A dedicated research effort is needed that will continue to support farmers to develop comprehensive alternative crop systems for the aggressive soil disturbing actions such as deep ripping and secondary tillage actions that is currently widely practiced.

On the sandy soils of North West the yield of maize was significantly higher under high density (i.e. narrower row width and higher plant population) in conservation agricultural systems (i.e. the so-called Argentinean system) (Smith et al. 2018, 2019). Haarhoff and Swanepoel (2020) reported on the effect of higher plant populations on the yield of maize grown in trials in the Eastern Free State. They found significant increases in maize yield with increasing plant density, the second year showed similar trends, but the results were not significantly different.

On the other hand, wider row-widths provided a better opportunity for intercropping, which is a preferred option for a small but increasing number of farmers. The yield of maize in local conventional systems were lower than the yield of no-till systems tested on three farmer-managed trials in the Ottosdal area (Smith et al. 2018, 2019). This yield increase, of up to 40%, is mainly due to an increase in the water infiltration rate of the soil, which can differ several fold between covered and uncovered soil in the area.

In crop rotation trials, some preliminary results suggest that the affect that a specific crop may have on the yield of a following crop, differs between conventional and no-till systems. Planting with disc or tine no-till planters showed no difference on crop establishment and yield performance in the Ottosdal area, and maize cultivar evaluation is a seasonal action due to the fast turnover of cultivars (Smith et al. 2019, 2020).

Major findings of Kruger et al. (2019) regaring CA FIP projects for smallholders:

CA maize intercropping systems (with dry beans or cowpeas) in the Bergville area had clear positive impacts on soil health and productivity, including increasing maize yields to an average of 5 t ha^{-1} in an average rainfall season, with maximum yields of around 10 t ha^{-1}, compared to below 1 t ha^{-1} on traditional plots. This increased productivity was in concurrence with increased biodiversity in crops and food, with an additional protein source from the beans. The higher density intercropping system resulted in a much better suppression of weeds and less herbicide or manual weed control actions.

Smallholders who were part of the CA FIP research process for five years were able to sustain the following actions without external support, showed a remarkable improvement in their rural livelihood and food security status:

- Implementing all three principles of CA
- Practising intercropping (after initial resistance from a significant portion of farmers)

- Improving yields
- Including CA into their overall farming practices; 73% have increased their field sizes using CA
- Saving money and increasing food security considerably
- Involved in local village savings and loan associations (the farmer group platforms used for the CA innovation process)
- Using traditional seed varieties alongside the more modern open-pollen and hybrid varieties (this situation is the reality that manifested, as various companies promote their own seed into these areas).

Soil health monitoring results from 2013 to 2019 are summarised as follows:

- The % SOM was the highest under summer cover crop systems, followed by maize + cowpea intercropping and then maize + dry bean intercropping
- Carbon sequestration in these CA mixed cover crop and intercropping plots was 2 - 3,5 t ha^{-1}, which was between 0,75 - 1,5 t ha^{-1} more than the single crop plots
- Crop diversity is crucial for soil health improvement; the more crops used in the system, the better
- Higher soil health and fertility levels resulted in significantly lower fertiliser requirements in some cases.

Recommendations regarding CA in summer rainfall area

The dominant tillage-based cropping systems in the summer rainfall area is at a dead-end as far as production, natural resource degradation and financial viability is concerned. As stated by Lal (2020), the only way forward is "a system-based conservation agriculture in managing soils for negative feedback to climate change and positive impact on food and nutritional security".

A much deeper awareness and understanding of the importance, properties and functioning of the natural resources (soil, biodiversity, water and climate) in the summer rainfall areas of South Africa as well as the CA principles are of utmost importance to design and implement pragmatic CA adaptation strategies in a wide variety of local contexts. This is also true for the rest of the country. In view of the dearth of research for CA in the summer rainfall areas of South Africa, especially in the maize quadrangle and the eastern seaboard, research involving CA should urgently be intensified in these areas through conducting well-designed and well executed participatory systems research initiatives at representative sites in each of the ecologically different areas. Taking a leaf from all the local and global CA experiences that a cornerstone for success of the development, adaptation and adoption thereof (through participatory systems research) is close collaboration between all key role players, especially researchers, extentionists and farmers (Evers and Agostini 2001). However, for many reasons described above, the participation and central role of farmers in the whole process are critical if there is any hope to accelerate the adaptation and adoption of appropriate CA systems in their unique local contexts.

Winter rainfall production

No-tillage systems

At the time of this review, most farmers in the Western Cape converted to no-tillage systems where seed-drills are used to place seed directly in soil, without any prior soil preparation activities. No-tillage is currently the preferred option for establishment of crops as soil quality is promoted and profits are optimised through reduced use of fuel and increased yields as a result of improved soil quality (Smith et al. 2020). Continuous tillage or sometimes even infrequent tillage within a no-tillage regime results in suboptimal yields or profitability (Tshuma et al. 2020). However, some issues have been reported with no-tillage. Soil compaction is one of the major issues (Li et al. 2020). Although the extent of soil compaction is not well understood in the winter rainfall region, some producers have adopted controlled traffic, and claim that they have seen benefits. In Western Australia, controlled traffic is successfully being applied by many producers (Tullberg et al. 2018). However, in South Africa, relatively small or fenced fields to accommodate integration of livestock, and an undulating landscape prevent producers from easily adopting controlled traffic. Ripping soil is one option to alleviate soil compaction in deep sandy soils (such as the Sandveld region), but results are inconsistent and ripping does not always improve production (Laubscher et al. 2020). Elsewhere in the Western Cape, soils have a high stone content, and ripping is generally limited by soil physical characteristics.

Another challenge is incorporation of immobile soil ameliorants or nutrients, such as lime or phosphorus (Tshuma et al. 2020). There is evidence of subsoil acidity problems or stratification of pH in the Swartland region, but subsoil acidity is generally not problematic in the southern Cape (Liebenberg et al. 2020; Van der Nest et al. 2020). More research is required to investigate ways to alleviate soil acidity issues in the subsoil, without compromising soil quality which may arise from excessive soil tillage to incorporate lime.

Crop rotation

Since the 17th century, small grain production in the Western Cape gradually increased following consumer demand. Until the 1980s, wheat and barley (*Hordeum vulgare*) were cultivated mostly in monocultures or in rotations with lupines. However, the lupine (*Lupinus* spp.) industry was practically wiped out by diseases such as powdery mildew and anthracnose. Wheat and barley monocultures selected for grassweeds, notably ryegrass (*Lolium rigidum*), build-up of pests and diseases and crop productivity ultimately declined (MacLaren et al. 2021). In the 1980s, the Western Cape Government Department of Agriculture subsequently promoted crop rotation systems and subsidised seed, lime, and other establishment costs of annual *Medicago* species (Swanepoel et al. 2016). Subsequently, cropping systems were integrated with livestock, specifically sheep, but occasionally also cattle and ostriches. Through time crop rotations systems developed into systems that include wheat, barley, canola (*Brassica napus*), rye (*Secale cereale*), oats (*Avena sativa*), triticale (*x Triticosecale)*, lupines, clovers (*Trifolium* spp.) and annual medics (*Medicago* spp.) and lucerne (*Medicago sativa*). Not all crops have equal markets. Wheat and barley, both Poaceae, remain the two most market-valued crops and hence, the winter rainfall region's cropping systems are anchored by these two cereal crops. Broadleaf crops in rotation with cereals are critical for weed control and to break pest and disease cycles. The only broadleaf cash crops are canola and lupines. Canola have been commercially incorporated in the crop rotation systems since 1994. Lupines are only produced on 10 000 to 15 000 ha every year since there is, *inter alia*, a lack of modern disease-resistant cultivars and there are various agronomic challenges related to establishment and production. Broadleaf forage crops provide opportunities to incorporate diversity into the system. However, not all farmers a favoured towards integrating livestock in the cropping systems. Lucerne is grown only in the southern Cape region, as the Swartland's rainfall distribution is too confined to the winter months to carry perennial crops through the summer. However, some southern Cape producers consider excluding lucerne from crop rotations since herbage productions are low in summer due to moisture stress and in winter because of physiological dormancy. Alternative crops or integration of multispecies pastures with lucerne should be investigated.

Crop rotation systems in the Swartland are mostly short rotations of cash crops with annual medics and clovers. A significant shortcoming of these crop rotation systems is the lack of locally adapted broadleaf cash crop, which could be used. Pulses such as chickpeas (*Cicer arietinum*), lentils (*Lens culinaris*), field peas (*Pisum sativum*) and faba beans (*Vicia faba*) or pseudograins such as quinoa (*Chenopodium quinoa*) or buckwheat (*Fagopyrum esculentum*) or other alternative crops like coriander (*Coriandrum* *sativum*), linseed (*Linum usitatissimum*) or brassicas other than canola, could be considered to increase diversity in the systems. However, currently there is extremely limited market, or seed is not commercially available for these crops.

Cover crops have also recently become an option to farmers. Although it is not yet widely incorporated in systems, there are increasingly more advantages that are demonstrated to producers. For instance, MacLaren et al. (2019a) have shown that cover crops can successfully be employed as a weed control measure. Smit et al. (2020) demonstrated how cover crops can be utilised as a forage. Other important agroecosystem functions may include improved soil quality, nitrogen fixation, prevention of soil erosion through runoff and reducing water loss through evaporation. More research to determine effective ways to incorporate cover crops in the crop rotation systems is needed.

Stubble management

Following harvesting, crop residues remain on the soil surface or may be partially grazed, opposed to the past practices of being completely removed through burning, baling or grazing. Covering the soil with crop residue from the previous crop buffers soil temperature, which leads to higher microbial activity (Kassam et al. 2012). It also protects the soil physically from wind and water erosion and protects soil water from evaporation. Crop residue are also an effective way to suppress weeds (Cook 2006; MacLaren et al. 2021). Through time, crop residue sequesters soil carbon (Friedrich and Kassam 2011). Although the benefits of crop residue surpass the disadvantages, there are certain challenges with crop residues for wheat and barley producers.

No-tillage seed-drills can become obstructed with crop residue, leading to uneven establishment of small grains (Swanepoel et al. 2019). Crop residue are often dragged along the planters, ending up in large heaps of residue through which no plant can emerge. Crop residue can also shade young seedlings or reduce the quality of light, which may delay establishment or reduce plant populations of small grains. Crop residues from the previous crop in rotation can interfere with crop development and growth through alteration of soil physical, chemical, and biological characteristics. A limitation is that of allelopathy, which is the process involving substances (metabolites) produced by plants, which may inhibit the growth and development of other plants of the same or different species. In the case of crop residues compounds (allelochemicals) can be released directly from crop litter or they can be produced by microorganisms that use plant residues as a substrate. This may have a significant adverse effect on yield of small grains in conservation agriculture systems and may become increasingly important as a diversity of crops in crop rotation systems are stressed more and more (MacLaren et al. 2019a).

Crop residue plays a vital role in soil health and can bring great advantages, but it needs to be managed well. Residue management starts when the crop is harvested and when the crop sequence is designed. The load of crop residues and the quality of crop residues, which determine the rate of decomposition, may be important factors to consider ensuring good establishment of the subsequent crop. Crop residues from leguminous crops (such as annual medics), or crop residues of grain crops which have been heavily fertilised with nitrogen, may decompose faster than crop residues that have a low nitrogen content.

From a soil quality and water conservation viewpoint, more crop residue would be better. However, from an agronomic point of view, there will be an optimum load which will conserve water and soil quality, without compromising crop establishment and yield. This critical point is not known for the CA systems in the Western Cape and should be investigated (Smit et al. 2020). Management practices could consequently be adapted, such as designing a cropping sequence to take allelopathy into account, choosing or altering chopper and spreader kits of combine harvester and degree to which crop residues can be removed through grazing or baling.

Economics and social aspects

Long-term trials in the Swartland demonstrated that the financial performance of various crop rotation systems differed significantly. Generally, the cropping systems integrated with livestock were more profitable and had less fluctuations than systems with cash crops only. Wheat-medic crop rotation systems with additional saltbush pastures were the most profitable (Basson 2017). Furthermore, Knott (2015) demonstrated that farming systems under conventional tillage returned negative net present values and an internal rate of return on capital investment lower than the real interest rate. The implication is that investment in conventional tillage will ultimately lead to financial losses. The financial benefits of no-tillage and crop rotation (Hardy et al. 2011; Strauss et al. 2011) are directly related to improved soil health, lower weed and pest stress and improved yields (MacLaren et al. 2019b). Crookes et al. (2017) modelled how drought affected the economics of these systems. The systems that were integrated with livestock had significantly better performance during times of drought, compared to the cash cropping systems.

Raaijmakers and Swanepoel (2020) showed that vulnerability attributes, especially the lack of financial, natural, human and physical capital, account for variation in form and extent of adopting CA adaptation. It is easier for commercial farmers to adopt conservation agriculture as a long-term investment to mitigate effects of drought, but emerging farmers have to take on drastic measures to cope with drought which are often not supporting conservation agriculture principles. In order to ensure inclusive agricultural adaptation, research is needed to find ways to further facilitate equal adaptation opportunities, especially for marginalised farmers.

Various long-term trials across the Western Cape managed by the Western Cape Department of Agriculture, are unique and invaluable assists. A more concerted focus to publish information from the long-term trials, and to incorporate component trials into the long-term trials, should be promoted. Multidisciplinary teams are critical in understanding the effects of the entire system on farming efficiency environmental soundness and sustainability.

Conclusions

Considering the dearth in appropriate research initiatives and published results of CA under rain-fed production in South Africa, it is of critical importance that this is prioritised. Farmers in South Africa, especially in the summer rainfall area, have had fairly little support from key stakeholders, such as research, extension and agribusinesses, in this regard. In the Western Cape and KwaZulu-Natal, farmers had much better support from research programmes. In general, farmers urgently need to have the best and most appropriate support in testing and adapting their systems to survive an increasingly challenging economic and biophysical environment. Participatory on-farm, systems research approaches, recognising and engaging farmers as key innovators, had much better success to adapt CA systems in local contexts. This approach also creates an ideal platform for more appropriate formal research collaboration leading to a stream of relevant and accessible publications. Conservation Agriculture is essential in developing climate-resilient, environmentally friendly and productive farming systems in the post-2020 period and need to be adapted locally within the socio-economic, soil and climatic conditions of the rain-fed crop production areas as discussed in the body of this article.

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