Soil Fertility Trends and Management in Conservation Agriculture: a South African Perspective

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ABSTRACT

Conservation Agriculture (CA) is an integrated approach that consists of a package of practices, namely no-tillage, cover crops, and a crop rotation which includes at least three crops. Globally CA is implemented widely in South America (Argentina and Brazil) and North America (USA and Canada), with a smaller proportion in Australia and New Zealand. There is very little implementation of CA in the rest of world, mainly due to natural resource constraints. Benefits of the system include increases in soil organic matter (SOM) and related increases in organic N in the soil. Experimental results show extremely strong stratification of important plant nutrients, like P, K and Ca, at very shallow soil depth (less than 5 cm) under no-till due to their low mobility in soil. Results show that there is poor root development near the soil surface under the extreme conditions in the marginal cropping areas that dominate most of South Africa's crop production areas. Plant nutrient uptake is thus much lower under no-till than under conventional tillage. Likewise very little movement of lime was found under no-till, hampering amelioration of soil acidity. Research confirmed international data that maize requires much higher N application under no-till than under conventional tillage.

Key words: conservation agriculture, soil fertility, nutrient losses, no-tillage, South-Africa

INTRODUCTION

General

Successful and effective transfer of technologies and farming systems is possible only between sites or areas with similar natural physical biological resources in terms of soils and climate. This is true for transfer within an area, within a country, between countries in a region and between countries on different continents. The climate and the properties, characteristics and qualities of the dominant soils differ between different areas within a country, between countries and between continents. Successful sustainable farming technologies and systems differ between these as dictated by the prevailing climates and dominant soils. Much cropping research is done in the developed countries of the northern hemisphere in North America and Europe, because they have the funding to support it. Attempts are continuously been made to transfer farming technologies and systems that are successful there to other parts of the world, especially to developing countries. There are, however, vast differences between the climates and dominant soils of the developed countries and those of the developing countries. The former has much more favourable climates and soil resources for crop production than the latter (Laker, 2005). The developed countries are in the temperate climate zone at relatively high latitudes (30^o to 60^o, mainly above 35^o) and the crop production areas are dominated by inherently fertile, deep soils with good physical conditions. The developing countries are in hot zones, dry in the mid-latitudes (Laker, 2003), and have predominantly poor-quality soils, such as shallow soils and infertile sandy soils (Laker, 2005). The grain producing areas of the American Midwest are for example, dominated by high quality Mollisols, according to the American Soil Taxonomy (Soil Survey Staff, 1999). These soils are classified as Chernozems, Kastanozems and Phaeozems in the world reference base for soil resources and the atlas showing the distribution of different WRB reference groups clearly shows the dominance of these soils in the American Midwest (ISSS Working Group RB, 1998). The atlas also shows the absence of such soils in Africa and the minimal presence of other soils that according to Driessen *et al.* (2001) are described as having good potential for crop production. This is also confirmed in the Soil Atlas of Africa (Jones et al., 2013) and is also true for South Africa. Thus, in general natural soil fertility in South Africa is much lower than in the inherently fertile dominant soils of Europe and North America (van der Merwe et al., 2001).

The adoption of no-till based conservation agriculture (CA), is highly skewed globally. Of the total area under CA 39% is in South America (Argentina/Brazil), 35% in North America (USA/Canada) and 13% in Australia and New Zealand, thus making up 87% of the total (Kassam et al., 2018). Of the rest, 8% is in Asia, 3% in Russia and Ukraine, 2% in Europe and 0.8% in Africa. It is important to summarise the climate and soil resources of the three main areas with high no-till based CA adoption rates and to compare these with South Africa.

- The favourable temperate climate and high-quality fertile soils of the grain producing areas of North America have been outlined above.
- Argentina's grain producing area has much the same situation. It has a favourable temperate climate, being in the southern temperate climate zone between latitudes 30° and 60°, with average annual rainfall ranging from 600 to 1 400 mm (Merlos et al., 2015). It has high quality fertile Mollisols with no root depth restricting layers, except in the south where it is underlain by a lime pan (Merlos et al., 2015).
- Australia's grain producing areas are divided into three regions. The northern region is in central and south Queensland and northern New South Wales. It has a sub-

tropical climate with summer rain in Queensland, the rainfall being high (AEGIS, 2016), becoming temperate in New South Wales. The soils are predominantly fertile clayey soils with high water storage capacities (AEGIC, 2016; GRDC, Undated), also indicated by ISSS Working Group RB (1998). The southern region include southern New South Wales, Victoria, south-eastern Southern Australia and Tasmania. It is at latitudes higher than 30° south and thus has a temperate climate, with somewhat more rain in winter than in summer. Rainfall varies from relatively low to high. Soils are variable and generally infertile, but with some high quality soils. The third area is the south-western corner of Western Australia. It has a temperate Mediterranean (winter rainfall) climate, with average annual rainfall in the crop growing areas ranging from 450 mm to 800 mm. It has variable soils, but generally with reasonable depth.

- The Cerrado, where no-till CA is practised extensively in Brazil, is a special case. The soils are strongly acidic, very infertile (particularly concerning P) and deep, with depths up to 25 metres (FAO, undated). Temperatures are temperate and average annual rainfall in the crop production areas is between 1 200 and 1 600 mm (FAO, Undated). It is a summer rainfall area. The high soil acidity and infertility of the soils are major constraints, but once these are overcome by liming and application of fertilisers the area has high cropping potential (FAO, undated).

South Africa’s grain production areas cannot be compared to any of the above, in terms of their combinations of soils and climate. None has rainfall comparable to that of the Brazilian Cerrado. As indicated earlier, none has Mollisols, the inherently fertile and physically favourable soils dominating the North American and Argentinian grain producing areas, or significant areas with other soils with equivalent properties. The bulk of South Africa's grain is produced in a summer rainfall area in the hot mid-latitudes. Potential evapotranspiration exceeds rainfall by far, even in the summer rain period (Schulze, 1997). Almost all of the grain here is produced in the so-called "Maize Quadrangle", covering the Highveld of Mpumalanga province, as well as Gauteng and North West provinces and the northern half of Free State province. Mid-summer drought is a serious problem in most of this area (Smith, 1998; Mbatani, 2000). Some important aspects include:

- The western part of the Maize Quadrangle, including the north-western Free State and much of North West province, has unreliable marginal rainfall of around only 500 mm per annum. The north-western Free State is totally dominated by Aeolian sandy soils, with maize in some areas being produced on soils with less than 5% clay, only 1-2% silt and the rest sand. The sandy soils of this area exceptionally vulnerable to wind erosion, very susceptible to subsurface soil compaction by in-field wheel traffic and infertile. Widespread, severe zinc deficiencies in maize, a crop that is very vulnerable to zinc deficiency, is a serious problem in this area (Laker, 1964; Van der Waals & Laker, 2008). North West province also has major areas of sandy soils. During the period 1990/91 to 2017/18, the Free State produced 42% of the country's white maize, the main staple food of a large proportion of the population (National Yield Estimates Committee, 2019). Almost all of this is produced in the marginal rainfall; sandy soil dominated north-western Free State. The temperate climate, with long cold winters, of the high rainfall eastern Free State causes a growing season that is too short for white maize and thus "prohibits" white maize production there (Smith, 1998). Rainfall in the south-western Free State is too low (Eloff, 1984), whereas the south-eastern Free State is dominated by non-arable, highly erodible soils (Eloff, 1984). North West province, with also marginal resources, contributes another 32% of the white maize, thus creating a situation that almost three quarters of the country's white maize is produced in the areas with marginal resources.

- In the eastern Highveld (eastern part of North West province, Gauteng and the Highveld of Mpumalanga annual rainfall increases from 650 mm in the west to 900 mm in the east (Smith, 1998). Although the average rainfall is adequate, periodic mid-summer drought is a problem. The short growing season in especially the higher rainfall eastern parts of this region prohibits white maize production "which usually results in surplus yellow maize production and a shortage of white maize" (Smith, 1998). The region has soils with favourable physical characteristics and high-water storage capacities (Smith, 1998). However, their limitations are low inherent soil fertility and high soil acidity, the latter causing Al toxicities and high P fixation into unavailable forms (Smith, 1998).
- The interior grain producing areas of KwaZulu-Natal province have the best crop producing potential in the summer rainfall area due to high rainfall (800-1 000 mm per annum), temperate climate and soils with good physical qualities, although acidic and infertile (Smith, 1998). However, it contributes very little to grain production in the country (National Yield Estimates Committee, 2019). Only 4.3% of the country's maize was produced there during the period 1990/91-2017/18, for example.

It is clear that low soil fertility is a major problem throughout South Africa's main grain producing region. The other major grain producing area in the country, but contributing much less than the former, is in the Western Cape Province. This area is in the temperate zone at latitudes higher than 30° S. It has a typical winter rainfall, Mediterranean climate, with about 80% of the rain falling in winter (Strauss, 2020). Because the winters are cold, evapotranspiration during the rainy season is low (Schulze, 1997), making the rain potentially effective. However, the rainfall is low, with average annual rainfall ranging between 400 and 420 mm over most of the crop production areas. The soils, mainly derived from shale, are relatively fertile, but are predominantly shallow (<500 mm) and stony (Strauss, 2020). The soils also have serious crusting problems, reducing the effectiveness of the rain and inhibiting the emergence of small grain seedlings unless appropriate measures are taken (Laker & Nortjé, 2019). Because the rain is so concentrated in winter and the water storage capacities of the soils are very low, crop production is restricted to one crop per year during the winter rain season, with summer fallow (Strauss, 220).

Purely based on the differences in natural physical-biological resources (climate and soils), it cannot be expected to achieve the same degree of adoption of no-till based CA in South Africa as in the countries where it has widely been adopted. That is without even considering other important factors. To mention just two factors: The less favourable the climate and/or soils of an area are, the smaller becomes the number of crops that can be produced successfully and profitably. This restricts the options of crop rotations. The more susceptible soils are to subsurface compaction by in-field wheel traffic, the less becomes the possibility to implement no-till successfully. The impact of differences in climate and soil resources is underlined, by the differences in degree of adoption between different provinces and areas in the two main crop production regions of South Africa. Findlater (2015) found the highest degree of adoption in the Western Cape with relatively favourable natural resources for adoption of no-till based CA. The soils are shallow, but relatively fertile. Rainfall is low, but very efficient due to (i) being soaking rains and not poorly distributed aggressive thunderstorms (as in the summer rainfall provinces) and (ii) the low PET during the rainy season. Second, is the area in KwaZulu-Natal, the summer rainfall area with the most favourable soil and climate combination, including high rainfall? In Mpumalanga, with somewhat less favourable natural resources, adoption is less. In the Free State and North West province, with large areas that are marginal for crop production, adoption is low.

Maize (*Zea mays* L.) is by far the most widely grown cereal crop in South Africa (Haarhoff et al., 2019). For many decades, it was mainly managed, with unsustainable systems, such as intensive mechanised soil tillage, maize monoculture and clean fallow. Several of these changed over the years in some areas, including less tillage, ripping, controlled traffic, etc. (Laker & Nortjé, 2020). The application of unsustainable systems led to very severe soil degradation in various forms, such as, for example, soil erosion (Laker, 2004), subsurface soil compaction (Laker & Nortjé, 2020) and soil crusting (Laker & Nortjé, 2019). These all have serious negative impacts in terms of soil fertility. It has been estimated that South Africa annually loses 30 000 t N, 26 400 t P and 363 000 t K due to soil erosion (Barnard et al., 2001). Subsurface soil compaction and soil crusting do not cause nutrient losses from soil, but inhibit uptake of various nutrients by plants (du Preez et al., 1979; Laker & Nortjé, 2019; Laker & Nortjé, 2020; and various others). Exhaustive cropping also reduces soil fertility (van der Merwe et al., 2001). Soil acidification under intensive cropping is another matter of great concern (Barnard et al., 2001; van der Merwe et al., 2001).

On the other hand, over-fertilisation is also a matter of concern, as indicated in reviews on soil fertility in South Africa by van der Merwe et al. (2001), Barnard & du Preez (2004) and Laker (2008). Concerns are particularly about over-fertilisation with nitrogen (van der Merwe et al., 2001; Barnard & du Preez, 2004) and phosphorus (Laker, 2008). It is important to consider both the extent of over-fertilisation and its consequences. Unnecessarily high P applications, for example, lead to a waste of money by spending a lot of money on something that gives no economic return, while excessive P levels even reduce yields (Laker, 2008). Over-fertilisation with nitrogen greatly contributes to soil acidification.

There seems to be a perception, *inter alia* in conservation agriculture (CA) circles, that there has been a general trend of unacceptably high fertilizer application under the continuous intensively cultivated monoculture grain cropping systems in South Africa. Smith & Trytsman (2017), for example articulated it that under these systems there has been a *"consistent recommendation of the use of huge quantities of chemical fertilizers that are biologically unnecessary, economically extravagant and ecologically damaging"*.

It is, however, important to look in a balanced way at all trends in fertilizer use and soil fertility and it is thus, equally important to look at the extent and consequences of reported under-fertilisation, as outlined by, for example, van der Merwe et al. (2001), Barnard & du Preez (2004) and Laker (2008). This is illustrated in Table 1 (Laker, 2008).

Table 1: Percentages of maize fields in different Bray-1 extractable topsoil P level ranges for two regions in the Northwest province of South Africa (Laker, 2008)

Year	**P class*** ($mg.kg^{-1}$)	**% of samples**	
		Region A	**Region B**
1994	0-9	26	24
	10-29	**56**	**48**
	30-49	12	15
	50+	**6**	**13**
	Median P content	17 $mg.kg^{-1}$	18 $mg.kg^{-1}$
2002	0-9	33	32
	10-29	**50**	**40**
	30-49	8	10
	50+	**9**	**18**
	Median P content	15 $mg.kg^{-1}$	18 $mg.kg^{-1}$

* Classes: 0-9 = Deficient; 10-29 = Adequate; 30-49 = Excessive; 50+ = Yield decreases probable

There seems to be an implied perception, e.g. in statements like that by Smith & Trytsman (2017), that over-fertilisation is an inherent weakness of conventional crop farming. The reality is that it is because of a type of mismanagement that can happen under any type of farming system.

Aims of Conservation Agriculture in regard to soil fertility and plant nutrition management

From a soil fertility aspect, CA is seen as a strategy to (i) to minimize or eliminate the soil fertility errors made under conventional tillage and (ii) reduce inputs of chemical fertilizers without compromising yields or the profits of farmers.

No-tillage, an important component of CA, aims to improve or increase the following conservation services: Soil Organic Matter (soil biodiversity, nutrient cycling), Aggregate Stability (macro pores, water infiltration), and Water Storage (nutrient storage, nutrient availability) (Smith, 2019).

In the CA principles manual of GrainSA (2016), it is stated that the focus of CA is soil biology, which drive soil chemistry and soil physics. "Once soil biology (ecology, soil food web, soil ecosystem functions) functions properly, it positively influences and restores soil chemistry and soil physics over the medium to long-term. In the short-term, a mixed, (integrated) biological-chemical soil fertility, strategy should be followed". 'Biology' refers to CA principles (Smith, 2019).

Smith (2019), gave the following explanation: One strategy in CA is to measure nitrogen (N)-content in the soil and to adjust fertilizer applications accordingly, since healthier soils will release more nutrients freely. The same accounts for phosphorus (P), where P fertilizer should in principle be reduced under healthier soil conditions, to allow for soil microbes, especially mycorrhiza to fully function and because organic P levels will rise. *Integrated Soil Fertility Management (ISFM) should be the new strategy!* ISFM is defined as "a set of agricultural practices adapted to local conditions to maximize the efficiency of nutrient and water use and improve agricultural productivity". ISFM strategies center on the combined use of mineral fertilizers and locally available soil amendments (such as lime and phosphate rock) and organic matter (crop residues, compost and green manure) to replenish lost soil nutrients. This improves both soil quality and the efficiency of fertilizers and other agricultural inputs. In addition, ISFM promotes improved germplasm, agroforestry and the use of crop rotation and/or intercropping with legumes (a crop that also improves soil fertility).

From a soil fertility viewpoint, the aim with conservation farming should thus be to bring the soil into an optimum chemical/fertility state and maintain that. This is where the challenges lie. There are continuous disputes about what the optimum status for specific factors should be, e.g. what is the optimum soil pH or the optimum soil P level, or any other factors.

Focus of this paper

The focus of this review paper is to give an integrated interpretative review of existing South African research data on soil fertility and plant nutrition under CA.

Due to permissible length constraints, the fertility findings cannot be related here to other important aspects related to CA. The other aspects are elaborated in the papers by Strauss (2020) and van Antwerpen et al. (2020) in this issue. A comprehensive review of existing data on soil fertility research in South Africa is not included here, because Barnard et al. (2001), van der Merwe et al. (2001), Barnard & du Preez (2004) and Laker (2008) gave comprehensive reviews of it, with van der Waals & Laker (2008) reviewing data on micronutrients.

Extremely little research on soil fertility and plant nutrition under CA has been done in South Africa, as in the rest of the world. Comparative studies between CA and conventional tillage regarding soil fertility and plant nutrition are even rarer. This poses a serious constraint on a review paper like the present one.

CONCEPT OF CONSERVATION AGRICULTURE

There seems to be wide acceptance of the FAO's definition of CA (FAO, 2018), namely:

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

The FAO lists the three principles of CA as follows:

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

According to Pittelkow et al. (2015), and others, these three CA principles should all be adopted for this system to be successfully implemented and not just some of them. The above is the concept and definition of CA against which further discussions in this paper will be done. Each of the three principles has specific roles and effects on soil fertility and plant nutrition. Details about their impacts will be discussed, but their most important general effects are:

1. No-till: In terms of soil fertility and plant nutrition no-till has two important effects, namely

a. Severe subsurface soil compaction, with South African research data having been reviewed by Swanepoel et al. (2017) and Laker & Nortjé (2020). This is because subsurface soil compaction in croplands is caused by wheel traffic (so-called traffic pans) and not by cultivation (plough pans) and even under no-till there is movement of heavy vehicles in the field such as tractors, harvesters, etc. (Laker & Nortjé, 2020). Formation of traffic pans is particularly severe in sandy soils and needs to be alleviated by means of tined implements. South African studies have shown serious depression of the uptake of several plant nutrients, including both macro- and micro-nutrients, due to soil compaction (Laker & Nortjé, 2020). In a study on a sandy soil in a relatively low rainfall, area in Germany, Huynh et al. (2019) found that during the first three years no-till gave similar yields to ploughing, but significantly lower yields than ploughed fields during the subsequent six years of the experiment. They refer to soil compaction as a possible cause of this.

b. Strong stratification of plant nutrients very close to the soil surface. Van der Merwe et al. (2001) reviewed South African data from high rainfall, areas in KwaZulu-Natal province, with more recent data from the semi-arid North West province reported by Nel (2016a) and Haarhoff (2020). The former found nutrient concentration build-up in the 0-5 cm soil layer. However, Nel (2020) was not unduly concerned about this because (translated from Afrikaans): *"The rooting density in the 0-5 cm horizon is usually good, probably due to the covering of the soil by plant remains and the lack of disturbance by cultivator actions. The nutrients that accumulate there are probably utilized well"*. Unfortunately, Nel (2020) could not provide root density measurement data to substantiate this. Haarhoff (2020) quotes international publications that also refer to high rooting density close to the soil surface. In a field trial on a sandy soil in the semi-arid Northwest province, this was not supported by the actual maize rooting density measurements of Haarhoff (2020), who found very low rooting densities in the 0-15 cm soil layer, with significant higher densities in deeper layers.

2. Mulching has large positive impacts in terms of alleviating soil crusting (surface sealing), thus improving water infiltration and reducing erosion on strongly crusting soils. This has also been proven in a number of South African studies, reviewed by Laker & Nortjé (2019). The question is to what extent mulching contributes to soil fertility. Since it is on top of the soil surface, the organic material will have to be incorporated into the soil, by soil organisms, where nutrients can then be released from it by means of the process of mineralisation. According to Huynh et al. (2019), compaction was found to be the primary problem causing no-till to give inferior results to conventional tillage while in Sweden and Norway lack of incorporation of the organic matter was the main problem.
3. In the case of crop rotations selection of crops, especially cover crops, that will render plant nutrients to be more available to the main cash crops, and thus reduce the amount of inorganic fertilizer needed, is a key element. Legumes are particularly important in this regard (Huynh et al., 2019).

SOIL FERTILITY MANAGEMENT, IMPACTS AND CHALLENGES UNDER CONSERVATION AGRICULTURE

SOM (Soil Organic Matter)/SOC (Soil Organic Carbon)

Soil organic matter, is often simply referred to as organic matter (OM) and soil organic carbon referred to as organic carbon (OC). SOM contains approximately 60% carbon

(Brady, 1984). Thus, the approximate conversion factors are SOM = SOC x 1.7 and SOC = SOM x 0.6.

SOM contents in South African soils are inherently low to extremely low, as shown by, for example, the findings of du Toit et al. (1994). The latter is due to unfavourable conditions for maintaining relatively high SOM contents, like sandy soils over large parts of the crop production areas and unfavourable climatic conditions, like high temperatures and low and erratic rainfall. Brady (1984) discussed the negative impacts of sandy soil, high temperatures low rainfall on SOM contents. Birch (1958) found that organic matter decomposition is more intense and that SOM stabilizes at a lower level under alternate wetting and drying than under continuous favourable soil water conditions. Thus, the erratic rainfall over much of the summer rainfall areas, combined with the high prevailing temperatures and dominance of sandy soils are conducive to extreme organic matter decomposition.

Serious reduction in soil organic matter (SOM) levels is probably seen as the most important soil fertility degradation under the continuous intensive cultivation that prevailed in monoculture cereal production in South Africa (Barnard et al., 2001; van der Merwe et al., 2001; Barnard & du Preez, 2004). Du Toit et al. (1994) collected paired samples of soils (at 0-200 mm depth) in cultivated fields and adjacent virgin areas at 50 sites in South Africa's summer rainfall areas. They found that the organic carbon contents (OC) of the virgin soils ranged between 0.33-3.63 percent, with an average of 1.19%. In the cultivated soils, the OC contents ranged between 0.15-2.08 percent, with an average of 0.64%. Thus, the average reduction in OC content due to cultivation was an absolute value of 0.55% or a relative value of 46%. According to du

Toit & du Preez (1994), the steadily declining SOM content of South Africa's soils is signalling unsustainability. CA is seen as, an approach to turn this trend around. It is; however, clear that it would be unrealistic to aim in South Africa for SOM levels similar to those in Europe and North America.

Several South African studies confirmed the positive effects of various CA management systems on SOM contents and soil fertility (Graham et al., 2002). Increases in SOC resulted from the following CA systems:

1. Reduced or no-tillage (Kotze & du Preez, 2008; Cheesman et al., 2016; Beukes & Swanepoel, 2017; Sosibo et al., 2017). No-till had a greater effect on increased SOC than other CA treatments (Kotze & du Preez, 2008).
2. Soil cover or mulch (Muzangwa et al., 2013) and diversified cropping (du Preez et al., 2011; Njaimwe et al., 2016).

Beukes et al. (2011) found a 164% increase in SOC under CA practices, compared with that under traditional small-farmer practices in a high rainfall area, in the Eastern Cape Province. In contrast, some studies reported only small increases in SOC under CA (Swanepoel et al., 2017). In a sandy soil, in the semi-arid North West province, Nel (2016a) found that no-till concentrated OC mainly in the top 0-5 cm soil layer, with a level close to the average of du Toit et al. (1994) for virgin soils. However, in the 5-15 cm layer it was only in the order of the average of du Toit et al. (1994) for cultivated soils. Haarhoff (2020), found in a field trial in a maize field on a sandy soil the semi-arid North West province that the OC level of the soil at the start of the trial in the seventh season under no-till was only 0.58% and remained the same in the next season.

Nitrogen (N)

Soil nitrogen (N) content, is positively linked to CA due to its link with SOM (Beukes, 1992; Loke et al., 2012; Swanepoel et al., 2014). While tillage practices were not reported to result in significant changes in soil N (Maali, 2003), cropping systems, especially those that included legumes, were strongly linked to positive N contributions (Maali & Agenbag, 2004; Beukes et al., 2011; Muzangwa et al., 2012; Muzangwa et al., 2013; Swanepoel et al., 2014).

Thibaud (2000; 2014) concluded that N availability in soil in the initial stages of no-till appears to be lower than for conventional tillage due to less rapid mineralization of soil organic matter and slower breakdown of surface residues because the soil tends to be wetter and colder due to the insulating effect of surface. Hence there is also potential for greater N loss in no-till through denitrification, leaching, immobilization and ammonia volatilization. As a result, higher rates of N fertilizer (30-70 kg N ha^{-1}) than those used for conventional tillage may be required for no-till, especially in the early stages after introduction of no-till such as less than 10 years. Trials by Thibaud (2014) with maize in the wet, cool KwaZulu-Natal midlands found that yields under no-till is only equal to conventional till at an N application of 180 kg.ha^{-1} (Figure 1). It was concluded that at relative low N applications, the yield under conventional till is much higher than under no-till, and it reached an optimum at much lower N applications than no-till. In a review of hundreds of fertilizer, trials in many countries Lundy et al. (2015) found that at low N fertilizer applications no-till give lower yields than conventional tillage. To avoid yield reductions of maize under no-till N applications had to be higher than 100 kg.ha^{-1}.

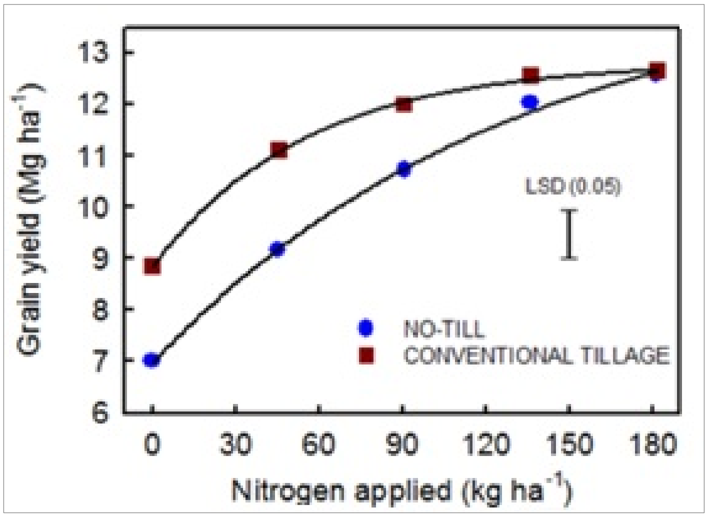

Figure 1: Tillage effects on maize grain response to Nitrogen (averaged over 11 seasons from 2003/04 to 2013/14 on a Hutton soil form near Winterton, KwaZulu-Natal (Thibaud, 2014)

Three aspects are important from the above results: First, the higher N applications required under no-till can be expected to increase soil acidity. This is probably why Thibaud (2000) put much emphasis on soil acidity management under no-till. Secondly, economics are important. Thirdly, it could be expected that the situation under the hot, dry conditions in the western maize growing areas would be much different from the area where Thibaud (2000; 2014) did his research. Unfortunately, no comparative data between no-till and conventional tillage are available for the former area, but Haarhoff (2020) obtained a yield as high 8.6 t.ha^{-1}, but an average yield of 5.4 t.ha^{-1}, with a standard N application of 99 kg.ha^{-1}. The latter closely concur with the finding of Lundy et al. (2015).

Phosphorus

In a study with high biomass yielding winter cover crops, namely grazing vetch (Vicia dasycarpa L.) and oats (Avena sativa L.), in low fertilizer input maize-based CA systems Dube et al. (2014) found that winter cover crops could improve phosphorus availability in soil. The maize–winter cover rotations increased total P and some labile P pools in the surface soil when compared with the maize–fallow rotation. This effect positively correlated to cover crop biomass. The contribution from the winter cover crops to P availability in the surface soil suggests that, in the long term, fertilizer P could be reduced in low fertilizer input CA systems (Dube et al., 2014).

Dube et al. (2014) and Loke et al. (2013) found increased build-up of P in surface soil layers, as well as improved P uptake by young maize plants under no-till. Du Preez et al. (2001), Kotzé & du Preez (2008) and Loke et al. (2013) determined soil P concentrations under no-till and stubble mulch and conventional tillage after 11, 20 and 32 years in an experiment with wheat in the eastern Free State. Soil P concentrations differed over time, but the values for no-till and stubble mulching were at all times at at all soil depths equal to each other and higher than for conventional tillage. Wheat yields were, however, lower under no-till and stubble mulching than under conventional tillage. The authors of the series of papers suggested that the lower levels of P, and other nutrients in the soil under conventional tillage (mouldboard ploughing) than under no-till or stubble mulching might partly have been due to removal of more nutrients by the higher yields, which were obtained under conventional tillage than under the CA systems. Different South African studies have shown that P is one of the plant nutrients of which uptake by plants is seriously depressed by soil compaction (Laker & Nortjé, 2020). Since soil compaction is a major problem under no-till, and since soils in the Free State are generally highly susceptible to soil compaction, this could have been a contributing factor. Loke et al. (2013) thus, recommend that studies involving scientists from different disciplines, to identify the reasons for the lower yields under CA, be conducted to ensure that all potential factors are investigated.

In studies on two sandy yellow-brown apedal soils in marginal rainfall areas of the North West province, Nel (2016a) and Haarhoff (2020) found strong stratification of Bray-1 extractable P near the soil surface under no-till. In the Nel study, it increased slightly from 50 to 52 mg.kg^{-1} in the 0-5 cm layer during the 3 years of the study, while it decreased from 38 to 31 mg.kg^{-1} in the 5-15 cm and from 13 to 6 mg.kg^{-1} in the 15-30 cm layer. Nel (2016b) refers to such effect as "mining" of a nutrient from the 5 to 30 mm soil depth under no-till. It should be kept in mind that band placement of P fertilizer is done in the 5-15 cm layer. In his study during the 7th and 8th year under no-till Haarhoff (2020) found Bray-1 P concentrations of 64 mg.kg^{-1} in the 0-15 cm layer, 36 mg.kg^{-1} in the 15-30 cm layer and 4 mg.kg^{-1} in the 30-60 cm layer. The value in the 15-30 cm layer probably stems from before the change to no-till was made, and it formed part of the plough layer. Bray-1 P levels of 50 mg.kg^{-1} and higher have been found to be "harmful", i.e. reducing yields, and values from 20 to 49 mg.kg^{-1} excessive (reviewed by Laker, 2008). Bray-1 P levels of the soils in the virgin state are less than 5 mg.kg^{-1} throughout the soil profile, even in the topsoil. P is immobile in the red and yellow-brown sandy soils of the area, as proven in several different types of studies, such as, for example reported by Laker (1964; 1967a; b), Eloff (1971) and Eloff & Laker (1976). A sharp drop in P content between plough depth and the soil below it, such as between the soil above and below 30 cm depth in the study of Haarhoff (2020) is thus common in fertilised fields on these soils.

In the higher rainfall, area of KwaZulu-Natal Thibaud (2000) found that applied P accumulates near the soil surface under no-till. Although surface root activity is promoted by no-till, P may become unavailable for plant uptake during hot dry spells and furthermore higher P levels are sometimes required to counteract the negative effects of surface compaction and lower temperatures on P uptake (Thibaud, 2000).

A special aspect concerning P is the ability of certain legumes to mobilise unavailable forms of soil P and thus make them available for uptake by other plants. This has been known in South Africa at least since the 1950s for lupins (Louw, 1960) and groundnuts Sellschop (1962). There is presently great international awareness of this aspect and there is a lot of research ongoing, especially on these two crops (Imai et al., 2019; Gaind, 2017). In a recent study on growing of various crops in rotation with wheat, it was found that wheat that followed lupins in a rotation gave higher yields than after any other crop (Strauss, 2020). In a field experiment at the University of Pretoria, maize (*Zea mays* L.) was rotated with field pea (*Pisum arvense* Poir.). This experiment, which ran over a 50-year period, has concluded, *"the legume crop apparently played a major role in the more efficient utilisation of nitrogen* ***and phosphorus,*** *by crops in treatments where these elements were not applied"* (Nel et al., 1996). Since P is, a very expensive fertilizer inclusion of such P mobilising crop in a rotation could bring about a great saving on fertilizer costs and reduce chemical fertilizer input.

Potassium

It was found that the impacts of CA practices like no-till and stubble mulching, compared with conventional tillage, on soil K are generally similar to those found for P and for the same reasons (du Preez et al., 2001; Kotzé & du Preez, 2008; Loke et al., 2013; Thibaud, 2000; 2014). Relevant discussions under P will thus, not be repeated here.

In the experiment in the Free State province, the differences between the treatments concerning the exchangeable K contents of the soils were very pronounced (du Preez et al., 2001; Kotzé & du Preez, 2008; Loke et al., 2013). After the experiment had been running for 11 years, the K content of the 0-5 cm soil layer was, for example, under no-till 26% higher than in the reference soil, while under conventional tillage it was 48% lower than in the reference soil (du Preez et al., 2001). The K content under no-till was 2.4 times as high as under conventional tillage. A similar result was found for the 5-15 cm layer (Kotzé & du Preez, 2008). Deeper than 15 cm the soil K levels under CA became lower than under conventional tillage, with the difference increasing with increasing soil depth. The general pattern is that the soil K contents under CA decreased with increasing soil depth to a depth of 45 cm, the depth to which it was determined. Under conventional tillage, it remained constant with increasing soil depth. The above type of effect was strikingly illustrated in the comparative study of till versus no-till for sunflower by Nel (2016a). The respective average K values under till and no-till were 224 and 315 $mg.kg^{-1}$ for the 0-5 cm soil layer, 128 and 86 $mg.kg^{-1}$ for the 5-15 cm layer and 60 and 46 $mg.kg^{-1}$ for the 15-30 cm layer. This was described by Nel (2016b) as proof of K "mining" from the 5-30 cm soil layer under no-till and accumulating it in the 0-5 cm layer. The results of Kotzé & du Preez (2008) clearly also indicate K mining from deeper soil layers and transferring it to shallower layers.

An important observation from the studies by du Preez et al. (2001) and Kotzé & du Preez (2008) is that although the difference between the K soils levels under CA compared with conventional tillage was highest in the 0-5 cm soil layer, it was substantially higher to a depth of 15 cm. In his no-till study, Haarhoff (2020) found 230 $mg.kg^{-1}$ K in the 0-15 cm soil layer, 206 $mg.kg^{-1}$ in the 15-30 cm layer and 96 mg.kg-1 in the 30-60 cm layer. The results from these studies appear opposite to the belief that K is very strongly retained at very shallow depth, even as shallow as 2-3 cm (van der Merwe et al., 2001), with the resultant problems outlined by Thibaud (2000). It clearly depends upon the type of the soil and environmental conditions.

Nel (2016a; b) found a 55% higher K uptake from the tilled than from the no-till plots by sunflower. In years with adequate rain, the tilled plots out yielded no-till by 17% (statistically highly significant) and 9%, respectively. Nel (2016b) pointed out that grain crops in that area seldom show yield responses to K applications because the soils contain adequate K for such crops. In the review of Laker (2008), it was shown that grain crops in South Africa have seldom been found to respond to K applications, except in some highly weathered soils in high rainfall areas. The poorer performance of the crop under no-till, implies that this factor will have to be monitored carefully when CA is applied. Several South African studies have found that K is one of the plant nutrients of which uptake by plants is suppressed by soil compaction (Laker & Nortjé, 2020). Due to the problem of soil compaction under no-till, this will also have to be studied closely.

Calcium, magnesium

Du Preez et al. (2001), Kotzé & du Preez (2008) and Loke et al. (2014) studied soil Ca and Mg trends under no-till, stubble mulching and conventional tillage, in the long-term experiment with wheat, near Bethlehem in the Free State. Contrary to expectations, no evidence of accumulation of these elements in the shallower soil layers under no-till was found. This was also the case in the no-till study of Nel (2016a). In the first year of Haarhoff's (2020) experiment both Ca and Mg were substantially higher in the 0-15 cm soil layer than in deeper layers. This could have been due to liming, because the soil pH was much higher in the 0-15 cm layer than in the layers below it.

Micronutrients

Studies on micronutrients under CA in South Africa are almost non-existent. Loke et al. (2013) determined the comparative distribution of extractable copper, manganese and zinc in soil under no-till, stubble mulching and conventional tillage in the long-term experiment near Bethlehem in the north-eastern Free State, after the trial had been running for 32 years. Type of tillage had very little effect on Mn concentrations. In the 0-5 and 5-10 cm soil layers, the extractable Cu content under no-till was significantly lower than under conventional tillage, with the value for stubble mulching in-between (Loke et al., 2013). Loke et al. (2013) attributed the lower extractable Cu levels under no-till and stubble mulching than under conventional tillage soil depths to strong binding of Cu by the higher organic matter levels in these layers. However, inspection of the data point to a strong movement of Cu from the 0-10 cm soil layers into the 10-35 cm layers under the two CA practices and not to binding of the Cu in the upper layers into non-extractable forms.

The extractable soil Zn contents were identical for the two CA treatments at 0-5, 5-10 and 10-15 cm soils depths and identical for the different soil depths and at all three depths significantly higher than for conventional tillage (Loke et al., 2013). Below 15 cm soil depth there was a linear decrease in the soil Zn contents with increasing soil depth and at each depth there was no difference between the three treatments. Barnard et al. (1990) found that fulvic acids are very efficient chelators of Zn to keep the Zn in a plant-available form, much more efficient than, for example, EDTA. Fulvic acids formed during decomposition of the higher SOM levels under the CA treatments could thus possibly explain the higher extractable Zn contents under the CA treatments in the upper three soil layers. This could be important in soils that have induced Zn deficiencies.

Soil pH

Soil pH is important in CA because it directly affects soil fertility. It is therefore essential, in crops under CA to create a soil pH that ensures long-term crop and orchard performance.

There is normally great concern about acidification of the upper soil layers under CA due to mineralization of the higher SOM levels, as well as by conversions of the nitrogen that is released during mineralisation of the organic matter (van der Merwe et al., 2001; Thibaud, 2000; 2014). Without intervention with liming, soil acidification is inevitable under such conditions. In reduced tillage systems and especially under no-till, there is little or no scope for incorporating lime, and it is critical that soil acidity problems be corrected before starting no-till. Prevention of acid build-up in surface layers, with subsequent encroachment of acidity to deeper soil horizons through regular surface liming, is furthermore essential if the system is to remain sustainable, i.e. it does not allow acidity to escape (van der Merwe et al., 2001; Thibaud, 2000; 2014).

Higher levels of SOM under CA, were linked to increased soil acidification in the studies of Graham et al. (2002) and Sosibo et al. (2017). The much higher N application rates required under no-till compared to conventional tillage, as found by Thibaud (2014) and others will also be a major source of increased soil acidification under no-till.

In the experiment with wheat near Bethlehem in the north-eastern Free State, burning versus non-burning was included (du Preez et al., 2001; Kotzé & du Preez, 2008; Loke et al., 2013). The soil pH results for the unburned plots are those to consider here. After the experiment had run for 11 years the pH (H_2O) of the 0-5 cm layer in the unburned plots decreased from the reference value of 6.0 to 5.7 under no-till, 5.5 under stubble mulch and 5.6 under conventional tillage (du Preez et al., 2001). In the 5-15 cm layer, the decreases were from the original 6.0 to 5.9, 5.8 and 5.8 respectively. In the 15-25 cm layer the pH under conventional tillage remained the same as the original value at that depth (5.9), but under no-till and stubble mulching it had dropped to 5.8 and 5.6 respectively. No measurements were made at deeper layers.

The above confirms that significant soil acidification occurred under cultivation and that the acidification was less under no-till than under stubble mulching and conventional tillage, which was a possible feature for no-till. This was opposite to the concerns that are sometimes expressed about more serious acidification under no-till. It must be kept in mind, however, that there was still acidification. It is important to note that the acidification under all three tillage treatments were down to a depth of 35 cm and not only in the top few cm, as is often stated.

There is concern regarding amelioration of subsurface soil acidity under no-till, because lime is immobile and under this system, lime is not incorporated into the soil (van der Merwe et al., 2001; Thibaud, 2000; 2014). The validity of this concern is clear from the analytical results for the soil in the no-till trial of Haarhoff (2020). In both years, the pH (KCl) of the 0-15 cm soil layer was 6.1, in contrast to 5.2 and 5.1 in the 15-30 and 30-60 cm soil layers respectively. Although Haarhoff (2020) does not indicate it, it is clear that lime had been applied on this soil at some stage prior to the experiment. This is further indicated by the fact that the exchangeable Ca content in the 0-15 cm layer was 638 mg.kg^{-1}, in contrast to 446 mg.kg^{-1} in the 15-30 cm and 440 mg.kg^{-1} in the 30-60 cm layer. The fact that there was still no increase in the pH value of even the 15-30 cm layer in the second year, and that this was a sandy soil, is important to note.

CONCLUSIONS AND RECOMMENDATIONS

There appears to be an alarming scarcity of research on soil fertility and plant nutrition under CA in various parts of South Africa, apart from looking at SOM and N. The situation is even worse concerning micronutrients than in the case of macronutrients. Comparative studies on soil fertility under different components of CA and conventional tillage are rare.

It is recommended that a major programme on comparative research under different types of CA and conventional tillage be conducted in all the major regions with different climates and dominant soils.

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