Review of Existing Knowledge on Subsurface Soil Compaction in South Africa

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Abstract

This paper reviews the existing knowledge on subsurface compaction in South Africa. Subsurface soil compaction is an extremely widespread and serious problem throughout all nine provinces of South Africa and neighbouring countries like Botswana, Namibia, Swaziland and Zimbabwe. It is indeed a widespread serious problem throughout the whole of Africa. Subsurface compaction has very serious implications regarding crop yields and quality, disease incidence and water use efficiency. Various research methodologies are used to study subsurface soil compaction. Soil factors determining the susceptibility of a soil to subsurface soil compaction include particle size distribution, soil organic matter content and clay mineralogy. Negative impacts of subsurface soil compaction include, increased soil strength and resultant negative impacts on root development and top growth, impacts on plant nutrient uptake, water use efficiency, reduction of hydraulic conductivity and inhibition of soil aeration. Management factors that cause or aggravate soil compaction are uncontrolled vehicular traffic, large numbers of shallow secondary tillage operations, cultivating or traversing wet soil, and high tyre pressures. Sub-surface soil compaction can be alleviated by ripping, the application of controlled traffic, refraining from conducting operations on wet soil, and the use of the lowest possible tyre pressures.

Keywords: Subsurface compaction, clay mineralogy, soil organic matter, penetrometer, soil strength.

ABBREVIATIONS

Ca calcium

CTF controlled traffic farming

ET evapotranspiration

Fe iron

K potassium

kPa kilo Pascal

Mg magnesium

Mn manganese

Na sodium

NAMPO National Maize Producers' Organization

ORD off-road driving

PIA photographic image analysis

PR penetrometer resistance

PWM profile wall method

RFP root fraction percentage

RSA root sorption area

SOM soil organic matter

1 INTRODUCTION

1.1 General

Subsurface soil compaction is an extremely widespread and serious problem throughout most of South Africa. Soil compaction has very serious implications regarding crop yields and quality, disease incidence and water use efficiency.

Intensive research on soil compaction has been conducted in South Africa, mainly during the period from the 1960s to the 1980s. The two main centres for this research were the University of the Orange Free State (now the University of the Free State) and the South African Sugar Research Institute. Other institutions also made significant contributions, however.

The senior author was fortunate to be involved with some of the initial observations and investigations on soil compaction in the Free State and Northern Cape provinces and conducted the first comprehensive field survey on it in the irrigated areas of the Lower Orange River (Upington) area. He was also closely involved with the first basic research on it in the country, namely as supervisor of the MSc Agric study of Bennie (1972).

1.2 Other review publications on soil compaction in South Africa

There are two useful earlier reviews of soil compaction in South Africa. These are:

- the paper by Bennie and Krynauw (1985);
- the CD-ROM compiled by the South African Sugar Technologist's Association of the papers presented at the SASTA workshop on soil compaction held in Durban on August 1, 2001 (SASTA, 2001). It contains several review papers on soil compaction, including both the text and the PowerPoint presentation of each. It also contains the records of a "panel discussion" on soil compaction. This was not an ordinary panel discussion in the sense that it contains mainly the responses of selected experts on soil compaction to questions about specific issues put to them by e-mail well in advance of the workshop and to which they responded before the workshop. At the workshop, these points were elaborated further. The CD-ROM also contains useful older papers on soil compaction which otherwise might have been forgotten or lost.

1.3 Extent, degree and spatial distribution of soil compaction in South Africa

Soil compaction is a widespread and serious problem in South Africa. Many South African soils have dense subsoils in their natural state. Some of these become very hard when they are dry and are called "hard-setting" soils. Virgin subsoils with natural bulk densities in the order of 1,650 kg.m^{-3} are not uncommon. This is becoming an increasingly more important consideration with the introduction of minimum and zero tillage (Mitchell and Berry, 2001).

Soil compaction is a particularly widespread and serious problem under intensive mechanised crop production – both rainfed and irrigated. During soil sampling in maize fields throughout the north-western Free State during the early 1960s young soil scientists of the Highveld region, including the senior author, found that there was almost no maize field in which they could sample to more than about half a spade blade depth, i.e. to more than 15-20 cm depth. At that depth, very, hard compacted layers were found in especially sandy soils dominated by fine sand, the most abundant soils in the area. Subsequent tillage research in South Africa has shown that soils with less than 15% clay in the plough layer are very vulnerable to compaction (Mitchell and Berry, 2001). According to Mallett et al. (1985), the soils of almost half of the somewhat more than four million ha under rain fed maize in South Africa falls into this texture class. According to Bennie and Burger (1979) there are more than 1.5 million ha of such soils in the "maize quadrangle" on the Highveld, with 584,000 ha in the western Free State province, 391,000 ha in the eastern Free State province, 320,000 ha in Northwest province and 261,000 ha in Mpumalanga province. Large areas north of the Orange River in the Northern Cape Province and the western and northern parts of Limpopo province are also covered by such sandy soils (Mallett et al., 1985).

During the mid to late 1960s, the senior author and others found widespread severe subsurface soil compaction at Vaalharts, South Africa's biggest irrigation scheme. The soils there have very high fine sand contents and predominantly less than 10% clay. According to Bennie and Burger (1979), such soils represent more than 95% of the irrigated area at Vaalharts. Dr. Dries van der Merwe pioneered soil compaction studies there and he and the senior author together and individually conducted several investigations into it, as documented by Burger et al. (1979).

Even earlier than this, Prof. Chris Theron in 1955 reported that extremely poor root systems and compacted layers ("plough pans") were the most striking features in sultana (Thompson seedless) vineyards in the Lower Orange River region – the area between the Boegoeberg dam and the Augrabies Falls. Prof. G.D.B. de Villiers confirmed these observations in 1962. Prof.

Theron was a Viticulturist and Prof. De Villiers an Agro-meteorologist. In 1967, the senior author was the first Soil Scientist to conduct a systematic survey of soil compaction in vineyards in the region – from Groblershoop in the east to the Augrabies Falls in the west. He found widespread occurrence of severely compacted layers in the vineyards, often as close as 20 cm to the soil surface. The main findings of the survey were later reported by Laker (1981, 1986). At the same time, Dr. Dries van der Merwe studied the widespread soil compaction in cotton fields in this region. Burger et al. (1979) have also documented the history of the studies by Theron, De Villiers, Van der Merwe and Laker in the Lower Orange River region.

Cleasby (1964) reviewed soil compaction in the South African sugar cane production areas, which are concentrated in KwaZulu-Natal province, with some areas in the eastern Lowveld of Mpumalanga province. The next review thereafter, on soil compaction in that industry was only in 2000 by Van Antwerpen et al. (2000). Both reviews concluded that soil compaction is a serious problem in the industry.

According to Mitchell and Berry (2001), the clay loam soils found towards the interior of KwaZulu-Natal province are the least compactible soils in the province, with the sandier soils towards the coast being more prone to compaction. In about 2002, the senior author studied a few cultivated sites in the Greytown area in the interior of KwaZulu-Natal province and found severe soil compaction at all of them.

Soil compaction is a widespread serious problem in what is presently the Western Cape Province. Van Huyssteen and Van Zyl (1981) stated that "*(...) it is a known fact that most of the vineyard soils in the Western Cape are prone to compaction (...)*". Considering the nature of most cultivated soils in the Western Cape, this will also be the trend for other types of crop production in the province. Moolman and Weber (1978) mentioned the high degree of compaction in fine sandy irrigated soils in the Southern Cape. Agenbach and Stander (1988) conducted soil compaction studies at the Outeniqua experiment station near George, showing the wide distribution of the problem on various types of soils in the Southern Cape.

In the Eastern Cape, significant areas are covered by soils that can be classified as either "hard setting" soils or soils with "dense subsoils" in the natural state. These have, *inter alia*, been found during several unpublished soil surveys by staff of the Department of Soil Science at the

University of Fort Hare during the 1970s and 1980s, where the senior author was at the time. Such soils are highly prone to compaction under intensive cultivation. Very poor citrus root development on farms in the Sunday's River Valley was ascribed to soil compaction. The compaction was alleviated by means of deep cultivation with a tined plough. (It was not a normal "ripper".) Overall, human-induced soil compaction has not been reported widely in the province, however. The widespread serious soil crusting found in the province has received much wider attention there.

During the early 1960s farmers, extension officers and researchers became acutely aware of the serious soil compaction problems in the north-western Free State and the central parts of Northwest Province, as indicated earlier. Through cooperative efforts between the farmers, extension officers and researchers, effective solutions to the problem were developed. To the east and north of these areas, in what are now the Mpumalanga and Limpopo provinces, soil compaction did not seem to be a problem. The authors are not aware of any major publications or research reports on soil compaction emanating from these areas. During the late 1990s, the senior author was requested to investigate production problems of tobacco near Mbombela (Nelspruit) in the Lowveld area in the east of Mpumalanga province. He found widespread severe soil compaction in the tobacco fields, especially on deep light grey sandy soils derived from granite. These are mainly soil of the Cartref and Fernwood forms according to the South African soil classification system (Soil Classification Working Group, 1991) or soils with sandy albic horizons according to the international World Reference Base classification system (WRB, 1998). Thus, the apparent absence of widespread severe soil compaction in the areas was clearly a false impression.

During the same period, the senior author was part of a team, which investigated problems in citrus orchards in the Kingdom of Swaziland, which borders on the Lowveld of Mpumalanga province, in areas with soils and geology like those in the neighbouring South African side. Again, widespread severe soil compaction was the most general feature, confirming the findings in the corresponding South African areas.

Because of the observations in the tobacco fields around Mbombela, a farmers' day was held there in 2000 to address the problem of soil compaction. The low level of awareness amongst farmers regarding the extent and implications of soil compaction was striking, especially since it was about 40 years after the farmers of the Western Highveld became acutely aware of it. Fortunately, a demonstration of tined implements, which illustrated the severity of the problem of which they were unaware absolutely, shocked the farmers who attended the farmers' day. The senior author was consequently invited to visit a few areas in the west of Limpopo province to investigate soil compaction. In irrigated areas in the Tom Burke area there was widespread soil compaction, but the degree was not extreme. However, in irrigated areas along the Crocodile River northwest from Thabazimbi soil compaction was not only widespread, but of an extremely severe degree. The same was found in irrigated tobacco fields near Brits in the east of Northwest province (Figure 1). The low level of awareness of the problem amongst farmers was almost frightening.

Fig. 1 Tobacco root severely affected by subsurface compaction

The extreme cases of soil compaction in South Africa are found in "rehabilitated" opencast coal mining areas on the Highveld of Mpumalanga province. Bulk densities greater than 1,750 $kg.m^{-3}$ are common in rehabilitated land (Nell and Steenekamp, 1998). At such bulk densities, few or no roots are found (Nell and Steenekamp, 1998). In spoil material a mean bulk density of 2,070 $kg.m^{-3}$ was found (Schoeman et al., 1997) – a value that is difficult to comprehend. According to Schoeman et al. (1999), high soil bulk density is the chief factor preventing rehabilitated opencast coal mining areas from being suitable to produce agronomic crops. This situation appears to persist for even five to ten years of the rehabilitated land being under pastures before planting of row crops (Schoeman et al., 1999). A further problem is that they found evidence of re-compaction. De Villiers (1992) found that in a high proportion of cover-soil layers compaction either totally prevented root penetration (mainly grass roots) below a certain depth (often close to the surface) or concentrated roots into cracks or faunal burrows where they formed "mats" or "beards". De Villiers (1992) found that red or yellow soils with micro-aggregate structure were most prone to compaction. Schoeman et al. (1999) pointed out that these represented *"some of the most productive agricultural land in South Africa"* before the advent of opencast coal mining in the area.

In South Africa, soil compaction is not only a problem in large-scale commercial crop production. It is also found in small-scale mechanised crop production, especially small-scale irrigation farming. In 2005, the senior author observed very serious soil compaction at the Dzindi small-farmer irrigation scheme in Limpopo province and thereafter at the Tugela Ferry small-farmer irrigation scheme in KwaZulu-Natal.

More recently the junior author studied the serious impact of "off-road driving" (ORD) by game drive vehicles on soil compaction and the environment in game parks (Nortjé, 2014; Nortjé et al., 2012a, 2012b, 2016). This is becoming a great concern in view of the increase in ORD to lure more tourists, especially rich ones from overseas, in pursuit of greater economic returns by the parks.

2 Research methodologies

Various methodologies have been used in soil compaction research in South Africa. The initial stages can probably not be described as actual research, since it consisted of *ad hoc* qualitative field observations while conducting field studies for other purposes. However, someone once made the statement that *"good observation is good research".* This was followed by unstructured and structured (systematic) field investigations in cultivated fields, both irrigated and rain fed, with the specific objective of identifying human-induced soil compaction. These investigations often included observations of possible relationships between soil compaction and abnormalities in crops, like "red death" in cotton or "growth stunting disease" in sultana vines. Investigations about abnormalities regarding rooting patterns and root morphologies were often also included. The latter were often recorded photographically.

Compaction was usually so severe that compacted layers could very easily and without doubt be identified by means of a spade or by pushing a steel rod into the soil. Some persons who tried to use the latter method complained that its results were inconsistent. This was usually due to incorrect application of the method. Such people usually tried to "hit" the rod into the ground instead of placing the tip of the rod on the soil surface and then pushing it in steadily.

The next step was to collect quantitative data on the severity of soil compaction by means of field measurements with very simple little pocket penetrometers. Penetrometer resistance (PR), simulating the mechanical resistance of a soil to the penetration of plant roots, was found to be the most efficient way to express soil compaction, better than bulk density. Some people questioned the accuracy and reliability of pocket penetrometers. Usually these people did not use this piece of apparatus correctly. If the soil is "hit" with the tip of the penetrometer, the results are be unreliable and inconsistent. The tip of the penetrometer must be placed against the soil, followed by steady pushing of the penetrometer into the soil. Bennie (1972) compared a pocket penetrometer with readings obtained with an electronic constant rate penetrometer. He found that field readings with the pocket penetrometer, if used correctly, were accurate and reliable. The pocket penetrometer is, therefore, a handy instrument for routine field determinations of PR, if used correctly.

Basic studies on soil compaction required the use of electronic constant rate penetrometers. No such apparatus was available in South Africa at the time of the first such basic study by Bennie (1972). Bennie thus designed a laboratory scale electronic constant rate penetrometer, in consultation with the main author. This apparatus was built in the science workshop of the University of the Orange Free State. It was later also used in various other soil compaction research projects at the UOFS, e.g. by Du Preez et al. (1979). Several probes with different shapes and sizes were produced that could be fitted alternatively in the apparatus. After comparative testing the best probe for general use was identified. Other probes were sometimes used for special studies (Du Preez et al., 1979). Bennie (1972) and Du Preez et al. (1979) give detailed descriptions of the apparatus, including information on the probes.

Later portable constant rate penetrometers became available for quantitative measurement of soil strength (PR) in the field. The advantage of these over pocket penetrometers is that it is not necessary to dig pits to take measurements, also that measurements are recorded digitally.

A key factor is the effect of soil compaction on the efficiency of roots to absorb water and plant nutrients. Qualitative observations regarding rooting depth and root morphology give useful general information. Information that is more accurate is required for useful interpretations, however. Root mass as such is not a useful parameter (Bennie, 1972). Data regarding the fineness of roots and total length of all the roots in the root system are required (Du Preez et al., 1979). Probably the most critical criterion is the "root sorption area" (RSA), which is a combined function of the fineness of the roots and root length (Bennie, 1972). Du Preez et al. (1979) discuss methodologies for the quantitative determination of root parameters. More recently root density distribution determinations were made in the ORD studies by means of a combination of the "profile wall method" (PWM) and "photographic image analysis" (PIA) (Nortjé, 2014; Nortjé et al., 2016).

Several laboratory studies on relationships between parameters such as soil strength, bulk density and particle size distribution have been conducted in South Africa. In almost all cases, compaction was done by means of a press at different soil water contents. Bennie (1972) and Bennie and Burger (1988) found that for bulk densities up to 1,650 $kg.m^{-3}$ dry compaction by means of a vibrating probe gave best results. Compaction to achieve higher bulk densities required the use of a press on moist soils.

Compaction of soil in pots for greenhouse studies requires special techniques and care. It is not possible to just fill the pot with soil and apply pressure. It must be done layer by layer. In order to avoid abrupt contact lines between layers, the top part of each layer must be loosened before the next layer is added (Bennie, 1972). Because the soil in pots does not dry to field capacity, suction must be applied to pots by means of a suction pump after watering pots (Bennie, 1972). To avoid soil fertility effects due to differential leaching of nutrients, each pot needs to have a suction trap for its drainage water, which is then added to the specific pot again during the next watering.

3 Types of compacted layers in soils

Bennie (1972) identified different types of compacted layers in cultivated soils (Table 1).

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Table 1 Types of compacted layers in cultivated soils (Adapted from Bennie, 1972)

0-2 cm depth*	IIIIIIIIIIIIIIIIIIIIIIIIII	ZONE 1 - Compacted crust
2-15 cm	OOOOOOOOOOOO OOOOOOOOOOOO OOOOOOOOOOOO	ZONE 2 - Relatively loose cultivated layer
15-25 cm	WWWWWWWWWW WWWWWWWWWW WWWWWWWWWW	ZONE 3 - Plough layer compaction
25-45 cm	UUUUUUUUUUUU UUUUUUUUUUUU UUUUUUUUUUUU	ZONE 4 - Sub-plough layer compaction
>45 cm	HHHHHHHHHHHH HHHHHHHHHHHH HHHHHHHHHHHH	ZONE 5 - Naturally compacted subsoil

*The depths at which the different layers occur, vary according to type of soil and type of implement used.

Adapted from Bennie, A.T.P., 1972. 'n Ondersoek na sekere aspekte van grondsterkte in gronde van die Manganoserie. (An Investigation Into Certain Aspects of Soil Strength in Soils of the Mangano Series). MSc Agric dissertation, UOFS.

- Zone 1, a compacted crust, is not always present in soils with subsurface compaction. Conversely, subsurface compaction is not always present in soils with dense crusts.
- Zone 3 is a zone of compaction that forms ***within*** the bottom part of the plough layer due to repeated secondary cultivation with shallow implements, as disc ploughs, after mouldboard ploughing. It is most often a traffic pan, caused by the wheels of tractors and/or heavy implements and/or other vehicular traffic like harvesters, spray carts, etc. Usually this very dense layer severely restricts root development. It can also develop in soil that had been ripped, i.e. cultivated with a tined implement.

- Zone 4 is a layer that can be a plough pan formed during primary cultivation with a mouldboard plough do to pressure or smearing actions of the plough. Under modern mechanised agriculture, these most commonly occur as traffic pans, forming even in minimum tillage and no-till situations.
- Zone 5 is a naturally compacted layer found in soils with strong tendencies to compact. Some subsoils in the Free State and Northern Cape provinces have bulk densities as high as 1 650 $kg.m^{-3}$ in the natural state. This value restricts root development. Minimum tillage or zero tillage are not viable options on such soils, as will be discussed later.

Human-induced subsurface compaction can be classified as traffic pans and plough pans. Traffic pans occur much more widely than plough pans. This is fortunate, because they are easier to overcome with appropriate management. Traffic pans occur mainly in sandy soils. Plough pans are less common and occur in clayey soils, where the tillage implements smear and compact the soil just below the plough depth. Severe compaction can be caused by treading by livestock under intensive farming systems, e.g. by dairy cattle on irrigated pastures (Mitchell and Berry, 2001). The worst compaction is by "pugging", i.e. plastic flow around the hoof, in wet clayey soil.

4 Effects of soil factors on soil compaction

4.1 Particle size distribution (soil texture)

Particle size distribution and related factors such as sorting and the shape and smoothness of particles are dominant soil factors affecting the susceptibility of a soil to compaction.

Mention has already been made of the high susceptibility of soils with high fine sand and low clay contents to compaction and the large areas of various parts of South Africa covered by such soils. This aerial dominance of fine sandy soils in areas that are susceptible to soil compaction is a unique situation. In Europe and North America, the main problem soils regarding soil compaction are the loess and glacial till derived soils, which are characterised by very high silt contents (often 60-80% silt), because of the areal dominance of such soils there.

Bennie and Burger (1988) describe most soils that are susceptible to compaction at the Vaalharts irrigation scheme as "*(...) characterised by a high fine sand fraction, low clay and* *organic matter content, single grain to weakly massive structure and particle size with good sorting*". The senior author remembers that multi-sieve analyses of the sand fractions of soils of the area in the late 1960s/early 1970s showed that they were very well sorted, and rounded and smooth (Unpublished data, Department of Soil Science, University of the Orange Free State). However, Du Preez et al. (1979) describe the soil particles as being moderately rounded and moderately sorted. In their particle size data, fine sand is also dominant, however, often comprising more than 70% of the soil mass.

In contrast to the rounded (spherical) nature of the fine sand fractions of the soils in the central parts of the country (due to their aeolian origin), electron microscopic analysis of the silt and fine sand fractions of a fine sandy soil from the Southern Cape showed that these particles were flat rather than round (Moolman and Weber, 1978). Bulk densities of higher than 1,700 $kg.m^{-3}$, and even as high as 1,930 $kg.m^{-3}$, are found commonly in compacted layers in these fine sandy soils according to Moolman and Weber (1978). Of the 75% that was then classified as fine sand, 65% had a radius of between 0.05 mm and 0.02 mm, i.e. in the present South African textural classification 65% will be classified as coarse silt and only 10% as fine sand. Somehow Moolman and Weber (1978) did not expect such well-sorted soil to be prone to compaction, but *"yet it happens"*. They expected that a well-graded (poorly sorted) soil, with a good mixture of different particle sizes would be a pre-requisite for severe compaction.

Henning et al. (1986) compared relationships between degree of sorting, soil compaction (measured in terms of bulk density) and soil strength (PR) for poorly and moderately sorted sandy soils from the north-western Free State. They found that moderate sorting gave higher PRs than poor sorting at equal bulk densities. Thus, there data confirm that the expectations of Moolman and Weber (1978) were not valid.

In studies on the identification of "hard setting soils", the senior author found that these were apedal (i.e. without moderate to strong macro-structure) soils with the following properties (Laker, 2001):

- More than 50% (fine sand + silt), with usually more than 20% silt ***and***
- Less than 35% clay

- The extreme ones are E horizons, i.e. albic horizons in international terminology.

Of course, if the (fine sand + silt) content of a soil is very high (in the order of about 70% or higher) the soil will be very prone to compaction even if the contribution of silt is low.

A common problem is that researchers usually group silt together with clay when relationships between particle size classes and soil physical parameters are studied. In the case of soil compaction, this is obviously incorrect. Silt, should be grouped together with fine sand.

Although there is no doubt that soils with high fine sand and/or silt contents are extremely prone to soil compaction, the potential occurrence of severe compaction on other soils cannot be ignored. The severe compaction observed by the senior author on bleached granite-derived relatively coarse sandy soils near Mbombela is a reality. No information is available on compaction in such soils because soil compaction research has not been done on them.

A well-known study by Van der Watt (1969) was probably the first basic study on relationships between particle size and soil compactibility in South Africa. He did not conduct his study on natural soils, but on prepared mixtures of particles of different sizes in different ratios. Unfortunately, it was not possible to obtain a copy of this article, and discussion of its findings are, therefore, based on references to it in the papers of Moolman and Weber (1978) and Mitchell and Berry (2001). The figure in which Van der Watt (1969) depicted his results could be obtained from these articles. The figure is somewhat confusing. Unfortunately, he groups clay and silt together, instead of grouping silt together with fine sand. Furthermore, in deriving his correlation equations he used coarse sand (the present medium + coarse sand) as factor to correlate with compaction, instead of looking at fine sand. Close inspection of the diagram shows that the compactibility of soils with less than 15% (clay + silt) and about 70% fine sand is very high. This is very similar to the situation in most of the soils in western Free State and Vaalharts, which are highly susceptible to soil compaction, as, indicated earlier. Thus, there is good agreement between the results found with artificial mixtures and those found with natural soils in the field.

Inspection of the figure of Van der Watt (1969) on the other hand indicates that the compactibility of sandy soils with relatively high coarse sand contents (up to the maximum of 50% that he studied) is also very high. The latter supports the validity of the observations by the senior author on the granite-derived, coarse sandy soils near Mbombela. It seems that moderate to good sorting of the sand fraction of a soil towards either the fine or coarse side is an important factor in determining the susceptibility of a sandy soil to compaction. The strong emphasis on fine sandy soils is due to their vast areal dominance among the sandy soils and because they are generally so much better sorted, especially the Aeolian ones.

In the South African forestry industry, it was also found that soil texture is a major factor determining the sensitivity of a site to compaction by harvesting extraction vehicles (Smith and Johnston, 2001), with the light grey sandy soils (E horizons; albic horizons) most vulnerable.

4.2 Soil Organic Matter (SOM) content

Since organic matter is in most soils the only structure stabilizing material, one would expect that any practice that will give an increase in "soil organic matter" (SOM), would reduce soil compaction. The senior author recalls that already in the 1950s or early 1960s there was a publication on research done by E. L. Greacen in Australia which showed that a permanent grass ley (cover crop) in orchards (or vineyards) will minimize soil compaction by the wheels of tractors, spray carts or loaded trailers moving between the rows. Compaction was severe in clean cultivated inter-rows, where the organic matter content was low.

Very little South African data are available on relationships between SOM content and soil compaction. Where data are available, particularly for annual crops, the results almost invariably seem to be opposite to what is expected. In their experiments with wheat in the Southern Cape, Agenbach and Stander (1988) found that minimum tillage and zero tillage ("direct-drilling with a no-till drill") gave significantly higher soil organic carbon and nitrogen contents than conventional mould board plough tillage or tillage with a tined implement. Minimum tillage and zero tillage also gave higher soil water contents at seeding. However, over the study period conventional tillage gave 62% higher yield than zero tillage. It also gave much higher yields than minimum tillage. This was because soil compaction, as indicated by PR, was much higher in the zero till plots than in the conventionally tilled plots down to a depth of 250 mm, and especially in the top 150 mm. Agenbach and Stander (1988) found that the low yields under zero tillage, was due to low plant densities as a result of poor emergence, because the seed drill could not penetrate the compact soil properly. Thus, this negative relationship between organic matter content and compaction may be artificial due to organic matter of the topsoil under no-till or minimum tillage being higher than under conventional tillage, but subsoil compaction also being higher due to wheel traffic and no alleviation of it.

Mitchell and Berry (2001) point out that differences between conventional tillage and zero tillage depend strongly on the inherent susceptibility of a soil to compaction and the inherent degree of compaction of a soil in the natural state. In soils that are highly susceptible to compaction no-till is not a viable option, as was mentioned earlier also. Under soils that are not highly susceptible to compaction it becomes a good option. Mitchell and Berry (2001) point out those fine sandy soils with less than 8% clay need to be cultivated every season. The number of seasons under no-till, before tillage is required, increases with increased clay content. At clay contents above, 25% it increases dramatically, especially under dryland cropping. They quote research, which showed that a sandy Avalon soil (Soil Classification Working Group, 1991) showed signs of compaction in the second season of no-till, and this led to reduced crop growth and yield. On the other hand, a Doveton series (Hutton form) soil with 35% clay still gave "excellent" maize yields of 6.9 $t.ha^{-1}$ after 28 consecutive seasons of no-till. This will be elaborated further later in the paper.

According to Mitchell and Berry (2001), it may take up to 50 years of no-till production of pasture grasses to return a previously tilled soil to the organic matter levels that it had when the soil was in its virgin state under natural veld. They point out that the choice of crop for increasing SOM level is important. Leguminous crops decompose more readily than grasses and contribute little to SOM levels.

An interesting point is that Botha et al. (1981) found that aggregate formation by application of PVA, an organic soil conditioner, to apedal sandy soils had highly beneficial effects concerning alleviation of soil crusting, but did not alleviate subsurface compaction problems. In fact, it aggravated the situation in some cases.

4.3 Clay mineralogy

No references on relationships between soil compaction and clay mineralogy were found from elsewhere. Several South African studies have shown the strong effects of clay mineralogy on soil dispersion and soil crusting. One would thus logically expect a strong relationship between clay mineralogy and soil compaction also.

Moolman and Weber (1978) made a very significant finding: Clay mineralogical analyses showed that the (silt + clay) fraction of the strongly compacting soil, which they studied, consisted mainly of quartz particles, with minor quantities of micas. Bühmann et al. (1996) found that clay-sized quartz and feldspars are the most active in disaggregation and that these occur widely in South African soils. It was found that this fraction is dispersed easily by sodium, but is not flocculated by calcium. This is considered an important factor contributing to the severe crusting and erosion of such soils, in some cases even at ESPs of only about 2%. It was found that the clay fractions of soils in the Eastern Cape Province derived from Beaufort mudstones and shales contain significant amounts of clay-sized quartz and this may be an important factor in their extreme dispersibility and erodibility (Laker, 2004). One can thus postulate that the dominance of quartz in the (silt + clay) fraction of the soil studied by Moolman and Weber (1978) would also have been an important factor in causing its high susceptibility to compaction.

5 Management factors that cause or aggravate soil compaction

Soil compaction first became a widespread severe problem in South Africa with the introduction of intensive mechanized plant production systems in the 1950s-1960s. In view of this, it seems anomalous that compaction is often a bigger problem under minimum and zero tillage systems than under sensibly implemented conventional cultivation on soils that are highly susceptible to compaction. It should be kept in mind, however, that with little exception, subsurface soil compaction is in the form of traffic pans, not plough pans. Even under minimum and zero tillage there are a number of passes with tractors, implements, heavy harvesters, etc. over the field each season. In annual cropping the passes under zero tillage, include at least planting, chemical weed control, pest control, nitrogen top dressing and harvesting. The cases of anomalous findings occur where ripping and controlled traffic is practised under conventional tillage, but not under minimum or zero tillage, as will become clear later.

A large amount of excellent research has been done in South Africa concerning identifying and understanding the effects of crop management systems that cause or aggravate soil compaction. Reference will be made to several publications during further elaboration in this section. Other comprehensive discussions on it can be found, *inter alia*, in the CD-ROM of SASTA (2001) and the group of Water Research Commission project reports by Burger et al. (1979), Bennie and Burger (1979) and Du Preez et al. (1979).

5.1 Effects of uncontrolled vehicular traffic

Vehicular traffic is the primary source of the mechanically applied forces to soils, which lead to soil compaction (Bennie and Krynauw, 1985). The senior author first observed the magnitude of the definite impact of this at the Lower Orange River Irrigation scheme in the late 1960s. A young farmer had very serious *"growth stunting disease"*, a problem caused by soil compaction, in his vineyard. On the neighbouring farm, his father had no such problem. The difference was that the young farmer was doing intensive cultivations by tractor, while his father was still using donkeys as draught power. Much later during 2005, the senior author found severe widespread soil compaction on the Dzindi small-farmer irrigation scheme in Limpopo province due to mechanised cultivation. On the plot of one very good and extremely successful old farmer, there was no soil compaction. It transpired that this old farmer each season did his first cultivation by tractor, but followed it up by an ox drawn cultivation during which any compacted layer that might have formed during the first tractor drawn cultivation, was broken up before he planted his crop.

The increased sizes and masses of vehicles operating in fields lead to increased forces applied to soils, the tractor with its great mass and concentrated pressure under the wheels perhaps being the greatest contributing factor (Bennie and Krynauw, 1985). They list several tractor factors causing increased compaction, *inter alia* including the following:

- Increased load on the drawbar;
- Travelling at lower speeds;

- Wheel slip, which is aggravated by an incorrect tractor/implement combination. I.e. where a tractor with too low power is used in an operation;
- Tractor vibration on sandy soils.

Du Preez et al. (1979) also emphasized the importance of the first and third bullets above.

Comprehensive panel discussions on aspects such as especially tyre configurations and tyre inflation pressures were reported in the CD-ROM of SASTA (2001) on soil compaction. Two key aspects were highlighted, namely:

- Wide tyres or dual wheels do not reduce compaction. In fact, they increase the area that is compacted during a pass over the field. The ideal is to have a narrow tyre with a big circumference. That will give the least compaction, because it is limited to a smaller area;
- The tyre pressure determines the degree of compaction.

The big impact of uncontrolled passing of vehicular traffic in a field is caused by the fact that by far the biggest part of compaction (up to 90%) takes place during the first pass of the wheels of tractors, implements or haulage vehicles over an area (Du Preez et al., 1979, 1981; SASTA, 2001). The dominant effect of the first pass in cultivated areas is most severe on loose soil, due to re-compaction of loosened soil, e.g. during the first secondary cultivation of soil that has undergone primary cultivation like ploughing or ripping (Du Preez et al., 1979, 1981). Results of field experiments by Du Preez et al. (1979) clearly showed that even where soil under a tractor wheel track had been loosened with a tined implement it was recompacted after just one pass by a tractor wheel over that track.

Du Preez et al. (1979) found that PRs, as indicator of degree of compaction, were generally higher where tractor tracks had been loosened with a tined implement and a tractor wheel then passed over it again, than where the original wheel track had not been loosened before the wheel passed over it again.

Subsequent passes over the same tracks as first one cause relatively minor further increases in the degree of compaction under and next to the tracks. Due to the dominant impacts of the first passes, uncontrolled haphazard movement of tractors, implements, etc. over cultivated fields during secondary operations can compact the soil over the whole field (Du Preez et al., 1979).

A dominant effect of the first pass was also found in studies on the impact of ORD by game drive vehicles on soil compaction in a game park (Nortjé, 2014; Nortjé et al., 2012a, b). The study was conducted in a private concession area in the very large (approximately 2 million ha) Kruger National Park in which there are several private concession areas. They are allowed to do ORD in order to enable tourists to get very close to members of the "Big Five" group animals (lion, leopard, elephant, rhino and buffalo). The objective is economic gain by attracting more tourists, especially rich ones from overseas. The ORD rule was that if more than one vehicle moved in on a sighting each vehicle had to drive along different tracks and not along the same track (Nortjé, 2014). This is exactly the opposite of what the rule should be to minimize soil compaction by the wheels of game drive vehicles due to ORD. It should be realised that the ORD is not practised just for a few metres from an existing road, but sometimes for substantial distances. The ultimate seen by the second author was where game driving vehicles for two kilometres followed a pride of lions. It should be kept in mind that sightings occur at random spots. Thus, over time there are large numbers of game drive vehicle tracks covering substantial areas in total. Nortjé (2015) and Nortjé and Nortjé (2017) in subsequent studies in the iconic Serengeti National Park in northern Tanzania also found serious soil compaction and other forms of soil and vegetation degradation due to ORD there. He quotes other studies that have found a tremendous increase in ORD in game parks in Africa.

The extent of the impact of wheel pressure on soil compaction by uncontrolled random vehicular traffic, becomes amplified when considering that the impacts are not only directly below the wheel tracks, but also wider than the tracks. Du Preez et al. (1979) tried to create a deeper volume of loose soil by creating ridges and planting on to the ridge. They found that it in fact did not create a deeper volume of loose soil than where they did not ridge. They found that wheel compaction occurred under the ridge while constructing the ridge. They found results of research by Bekker (1961) that indicated that compaction does not take place only directly under the track of the wheel, but also at an angle of 45 degrees from the outside of the track downwards away from the track. By applying the model of Bekker (1961), Du Preez et al. (1979) could explain their finding.

In about the late 1980s the senior author was shown an experiment at the Federal Agricultural Research Station at Braunschweig in Germany that studied tractor wheel impact on soil compaction and crop growth. Not only was the growth of sunflower in the row next to the tractor wheel track very poor, but even growth of sunflower in the second row from the track was seriously affected. Only from the third row away from the tractor wheel track onwards was growth of the sunflower plants normal. Later, Nortjé (2014) found that soil compaction due to wheel impact of game drive vehicles during ORD was up to as far as one metre from the track and that to obtain control measurements in uncompacted soil such measurements had to be taken at least that distance from vehicle tracks. Nortjé (2014) offers a hypothesis postulated by the senior author of this paper as possible explanation for the compaction outside the vehicle tracks. It amounts to a combination of two vector forces operating in combination. The first is that when the wheel applies a strong vertical downward force some particles near the outer edge of the wheel track follows the route of least resistance, move horizontally outward between the existing particles there, and thus cause a denser layer. On top of these other particles are displaced by a diagonal force caused by the outer rim of the vehicle tyre, like the 45^{o} diagonal force explained by Bekker (1961), as mentioned earlier. These particles are then packed into the already denser zone caused by the lateral displacement of particles, leading to substantial compaction outside the wheel track.

Some people question the validity of the big concern about soil compaction by the wheels of game viewing vehicles in game parks, considering the large number of animal tracks in such areas. Nortjé (2014), therefore, also studied soil compaction in existing animal tracks and compared these with the impacts of wheel tracks. He studied both elephant tracks and antelope tracks. For both soil compaction was caused at shallow soil depth, mainly causing a crust, in contrast to the compaction found deeper at wheel tracks. The actually measured values obtained by Nortjé (2014) in the antelope tracks appear to contradict the views advocated by Savory (1988) that the small sharp hooves of small stock do not compact soil, but alleviate especially soil crusting by cracking the crusts. The absence of deep compaction by elephants, despite them being such large, heavy animals, can be ascribed to the fact that they have very large flat feet and that the cushions of their feet are quite soft. Another major difference that Nortjé found between animal tracks and wheel tracks is that in the case of animal tracks compaction is only directly beneath the track and does not extend beside it. This is clearly illustrated by the lush vegetative growth right up to the side of an elephant track (Figure 2).

Fig. 2 Illustration of lush vegetative growth right up to the side of an elephant track

5.2 Impacts of large numbers of shallow secondary tillage operations

There used to be a tendency among many farmers that implement conventional tillage to conduct large numbers of secondary shallow cultivations with disc ploughs after deeper primary cultivations have been done with mouldboard ploughs or tined implements. It was often excessive. It differs between crops, but for a crop like cotton, it can be up to as many as 10 per growing season (Du Preez et al., 1979). In the late, 1960s/early 1970s the senior author found for cotton that up to eight shallow pre-plant cultivations were done where chemical weed control was used. Thus, the soil was recompacted even before the crop was planted. The situation has since improved, but it is still often a problem under conventional tillage.

Numerous shallow cultivations are artefacts that became a problem after the large-scale introduction of mechanised cultivation after World War II. Previously it was not possible to do it with animal draught power. The shallow cultivations cause the plough layer compaction in the bottom part of the plough layer (Table 1). The upper limit of this compacted layer is at a very shallow depth of only about 15 cm from the soil surface. Uncontrolled tractor wheel passes are major causes of compaction due to these multiple shallow cultivations.

In the vast majority of cases, the shallow secondary cultivations are done with disc ploughs. Farmers like the actions of disc ploughs, because they give a smooth seedbed and cut plant material effectively into the soil. However, the use of disc ploughs aggravates subsurface compaction, since they are aggressive implements that destroy soil structure. In unpublished agronomy, lecture notes at Stellenbosch University Prof. J.T.R. Sim in 1959 already warned against injudicious use of disc ploughs (personal attendance of the course by the senior author). Much more recently it was *inter alia* shown elsewhere in Africa (Tunisia) that ploughing with a disc plough gave high PRs at shallow soil depths from the soil surface down to 20 cm, whereas mouldboard ploughing gave loose, uncompacted soil to a depth of 50 cm (Abrougui et al., 2012).

In the early 1990s the senior author conducted investigations in several citrus orchards in neighbouring Swaziland in which serious soil compaction occurred. One was a young orchard that was performing extremely poorly, despite the fact that the developers went to great lengths with soil preparation before planting the orchard. The developers could not understand what went wrong, because they ripped the soil in four directions: across and in two diagonal (corner-to-corner) directions. It then transpired that after ripping they did eight shallow cultivations with a disc plough, traversing the area uncontrolled during these operations. They thus recompacted the soil to higher densities at shallow depth than it was before ripping.

5.3 Cultivating or traversing wet soil

Each soil has a specific soil water content at which it is most susceptible to compaction when pressure is applied to it, e.g. by the tyre of a tractor or other vehicle. Numerous South African studies have been done on this, as e.g. reported in several papers in SASTA (2001) and by Bennie (1972), Du Preez et al. (1979), Henning et al. (1986) and others. Maximum compaction occurs at high soil water contents – just below field capacity (Bennie, 1972; Du Preez et al., 1979).

During research comparing different cultivation strategies it was found that working with the tractor wheel in the open plough furrow, especially during mouldboard ploughing, gives more severe compaction and to greater depth than where the wheel does not run in the plough furrow (Du Preez et al., 1979, 1981; Mallett et al., 1985). The higher soil water content in the soil at the bottom of the plough furrow was considered an important contributing factor to the serious compaction caused by the tractor wheel running in the furrow (Du Preez et al., 1979; Bennie and Krynauw, 1985). A second factor is, of course, the bigger weight resting on the wheel that runs lower down in the furrow.

Cultivating or traversing soil that is too wet is an important factor aggravating soil compaction under intensive mechanised agriculture, because there are many more opportunities for this to be done. This tendency is especially large in irrigated agriculture. This is probably one of the reasons why the length of the period under no-till before cultivation is required again is shorter under irrigation than under dryland cropping (Table 2).

Table 2 Suggested number of seasons under no-till before tillage may be required again to alleviate soil compaction (from: Mitchell and Berry, 2001)

Clay content of tilled layer (%)	**Maximum permissible number of seasons without tilling**	
	Rainfed grain crops	**Irrigated grain crops**
1-8	1	1
9-16	2	2
17-24	4	3
25-32	8	5
33-40	16	8
>40	32	11

Soil compaction is also aggravated when heavy harvesting or haulage vehicles operate in a field when the soil is too wet. This is compounded by the fact that harvesting and haulage vehicles are presently very big and heavy, especially when fully loaded. This, for example, poses big management challenges concerning the harvesting of sugarcane, as *inter alia* outlined in the panel discussion report in SASTA (2001).

Off-road driving trials on soil compaction with a game viewing vehicle were conducted under both dry and wet soil conditions on different soils (Nortjé, 2014; Nortjé et al., 2012a, b). Compaction due to wheel impact was found under both dry and wet soil conditions, but it was more severe when driving on wet soil.

Treading by livestock can cause severe soil compaction under intensive livestock farming systems, e.g. by dairy cattle on irrigated pastures (Mitchell and Berry, 2001). The impact is larger the wetter the soil is when the animals are in the paddock. The worst compaction is by "pugging", i.e. plastic flow of soil around the hoof of the animal, in wet clay soil. When the soil then dries out it consists of very hard structureless clods. The senior author saw a very good example of this in a vertic (black swelling clay) soil in a paddock on the research farm of the world-renowned Onderstepoort Veterinary Research Institute near Pretoria.

5.4 High tyre pressures

It has been found that the higher the tyre pressure is, the more severe is soil compaction by the wheels of machines or equipment travelling over the soil (SASTA, 2001). The heavier a tractor, harvester, haulage vehicle, etc. is, the higher is the lowest tyre pressure that can carry it. This imposes an additional constraint that increases soil compaction due to vehicular traffic, because of the big, heavy equipment that are presently used. In studies on the impact of ORD by game viewing vehicles in a game park on soil compaction Nortjé et al. (2016) also found that the degree of wheel compaction increased with increased tyre pressure, although it was significant even at the lowest pressure. It was found that the impact of high tyre pressures was more severe when driving on wet soil than when driving on dry soil (Nortjé, 2014; Nortjé et al., 2016).

6 Effects and consequences of soil compaction

Soil compaction has several impacts that have large effects on plant growth and production. Comprehensive research on these has been done in South Africa. Some of the most important impacts are discussed here.

6.1 Increased soil strength and resultant negative impacts on root development and top growth

The effects of soil compaction on soil strength (the mechanical resistance of soil against root penetration) has been studied intensively in South Africa, especially by UOFS teams in the 1970s (e.g. Bennie, 1972; Bennie and Laker, 1975; Burger et al., 1979; Bennie and Burger, 1979; Du Preez et al., 1979, 1981). Under field conditions high soil strengths in compacted layers limit roots to very shallow depths above the compacted layers. This is true for both annual crops (refer to Figure 1) and perennial crops, such as fruit trees and grapevines (Figure 3).

Fig. 3 Shallow root growth in grapevines due to subsurface compaction

There are large differences between different crops concerning the degree to which their root development is restricted by high soil strengths. The root systems of plants with taproots are more seriously affected than those of other plants. At Vaalharts irrigation scheme, it has repeatedly been found that cotton roots are extremely sensitive to high soil strengths (e.g. Du Preez et al., 1979). Observations at Vaalharts showed that groundnut roots are even more severely affected than cotton roots (Bennie, 1972). Photographic evidence is recorded in Bennie (1972) and Du Preez et al. (1979). During a visit to experiments on the effects of soil compaction by tractor wheel traffic on sandy soil at the Federal Agricultural Research Centre at Braunschweig, Germany, the senior author observed the extreme sensitivity of sunflowers to soil compaction. Maybe the worst that the senior author saw was the impact on tobacco roots in a tobacco field near Brits in Northwest Province (Figure 1). Among the grain crops Du Preez et al. (1979) found that maize root development was restricted four times more than wheat root development by high soil strengths. The general finding has always been that wheat has an exceptionally robust root system that is able to penetrate quite dense soil layers.

Van Huyssteen and Van Zyl (1981) found a linear decrease in the mass of grapevine roots due to soil compaction. In pot experiments with wheat and cotton it was in contrast to this in both cases found that increases in soil strength did not affect total root mass (Bennie, 1972; Bennie and Laker, 1975). However, other important root parameters were strongly affected by increased soil strength. Upon visual inspection, it was decided to determine the mass of wheat roots shorter than an empirical cut-off length of 10 cm and the mass of roots longer than 10 cm (Bennie, 1972: Bennie and Laker, 1975). There was a statistically significant linear increase in the mass of roots shorter than 10 cm with increased soil strength ($r = 0.56$, significant at $p = 0.05$). On the other hand, there was a statistically highly significant linear decrease in the mass of roots longer than 10 cm with increased soil strength ($r = -0.85$, significant at $p = 0.001$). In other words, with increased soil strength the roots became shorter and thicker. In the case of cotton there was a statistically highly significant linear decrease in taproot length with increasing soil strength ($r = -0.83$, significant at $p = 0.01$).

Bennie and Burger (1979) conducted later a more comprehensive follow-up study where plants were grown for a longer period in much bigger pots on three sandy soils similar to the one used in the study reported by Bennie (1972) and Bennie and Laker (1975). The study of Bennie and Burger (1979) again included wheat and cotton, and in addition maize and groundnuts. They found drastic, statistically highly significant reduction in root lengths of wheat and cotton with increasing PR – confirming the earlier findings reported by Bennie (1972) and Bennie and Laker (1975). In addition, Bennie and Burger (1979) found a drastic negative effect by soil compaction on secondary root development in both. Development of secondary roots is an important yield factor in wheat since the number of tillers (and consequently ears) that form is strongly related to the development of secondary roots (Vanassche and Laker, 1989).

In an avocado orchard near Tzaneen in Limpopo Province, the authors observed a similar effect to the above in practical farming: where there was a compacted soil layer there were only thick roots and to only about 25 cm depth and no fine roots. Where there was no compacted layer there were abundant fine roots well distributed through the soil from the soil surface to a depth of about 1.3 metres.

Results from elsewhere in the world by Gill and Bolt (1955), Abdalla et al. (1969) and Batchelder (1971), as quoted by Bennie (1972) and Bennie and Laker (1975), indicated that increased root diameter and decreased root ramification due to increased soil strength, lead to a corresponding decrease in active sorption area per unit root mass. Bennie and Burger (1979), in their study referred to above, indeed found drastic, statistically highly significant reductions in RSAs for wheat, cotton, maize and groundnuts with increased soil PR. This leads to a decrease in the efficiency of roots concerning important functions, as will be discussed later. This type of effect is clear from top growth responses to increasing soil strength in the pot experiments discussed above (Bennie, 1972; Bennie and Laker, 1975). In the case of wheat there was a statistically highly significant linear decrease in top growth mass with increasing soil strength ($r = -0.75$, significant at $p = 0.001$). In the case of the, somewhat pot bound, cotton top growth mass also decreased with increasing soil strength, but the relationship was not statistically significant. The effect of the decrease in root efficiency due to the impact of soil strength was seen very clearly in the results reported by Bennie (1972) and Bennie and Laker (1975) for the (top growth mass):(root mass) ratios. In the case of wheat there was a statistically highly significant curvilinear (logarithmic) decrease in the ratio with increasing soil strength ($r = -0.84$, significant at $p = 0.001$). Even in the case of cotton there was a statistically highly significant linear decrease in the ratio with increasing soil strength ($r = -0.67$, significant at $p = 0.01$). Similarly, Bennie and Burger (1979) found a strong, statistically highly significant increase in unit above ground plant mass (top growth) per increasing unit root length and per increasing unit RSA for all four crops (wheat, cotton, maize and groundnuts) on all three soils in their study.

The soil compaction due to the impacts of the wheels of game viewing vehicles during ORD in a game park was discussed earlier. It is manifested in the form of increased PR (Nortjé, 2014; Nortjé et al., 2012a, b). The impacts of this on both root growth and top growth were also studied (Nortjé, 2014; Nortjé et al., 2016). Quantitative root density determinations were made by recording so-called "root fraction percentages" at exposed soil profile pit walls, using recognised published techniques. Qualitative top growth observations were recorded. These were done on three different soils at different ORD trial sites. The determinations were done 8.5 months after ORD was done and after 218 mm, rain had fallen, to give both root and top growth opportunity to recover after the ORD. At Site 1, which had sparse vegetation during ORD, there was a huge decrease in "root fraction percentage" (RFP) between the control and driving at the lowest tyre pressure (80 kPa or 0.8 bar). From there RFP decreased linearly with driving at increased tyre pressures from 80 kPa up to the highest value used, namely 320 kPa (3.2 bar). The RFP values decreased sequentially statistically significantly between the different tyre pressures as they increased, that is in the order 80 kPa>160 kPa>240 kPa>320 kPa. At Site 2, with somewhat better vegetation cover during ORD there was a statistically highly significant linear decrease in RFP from the control to the highest tyre pressure used, with statistically significant differences between the different treatments. Site 3 had relatively good vegetation cover during ORD. Its control then also had 1.5 times as high RFP as the controls at the other two sites. However, even here RFP decreased linearly from the control to the highest tyre pressure. Most glaring were the extremely low RFP values, i.e. poor root growth, at the two highest tyre pressures, namely 240 kPa (2.4 bar) and 320 kPa (3.2 bar) at all three sites, irrespective of the amount of vegetative cover at the time of conducting ORD. Most disconcerting is the very big impact at a tyre pressure of 240 kPa, which corresponds closely with the tyre pressure normally used for game drive vehicles that are used in ORD. The RFPs where driving was done at a tyre pressure of 240 kPa were only 13% (Site 1), 14% (Site 2) and 10% (Site 3) of the RFPs for the controls, i.e. where no driving was done.

Poor root growth due to ORD in the trials, especially at high tyre pressures, generally translated into poor top growth. Investigations were conducted at the trial sites in subsequent seasons to check whether there was improvement from the poor conditions. It was found that there was not only lack of recovery of vegetative growth, but that the situation deteriorated due to increased predisposition of the vegetative cover to progressive degradation. Nortjé (2014) and Nortjé et al. (2016), the second author of this paper, photographically monitored the impact of an actual tourist ORD incident in the area where the above research was conducted. Shortly after the driving incident (14 August 2009) the serious damage by the wheel tracks was clearly visible (Figure 4). Photographs were thereafter taken twice in each season over a two-year period, i.e. a further 12 sequential photographs. After two years, *inter alia* including two summer rainfall periods, the negative impact of that once off ORD incident was still clearly visible on 19 August 2011 (Figure 5). The results of the ORD trials described above provided explanations for these observations. The fact that the tourist driving was done at the normally used tyre pressure of about 240 kPa (2.4 bar) is particularly relevant in view of the high soil strength and very low RFP found at this tyre pressure in the trials.

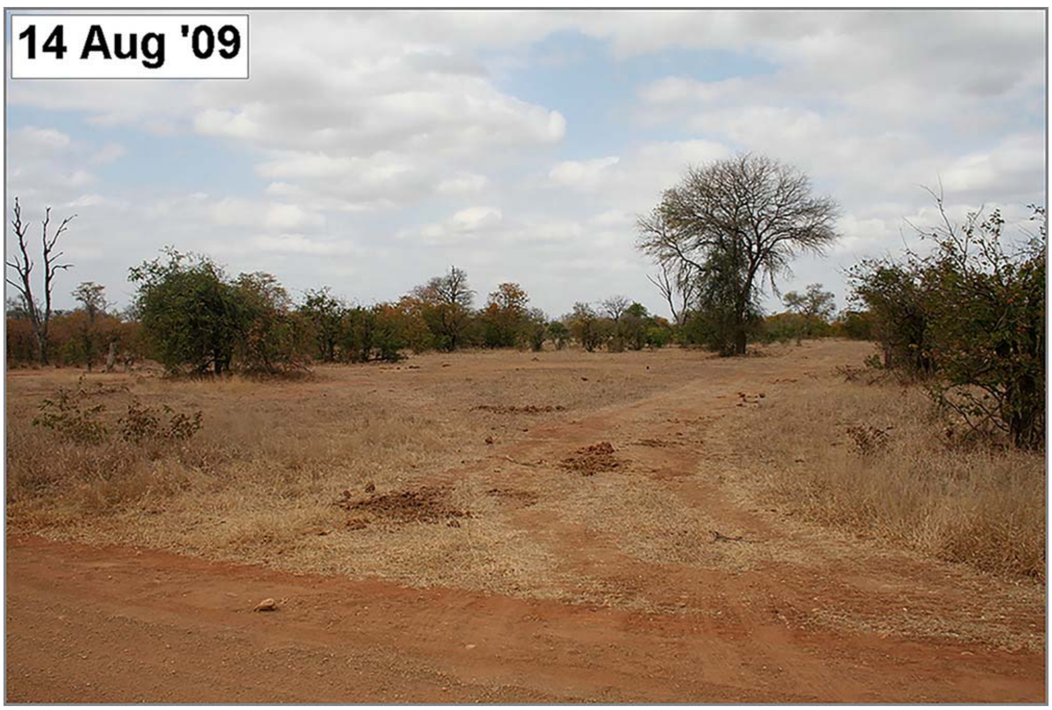

Fig. 4 Damage by wheel tracks shortly after ORD

Fig. 5 Damage by wheel tracks two (2) years after ORD

6.2 Impacts on plant nutrient uptake

Uptake of plant nutrients, especially P and K and the micronutrients Fe, Mn and Zn, is strongly reduced by soil compaction (Bennie and Laker, 1975; Bennie and Burger, 1979; Du Preez et al., 1979; Dreyer et al., 2000; Laker, 2001). Bennie and Burger (1979) give comprehensive discussions on this aspect of soil compaction. They found that the plant nutrients of which the concentrations (% or $mg.kg^{-1}$) in the top growth were reduced the most times by soil compaction, as indicated by increased PR in their 12 experiments were in the order P>K>Ca=Mn. Bennie and Burger (1979) found that the degree to which compaction reduced nutrient uptake amount differed between the different crops that they included in their study, the reduction in nutrient uptake being in the order cotton>groundnuts>maize>wheat. This was the same order in which root growth of the different crops was restricted by soil compaction.

In the pot experiment with wheat that was discussed earlier in terms of the effects of soil strength (PR) on root and top growth, very strong negative relationships were found between increased soil strength and uptake of key nutrients (Bennie, 1972; Bennie and Laker, 1975). Statistically highly significant negative linear relationships between soil strength and nutrient concentration (%) in the top growth were found for K ($r = -0.93$, significant at $p = 0.001$) and Ca ($r = -0.86$, significant at $p = 0.001$), while there was also a significant negative relationship for P ($r = -0.58$, significant at $p = 0.05$). The K concentration in top growth was for example, reduced as much as 40% by simply compacting the soil, without any changes to plant-available soil K levels (Bennie, 1972; Bennie and Laker, 1975). Nutrient uptake (mg/pot) does not always follow the same pattern as nutrient concentration. In this case it did for all three the nutrients mentioned, with correlation coefficients (R-values) of -0.88, -0.85 and -0.69 for K, Ca and P respectively. For K and Ca this was very strongly related to the negative impact of increased soil strength on root efficiency, as manifested in the mass of roots longer than 10 cm, as discussed earlier. This is shown by the very strong positive linear correlation between mass of roots longer than 10 cm and the concentrations (%) in top growth of K ($r = +0.82$) and Ca ($r = +0.70$). The same was found for the uptake (mg/pot) of these two nutrients. Since neither the concentration in top growth nor uptake of Mg was affected by soil strength, there were highly significant decreases in the K:Mg and Ca:Mg ratios in the top growth due to increased soil strength (compaction) with r values of -0.84 and -0.89 for the K:Mg and Ca:Mg ratios respectively. The K and K:Mg results are strongly supportive of the important practical findings in field research described in the second paragraph below.

In the study of Bennie and Burger (1979), discussed earlier, statistically significant negative relationships between soil strength (PR) and nutrient concentrations in plant top growth in all three soils were found only for K in maize and P in wheat and cotton. However, statistically significant (most highly significant) positive relationships between RSA and nutrient concentrations in top growth were found in all three soils for all four crops (maize, wheat, cotton and groundnuts) for Ca, Mg and P and for maize, cotton and groundnuts also for K. For wheat highly significant relations for K was found in two of the soils. Three micronutrients (Fe, Mn and Zn) were also determined. For cotton and groundnuts statistically significant positive relationships between RSA and nutrient concentration in top growth were found on all three soils for all three these micronutrients. For wheat, significant relationships were found on all three soils for Fe and Mn. Since RSA was strongly reduced by high soil PR, soil compaction thus had a strong indirect negative impact on nutrient uptake.

In the 1950s/1960s, very serious widespread problems with so-called "growth stunting disease" were observed in sultana (Thompson seedless) vineyards in the Central Orange River irrigation scheme. In spring shoots did not develop normally and most bunches were shed, leading to very poor yields. Because of the symptoms, it was believed that this was due to some disease organism. However, studies by plant pathologists of different kinds could not find any evidence for this. When material from "sick" vines were taken to a research station and planted there for virological studies, they actually grew very luxuriously. The common denominator found for the "sick" vineyards by the senior author and non-soil scientists before him was severe soil compaction at shallow depth, as mentioned early in this paper (Laker, 1981, 1986). During the 1960s/1970s, very serious widespread problems with so-called "red death" were observed in cotton fields in the same area and at the Vaalharts irrigation scheme. Again, it was believed that it was due to some disease organism and again studies by plant pathologists could not find any evidence of any disease. Again, it was found that red-death cotton fields were characterised by very severe soil compaction at shallow depth (Van der Merwe, 1969). Due to the soil compaction, the root systems of both growth stunting disease and red death plants were very poor.

In the late 1960s, the senior author took comparative leaf samples from growth stunting and healthy sultana (Thompson seedless) vineyards (Laker, 1981, 1986). There was a clear-cut difference between the low K concentrations in leaves from growth stunting disease vineyards and the high values from healthy vineyards. There was not even any overlap between the highest value in a growth stunting disease sample (0.93%) and the lowest value in a healthy sample (1.51%). Likewise, the K:Mg ratios in leaves from growth stunting disease vineyards were much lower than in leaves from healthy vineyards. Again, there was not even an overlap between the highest value for a leaf sample from a growth stunting disease vineyard (2.42) and the lowest value for a sample from a healthy vineyard (4.44). Much earlier Boynton et al. (1958) in the USA already found that poor K uptake by grapevines were caused by limited root growth due to poor soil physical conditions.

Comparative leaf samples from red-death and healthy cotton fields in both this area and at Vaalharts showed similar K concentration trends to those found for grapes (Van der Merwe, 1969). Analysis of a special set of cotton leaf samples by the senior author confirmed this. Again, the highest K concentration in a red-death leaf blade sample (0.51%) did not even overlap with the lowest concentration in a healthy sample (0.78%), similar to the case with grape vine leaves.

In the earlier described pot experiment with cotton P concentrations in the leaves decreased sharply with increasing soil strength even at relatively low soil strengths (Bennie, 1972; Bennie and Laker, 1975) and then more-or-less levelled off, giving a statistically highly significant negative relationship between soil strength and P concentration ($r = -0.85$, significant at $p = 0.01$). In a pot experiment with tobacco P uptake was reduced by 37% by increasing the bulk density of the soil from 1,400 $kg.m^{-3}$ to 1,600 $kg.m^{-3}$ (Dreyer et al., 2000; Laker, 2001). Within the South African context, a bulk density of 1,600 $kg.m^{-3}$ is not even a high value. Many South African subsoils have bulk densities of this order and even higher in the virgin state.

To what extent relative reductions in nutrient uptake will reduce plant growth and yield will depend on the inherent fertility status of the soil. I.e. fertility factors can mask the effects of soil compaction and of measures to alleviate it on plant growth and yield (Laker, 2001). If the fertility level of the soil is very high, the crop may perform well even in the presence of severe soil compaction. If the fertility level of the soil is very low, alleviating compaction will not give a significant growth response.

6.3 Water use efficiency

In a country like South Africa, with its low and unreliable rainfall and limited availability of irrigation water, the effects of soil compaction on water, use efficiency is probably the most important factor affecting its influence on plant growth and crop production. The area of the biggest concern is the western half of the so-called "maize quadrangle" in the north-western Free State province and in Northwest province with an unreliable annual rainfall of between 400 and 550 mm. In addition, large areas are covered by sandy soils that are highly susceptible to soil compaction. In some years over 70% of South Africa's white maize, the staple food of the major part of the country's population, is produced in this marginal production area. Thus, elimination of soil compaction is a critically important part of the effective soil water management in this marginal production area in order to ensure food security.

In dryland cropping in marginal rainfall areas, it is essential that plant roots must have free access to the water that is stored deep in the subsoil. This is illustrated very clearly by the results of Mallett et al. (1985) in an area in KwaZulu-Natal with high average annual rainfall. In the unusually dry 1979/80 season, following on a very dry 1978/79 season, a rip-under-row treatment, which enabled deep root penetration, very far out yielded the shallower mouldboard plough treatment (5.4 t. ha^{-1} maize vs. 3.3 t. ha^{-1}). In normal high rainfall years, rip-under-row was inferior to mouldboard ploughing, possibly due to excessive leaching of N. The rip-under-row treatment had much more roots at all depths, the percentage differences being very high deeper in the soil. Abundant roots in the deeper soil layers that can exploit water stored there is very important for enhancing higher water use efficiency, expressed as crop yield per unit water. In especially the high drought risk (marginal) areas of the western part of the maize quadrangle, characterized by high temperatures, very low relative humidity's and very high potential "evapotranspiration" (ET), the top 10 cm of the soils dries out very quickly to an air-dry state (Bennie, 1984). Note: Air dry, i.e. absolutely dry, not just to the so-called permanent wilting point, the lowest level of plant-available water in the soil. During numerous soil augerings in mid-winter, the middle of the dry season, in sandy soils in the north-western Free State the senior author and colleagues repeatedly found that the top about 15 cm of the soil was dry, but that the parts of the soil profile deeper than that were moist to substantial depth – due to late summer rains. With often, long periods between successive rains during the summer cropping season the devastating effect of boxing roots into a very shallow very dry soil layer by a compacted layer is clear. Thus, there can be a crop failure on a soil with adequate water in the subsoil because the roots of the crop cannot reach and utilize that water.

The senior author made an important strikingly clear observation in this regard in a cultivated *Eragrostis curvula* (grass) field, on a coarse sandy, granite derived soil near Mbombela in Mpumalanga Province. Half of the field was ripped before planting and the other half not. The two parts were side-by-side on the slope and not one lower down the slope than the other. The whole field received the same rain. The grass on the ripped side grew much better than where the soil was not ripped. Soil pits were dug close to each other in each part. There was a severely compacted layer about 20 cm from the soil surface in the soil that was not ripped, with no compacted layer on the ripped side. On the ripped side, the soil was slightly moist. Where ripping was not done the topsoil above the compacted layer was dry and the compacted layer bone dry and as hard as rock. Consequently, no roots got through this layer. Below the compacted layer the soil was soaking wet, so wet that water could be pressed from it by hand. So, the crop performed poorly on wet soil, because the compacted layer prevented the roots from reaching the wet soil. From this and other observations, it is seen that in sandy soils compacted layers may have enough pores that are large enough to allow percolation of water through them. This is unlike the situation in finer textured soils where such water percolation is restricted and waterlogged conditions develop on top of the compacted layer. However, in the compacted sand there are not enough of the macro pores through which the water percolates that are large enough to allow root penetration. Macro pores are pores with diameters > 0.075 mm, but root penetration requires pores of at least 0.20 mm diameter (Wiersum, 1957).

The water use efficiency of dryland maize in the Free State, expressed as kilograms grain yield per hectare per mm ET, was nearly 40% higher in uncompacted soil than in even only moderately compacted soil (14.3 vs 10.5) (Bennie and Krynauw, 1985).

Although De Ronde and Spreeth (2007) did not look at the abilities of the roots of different cowpea lines/cultivars to overcome compaction, their findings are very interesting in terms of the importance of accessing water in subsoil. The striking difference between the so-called drought tolerant control line IT96D-602 and the drought sensitive control line Tvu7778 was concerning their root distribution with depth (Table 3). The total root lengths for the two lines were almost identical, but the drought tolerant line had much more roots below 25 cm depth than the sensitive line. The root lengths of two drought tolerant mutants (217 and 164) in the soil below 25 cm depth were even bigger than that for the drought tolerant line. Under water stressed conditions, the latter two gave about double the seed grain yield compared to the tolerant control line, with factors of 1.7 for Mutant 164 and 2.1 for Mutant 217, respectively. This shows the importance of bigger root lengths, especially below 25 cm depth. (The drought sensitive control line was not included in the yield experiment). It is clear what the impact would be if a compacted layer would prevent roots from accessing water in deeper soil layers.

Table 3 Root lengths of four cowpea lines and mutants in the topsoil, subsoil (below 25 cm) and total soil profile (from De Ronde and Spreeth, 2007)

Line/Mutant	Root length (mm)		
	Top 25 cm	Below 25 cm	Total
Tvu7778*	557	475	1032
IT96D-602	452	586	1038
Mutant no. 217	519	676	1195
Mutant no. 164	520	659	1179

*Drought sensitive

From De Ronde, J.A., Spreeth, M.H., 2007. Development and evaluation of drought resistant mutant germ plasm of *Vigna unguiculata*. Water SA 33, 381–386.

Under irrigation, the negative effects of compaction concerning water extraction from the subsoil, can be overcome by means of frequent light irrigations to ensure adequate water supply to the shallow root system that is restricted to the topsoil above the compacted layer. This is at a high price, however. The topsoil dries out quickly and during the frequent irrigations, a lot of water is lost unproductively through ET (Burger et al., 1979). Consequently, more irrigation water must be applied and the irrigation water use efficiency, i.e. the grain yield per ha per mm irrigation water applied, is reduced. For maize, irrigation water-use efficiency was 10.8 $kg.ha^{-1}.mm^{-1}$ for uncompacted and 9.4 $kg.ha^{-1}.mm^{-1}$ for moderately compacted soil respectively (Bennie and Krynauw, 1985). For wheat, the respective figures were 8.4 $kg.ha^{-1}.mm^{-1}$ and 6.9 $kg.ha^{-1}.mm^{-1}$. In studies under irrigation, on a deep well-drained soil at Pongola, Johnston and Wood (1971) found no effect by compaction on sugarcane yield. They concluded, "*(...) regular irrigation was mainly responsible for the absence of any decline in yield due to various compaction treatments. Under a less favourable moisture regime or normal rain fed conditions it is considered likely that notable reductions in yield would have been obtained"*.

Very high frequency light irrigations (up to a few times a day) not only leads to high "non-beneficial" water losses due to ET, but the resultant shallow root systems put perennial crops, like fruit orchards, are at very high risk in the event of a system breakdown, heat wave or water restrictions due to prevailing drought and limited irrigation water availability (W.P. de Clercq, irrigation expert, Stellenbosch University, personal communication, January 2019).

6.4 Reduction of hydraulic conductivity and inhibition of soil aeration

Reduced hydraulic conductivity is one of the consequences associated with soil compaction (Bennie and Burger, 1979; Mitchell and Berry, 2001). This is caused by a reduction in the number of macro pores and an increase in tortuosity (path length) of water flow. This is not a serious problem in sandy soils, as indicated earlier, because adequate percolation of water through the compacted layer still occurs. However, in medium-textured to clayey soils this can result in waterlogging and anaerobic conditions in and/or above compacted layers, particularly under irrigation. The senior author has observed several serious cases of this nature in fruit orchards, for example. Negative effects of such situation include:

- It enhances the possibility that field operations will be done under too wet conditions, leading to further aggravation of compaction;
- Root respiration is impaired, negatively affecting uptake of both plant nutrients and water;
- The activities of favourable microorganisms are restricted and negative organisms are promoted. This can *inter alia*, lead to denitrification losses of nitrogen;
- Incidence and severity of root diseases can be increased. This is discussed in some more detail later.

In very sandy soils (<5% clay) which have extremely high hydraulic conductivities and excessive drainage, reductions in pore size by compaction can under certain conditions have positive effects, by somewhat slowing down water movement and increasing the effective available water capacity of the soil (Smith and Johnston, 2001). Under such circumstances, soil compaction even increased tree growth in a forest plantation, although not dramatically (Smith and Johnston, 2001). This may also partially explain the better maize yields obtained by Mallett et al. (1985) on an extremely sandy (3.1% clay) soil with mouldboard ploughing than with rip-under-row in seasons with high and well-distributed rainfall. Burger et al. (1979) also concluded that in sandy soils reduction of hydraulic conductivity and increasing of soil water retention is not harmful, but would rather be beneficial. The conditions under which these were found should be carefully noted: The forest plantations are grown in areas with high and reliable rainfall, Mallett et al. (1985) specified *"seasons with high and well-distributed rainfall"* and Burger et al. (1979) worked under irrigation. Under conditions of low and/or erratic rainfall, the impact of soil compaction on water use is completely different, as discussed earlier. The negative impacts on irrigation water-use efficiency, by boxing roots into a shallow depth due to soil compaction should also be brought into consideration as a counter effect.

6.5 Impact of soil compaction on root diseases

Soil compaction, especially at shallow depth, weakens root systems and predisposes them to heavy infection of root rot diseases. In basic pot experiments Joubert (1993), for example, found that the effects of *Phytophthora nicotianae* root rot in citrus was greatly aggravated by soil compaction – especially where both high soil compaction and wet soil conditions prevailed. Serious phytophthora infection is normally ascribed to the effect of excessively wet soil conditions, but Joubert (1993) found that wetness on its own did not lead to very serious phytophthora infestation. Joubert's results are summarized in Mkhize et al. (1996).

A weak root system caused by compaction is compromised to infestation by the disease organisms. In citrus orchards, this leads to the type of situation in Figures 6 and 7, photographed in Swaziland. Figures 6 and 7 represent a type of situation that was observed in several cases during a field survey in which *inter alia* Joubert and the senior author participated upon invitation. The survey was conducted at the request of a company that marketed fungicides. They found that farmers were no longer buying their products because they were not effective. They wanted an explanation for why their products were not effective. The investigating team then found that it was due to this over-riding impact of serious soil compaction, which caused a combination of weakened root systems and excessive wetness. The senior author afterwards received a wall clock with the words "root care" and a spade in soil on its face – instead of a fungicide advertisement – from the company, illustrating that they realised that the key requirement was to avoid a poor soil physical condition. In 2016, the authors observed a similar situation of very serious phytophthora infestation of avocado roots, in wet soil above a compacted soil layer, in an orchard near Tzaneen in the north of Limpopo province. In another row in the same orchard where there was no soil compaction there was also no phytophthora infestation under the same irrigation management.

[Insert Figure 6 (Old Plate 5) here]

Fig. 6 Subsurface compaction in a citrus orchard

Fig. 7 *Phytophtora cinnamomi* diseased citrus tree due to subsurface compaction

7 Management systems to minimize subsurface soil compaction and its impacts on plant growth and crop production

7.1 Ripping

There is no doubt that ripping, i.e. working with tined implements, ***if done correctly***, will break up compacted layers in soils. Ripping was in the past called subsoiling, when rippers with tines of about 90 cm long were used. It is important to note that one does not need subsoilers with 90 cm tines to break up the compaction caused by wheel traffic or repeated shallow cultivation. A tined implement that can work to 45 cm depth, just gets in under the compacted layer, and break it up is usually adequate (Mallett et al., 1985; Laker, 2001). Of course, in a soil with a naturally very dense subsoil, it is important to do deep subsoiling before an orchard or vineyard is established or before a new field is planted. This was the original use and objective of rippers.

Plant responses to ripping (and other forms of deep cultivation) often seem to be confusing, and even conflicting. This is *inter alia*, illustrated in several papers and the panel discussion report in SASTA (2001). Close inspection of cases where ripping has not succeeded in improving production or even had negative effects usually reveals very logical explanations for such apparently anomalous results.

In the first place, a farmer (or maybe even researcher) may be under the false impression that a tined implement had penetrated below a compacted layer and broken it up, while this was actually not the case. In the early 1970s Dr. Boet Human, then senior lecturer and later professor in Agronomy at the UOFS, did inspection at a farm where the farmer was very proud of how fast he could break up a compacted layer with an implement with a number of tines drawn by a small tractor. Inspection of the soil revealed that the tines never penetrated below the compacted layer and did not break it up, but only scratched shiny streaks on top of it. When the implement was loaded and the tines pulled in under the compacted layer, the tractor could not move the implement. The tractor could not even push out the tined implement backwards again. The tines had to be dug open with spades before the tractor could push them out backwards. The senior author saw similar situations a few times. It was for example, striking how a tractor with a deep mouldboard plough was racing at high speed in a field with severe soil compaction at the Tugela Ferry small-farmer irrigation scheme in KwaZulu-Natal. He observed that in fact the plough was seldom more than shear depth in the soil and in some places running virtually on top of the soil. Observations in the Free State (e.g. by Prof. Alan Bennie) found that a tine does not penetrate under a compacted layer if the angle of the tine is not correct.

Secondly, the positioning of the crop row relative to the rip line is critically important. In an investigation the maize growing areas in the northern Free State in the early 1970s C.D. Koch (personal communication) found that the worst possible situation was where the rip line was in the inter-row area and the tractor wheel ran between the rip line and the plant row during a subsequent secondary cultivation or other type of operation. The tractor wheel had the most severe impact the closer it ran to the row, boxing the maize roots into a very narrow and shallow confined area. The roots are boxed in from the side by the wheel impact and at the bottom above the existing compacted layer. This has led to the practice of rip-under-row, sometimes also called rip-on-row, where it is ensured that maize (for example) rows are planted right on top of the rip line. Therefore, they cannot, be boxed in away from the rip line. In the study of Mallett et al. (1985), it was striking how poorly crops under uncontrolled ripping (chisel ploughing) performed compared to those where rip-under-row was applied. Uncontrolled ripping was even inferior to shallower mouldboard ploughing. Rip-under-row particularly outperformed the other cultivation systems during the second in a sequence of consecutive abnormally dry seasons. Determination of volumes of loose soil and rooting patterns showed that only rip-under-row enabled roots to penetrate deep enough to use subsoil moisture reserves during abnormally dry seasons to ensure good yields during such seasons (Mallett et al., 1985). The potential magnitude of the effect of rip-on-row on dryland maize yields is illustrated in Table 4, obtained in a field experiment on a sandy soil in the northwest Free State in the 1980s. During the same period a farmer from this area, also told the senior author that his maize yields increased from 0.5 $t.ha^{-1}$ to 6 $t.ha^{-1}$ after he switched to rip-on-row and controlled traffic.

Table 4 Experimental results of rain fed maize yields under different cultivation systems on apedal sandy soils, which are prone to compaction, in the northwest Free State (results from research by Astrid Hattingh)

Cultivation system	Maize grain yield (t/ha)
Rip-on-row	5.2
Plough – 25 cm	1.5
Cultivator – 15 cm	1.2

Observations have made it clear that uncontrolled secondary cultivations can nullify any positive effects of ripping and even create situations that are worse than if no ripping was done. Loose ripped soil predisposes the soil to worse compaction than if no ripping was done, as explained earlier. Thus, Mallett et al. (1985) state: *"A controlled traffic system is therefore*

According to Mallett et al. (1985), it has been found that at farm scale rip-underrow maize production *"it is most practical, economically feasible and timely to do the ripping some time before planting"*. An extremely enlightening and important related finding by Van Averbeke (2003) is that traditional small-scale Xhosa farmers in the Eastern Cape province used to have a production system, called *Gelesha*, based on animal drawn implements, including ox-drawn rippers, *"that involved mid-winter ripping of the sod of the previous crop, followed by seed bed preparation after the first good spring rains. Ripping left the soil surface in a rough state, improving the infiltration rate of soils, which are notorious for their susceptibility to soil surface compaction. Stover and weeds, which were valued as winter feed supplement for the cattle, were left at the soil surface"*. By improving water, infiltration optimum use was made of the important spring rains in this area with mid-summer drought and spring and autumn rainfall peaks. According to Van Averbeke (2003), this system was still in general use in the 1940s and 1950s and possibly into the 1960s. Even in the early 1990s, ox-drawn rippers were still used in neighbouring Lesotho (IFAD, 1992). Small-scale farmers in the Eastern Cape Province discontinued mid-winter ripping when government subsidised tractor schemes were introduced during the homeland era (Van Averbeke, 2003). By shifting cultivation to early summer, the beneficial effects of the significant spring rains in the area became greatly reduced.

When the senior author identified severe soil compaction close to the soil surface, with its upper limit at about 15-20 cm depth, as being closely associated with growth stunting disease in sultana vineyards, he conducted field trials in four vineyards to determine whether breaking up the compacted layer by ripping or deep trenching would alleviate the "disease" and improve yields. Two of the vineyards had serious growth stunting disease. The other two were healthy vineyards that were included for comparative purposes. Four treatments were compared, namely:

1. The farmer's normal shallow disc cultivation;
2. Ripper (45 cm) without addition of organic matter;
3. Trench (90 cm deep), filled up again, with organic matter added at the bottom;
4. Trench (90 cm deep), filled up again, with organic matter mixed right through.

The latter two were included, because the senior author earlier in a viticulture science course at Stellenbosch University was taught that good grape farmers at the stage in the 1950s made 90 cm deep trenches in every fourth interrow in vineyards, added the prunings of four rows in it and covered it again. The trench was shifted each year, so a specific interrow would receive it once every four years.

The different treatments were applied in July 1968, i.e. in mid-winter. Since in deciduous fruit trees and grapevines a harvest is mainly determined by reserves accumulated in the trunks during the previous late summer/autumn yield differences were not expected during the first (1968/69) season after applying the different treatments. Yield determinations during that season confirmed these at all four vineyards. The next season (1969/70) gave very exciting results. In both the healthy vineyards, the yields were virtually identical for the four treatments, as could be expected (Laker, 1981, 1986). In one growth stunting disease vineyard the deep cultivations gave statistically significant higher yields than the shallow cultivation, with the average yield for the three deep cultivations being 20.9 kg fresh fruit per vine, compared to only 12.4 kg per vine for the shallow cultivation. This is an increase of 69%. Maybe more importantly the average yield for the deep cultivations compared very favourably with the average yields of 17.3 kg and 21.4 kg per vine for the 2 healthy vineyards respectively. Important to note is that the average yield for the 45 cm deep rip treatment without organic matter (24.6 kg per vine) was actually slightly better than for the deeper treatments with organic matter. It shows that breaking up of the compacted layer was the key. The 1970/71 and 1971/72 were climatically very poor seasons. Therefore, average yields were in both seasons low, but the once-off deep cultivations applied in 1968 still increased the yield by an average of 55% in 1970/71 and 39% in 1971/72, compared with the shallow cultivation.

In the other growth stunting disease vineyard, the deep cultivations had no effect on yield during the first responsive season (1969/70). The yields for the four different treatments were virtually identical, but were very low, with an average of only 11.1 kg fresh fruit per vine. The two healthy vineyards that did not respond, but had high yields, had relatively high exchangeable soil K contents and the growth stunting disease vineyard that responded to deep cultivation a moderately low content. The growth stunting disease vineyard that did not respond to deep cultivation had a very low exchangeable soil K content. It is clear that in such seriously deficient soil elimination of a compacted layer alone could not overcome the problem.

Growth stunting disease ratings were done in the 1971/72 season in the vineyard that gave yield responses to deep cultivation. Not even one of the test vines in the deep cultivated plots had any sign of growth stunting disease. In contrast, 23 of the 24 vines in the shallow cultivated plots had serious growth stunting disease symptoms. This convincingly shows the alleviation of the "disease" by the breaking up of a compacted soil layer, even by just a 45 cm tine if there is no other serious limiting factor, like low soil fertility.

7.2 Controlled traffic

Controlled traffic is very important to minimize compaction, as e.g. pointed out in the SASTA (2001) CD-ROM. As indicated earlier, it became clear that under mechanised agriculture the impact of wheels of vehicular traffic is the main cause of subsurface soil compaction. Consequently, uncontrolled traffic leads to severe compaction over the whole field.

Awareness of the serious consequences of uncontrolled traffic over a field was amplified by the findings that it can actually nullify the beneficial effects of ripping. Driving in the same tracks during all operations does not significantly affect the degree of compaction under the tracks, but greatly reduces the compacted area. Identification of the above then led to the realisation that a system of controlled traffic must be implemented. With controlled traffic is meant that wheels must during all operations in the season follow in the same tracks as during the first operation. Du Preez et al. (1979, 1981), for example, found that a simple cultivation system of controlled traffic gave the same amount of loose soil as ridging. In research on a sandy soil in the north-western Free State, Bennie et al. (1982) found that deep tillage followed by controlled traffic practices gave increased maize yields, better water use efficiency, increased total dry mass production and more profuse rooting than where controlled traffic was not implemented. Farmers in various parts of the world as an effective management technique to minimize soil compaction under intensive crop production systems for more than 50 years have used controlled traffic. Some South African farmers, especially in the Free State and Northwest Province, have also used it very effectively for about that same period. Originally, it was done visually, but nowadays it can be done accurately and efficiently with the aid of GPS technology.

Permanent controlled traffic, where vehicular traffic in a field is confined to specific lanes not only during a single production season, but also during driving is done in the same lanes year after year, is a relatively new innovation. It is made possible by the use of GPS guidance. It is also called "controlled traffic farming" (CTF) and presently apparently used fairly wide globally.

One of its advantages is that firm "roads" are created, leading to considerable fuel savings. It is also starting in South Africa, but no comparative research results seem to be available.

In the forestry industry it was also found that overall productivity decline depends on the areal extent of the harvesting operation and thus on the area compacted during harvesting (Smith and Johnston, 2001). Smith and Johnston (2001) point out that 40% growth loss over 10% of the area is very small compared to 20% growth loss over 80% of the area, *"which is considerable"*.

An important aspect related to controlled traffic is positioning of vehicular tracks relative to the plant rows. The tracks should be as far as possible away from plant rows. In a fertiliser experiment with maize in the northern Free State in the early 1970s, it was noted that yields differed per row and not per treatment (C.D. Koch, personal communication). It was then found that yield depended on the distance between the tractor wheel track and the maize row. Rows where the wheel track was closer to the row gave lower yields than where the tractor wheel track was further from the row. In the sugarcane industry, it has been found that in the traditional 1.5-metre row spacing tractor and vehicle wheels running on the side of rows have very bad impacts due to compaction, giving low yields (SASTA, 2001). Elsewhere very high yields were obtained by 1.8 metre row spacing, with wheel tracks running in the middle of the interrow areas, i.e. at the furthest possible distance from the sugarcane rows.

Understanding the wheel track factor is also important in the South African forestry industry, according to Smith and Johnston (2001), who stated that: *"The effects of soil disturbance, e.g. rutting, loosening and compaction in close proximity caused by logger operations, have had a greater effect on growth than operations causing deep compaction. This suggests that key growth processes, such as fine root development and nutrient cycling in the topsoil, have been affected"*.

Based on the results of studies on the impacts of ORD in wildlife areas it is strongly recommended that controlled traffic, driving in the same tracks, should also be implemented as far as possible where ORD is permitted (Nortjé, 2014; Nortjé et al., 2012a, b). Since this will only have limited impacts, because sightings occur random, the ideal is to prohibit ORD completely or at least reduce it drastically. This will require a big change in the mind-sets of wildlife tourists so that there will not be such a big demand for ORD for game viewing, preferably no demand (Nortjé, 2014).

7.3 Refrain from conducting operations on wet soil

Since studies have proven, as indicated earlier, that soil compaction by the wheels of vehicular traffic is much more severe on wet soils than on dry soils it is imperative that no operations should be conducted on wet soil. This becomes even more important when big, heavy equipment is used, as is presently the general trend. Among the heaviest equipment, especially under full load, are combine harvesters and grain carts, grain trailers and grain trucks. The ideal is to stay away from soils that are likely to be too wet during wet weather conditions, like wet periods or rain seasons with operations like harvesting. In the relatively high rainfall, eastern Free State this in some years poses serious problems with the harvesting of wheat if harvesting is not completed before the onset of the summer rain season.

This is amplified by the fact that the best wheat soils in that area are soils that are somewhat poorly drained. This is because the wheat is grown during the rainless winter season of the area and needs extra soil water to pull it through. In this same area harvesting of maize does not pose any problem, because it is harvested in the middle of the dry winter season. In an excellent extension paper from Virginia in the USA on the management of soil compaction, Thomason et al. (2009) recommend that the impact of a situation such as that for wheat above can be mitigated by (i) not filling the bin of the combine to full capacity before emptying it, i.e. keeping it lighter, and (ii) by not allowing grain carts or trucks into the field, but emptying the combine into them outside the edge of the field.

South African sugarcane farmers enter into contracts with sugar mills before they plant any block of sugarcane (SASTA, 2001). Contracts are designed to enable sequential relay harvesting so that the mills can operate fully continuously. Thus, farmers have to harvest according to a schedule. Harvesting is the most damaging operation in terms of compacting the soil, because the haulage vehicles that collect the cane in the field are very heavy when loaded. Planning should be such that during wet seasons harvesting will be done on soils that are inherently dry, while doing harvesting during dry seasons on soils that inherently tend to be too wet during wet seasons (SASTA, 2001).

Due to the much more severe soil compaction caused in game parks by ORD vehicles when driving on wet soil than when driving on dry soil it is recommended that ORD should not be allowed on wet soil (Nortjé, 2014). This would include not allowing ORD within a few days after a rainstorm. Wetlands should always be demarcated as no-go areas for ORD. Off-road driving in wetlands is unfortunately seen at times (Nortjé, 2014). It should especially be strictly prohibited in wetlands with RAMSAR status.

7.4 Use the lowest possible tyre pressures

Since it has been proven that tyre pressure is a major factor determining the severity of soil compaction, the ideal is consequently to work at the lowest possible tyre pressure that can carry a specific load (SASTA, 2001; Nortjé, 2014). The lowest pressure at which a tyre can operate safely differs much between different types of tyres (SASTA, 2001). Thus, it is very important to select the type of tyre that can operate at the lowest pressure. There is especially a specific type of radial tyre that has been developed to operate at very low pressures (SASTA, 2001). Brand names cannot be mentioned in a paper like this, but there are numerous references to this type of tyre, which was specially developed for heavy mining equipment, on the internet.

8 Implementation of rip-on-row and controlled traffic by farmers in the western part of the maize quadrangle

The great importance of the western part of South Africa's maize quadrangle for the country's food security was mentioned earlier in this paper. The largest proportion of the country's white maize, the country's main staple food, is produced in this area, as mentioned. It was explained that subsurface soil compaction is a major problem in this area.

The successes that have been achieved with practices of rip-on-row and controlled traffic in experiments have been discussed, as well as on-farm successes with them. The important question for the authors now was to establish to what extent farmers implement these practices, especially at present times. There are often very big gaps between what research has achieved and the implementation of those results by farmers. It has, for example, been found that millions of rand (the South African currency) have been spent in South Africa on research on irrigation scheduling, but that only 18% of the country's irrigation farmers implemented the excellent results emanating from this in practical on-farm irrigation scheduling (Annandale et al., 2011).

Therefore, in March 2019 the authors collected information on the present implementation of rip-on-row and controlled traffic in the mentioned area by means of seven leading questions to two experts with intimate knowledge of the situation, to which the experts gave comprehensive narrative replies. The experts responded completely individually, without any interaction between them. They were:

1. Prof. A.T.P Bennie, Emeritus-Professor of Soil Science, University of the Free State: One of the pioneers of research on soil compaction in the *Free State* and at the Vaalharts irrigation scheme, as can be seen from the several references to his research in this paper. *Particularly an expert on sandy soils.* He is highly rated as scientist, as seen by the fact that he is one of only four individuals who have ever received gold medals from the Soil Science Society of South Africa, in 2012. He is also renowned for his efficient dissemination of scientific knowledge to farmers, as proven by the fact that in 1983 he was the agricultural journalists' South Africa's "Agricultural Scientist of the Year" and in 1989 the "Maize Scientist" of the National Maize Producers' Organization (NAMPO).
2. Mr. M. du Plessis, Manager: Precision Farming at Northwest Cooperative in Northwest province: For the 2019 and 2020 term, he is President of the Soil Science Society of South Africa. He is advising and is closely involved with farmers in the Northwest province, especially the more marginal western parts, where soils are generally less sandy than in the northwest Free State.

Bennie: *"The soils of the Central and Western Free State are sandier than those of Northwest* (province). *The general practice is still* (note) *deep rip combined with controlled traffic, which gives the same effect as rip-on-row. Self-steering tractors make this practice easy. I estimate that 80% or more of the 1.5 million ha deep sandy soils are cultivated like this. At least 30% of the plant rests are left on the surface, which qualifies it as conservation tillage. Secondary cultivation is increasingly replaced by chemical weed control, to ensure better stover coverage. The remaining shallower loamy and sandy loam soils are managed like those in Northwest province.*"

In a follow-up question to Bennie regarding what he meant with deep ripping, he replied: *"It is 400-600 mm, depending on the clay content of the soil. The sandier the soil, the deeper. 600 mm for a clay content of <6% clay, 400 mm for 6-8% clay, shallower for 8-15% clay"*. It may surprise readers from elsewhere in the world to see reference to cultivated soils with <6% clay, but this is a reality. Very good yields are obtained on such soils where the soil is deep enough onto a fluctuating water table, which is quite a common scenario. When the senior author started working in the Highveld region in 1962, he studied soil profiles on the farm of one of the top maize farmers, on soil with 2% clay, 0% silt and 98% sand. This is where elimination of any compacted layer to enable roots to extract water from the deep subsoil becomes critically important, especially in a marginal rainfall area.

Du Plessis, writing about Northwest Province. Little bit of cut and paste here to get a more logical sequence: *"Rip-on-row was never a general practice here. There are farmers that implement it, but they are less than 10%. General rip is common, applied by 50-60% of farmers. Controlled traffic is increasing strongly. High cultivation costs force farmers to save on cultivation costs a controlled traffic is the answer. With GPS it is becoming much easier. More than 50% of farmers do it for one year, loosen the soil and new tracks are formed for the new season. A good practical variation is where controlled traffic is combined with rip-on-row once or once every second, third or fourth year. I have several farmers who apply rip-on-row in this way as a minimum cultivation system and it works excellently. Row widths and crops can also be adapted here with good planning. I propagate controlled traffic in a permanent system, were tractors and all traffic drive year-after-year in the same tracks. The tracks are not loosened and the plant areas remain loose. If cultivation is done, it is done only in the plant areas. It amounts to minimum cultivation. One of my farmers is on this system for 11 years already"*.

The reference of Du Plessis to ripping once or once every two, three or four years reminds one of the results of Mitchell and Berry (2001) given earlier in Table 2 regarding the number of permissible years without ripping, according to clay content of the soil.

According to Du Plessis about 30% of the soils in Northwest province are still ploughed, mainly with mouldboard ploughs to a depth of 25 cm, sometimes 20 cm. According to Bennie, less than 5% of the soils in the Central and Western Free State are still cultivated with mouldboard ploughs.

Bennie, gives a brief, but very important comparison with the Eastern Free State, where the rainfall is higher, and more reliable and the soils more clayey than in the Central and Western Free State: *"In the Eastern Free State, with shallower and more clayey soils, the soils are cultivated shallower with tined implements, combined with chemical weed control, which qualifies it as conservation tillage. In most cases it is done with controlled traffic"*.

Because of the concern of many South African soil scientists about the way that no-till is promoted, without apparent attention to required adaptation to the high drought risk marginal areas, especially on the sandy soils, Bennie and Du Plessis were requested to briefly comment also on this. Especially on the importance of ripping and controlled traffic under no-till in these areas and whether these are implemented.

Du Plessis: *"No-till is practised on probably <5% of soils in Northwest province. I am of the opinion that controlled traffic with permanent tracks is the only sustainable method of no-till. Compaction is a destroyer of sustainable no-till. Permanent controlled traffic is the only solution. This implies that planting must be done in the same row every year. The obstacle is the stubble in the row that packs against the planter, causing the no-till practice of changing the direction of the row each year. The solution is to shift the rows with GPS such that planting is done each year next to or between the rows of the previous year. Controlled traffic can then be done in no-till and I believe that no-till can potentially be sustainable"*. Note: The latter would imply annual controlled traffic and not permanent controlled traffic. The packing of stubble against ripper tines and planters needs not be a problem, since there are numerous references to and pictures of special no-till rippers, with a coulter in front of the ripper tine that moves away the stubble, e.g. Thomason et al. (2009). Such implements should just simply be used.

Bennie: *"I am not aware of farmers that implement no-till successfully on sandy soils in the Central and Western Free State. No-till, where only chemical weed control without any disturbing of the soil is used, is increasing in the Eastern Free State, but mainly on sandy clay loam and clay loam soils. I estimate it as on less than 5% of the soils. With no-till the farmers there also apply controlled traffic, since it is essential. With self-steering technology it is logical and easy."*

9 Concluding remarks

It has been indicated that subsurface soil compaction at shallow depth is a very serious and widespread problem throughout South Africa, as are the closely related problems of soil crusting (Laker and Nortjé, 2019) and soil erosion (Laker, 2004). The severity and wide geographic distribution of soil compaction is due to the inherent vulnerability of most of the country's soils to compaction. It should be realised the South Africa falls into what the senior author of this paper termed the "relatively unknown third major soil region of the world" (Laker, 2003), and which has been adopted by international soil scientists. This region has two parts, covering the mid-latitudes in both the southern in northern hemisphere. The areas are characterised by low and erratic rainfall, high temperatures and poor-quality soils. The soils differ vastly from the soils in the better known other two major soil regions of the world defined by Laker (2003), namely the soils at the high latitudes where the rich countries are and the soils of the humid tropics. Great care must therefore; be exercised when trying to compare findings in soil studies in those two regions with those for the soils of the mid-latitudes. Technologies from them cannot be adopted unless adapted to local soils and conditions in the mid-latitudes.

Much research has been done to gain an understanding of subsurface soil compaction in the soils of this third major soil region especially on the sandy soils. Soils factors that affect the vulnerability of soils to compaction have been identified. Management practices that aggravate soil compaction have been identified, with compaction by wheels of traffic, being a key one. Management practices to avoid or alleviate compaction have been identified, with ripping and controlled traffic found to be key practices to implement.

It is clear that technologies from other soils regions cannot be simply adopted, but that even within South Africa technologies have to be adapted to different soils and climatic conditions. Even within a narrow agro-ecological region, like the maize quadrangle there are major differences between the management requirements of different soils and climates. Very important is that the very important sandy soils, especially in the high drought risk areas, cannot be managed in the same way as less sandy soils and soils in higher rainfall areas. The reality that there is no possibility of "one fits all" scenario is echoed by Thomason et al. (2009) in Virginia in the USA, who found that success with deep tillage, for example, *"is dependent on soil type and conditions at an individual site and that generalized recommendations are inappropriate"*.

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