Review of Existing Knowledge on Soil Crusting in South Africa

M.C. Laker[1] and G.P. Nortjé[2,*]

[1]University of Pretoria, Pretoria, South Africa
[2] Environmental Sciences Department, University of South Africa, Johannesburg, South Africa
*Corresponding author; e-mail address: nortjgp@unisa.ac.za

Contents

1 Introduction 4

1.1 General 4

1.2 Extent, degree and spatial distribution of soil crusting in S.A. 5

1.3 Types of crusts in and on soil 7

2 Research methodologies 9

3 Effects of soil factors on soil crusting 13

3.1 Clay mineralogy 13

3.2 Particle size distribution (soil texture) 15

3.3 'Soil Organic Matter' (SOM) 18

3.4 Sesquioxides 19

3.5 'Exchangeable Sodium Percentage' (ESP) 21

3.6 Exchangeable magnesium and Mg:Ca ration 23

3.7 Parent material 24

4 Effects of environmental factors on soil crusting 26

4.1 Vegetative cover 26

4.2 Rainfall 26

5 Effects of soil crusting 27

5.1 Reducing infiltration 28

5.2 Inhibiting aeration 31

5.3 Inhibiting germination and seedling emergence 33

5.4 Limiting development and functioning of roots 34

6 Effects of management factors on soil crusting 34

6.1 Rangeland management 35

6.2 Management of cropland, orchards and vineyards 36

6.3 Irrigation management 40

7 Prevention and/or amelioration of crusting by means of gypsum/phosphogypsum or soil conditioners 43

8 Special effects of 'Biological Soil Crusts' (BSCs) 49

9 Soil crusting and "fairy rings" in South Africa (Northern Cape) and Namibia 50

Acknowledgements 53

References 53

Abstract

Soil crusting (surface sealing) is a widespread and serious problem throughout all nine provinces of South Africa and in neighbouring countries, like Botswana, Namibia, Swaziland and Zimbabwe. It is a problem in extensive rangelands and game parks and under rain-fed cropping and irrigated agriculture. Both mineral and biological soil crusts are problems. Various research methodologies are used to study soil crusting. Soil factors determining the susceptibility of a soil to crusting include soil organic matter, sesquioxides, particle size distribution, exchangeable sodium percentage, magnesium:calcium ratio and parent material. Negative impacts of soil crusting include reduction of water infiltration, leading to increased runoff and erosion and induced drought; inhibiting soil aeration; inhibiting germination and seedling emergence; inhibiting root functioning and development. Management practices that lead to the development of bare areas on crusted soils or those are aimed at deliberately maintaining bare areas, e.g. under drip and micro irrigation, aggravate soil crusting and its negative impacts. Crusted soils often do not recover even after several decades. Soil crusts can be ameliorated by means of mulching or application of gypsum (or phosphogypsum) or organic soil conditioners, such as polyacrylamide.

Key words: Soil crusting, clay mineralogy, parent material, mulching, soil conditioners

ABBREVIATIONS

BSC biological soil crust

C carbon

Ca calcium

CO_2 carbon dioxide

CSI crusting susceptibility index

EC electrical conductivity

EPS extracellular polymeric substances

ESP exchangeable sodium percentage

Fe iron

FIR final infiltration rate

gf germination force

HP humic products

K potassium

KCl potassium chloride

kPa kilo Pascal

Mg magnesium

Mg:Ca magnesium to calcium ratio

Mn manganese

MOR modulus of rupture

MPa mega Pascal

Na sodium

NaOH sodium hydroxide

PAM polyacrylamide

PG phosphogypsum

pH degree of acidity of a soil

PVA polyvinyl acid

SAR sodium adsorption ratio

SOM soil organic matter

Zn zinc

1 Introduction

1.1 General

This paper reviews the existing knowledge on soil crusting (surface sealing) in South Africa. Soil crusting 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 (Van der Watt and Valentin, 1992; Jones et al., 2013). Soil crusting has very serious implications regarding crop yields, water use efficiency and aggravating of soil erosion.

Intensive research on subsurface soil compaction has been conducted in South Africa since more than 50 years ago, mainly during the period from the 1960s to the 1980s. However, for a long period soil crusting received very little attention in South Africa. Most people seemed to be unaware of its extent and severity and many still are. Although some studies were conducted earlier, e.g. by Van der Merwe (1965) and Hutson (1971), intensive research on it was conducted really only during the late 1980s and the early 1990s. Major studies during this period were combined efforts between the University of Pretoria and the ARC-Institute for Soil, Climate and Water. Several major studies were also conducted at the then Potchefstroom University for CHE (now the Potchefstroom campus of Northwest University). Other institutions also made significant contributions. Only a small number of studies followed since.

The senior author has been involved with several field investigations on soil crusting in various parts of South Africa and Swaziland. He was also involved with a number of the comprehensive studies on soil crusting at the University of Pretoria, in collaboration with the ARC-ISCW, and by the Potchefstroom University for CHE, e.g. those by Nel (1989), Stern (1990), Bloem (1992), Bloem et al. (1992) and Van Deventer (2000).

No comprehensive review has been published on soil crusting in South Africa. Van der Merwe (1973) wrote an excellent general review on soil crusting, especially on the effects of crusting. What he wrote is still valid and is applicable to soil crusting in South Africa. Van der Watt and Valentin (1992) reviewed soil crusting in Africa, including much of the then existing knowledge on soil crusting in South Africa. Mills and Fey (2004a) published a relatively brief paper on soil crusting, including reference to some South African research.

Note that all soil form and series names used in this paper are according to *Soil Classification: A Binomial System for South Africa* (MacVicar et al., 1977).

1.2 Extent, degree and spatial distribution of soil crusting in South Africa

Soil crusting is found widespread in all nine provinces of South Africa and neighbouring countries like Botswana, Namibia, Swaziland and Zimbabwe. Unlike subsurface soil compaction, human-induced soil crusting is not confined to cultivated areas but is also a widespread problem in overgrazed rangelands and overgrazed areas in game parks.

Extreme crusting is found on soils of the Rûens and Swartland areas of the Western Cape, two of South Africa's main wheat and other small grain producing areas (Stern, 1990). The senior author found severe crusting in a peach orchard under drip irrigation near Tulbagh. Thus, severe soil crusting appears to be a quite widespread problem in that province.

Likewise, extreme crusting is found widely in soil of the Eastern Cape, especially irrigated alluvial soils. Soils derived from mudstones and shales are the most severely crusting soils in that province. The crusting problems in that province are so severe that Bloem (1992), in his comprehensive study on soils from seven provinces, did not only discuss them as part of the overall package, but also extracted the Eastern Cape soils as a separate chapter. He found that with water with low EC (10 $mS.m^{-1}$) some Eastern Cape soils *"totally seal"* at ESP values higher than 4% and concluded that this would place *"a big limitation on any overhead irrigation".* The senior author found oranges floating in water under micro-sprinkler irrigation in a citrus orchard near Addo National Park (Addo) in the Sundays River Valley, Eastern Cape. This case was further researched by *inter alia* Laker and Vanassche (2001). The senior author observed similar situations in citrus orchards elsewhere in the Eastern Cape. Severe crusting has also been reported from irrigated areas under other crops in the province, e.g. Loxton et al. (1987).

The senior author also observed widespread extreme crusting on abandoned rain-fed cultivated areas and bare overgrazed areas in that province.

Ellis (1988) observed that bleached A horizons in the Karoo (Northern Cape) have a strong tendency towards crusting. According to Botha et al. (1981) soils with high fine sand contents, which occur widespread on several irrigation schemes in the Northern Cape and Free State, normally have an *"inherent inclination"* towards crust formation. In the late 1960s/early 1970s A.J. van der Merwe (personal communication) identified serious crusting in red sandy soils of the Sandvet irrigation scheme in the Free State. Van der Merwe (1973) found that the red sandy Mangano series soils of the Hutton form, which cover most of the Vaalharts irrigation scheme in the Northern Cape, are prone to crusting. These are sandy soils with 8-10% clay and very high fine sand contents. According to personal communication from C. van der Ryst, former Professor of Agricultural Engineering at the then University of the Orange Free State, in the 1980s soil crusting on the sandy soils on irrigation schemes of the Northern Cape and Free State became a problem only after the introduction of overhead irrigation, replacing flood irrigation. A farmer south of Ladybrand in the eastern Free State explained that soil crusting was the main problem in his wheat production. He sometimes had to replant three times to get acceptable emergence of wheat seedlings through the crust.

In 1962, the famous J.P.F. Sellschop, at the time South Africa's foremost expert on oil seed crops, stressed to the senior author that soil crusting was a major limiting factor in rain-fed production of groundnuts in the then Highveld region. This region included what is now the eastern half of the North West Province, the northern Free State, Gauteng and the Highveld of Mpumalanga. Crusting was found to be a widespread problem on red sandy soils of the Hutton form in parts of the North West Province (Molope, 1992; Materechera et al., 2007). The senior author similarly found severe crusting in a red sandy soil near Radium, south of Bela-Bela in the south of Limpopo.

The senior author observed severe soil crusting in black swelling clay (vertic) soil of the Arcadia form on the Springbok flats in Limpopo. Snyman et al. (1985) found that the crust of a crusting black clay (vertic, Arcadia form) soil north of Standerton, on the Mpumalanga Highveld, had a MOR value that was four to five times higher than the value (60-80 kPa) which they considered as detrimental to seedling emergence.

Since about 2013, the senior author has received several reports, with photographic evidence, of severe soil crusting in drip irrigated citrus and subtropical fruit and nut orchards in various parts of the Lowveld of Mpumalanga and Limpopo. The senior author recently observed severe crusting in an avocado orchard near Tzaneen, Limpopo. Severe soil crusting has also been found in irrigated areas along the north-western boundary of Limpopo.

Soil crusting is also a serious problem in KwaZulu-Natal, as evidenced by the studies of Hutson (1971), Van der Watt and Claassens (1990) and others. Mills and Fey (2004b) studied soil crusting at 19 sites in Limpopo, Mpumalanga, KwaZulu-Natal and Eastern Cape. The site with the lowest infiltration rate, ascribed to crusting, was in KwaZulu-Natal.

Both authors have observed severe soil crusting in several overgrazed bare areas in the Kruger National Park (KNP), as well as in overgrazed rangelands and overgrazed areas in nature reserves in the central parts of Limpopo. Mills and Fey (2004a) observed crusting in granitic landscapes of the southern KNP. The large bare areas with severe soil crusting in the Pafuri area in the far north of the KNP are not overgrazed areas but were the former cultivated fields of the Makuleke people who lived there up to 1969 (Nortjé, 2014).

Across the border in Swaziland, the senior author found widespread severe crusting in irrigated citrus orchards under drip irrigation. Nyamapfene and Hungwe (1986) mapped the distribution of crusted soils in Zimbabwe. They found crusts on both sandy and silty soils. Crusting soils are among the most problematic soils to farmers in Zimbabwe (Nyamapfene, 1991). Molope (1992) reported widespread soil crusting on red sandy soils in Botswana. Cyanobacterial crusts cover between 19 and 55% of Kalahari Sand areas studied in Botswana (Dougill and Thomas, 2004; Thomas and Dougill, 2006). Soil crusting is widespread in Namibia, as also evidenced by the senior author in some areas. Much attention has been given to lichen crusts in Namibia by several researchers.

1.3 Types of crusts in and on soil

Two main groups of crusts are found in and on soils, namely mineral crusts, formed by dense packing of soil particles and biological crusts.

Formation of ***mineral soil crusts*** is due to the disintegration of soil structure, leading to the formation of a dense layer at the soil surface. Stern (1990) and Bloem (1992) confirmed that it is important to recognise the two mechanisms of crust formation distinguished by Agassi et al. (1981). These are:

- Crusting that occurs due to chemical dispersion of a soil (i.e. where a crust forms even under very low to zero water drop energy). Crusts formed in this way are sometimes called *depositional* crusts (Van der Watt and Valentin, 1992);
- Crusts that form primarily because of the physical (mechanical) impact of water drops (either from rain or overhead irrigation). Bühmann et al. (1996) pointed out that this should be referred to as *disaggregation* of soil aggregates by drop impact and not as *dispersion*. Crusts formed in this way are sometimes called *structural* crusts (Van der Watt and Valentin, 1992).

It should be kept in mind that these mechanisms often operate together in crust formation, but the key is to identify the dominant one for each case.

Gerber and Harmse (1987) stress a third mechanism for mineral crust formation, namely slaking. Slaking, is defined as the breakdown of large soil aggregates when they become immersed in water, by a process where clay swells upon wetting and air bursts out. The senior author observed this where subsoil with unstable coarse structure has been exposed at the soil surface due to removal of the topsoil by means of sheet erosion. Such crust becomes extremely hard when it dries.

Extremely dense and highly impermeable (to both water and air) mineral soil crusts are often extremely thin, thinner than the blade of a pocketknife, i.e. only a few millimetres thick. Some crusts are multi-layered and somewhat thicker.

According to Menon et al. (2011), BSCs *"are formed by an intimate association between soil particles and cyanobacteria, green algae, micro-fungi, bacteria, lichens and bryophytes which live within or immediately on top of the uppermost millimetres of soil"*. Different BSCs are colonised by different organisms and there is much heterogeneity between different BSCs (Mager and Thomas (2011). The dominant organism causing big differences, between different BSCs, determine the characteristics and influences of any specific BSC. According to Mager and Thomas (2011), BSCs are a common feature of all drylands (arid to hyper-arid areas). A.J. Dougill and A.D. Thomas and co-workers have conducted numerous studies on especially cyanobacterial crusts in arid areas of Southern Africa. They concentrated mainly on the Kalahari sands in Botswana, but also conducted some studies in adjoining areas in South Africa and Namibia. An internet search with their names will yield references to their publications and information on publications by others that are not part of their team.

Elsewhere in South Africa, serious biological crusting is quite common in irrigated orchards, especially under drip irrigation. These include subtropical fruit and nut, citrus and deciduous fruit orchards from the north of Limpopo, along the Lowveld of Limpopo and Mpumalanga and right around to the Western Cape, in the south. The crusts are concentrated on the moist soil areas where irrigation is applied, mainly in the shaded areas under the tree canopies. It has also been found in other irrigated areas, e.g. on the Tyefu small-farmer irrigation scheme in the Eastern Cape (Loxton et al., 1987). Van der Watt and Claassens (1990) studied biological crusts in an irrigated area at Makhatini, in north-eastern KwaZulu-Natal. Hutson (1971) found biological crusts in an eastern coastal area in KwaZulu-Natal. Mills and Fey (2004a) also found biological crusts in granitic landscapes of the southern KNP, a sub-humid area. All the above-mentioned areas have opposite soil moisture regimes to those of the arid areas where research on biological crusts had been concentrated. It seems as if very little, if any, research on BSCs under sub-humid to humid soil moisture regimes had been done.

There is technically also a third group of soil crusts, namely ***chemical crusts*** (or salt crusts), such as found on large salt plains or on saltpans. The best-known large salt plain/pan in South Africa is Verneukpan in the Northern Cape. Chemical crusts are normally not included in discussions on soil crusting, because it is not of agricultural or environmental significance. Apart from this reference to its existence, it will not be discussed in this review.

2 Research methodologies

Various research methodologies have been used in studies on soil crusting in South Africa. These range from broad scale field observations, through field experiments to detailed laboratory studies.

Ad hoc field observations and investigations are extremely valuable to gain information as first step in studying something like soil crusting, which can visually be observed easily in the field. Recording, integrating and interpretation of visual observations can be more valuable than trying to start "blindly" with qualitative (or even quantitative) measurements under field conditions in unknown situations, because the latter can sometimes be quite misleading. The value of field observations can be enhanced by combining it with collecting information on the practical experiences of local farmers.

The types of information that can be obtained by means of *ad hoc* field observations and investigations, and informal discussions with farmers, include:

- The occurrence (where), extent and severity of crusting;
- The characteristics of crusts, especially morphological characteristics;
- The practical effects and impacts of crusts and economic implications thereof;
- Causes of crusting.

In Zimbabwe structured field soil sampling and collection of information by means of questionnaires was used (Manyevere et al., 2015).

Experimental runoff plots used for soil erosion studies often offer good opportunities for indirectly or informally collecting additional data on various aspects regarding soil crusting in the field. Important information regarding soil crusting was, for example, obtained from runoff plots researched by Stern (1990). Unfortunately, such "incidental" information is usually not recorded in research reports or publications. In the case of incidental information obtained during the research by Stern (1990) the senior author only knows about it because he was supervisor for Stern's study.

Runoff plots have over many decades been used by non-soil scientists in numerous studies in South Africa and Zimbabwe on relationships between runoff and erosion. Soil scientists have used runoff plots in studies on relationships between soil factors, crusting, runoff and erosion in South Africa (e.g. Stern, 1990; Stern et al., 1991b; Stern et al., 1991c).

Irrigated field plots have often been used in studies on soil crusting in South Africa, especially in research on the use of different types of soil conditioners for ameliorating soil crusting (e.g. Botha et al., 1981; Stern, 1990; Stern et al., 1992; Laker and Vanassche, 2001). Rain-fed field plots have also been used (Materechera et al., 2007; Materechera, 2009).

Field scale rainfall simulation, with rotating boom simulators, has been used in several studies on soil crusting in South Africa (e.g. Stern, 1990; Van der Watt and Claassens, 1990; Bloem et al., 1992; Bloem and Laker, 1994a). Custom-built rainfall simulators, described in these papers, were designed and built at research institutions like the ARC-ISCW and the University of Pretoria.

Intensive laboratory scale research on soil crusting, runoff and erosion has been conducted in South Africa. Custom-built laboratory scale rainfall simulators were used in these studies. At the ARC-ISCW a rotating disc type laboratory scale rainfall simulator was used in several studies, such as those reported by Levy (1988), Levy et al. (1988), Levy and Van der Watt (1988), Stern (1990), Laker and Bredell (1990), Smith (1990) and Stern et al. (1991a,b,c). Such simulator was also used in the studies of Louw (1991). For a comprehensive study conducted at the Potchefstroom University for CHE, a needle type laboratory scale rainfall simulator, was designed and built in the Department of Agricultural Engineering of the University of Pretoria. A description of this instrument is shown in Bloem et al. (1992). Results obtained with this instrument are discussed in Bloem (1992), Bloem et al. (1992), Bloem and Laker (1993) and Bloem and Laker (1994a, b).

In most of the studies mentioned above, combinations of different types of research methodologies were used, mainly combinations of field scale studies with runoff plots and/or field scale rainfall simulation with laboratory scale rainfall simulation. The comparative study reported by Bloem (1992) and Bloem and Laker (1994b), showed that results obtained with laboratory scale rainfall simulation studies should be treated with caution when extrapolating it to the field, since infiltration in the field can be considerably higher than in the laboratory due to greater surface roughness and porosity, the latter e.g. due to cracking, in field soils. In the study of Stern et al., (1991a) results from field and laboratory scale rainfall simulation studies were correlated with a basic laboratory study involving dispersion of soil by means of ultrasonic vibration and determination of the particle size distribution in the soil suspensions by means of a laser beam light scattering technique.

Massingue (2002) used pot experiments to study the effects of soil crusting on seedling emergence. The senior author and co-worker Ingrid Bredell conducted numerous greenhouse pot experiments on the effects of different types of soil conditioners on a number of severely crusting soils. Positive results were obtained, even on physically extremely unfavourable gold mine slimes dam material. Laker and Bredell (1990) reported a small selection of results obtained with coal-derived humic substances.

Reliable measurement of crust strength is problematic because crusts are so thin and unconfined at the surface. Because of the latter penetrometers with cone shaped tips, where soil can move around the tip, were decades ago not considered suitable for determining crust strength. Probes with flat tips have been used successfully elsewhere in Africa, however (Van der Watt and Valentin, 1992). Hutson (1971) and Snyman et al. (1985) used MOR to determine crust strength. However, elsewhere, Page and Hole (1976) found that MOR had disadvantages and proposed that Shear Vane should rather be used to determine soil crust strength. In the 1960s and early 1970s, when the senior author was involved in soil compaction research it was believed that the Torvane Shear apparatus was the most suitable for determining crust strength, while penetrometers could be used for determining strengths of subsurface compacted soil layers. However, more recently, Massingue (2002) compared penetration resistance, MOR and emergence force as indicators of crust strength. She concluded that all gave good results and that any could be used to assess the crust strength of soils. Materechera et al. (2007) and Materechera (2009) measured penetration resistance to a depth of 10 cm by means of a hand-operated soil cone penetrometer. Manyevere et al. (2015) did not determine crust strength, but only crust thickness, which they found to vary between 1 and 10 mm (0.1 to 1 cm) in different soils.

Detailed South African investigations on the characteristics of soil crusts, by scanning electron microscopy, have been made by Levy et al. (1988) and Van der Watt and Claassens (1990).

3 Effects of soil factors on soil crusting

These discussions on the effects of soil factors on soil crusting refer to the effects on mineral crusts, except where it is specifically indicated that effects on biological crusts are meant.

The relationships between various soil factors and crusting have been studied intensively in South Africa. Many of these were studies directly focused on crusting, but in some deductions were made from studies on aspects related to crusting, such as soil erosion. The soil factors related to crusting are essentially the same that determine the susceptibility of soils to subsurface soil compaction and the hard-setting tendencies of different soils.

Although the effects of individual factors are discussed separately, it must be kept in mind that they operate interactively and that in practice the potential effects of a certain factor can be masked or overridden by effects of another factor that dominates in a specific soil or situation.

3.1 Clay mineralogy

Clay mineralogy has been identified as one of the most dominant soil factors affecting soil crusting in South Africa. This effect is so strong that soils have to be grouped according to their clay mineralogy before meaningful models describing relationships between crusting and various other soil factors can be derived (e.g. Bloem, 1992; Bloem and Laker, 1994a, b).

In line with international findings it has been found that smectite-dominated soils are highly dispersive (Levy and Van der Watt, 1988; Bloem, 1992). Because the clay fractions of the vast majority of South African soils are dominated by kaolinite orillite, the findings of a large amount of overseas crusting research, done predominantly on smectite-dominated soils, cannot be applied indiscriminately to South African soils (Du Plessis and Shainberg, 1985). Levy and Van der Watt (1988), in fact, used smectite-dominated soils from Israel to compare with kaolinite and illite dominated South African soils.

Levy and Van der Watt (1988) found that the illitic soils of South Africa had less severe crusting than the smectitic soils from Israel. On the other hand, they found that the illitic soils were much more susceptible to crusting than the kaolinitic soils. The latter was confirmed in subsequent studies (Stern, 1990; Stern et al., 1991b). Stern (1990) found that illitic soils from the Western and Eastern Cape especially were extremely prone to crusting, leading to exceptionally high runoff from even small rainstorms. Stern et al. (1991b) also discuss a few examples from these. The vulnerability of illitic soils is a major problem, because major areas of South Africa include such soils.

Soil, of which the clay fraction is dominated by kaolinite, is normally considered stable against dispersion and crusting. South African research, especially on red apedal (Hutton) soils dominated by kaolinite clay mineralogy, has shown that this is often the case, but that it is a very dangerous generalization to make. The study of Hutson (1971) included a large area where red soils with low infiltration resulting from crusting are found. Du Plessis and Shainberg (1985) also found that some red soils did not have the high stability, usually believed to be associated with such soils. It has been found that kaolinite soils, which contain a small amount of smectite, are much more susceptible to crusting than those without it (Cass and Johnston, 1985; Levy and Van der Watt, 1988; Stern, 1990; Stern et al., 1991c; Bloem, 1992; Bloem et al., 1992; Bloem and Laker, 1994a). Rapp (1998) ascribes this to a mechanism described by Schofield and Samson (1954): *"negatively charged smectitic platelets neutralize the positive charges on the edges of kaolinite and interfere with edge-to-face flocculation. Therefore, the ability of smectite contaminated kaolinite clay particles to form a bridge between two adjacent particles, to form a cohesive aggregated structure, is quite limited."*

Van Deventer (2000) studied the effects of water with different **electrolyte concentrations** (determined as electrical conductivity, EC) and SARs on surface sealing and infiltration on soils with different clay mineralogies, but similar textures. The susceptibility of the soils to crusting followed the sequence smectitic>illitic>kaolinitic.

Bühmann et al. (1996) found that for many South African soils mild mechanical shaking in water results in greater disaggregation of clay-sized quartz and feldspar than layer silicates. These "inert" materials were also found to disperse easily with increased Na levels, but do not flocculate upon addition of Ca. Since the silt fraction of soils contains considerable amounts of quartz and feldspars, it is postulated that this is a major reason for the severe crusting of silty soils. This was further elaborated by Bühmann et al. (2006). Mineralogical analyses showed that the (silt + clay) fraction of a strongly compacting soil from Riversdale in the Rûens area of the Western Cape consisted mainly of quartz particles, with minor quantities of micas (Moolman and Weber, 1978). One can thus postulate that dominance of quartz in the (silt + clay) fractions may be an important contributing factor to the high susceptibility of soils of the Rûens area to crusting and erosion. Quartz is the main component of the clay fractions of the soils at two of the sites studied by Nortjé (2014) and Nortjé et al. (2012) in the Pafuri area in the north of the KNP, with the soil at the third site also containing significant quantities.

Due to the big influence of clay mineralogy on crusting, and consequently infiltration, implementation of the criteria derived for the planning and design of overhead irrigation systems requires at least semi-quantitative clay mineralogical analysis of soils (Bloem, 1992; Bloem and Laker, 1994a). Because of this, and the big influence of clay mineralogy on soil crusting found by the other researchers mentioned above, Bloem (1992) recommended that the facilities and personnel to do such analyses be expanded in South Africa.

3.2 Particle size distribution (soil texture)

No comprehensive systematic studies regarding relationships between particle size distribution and soil crusting have been done in South Africa. The closest to this is the study by Bloem (1992), also partially reported by Bloem and Laker (1993, 1994a), in which aspects such as relationships between particle size and infiltration rate were studied for 67 soils from all over South Africa. This enables indirect deductions regarding relationships between particle size distribution and soil crusting (Mills and Fey, 2004a). Indirect deductions are also made from data obtained with related research, such as soil erosion research, as was also pointed out by Van der Watt and Valentin (1992).In addition, one has to rely on integrating data and information from studies based on small numbers of samples, qualitative studies and field observations.

It seems as if severe soil crusting occurs in soils with widely different particle size distributions, from sandy soils to vertic clay soils. According to Van der Watt and Valentin (1992), soils with less than 20% clay are usually very susceptible to crusting, with soils with approximately 90% sand and 10% (silt + clay) the most prone to crusting.

In the study with 67 South African soils it was found that FIR, as influenced by soil crusting, decreased with increasing clay content up to a specific clay content (Bloem, 1992; Bloem and Laker, 1993; Bloem and Laker, 1994a). Above that clay content it remained constant with increasing clay content. For smectitic soils the minimum FIR was reached at about 20% clay. This agrees well with the findings reported for smectitic soils in Israel (Ben-Hur et al., 1985) and the Sahel Desert (Valentin, 1995). The big difference is that in both the latter cases infiltration thereafter increased again with increasing clay content above 20% clay, indicating less severe crusting at higher clay contents in smectitic soils. Massingue (2002) found that crusting increased with increased clay content up to 20 to 25% clay. At higher clay contents the degree of crusting decreased because of cracking of the soil due to the effect of swelling smectitic clay. Generalization of such results can lead to big errors, however. Severe soil crusting has also been found on smectite dominated vertic soils with high clay contents, for example as reported by Snyman et al. (1985) and observed by the senior author. In the first version of the South African soil classification system soils of the Arcadia form (swelling clay vertic soils) were at series level differentiated into series with "strongly crusting surfaces" and series with "self-mulching or weakly crusting surfaces" (MacVicar et al., 1977). This distinction is very important from a practical land use point. Snyman et al. (1985) emphasised the value of self-mulching characteristics in vertisols for alleviating soil crusting. Unfortunately, this very important criterion was not retained in the revised South African soil classification system (Soil Classification Working Group, 1991). The findings of Ben-Hur et al. (1985), Valentin (1995) and Massingue (2002) would be valid only for self-mulching relatively clayey smectitic soils.

Bloem (1992) found that in kaolinitic soils the FIR decreased with increasing clay content. The lowest FIR occurred at 40% clay, above which it remained constant with increasing clay content. For the kaolinitic soils, this lowest FIR value was much higher than that for smectitic soils.

On the other hand, Smith (1990) found that crusting decreased and infiltration increased with increasing clay content. In this case increased clay content was a result of increased degree of weathering, which was also associated with decreased smectite content and increased kaolinite and sesquioxide contents in the soils. The latter all give more stable soils with less crusting and were possibly the overriding factors.

Bloem (1992) quotes Israeli data according to which the silt contents of soils do not have any influence on crusting. However, the South African situation probably more closely resembles those in the Sahel Desert, where it was found that soils richer in silt *"generally experience more severe crusting problems"* (Valentin, 1995). This is supported by the finding of Loxton et al. (1987) in the Lower Fish River area of the Eastern Cape that: *"because of the high silt and fine sand content and relatively low clay content, all the lower terrace soils display crusting problems"*. Some of this crusting is extremely severe. In a study of data for several so-called hard-setting soils, mainly from the Eastern Cape, the senior author concluded that it could be expected that soils with more than 50% (silt + fine sand) — especially those with more than 20% silt — and less than 35% clay would be most susceptible to crusting (Laker, 2001). From data for a few soils, Massingue (2002) concluded that crusting could be predicted by the (silt + clay) content of the soil. She recommended that this potential relationship should be studied with a much larger number of soils with different (silt + clay) contents. Manyevere et al. (2015) defined the CSI of soils as the ratio between the percentage (fine sand + silt) and the percentage (clay + coarse sand + medium sand).

Bühmann et al. (1996) developed the hypothesis: *"the marked susceptibility of silty soils to erosion is directly related to the chemically inert character of their dominant soil constituents, i.e. quartz and feldspar"*. The effects of the latter have been discussed in the section on clay mineralogy.

In line with findings regarding relationships between particle size distribution and subsurface soil compaction, there appears to be a perception that soil crusting is strongly related to increased fine sand and/or silt content. Fine sand (including the present very fine sand) is a dominant factor in the crusting of sandy soils at, for example, the Vaalharts irrigation scheme (Botha et al., 1979, 1981). Manyevere et al. (2016) found that the fine and very fine fractions of soils were the most important factors controlling soil erosion in arid and semi-arid areas in the central Eastern Cape. This agrees with results reported by D'Huyvetter (1985), Laker and D'Huyvetter (1988) for the same area. It can be deduced that this will also apply to soil crusting in view of observed close relationships between crusting and erosion in the area.

According to the various publications on biological crusts on the "Kalahari sands" in the drylands of Botswana, these soils have up to more 95% "fine sand" and less than 10% clay (e.g. Menon et al., 2011). In the photo of "Type 1" (first stage) cyanobacterial crust in Menon et al. (2011), it is clear that this is simply a very thin typical mineral crust found on such sandy soil. It is in appearance identical to such very thin mineral crusts found (and photographed) by the senior author in sandy soils in the Namib Desert southwest from Maltahöhe in southern Namibia. Menon et al. (2011) describes it as simply a thin sand layer "at the surface". They then show photographs of different stages of biological crust development on (and in) such mineral crust. In the irrigated areas of South Africa, biological crusts have been observed on soils with different textures, *inter alia* including sandy and silty soils.

3.3 'Soil Organic Matter' (SOM)

Soil crusting occurs when soil structural units (peds) at the soil surface disintegrate due to chemical dispersion or physical disaggregation. Thus, crusting is related to the stability of soil structure in the surface soil. Stable soil structure refers to structure that is resistant against disintegration due to dispersion and/or disaggregation. The less stable the structure of the surface soil is the more vulnerable is the soil to crusting. Stable structure must not be confused with strong structure. Strong structure refers to how well structural units (aggregates, peds) are developed. Especially in Africa, including south and Southern Africa, strong structure is often very unstable structure.

Soil organic matter and sesquioxides are the main aggregate stabilizing agents in soils. Various other factors are involved in aggregate formation, but they do not contribute to aggregate stabilization. It would therefore be expected that increased soil organic matter content will feature as one of the main factors reducing soil crusting as found by Du Plessis and

Shainberg (1985). In temperate areas with inherently fertile soils, such as in the developed countries at high latitudes in the northern hemisphere, it is possible to maintain high SOM levels. However, the high organic matter decomposition rates in warmer climates such as in southern Africa make it very difficult to maintain high SOM levels (Van der Watt and Valentin, 1992). The low and unreliable rainfall aggravates this. Consequently, SOM has not consistently in South African research on soil crusting been found to be a significant factor.

In the study with 67 soils, SOM did not feature as a factor in multiple regression equations of infiltration vs. soil factors (Bloem, 1992; Bloem and Laker, 1994a). It was, however, found that all soils with extremely low SOM contents (<0.2%) are dispersible and strongly crusting. A significant finding was that SOM did not feature as a factor where moderate to high energy "rain" was applied but was a significant factor where low energy rain was applied. Thus, it seems as if SOM was more important where chemical dispersion became relatively dominant than where physical disaggregation was relatively dominant. The results regarding SOM in the study of Smith (1990) are inconclusive because too many factors were involved simultaneously.

Frenkel et al. (1989, 1992) found that humic substances increased dispersion of soils, which is contrary to all expectations. The effect was bigger on kaolinitic soils than on smectitic soils. In numerous unpublished studies on strongly crusting soils with a large number of coal-derived humic substances produced by CSIR (South Africa's Council for Scientific and Industrial Research), the senior author and co-worker Ingrid Bredell found that only an extremely small number of the products had the ability to produce stable aggregates in crusting soils. According to Mills and Fey (2004a), the variable results obtained with organic matter prompted Sumner to state, *"a cohesive theory on the effects of different fractions of organic matter on clay dispersion has yet to be developed and this remains as a substantial gap in our understanding of how soils degrade"*. Sumner probably referred mainly to the results of Frenkel et al. (1989, 1992).

3.4 Sesquioxides

In warm sub-humid to arid tropical and subtropical areas, where the role of SOM in soil structure stabilisation is small and uncertain, sesquioxides, especially ferric oxides, become the dominant factor in soil structure stabilisation, and thus also in counteracting soil crusting and erosion. It is also a major factor in South Africa, as has been shown in studies related to soil structure stability, such as those by Sumner (1957), D'Huyvetter (1985), Stern (1990), Rapp (1998) and Manyevere et al. (2016).

Du Plessis and Shainberg (1985) showed that sesquioxides stabilize soil aggregates and reduce the effects of sodicity on clay dispersion and crusting. Thompson (1986) found that a red sesquioxic soil from the Mpumalanga Highveld did not even disperse at an ESP of over 40%, an extremely high value. In the same area, Smith (1990) also found that increased stability of very stable red soils against crusting was related to increased sesquioxide contents of the soils.

Stern (1990) and Rapp (1998) did intensive laboratory-scale erosion studies on a red structured clayey soil of the Shortlands form from Upper Ncera, near Alice in the Eastern Cape after field research by D'Huyvetter (1985) identified it as a very stable soil. In his rill erosion studies, Rapp (1998) found that it was impossible to erode this soil. Microscopic study of a thin section of this soil by the senior author and M. Samadi, for a World Reference Base for Soil Resources working group (WRB) workshop in South Africa, showed that even the topsoil of this soil is virtually completely impregnated with ferric oxides, causing it to be so stable.

The stable South African Shortlands soils are quite similar to the Nitisols of the WRB soil classification system (FAO/ISRIC/ISSS, 1998). Nitisols are by definition recognised as soils with low dispersible clay contents. Tengberg and Stocking (1997) found Nitisols to be extremely stable against degradation. Farmers in east Africa (ISSS Working Group RB, 1998) describe these soils as highly sought-after soils.

At the other end of the scale, Ellis (1988) observed that in the Karoo bleached A horizons had a greater tendency to crust than non-bleached A horizons. He suggested that iron oxides are critical for stabilization of structure in these surface horizons and that the loss of iron oxides from them (evidenced by their bleached colours) causes their high susceptibility to crusting. Elsewhere, extreme crusting has also been found in soils with bleached A horizons, for example in various parts of the Eastern Cape. In the revised South African soil classification system, soils are in various soil forms at family level separated between those having bleached A horizons and those that do not (Soil Classification Working Group, 1991).

3.5 'Exchangeable Sodium Percentage' (ESP)

Exchangeable sodium percentage is worldwide considered to be probably the most important soil factor affecting dispersion in soils and, consequently, soil crusting. It has also in several South African studies been found to be one of the most dominant factors in soil crusting.

There has traditionally been a very simplistic view that serious negative effects of Na on soil physical conditions, such as crusting and reduction in infiltration, due to clay dispersion occur when the ESP exceeds 15%. This was prompted by the classical publication of Richards (1954). An ESP, of 15% as threshold above which Na becomes a problem, is apparently still generally used as norm in many countries. In countries like Australia, Zimbabwe, Russia and South Africa, it has conclusively been shown that there is no such single "magical" ESP figure. The critical ESP differs widely for different soils and conditions.

South African research, like that in the other countries mentioned, has shown that in soils that are very prone to crusting, dispersion and crusting take place already at extremely low ESP levels. An extreme example is the finding of Du Plessis and Shainberg (1985) that reduction in water infiltration, due to surface sealing of the soil, can occur at an ESP as low as 1% — if water with low electrolyte content is used. They noted that many arable soils in arid and semi-arid regions of the world have ESPs between 1% and 5%, which until then, had not been considered to pose problems in terms of crusting. They concluded that crusting on such soils could be severe under irrigation.

The study of Du Plessis and Shainberg (1985) comprised soil-crusting studies on seven South African soils, using laboratory-scale rainfall simulation. Four of the soils showed a drastic increase in crusting upon a small increase in ESP. In these four soils, FIR decreased from 7.2 $mm.h^{-1}$ at an ESP of 0.6% to an extremely low 1.5 $mm.h^{-1}$ at an ESP of only 4.6%. The other three soils were more stable against crusting and maintained higher FIR values and showed very little reduction in FIR with increase in ESP. This was ascribed to the higher sesquioxide and organic matter contents of the latter soils (Du Plessis and Shainberg, 1985).

Levy and Van der Watt (1988) found that a highly weathered red oxic soil (Hutton form) with 30% clay, absolutely dominated by kaolinite, had a surprisingly low FIR (average about 6 $mm.h^{-1}$), but that increasing ESP from 1.2 to 8.9% had no effect on FIR. A somewhat less highly weathered Hutton soil with only 7% clay had almost identical FIRs of just over 21 $mm.h^{-1}$ at ESPs of 1.0 and 6.3, but the FIR dropped by almost 50% to 11.0 $mm.h^{-1}$ at an ESP of 13. The clay fraction of this soil was dominated by kaolinite and some other 1:1 minerals, but also contained a small amount of smectite. In an Avalon form soil with 20% clay dominated by kaolinite, but with significant quantities of illite and smectite FIR decreased drastically from 12.9 $mm.h^{-1}$ at ESP <1 to only 4.1 $mm.h^{-1}$ at ESP 4.8 and even further at ESP 9.7. Stern (1990) found similar trends where kaolinitic soils contain significant amounts of smectite. The response of the Avalon soil to increased ESP was even more drastic than the response of a Swartland form soil with 15% clay. The clay fraction in the Swartland soil form was absolutely dominated by illite and swelling interstratified minerals, where FIR also decreased drastically with an increase in ESP from 1.1 to 4.3 and further at an ESP of 11.3 (Levy and Van der Watt, 1988).

The biggest problem soil, from a practical point, in the soil erosion studies of Stern (1990) and Rapp (1998), namely an extremely severely crusting illitic soil of the Trevanian series of the Glenrosa form from Piketberg in the Western Cape had high sheet and rill erodibility even at an ESP of only 1%. Soil loss doubled at an ESP between 4 and 5%.

Based on the data of laboratory-scale rainfall simulation studies on 67 South African soils from all over the country it was concluded that, soils with ESP values over 2.0% could be classified as chemically dispersive and thus strongly crusting (Bloem, 1992; Bloem and Laker, 1994a). Water with different ECs was used in the study. As is well known, dispersion occurs if the EC is below the threshold concentration for a specific ESP, so the lower the EC, the lower is the ESP at which dispersion and crusting occurs.

Van Deventer (2000) studied the effect of water with different ECs and SARs on soil crusting and infiltration. On kaolinitic soils, water with low EC caused dispersion, crusting and reduction in FIR. When irrigated with water with high EC, these soils remained stable, even at high SAR values. Illitic soils responded similar to kaolinitic soils to the effects of Na up to an ESP of 10, above which FIR of the illitic soils decreased sharply. Smectitic soils were very sensitive to the SAR of the irrigation water.

It must be kept in mind that rainwater has an extremely low EC and will thus cause extreme crusting and runoff on problem soils (Nel, 1986). According to him it often happens in summer rainfall areas that early spring rains can cause irreversible damage to the physical condition (severe surface sealing) of irrigated top soils in which Na has built up to potentially harmful levels during winter. According to Nel, the latter happens when the ESP exceeds 5%. Nel (1986) discusses the reasons for this situation and recommends possible mitigating measures.

Nel (1986) also discusses the concern at the time about possible negative effects if a fast change would be made from high EC Fish River water to low EC Orange River water in the Lower Fish River irrigation schemes, like Tyefu, in the Eastern Cape. In his study of the area, Nel (1986) pointed out that the danger always exists that the sensitive relationship between the salt concentration of irrigation water (as indicated by EC) and the ESP of the soil can be disturbed. As soon as the salt concentration drops below the threshold concentration, the soil will disperse and crust.

It is clear that there is no single critical ESP value. The critical ESP value depends on various other factors, which must be understood well and taken into account. The big concern in South Africa is the very low critical ESP values above which serious dispersion and crusting occurs in many of our soils.

3.6 Exchangeable magnesium and Mg:Ca ratio

Note that in the following discussions exchangeable cation concentrations are always implicitly given as $cmol_{(+)}.kg^{-1}$.

It is well-known that high exchangeable Mg levels and lopsided Mg:Ca ratios are important factors contributing to dispersion and crusting of soils in South Africa. Van der Merwe (1965) was the first to "expose" the magnesium problem in South African soils. In basic studies with sodic soils from the Riet River irrigation scheme he found that in the case of Na-Mg systems about double the amount of electrolyte was required as threshold to prevent dispersion as was required in equivalent Na-Ca systems.

In studies on the relative effects of Ca and Mg on the physical conditions, mainly dispersion, of clayey vertisols from the Mooi River area near Potchefstroom, the negative effects of high exchangeable Mg levels and lopsided Mg:Ca ratios were clearly shown (Nel, 1989; Nel et al., 1989). In these soils, it was found that a major factor aggravating dispersion in the high

Mg systems was the replacement of Fe by Mg and leaching of the Fe from the soil. It was indicated earlier that iron oxides are important aggregate stabilizing agents in soils. Dispersion will thus be aggravated by their removal. It was found that the threshold Mg:Ca ratio above which clay dispersion notably increases is somewhere between 1.5:1 and 3:1. This is also the threshold value above which Fe removal from the clay complex was found to increase sharply. Nel (1989) emphasizes that the obtained threshold ratio was found for a vertisol with an ESP of 15% and that it may not be valid for other situations.

Unpublished studies of analytical values of highly unstable duplex soils from the south-eastern Free State by the senior author over many years, showed that serious soil physical problems on these soils are also encountered where the exchangeable Mg:Ca ratio is higher than about 1.5:1, which is a quite widespread situation in the area. Duplex soils here are solonetzic type soils, but mostly not real Solonetz soils according to international definition. Studies on 67 South African soils showed that dispersion and crusting is a problem whenever the exchangeable Mg:Ca ratio is more than 1:1 (Bloem, 1992; Bloem and Laker, 1993, 1994a).

At the Tyefu irrigation scheme along the Lower Fish River, Nel (1986) found that the problem soils in terms of crusting had Mg:Ca ratios of as high as 3:1. Nel (1986) furthermore pointed out that these soils predominantly have illite clay mineralogy and that it has been found that the negative effects of magnesium are more pronounced in illitic clays.

3.7 Parent material

Parent material has a major influence on the susceptibility of South African soils to crusting. This is through their influence on the factors discussed above.

The extreme dispersibility and susceptibility to crusting of soils derived from Beaufort mudstones and shales, which occur widely in South Africa, can largely be ascribed to the clay minerals inherited from these parent materials. The critical minerals in this regard are illite and clay-sized quartz (Laker, 2004; Mills and Fey, 2004a). These mudstones and shales are also rich in Mg, which is not removed by leaching under the low and inefficient rainfall, thus aggravating the susceptibility of soils derived from them to crusting.

Several South African researchers have shown the much greater aggregate stability of soils derived from basic igneous rocks, like dolerite, diabase and basalt, than those derived from granite and especially mudstones and shales (Sumner, 1957; D'Huyvetter, 1985; Thompson, 1986; Smith, 1990; Rapp, 1998; Maswana, 2001). Manyevere et al. (2016) confirmed the big difference in susceptibility to crusting in arid, semi-arid and sub humid regions between soils derived from dolerite and those derived from mudstones and shales. According to Manyevere et al. (2016), the lower susceptibility to crusting in soils derived from dolerite is in sub humid areas due to the effect of higher contents of sesquioxides (and kaolinite). The higher iron oxide content of soils derived from basic igneous rocks is due to the abundance of iron-bearing minerals in these rocks (e.g. Smith, 1990). It has been indicated earlier that sesquioxides are extremely important aggregate stabilizing agents. This is especially important in top soils with low organic matter contents. Most notably is the high aggregate stability of the top soils of Shortlands form soils derived from basic rocks (Stern, 1990; Rapp, 1998). Thin section microscopic studies showed that both the topsoil and subsoil of an extremely stable dolerite-derived Shortlands soil from the central Eastern Cape (former Ciskei) were absolutely impregnated with amorphous iron oxides, as seen for the top soil in Figure 1.

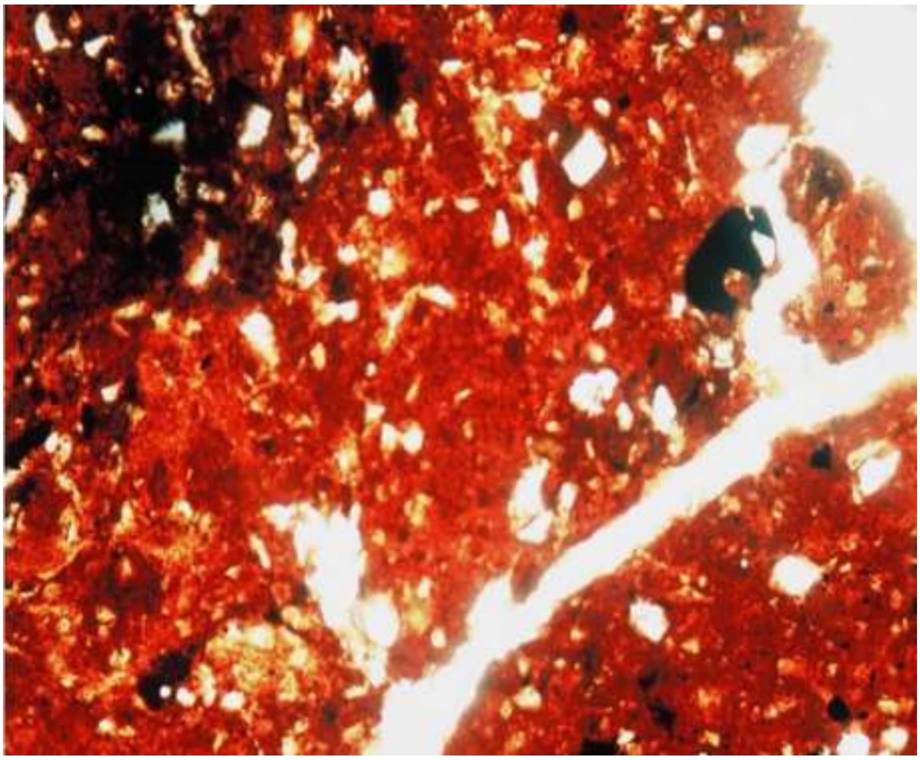

Fig. 1 Shortlands soil form impregnated with amorphous iron oxides

Manyevere et al. (2016) found that in humid areas soils were stable, irrespective of parent material, with their stability being controlled by kaolinite clay mineralogy and sesquioxides.

During field studies in Swaziland, the senior author observed that the red sandy soils derived from biotite granite were strikingly more stable than those derived from other granites in the same area. This was also noted that, during somewhat more superficial field observations by the senior author in the Mbombela area in the Mpumalanga Lowveld. The soils derived from the biotite granite have higher iron oxide contents, derived from the iron contained in the biotite. It is clear that with a view to derivation of the vulnerabilities of soils to degradation, like crusting and erosion, it is important to distinguish between soils derived from biotite granite and those derived from other granites and gneisses.

Maribeng (2007) studied soils derived from granite and schist respectively near Polokwane, Limpopo. He found that the soils derived from schist had relatively high silt contents. In the Sahel Desert, Valentin (1995) found that: *"soils derived from schist, richer in silt, generally experience more severe crusting problems ... than those originating from gneiss or granite ..."* Maribeng (2007) concluded that for this reason the soils derived from schist in Limpopo may be more susceptible to crusting than those derived from granite and pointed out that this would be very important in land suitability evaluations.

In Zimbabwe, crusting soils are mainly associated with banded ironstone, phyllites and schists (Nyamapfene and Hungwe, 1986). These rocks produce soils with high (for southern Africa) silt contents of between 25 to 35% (Nyamapfene, 1991). Manyevere et al. (2015) found that the severely crusting soils were derived from schists.

4 Effects of environmental factors on soil crusting

4.1 Vegetative cover

Bare soil areas are exposed to the beating action of raindrops. This leads to physical/mechanical disaggregation of structural units (peds) at the soil surface and consequently soil crusting. This is especially severe in unstable top soils, which are by far the majority in South Africa. Bare areas can be cultivated areas, rain-fed or irrigated, or overgrazed rangeland. Thus, it is essential to maintain a dense continuous basal (grass) cover that can dissipate raindrop energy before it reaches the soil in rangelands and as much vegetative cover as is practically possible in cultivated areas.

4.2 Rainfall

Rainfall has major effects on crust formation in soils. Even in irrigated areas it is often a main cause of crusting (Nel, 1986). There are at least two major aspects responsible for the major impacts of rainfall about soil crusting, viz.:

a. As was indicated earlier, the EC of rainwater is extremely low. Thus, it is far below the threshold value required to avoid dispersion of the clay fraction of soils, especially in soils in which there is some Na and/or have lopsided Mg:Ca ratios. The effect of this factor is extremely severe especially on soils that are inherently highly susceptible to crusting, such as soils with smectite or illite clay mineralogy and low sesquioxide contents, for example;

b. During aggressive thunderstorm type of rain, high intensity energy is imparted on the soil surface. This leads to physical/mechanical disaggregation of aggregates at the soil surface, followed by compaction of the disaggregated material into a thin very dense layer at the soil surface (Bloem, 1992). It is important to note that one should not look at the different components of rain, viz. drop size, falling height and rain intensity in isolation (Bloem, 1992; Bloem and Laker, 1994a). They must be combined into one term, called the energy flux. Energy flux is given by the following equation:

   $EF = KE \times I$

   Where EF = Energy flux ($W.m^{-2}$)

   KE = Kinetic energy ($J.mm^{-1}.m^{-2}$), given by the combination of drop size and falling height

   I = Rainfall intensity ($mm.s^{-1}$)

On soils that are susceptible to crusting, even a quite small, short intense aggressive shower can produce severe crusting. Results from runoff plots in the study of Stern et al. (1991b) showed that rainstorms with more cumulative rain, but lower intensities produced less runoff than storms with less cumulative rain, but higher intensities.

Once a crust has been formed, it persists. A crust can be broken up by cultivation, but during the first big enough rain, it will reform. Only in self-mulching strongly swelling clays will a crust break up by itself when it dries out.

On chemically dispersive soils, rainfall energy is irrelevant. On such soils, severe crusting takes place even under almost zero-energy mist rain. In an unpublished study by the senior author, quoted by Bloem (1992), it was found that soil from a citrus orchard in the Sundays River Valley sealed under the mist rain used to wet the soil before starting laboratory scale rainfall simulation. The infiltration rate dropped to 4.5 $mm.h^{-1}$ under the mist rain and did not decrease further under high-energy rain applied subsequently.

5 Effects of soil crusting

5.1 Reducing infiltration

Greatly increased runoff, due to decreased infiltration, is the best known and most visible effect of soil crusting.

The increased runoff almost invariably leads to seriously increased water erosion. Laker (2004) compiled a comprehensive review of South African information and research data on this. On the other hand, a very stable crust can protect a soil against erosion, despite higher runoff. In a laboratory-scale rainfall simulation study, with a soil from Tygerhoek experimental farm near Villiersdorp in the Rûens area of the Western Cape, Stern (1990) found higher infiltration and less runoff at 30% slope than at 5% slope. This is contrary to what would be expected. The explanation for this apparent anomaly was found by studying sediment yield data. At 30% slope, sediment yield was much higher than at 5% slope, despite less runoff. At 5% slope the crust protected the soil against erosion, despite the higher runoff. At 30%, the higher velocity of the runoff water stripped the crust from the soil. With the infiltration limiting crust removed, infiltration was higher at the steeper slope. Stern (1990) obtained similar results on an unexpectedly relatively unstable red Shorrocks series (Hutton form) soil from Roodeplaat.

From biological crust studies in Botswana, Thomas et al. (2008) reported that many cyanobacterial crusts produce EPS which bind soil particles together and decrease erodibility.

This is, for example, important in the case of sandy soils in arid areas that are prone to wind erosion.

According to Mills and Fey (2004a), Sombroek (1986) overseas noted that crusting may give *"a measure of protection against wind erosion and, sometimes, against water erosion"*.

Soil erosion in rangelands and rain-fed cropping areas are well known and has been studied intensively over many decades. However, it seems as if the serious soil erosion found in irrigated areas is much less well known and documentation on it is sparse. The author has earlier and again very recently received reports of serious gully (donga) erosion that developed where centre pivot irrigation was implemented on severely crusting very unstable soils, e.g. from the Eastern Cape and the Lowveld of Mpumalanga. These developed very quickly after implementation of the irrigation. More unexpected was a recent report on serious erosion by rainfall in a clean cultivated subtropical fruit orchard under drip irrigation in Limpopo. The only documented South African research data that the author could find in this type of scenario is by Louw and Bennie (1992), who found severe crusting in clean cultivated vineyards, leading to serious erosion by both rainfall and irrigation.

Reduced infiltration leads to less water entering the soil and stored in it for utilization by plants. This causes artificial droughts that can be very damaging to crop production, especially under rainfall that is unreliable and erratic in areas that are marginal for cropping. The negative effect on yield of the much lower quantity of water stored in the soil over a season in a crusted soil than where the crust was alleviated by means of mulching or ameliorants was conclusively shown experimentally (Stern, 1990; Stern et al., 1991b, 1992).

Reduced infiltration due to crusting also influences negatively on rangeland productivity. Harmse and Nel (1990) showed that crusted, bare patches in natural veld had lower water content in the top 300 mm of the soil than in uncrusted areas. Harmse (1989) refers to crusting of soils with high clay content due to the incursion of Karoo (shrub) vegetation into the "highveld environment" (grassland). Measurement of infiltration after careful removal of crusts indicated that the crust was inhibiting infiltration of water into the soil.

Reduced infiltration due to crusting is a widespread phenomenon in irrigated agriculture in South Africa, leading to serious problems. Two main consequences of reduced infiltration under irrigation are poor irrigation water-use efficiency and poor crop performance due to artificial drought conditions in the soil.

Low water use efficiency on crusted soils in irrigated agriculture stems on the one hand from runoff losses or on the other hand, if frequent light irrigations are made to avoid ponding and/or runoff that would occur if heavier applications are made. Frequent light irrigations have a high non-beneficial evaporation component of evapo-transpiration.

Very big evaporation losses occur when ponding of water occurs during irrigation. The author asked a farmer where water ponded under micro-sprinklers in a citrus orchard, such that oranges were floating in the water, how long it would take the water to infiltrate. The farmer's reply was that it would take about 24 hours. The Sundays River valley, in the Eastern Cape, where this orchard is, is one of the hottest and driest parts of the country. Thus, the author's conclusion was that in 24 hours almost all the ponded water would evaporate and about nothing would infiltrate. In their survey at Tyefu irrigation scheme along the Lower Fish River in the Eastern Cape, Loxton et al. (1987) concluded the following: *"in some of the more strongly crusting soils under irrigation the presence of green algae in micro-depressions in the irrigated fields indicate that pools of irrigation water remain on the surface for a considerable time before slowly infiltrating. A certain percentage of this water obviously evaporates from the surface."*

In the citrus orchard in Swaziland, where severe crusting and poor infiltration, leading to ponding of water, was observed under drip irrigation, large areas of the crusted zone under the canopies of the trees became covered with green algae. This indicates that there must be prolonged periods with water ponded on the soil surface. In an irrigated area on the Makhatini Flats, Van der Watt and Claassens (1990) found a crust formed by bacterial slimes and algal and fungal hyphae under "continuously moist conditions".

Mills and Fey (2004a) theorize that colonization of mineral crusts by biological crust organisms may be a mechanism by which the potentially negative effects of mineral crusting (e.g. reduced infiltration) are alleviated in some ecosystems. They quote international literature on research elsewhere either indicating that biological crusts may increase or decrease infiltration relative to where such crusts do not exist, however. Menon et al. (2011) give some details of a review paper based on results from 24 studies: in seven of the studies BSCs increased infiltration, in six they had no effect and in eleven they decreased infiltration. BSCs decreased infiltration at high sand contents (>66%) and increased infiltration as the clay content increased (>15%). The author concluded from his observations in the Swaziland case that conditions were worse and infiltration less where the biological crust was present than where there was only a mineral crust.

If infiltration is lower, it means that less water enters the soil and is stored in it. In practical field situations, the author observed dry soil profiles, due to reduced infiltration caused by crusting, under centre pivot irrigation. Three examples are:

a. Soil profile studies in a maize field on a typical Eastern Cape crusting soil, near the town of Hofmeyr in the Eastern Cape revealed that only the top 30 cm of the soil was moist. Below it, the soil was bone dry and as hard as a rock. Based on his irrigation applications the farmer was under the illusion that the water content of whole soil profile was close to field capacity;
b. A maize seed farmer on the Springbok Flats near Settlers experienced tremendous problems. He and his expert advisors tried everything, even spaying with different trace elements, without any success. Again, investigation of the black swelling clayey (vertic) soil showed that it was crusted and that the soil profile was bone dry;
c. In a seed maize field on a sandy soil near Radium (south of Bela-Bela), the growth of the maize plants was very poor in patches. Again, investigations into plant nutrition aspects by experts could not find any explanation. Soil profile investigation by the author revealed that the poor growth patches were on "hills" in this ***slightly*** undulating field. Plant growth in the depressions was good. It was found that the soil was crusted and that the soil on the hills was dry, while in the depressions it was moist. The investigations were done at sites where the centre pivot had passed barely an hour before. It was clear that the problem was excessive runoff from the "hills" because of the crusting. Because of the sandy nature of the soil this runoff water infiltrated in the depressions and did not pond there. The farmer estimated a 10% yield loss due to the problem, which could mean losing his profit.

Stern et al. (1992) found that the amount of irrigation water stored in a soil profile was much lower in the control-crusted soil as where the crust was alleviated by means of a combined application of PAM and gypsum.

5.2 Inhibiting aeration

Inhibition of aeration (gas exchange) is a well-known serious negative effect of soil crusting (e.g. mentioned by Mills and Fey, 2004a). Due to strong lowering of the O_2 content of the soil atmosphere and build-up of CO_2 anaerobic conditions develop in the soil. This has several negative effects, including:

- Inhibition of favourable soil micro-organisms and stimulation of unfavourable organisms, such as nitrogen denitrifying organisms;
- Inhibition of germination of seed;
- Inhibition of root functioning. Root functions like water and nutrient uptake depend on effective root respiration. Thus, these functions are inhibited by anaerobic conditions.

The author could not find information on any South African research about the effects of crusting on soil aeration and the consequences thereof. In practice, he could visually observe it when he received topsoil from an irrigated field in the northwest of Limpopo, however. Serious problems were experienced in this field and no measures that were tried, helped. A fertilizer advisor in the area then looked at the possibility of a physical soil problem. He identified crusting as the potential problem and brought an undisturbed surface soil sample to the author. It had a very thin (<1 mm), but very dense crust. Beneath the crust the soil was full of air bubbles, resembling an Aero chocolate. The same phenomenon is very clearly illustrated under the Type 1 crust (a thin mineral crust) in Figure 1 of the paper by Menon et al. (2011). These clearly indicate that even an extremely thin crust can be so dense that it prevents gas exchange and traps foul air pushed up during wetting of soil below it.

The author observed a case of what is clearly due to the limiting of soil aeration due to a very dense soil crust in a peach orchard with serious problems of excessive leaf Mn levels under drip irrigation near Tulbagh in the Western Cape. Since the 1950s, it is known that in Tulbagh district there are strongly acid soils in which Mn induced iron deficiencies are found in peaches. The problem is usually solved by liming the soil to reduce the plant-availability of Mn in the soil. At higher pH, Mn availability is not reduced by chemical precipitation. It becomes oxidized to Mn^{+4}, which is not plant-available, by specific micro-organisms which are active only at soil pH (Water) >5.5, i.e. at pH (KCl)>4.5. In the specific case the pH (KCl) had already been limed to 6.5, which is far too high, and Zn deficiencies were already seen in the leaves. Thus, the farmer's fertiliser advisors recommended no more lime. For peaches, which is very sensitive to Mn toxicities, >150 $mg.kg^{-1}$Mn in the leaves can be toxic. Despite the high soil pH, the peach leaves in this case contained >1 300 $mg.kg^{-1}$Mn. The author inspected the situation and found extremely severe crusting on the areas under the canopies in the tree rows, which were kept bare, devoid of any vegetation. The crust obviously caused anaerobic conditions below the crust, preventing the Mn oxidizing organisms from oxidizing the Mn and lowering its plant-availability. The soil beneath the crust was also bone dry. Significant parts of the bare areas were covered by BSCs.

5.3 Inhibiting germination and seedling emergence

Soil crusting inhibits germination due to its effect on soil aeration discussed above.

Seedling emergence is affected by the high mechanical strength of the soil crust, preventing the coleoptile from breaking through the soil surface. This effect is particularly severe for dicotyledons, such as the various types of beans, which have to "pull" the cotyledons through the soil surface. It has been mentioned that in the 1950s Sellschop identified this as a major problem in the growing of groundnuts in the then Highveld region. Materechera et al. (2007) found that seedling emergence of Bambara groundnut (*Vignasubterranea* L.) was inhibited by soil crusting in sandy soils in North West Province, giving only 64.8% emergence compared with 87.9% where the crust was alleviated. Massingue (2002) showed that seedling emergence decreased with increasing crust strength above a critical value. Crust strengths up to 0.7 MPa (penetrometer resistance) or 500 gf (germination force) did not decrease seedling emergence of the test crops (soybean, sunflower and wheat). However, no seedling emergence occurred at crust strengths above 2 MPa or 2 000 gf. Seedling emergence of the dicotyledons (soybean and sunflower) did not differ but were both affected more than emergence of wheat. In a small-farmer area in Zimbabwe, poor seedling emergence of cotton (a dicotyledon) due to crusting is a major problem (Manyevere et al., 2015).

Small seeded crops are also severely affected by soil crusting, because their weak, thin coleoptiles cannot push through the crust. Thus, grasses cannot re-establish in bare crusted areas in rangelands. An important agronomic crop, which is known, to be very vulnerable to soil crusting in this regard, is wheat. J.N. Marais from the University of Fort Hare, showed this very clearly in an unpublished field experiment at the University of Fort Hare, in 1992. As has been mentioned, a wheat farmer south of Ladybrand in Free State indicated that soil crusting was his biggest production problem. In some years, he had to replant three times due to this before getting a proper plant density. Where the runoff experimental site of Stern (1990) near Piketberg in the Western Cape was, the farmer indicated that he was not concerned about the extremely high runoff due to soil crusting, but because he was struggling tremendously to get a good wheat stand because of the crust.

Large areas, which developed strong crusts and became bare after having been overgrazed or injudiciously cultivated and then withdrawn from cultivation or abandoned, do not recover again. In some cases, they remain virtually completely bare. Some of the severely crusted areas in the Pafuri area in the northern KNP where the Makuleke people had their cultivated areas up to 1969 were in 2011, 42 years later, still *"barren and devoid of any vegetation, showing the very poor resilience (recovery potential) of these soils"* (Nortjé, 2014). In other cases, for example in abandoned cultivated areas in the former homelands of the Eastern Cape, the areas are after several decades not completely bare, but covered only by sparse small shrub vegetation where there used to be very high-quality grassland. Inhibition of seedling emergence by the high mechanical resistance of the soil crusts, in the latter example of grasses, which are small-seeded, leads to this lack of recovery. Recovery will not happen unless special artificial management steps are introduced. It will then become a question whether it will be economically feasible to implement such steps.

5.4 Limiting development and functioning of roots

Laker and Vanassche (2001) found it strange that root development of the citrus trees in the problem orchard near Addo with severe ponding of irrigation water was very poor, because the soil did not have a bulk density that was high enough to cause such drastic restriction of root growth (approximately 1 400 $kg.m^{-3}$). The soil only had a very severe crust under the canopy strip of the trees. Experimentally, they found that surface application of an organic soil conditioner (with the soil scratched loose to no more than 1 cm depth) to alleviate the crusting, and no other cultivation, gave a very big improvement in root development, especially of fine roots. Deep cultivation had no effect on root development. Laker and Vanassche (2001) concluded that the improved root growth due to elimination of the crust was largely due to improved soil aeration. Alleviation of the crust gave significant yield increases, while deep cultivation did not. Mills and Fey (2004a) mention overseas research indicating, *"The strength and oxygen-excluding nature of crusts may impede root growth near the surface"*.

6 Effects of management factors on soil crusting

6.1 Rangeland management

In rangeland management, the aim should be to avoid development of bare areas on soils that are prone to crusting. Such situations develop mainly due to overgrazing. Overgrazing leading to bare patches, is often localized due to animals concentrating on areas with palatable nutritious grass. These are almost invariably also the areas with soils that are most prone to crusting (Nortjé, 2014). Any rangeland management system that does not avoid such localized overgrazing will lead to severe crusting. This is especially a major problem in nature reserves and the ranches of game lodges, where fencing off vulnerable areas is not acceptable for aesthetic reasons (Laker, 2004).

Development of bare areas usually leads to increased soil erosion. Development of bare crusted areas is not always followed by erosion of such areas. Sometimes a crust is so resistant that it actually protects the soil against erosion, as has been indicated. The problem is that such crust prevents re-establishment of vegetation, especially grass, on the bare areas and thus causes a major reduction in the productivity of the rangeland (Nortjé, 2014; Nortjé et al., 2016). Several instances have been observed where little or even absolutely no recovery of bare patches has occurred after 20 to 40 years, *inter alia* by both authors on several different occasions.

A bare crusted area is not always totally devoid of vegetation. It sometimes has sparse shrub and/or bush vegetation.

Incorrect rangeland management causing bush densification in savannah areas or bush encroachment into grasslands leads to soil crusting (followed by erosion) in many areas in South Africa (Laker, 2004). Bush densification or encroachment leads to elimination of the full basal grass cover. This leaves large areas between the shrubs or trees bare, predisposing them to crusting. Management errors leading to such situation include over-stocking and/or incorrect browser/grazer ratios (Laker, 2004).

In addition to livestock/game management, judicious veld burning is used as rangeland management tool to maintain rangeland productivity, and/or prevent bush encroachment or bush densification. Unfortunately, burning is not always correctly managed. Mills and Fey (2004b) analysed data from 19 sites in various parts of the country where long term annual burning and fire exclusion experiments had been conducted for at least 28 years. They found that frequent fires intensify soil crusting. Rainfall simulation studies showed that burnt plots crusted more rapidly than unburnt plots and at lower rainfall intensity (19 vs. 35 $mm.h^{-1}$). Sampling at 1 cm depth intervals revealed that the biggest differences between the burnt and unburnt plots were in the 0-1 cm soil layer. Mills and Fey (2004b) ascribed the increase in dispersion of clay that they found in the burnt plots partly to the decrease in humus content (and associated disaggregating effect). The increase in clay dispersion, that they found, can partly be ascribed to a combination of the following two effects that they found in burnt plots:

- Lowering of the EC of 1:5 extracts, i.e. lowering of the electrolyte concentration;
- Increasing of the ESP.

It has been pointed out earlier that such combination aggravates dispersion of clay and crusting. They found that nutrients were lost from burnt plots over time and ascribed it to the removal of ash, containing salts, in surface runoff. This would explain the lower EC of surface soil extracts. Furthermore, Ca, Mg (and K) were removed in larger quantities than Na, thus leading to the increased ESP. Mills and Fey (2004b) concluded that crusting on burnt plots may be self-perpetuating, because increased runoff will probably further increase the loss of soluble salts from the soil (through removal of the ash).

6.2 Management of cropland, orchards and vineyards

Irrigation management is not discussed in this section. It is discussed separately later.

From a crusting point of view the ideal situation would be to keep the soil surface in cultivated areas as fully and as continuously as possible covered with vegetation or dead plant material to protect it against raindrop impact. This has been discussed comprehensively by Laker (2004). In practice, this is unfortunately often not a viable option in annual cropping systems.

Stern et al. (1991b) found huge reductions in runoff by application of 3 $t.ha^{-1}$ straw mulch, due to prevention of surface sealing (crusting), compared with control plots at all three field sites where they studied this (Table 1). Stern et al. (1991b) also give photographic images of the difference in surface roughness between the crusted control and the mulch treated plot.

Table 1 Seasonal runoff figures for control and mulch plots from three runoff field plot sites (extracted from **Stern** et al., 1991b)

Site	**Soil form**	**Seasonal rain** (mm)	**Runoff as % of rain**	
			Control	**Mulch**
Irene	Hutton	340	32.9	3.5
Potchefstroom	Hutton	316	63.6	4.6
Aliwal North	Estcourt	501	66.9*	8.8*

*These figures include one abnormal rainstorm of 140 mm for which the runoff percentages were 94.6% for the control and 25.8
% for the mulch treatment. If this storm is excluded the figures become 56.0% for the control and only 1.4% for mulch.

Stern et al. (1991b) ascribe the high effectiveness of mulch to:

- Dissipation of raindrop impact energy by the mulch, thus reducing the physical disintegration of aggregates;
- Prevention of the "stirring" effects of raindrops, thus inhibiting chemical dispersion processes.

Both of the above effects could explain why mulch was much more effective than PG in reducing crusting and runoff at all three sites. This is elaborated further later. The second effect could also explain why mulching was (almost unexpectedly) extremely highly effective on a chemically highly dispersive soil from Aliwal North, included in their research.

In a field experiment with Bambara groundnut on a crusting soil, Materechera et al. (2007) found significant alleviation of the impacts of crusting by application of 3 $t.ha^{-1}$ straw mulch. Seedling emergence was increased from 64.8% in the control to 87.9% in the straw treated plots, pegging from 58.7% to 78.9%, podding from 60.0% to 78.6%, pod yield from 807.3 to 1846.1 $kg.ha^{-1}$ and grain yield from 603.0 to 1115.0 $kg.ha^{-1}$. All these were statistically significant improvements above the control. Mulch also gave statistically significant better results than all the other treatments (gypsum, manure and polymer gel) included in the experiment about seedling emergence. Regarding pegging mulch was still the best, but not statistically significant better than any of the other three treatments. For podding, mulch gave the best results, but not statistically significant better than gypsum or manure. (Note that all these interpretations are based on recalculated two-year averages by the senior author from the year values given in Table 1of the Materechera et al. (2007) paper and not on the two-year averages given in the table.)

Massingue (2002) found that increasing mulch applications from 0 to 6 $t.ha^{-1}$ "considerably" improved the emergence of seedlings in a crusting soil. She found that more than 70% soil cover by crop residues is highly effective in reducing crust strength. On a strongly cracking (self-mulching, non-crusting) smectitic soil with more than 25% clay the mulch application had no effect, with the self-mulching nature of the soil being adequate to counteract any crusting effect.

Louw and Bennie (1991, 1992) found that both a cover crop and straw mulching could combat erosion effectively in a crusting vineyard soil. They deemed the cover crop to be economically more feasible and environmentally friendlier than straw mulching.

Removal of vegetation when land is cultivated can have a marked effect on crusting by exposing the soil to raindrop impact and altering soil properties such that the soil becomes more prone to crusting (Meyer et al., 1996). Smith (1990) showed that cultivation caused a decrease in aggregate stability and increased crusting in relatively unstable soils, possibly partly due to mechanical disintegration of structural units by implements. This was shown by a sharp decrease in FIR. FIR decreased from 14 mm.h^{-1} in the uncultivated soil from basic igneous rock to 6 mm.h^{-1} in the cultivated soil. For soils from acidic rocks, the relative values were 11 and 6 mm.h^{-1}, in the uncultivated and cultivated soils, respectively. On the other hand, cultivation had absolutely no influence on FIR in the stable highly weathered soils in his study, i.e. in those soils that were stabilised by sesquioxides.

Whereas substantial research has been done in South Africa on the effects of cultivation practices on soil compaction, the author has not come across any research on the effects of cultivation practices on crusting in this country. It is known however, that soils, which are sensitive to physical disintegration of aggregates, are very prone to structure disaggregation by aggressive pulverizing implements. Sodium-affected soils are, for example, very sensitive to mechanical disturbance by means of cultivation (Smith, 1990). As far as destruction of surface soil structure is concerned, nothing is more damaging than rotavators. Of course, structure destruction of the surface soil by such implement and creation of a smooth soil surface also predisposes the soil to severe crusting during the first rain (or irrigation) thereafter. Manyevere et al. (2015) ascribes the serious problems experienced due to crusting by cotton farmers in Zimbabwe to *"the fine tilth needed for good establishment of cotton, which is achieved by soil pulverisation during land preparation".* They mention that: *"pulverisation destroys soil structure and exposes the soil to raindrop impact"*. It is aggravated by the fact that: *"in Zimbabwe cotton fields are usually kept free of weeds and national agricultural legislation requires that cotton farmers burn crop residues after harvesting"*. An effective management practice by small-scale farmers in the study area to improve seedling emergence is by using ox-drawn harrows to break the soil crusts (Manyevere et al., 2015).

In the case of permanent crops, it is possible to grow cover crops to stabilise and protect the soil between the rows. These can be permanent cover crops or seasonal cover crops. About 50-60 years ago, winter cover crops were widely grown in orchards and vineyards in the Western Cape. A lupine/oats mixture was a popular winter cover crop. The advantages of a winter cover crop in a winter rainfall area are that it (i) protects the soil surface during the rainy season and (ii) does not require any water during the dry summer season. This was followed by an unfortunate period during which it was believed that "clean cultivation", giving a clean soil surface, was a sign of a good farmer. Thereafter, farmers started using a better system of "dirty cultivation", just leaving weeds to grow in the orchards or vineyards or using a winter cover crop system again. A management change introduced during the latter period was to just slash the weeds or cover crop at the end of the winter season and leaving it on the soil surface, instead of incorporating it into the soil. In terms of preventing crusting leaving the material on the soil surface will be much more effective than incorporating it into the soil.

With the advent of micro-irrigation systems (micro sprinklers and drippers) a new management problem appeared which leads to very severe soil crusting with extremely serious implications in permanent crops like orchards and vineyards. By means of weed killers, the strips of soil in the rows, as wide as the drip line of the trees, are kept permanently free of weeds. These areas are consequently permanently bare, with extremely low organic matter content in these strips. On chemically highly dispersive soils, this leads to extreme crusting and extremely poor water infiltration. The author has seen numerous extreme cases of this nature, both in South Africa and California. The author has also seen this effectively alleviated by mulching. One type of "mulching" that the author observed in winter rainfall areas was to allow weeds to grow under the canopies of the trees during winter, kill them by means of suitable mild weedicides in spring, and just leave them to lodge on the ground. This has the further advantage of the soil structure being stabilised by the organic matter provided by the decomposing roots, very effectively distributed in the soil.

Paterson and Barnard (2011) and Paterson et al. (2011) studied a special type of "mulch", namely biodegradable organic mats woven from palm leaves, and found them to be effective in protecting and stabilising the soil surface.

6.3 Irrigation management

In view of the big differences between different soils about crusting, and especially because such a large proportion of the irrigated and potentially irrigable soils in South Africa are very prone to crusting, it is extremely important to:

- Select an appropriate irrigation system that is suitable for each case;

- Adapt the design of the selected system to the requirements of the specific soil;
- Adapt irrigation management to the requirements of the crop and the specific soil.

Soil crusting potentially poses problems for all types of overhead irrigation systems, depending on the degree of vulnerability of the soil to crusting and the cause of crusting (physical/mechanical disaggregation and/or chemical dispersion). At the top end of the scale are the two most aggressive types of systems that will cause crusting on the widest range of soils, viz. centre pivots and floppy irrigation.

In the case of floppy irrigation, the combination of big drops and high falling heights give energy fluxes that exceed the value that most soils can tolerate before they crust.

In the case of centre pivots, the problem is the high application rate, especially in the outer parts of the circle. This has two implications:

- The application rate exceeds, often very far, the infiltration rate of the soil, leading to a lot of runoff and in some cases even erosion. In an unpublished rainfall simulation study, the author found that the FIR of a strongly crusting soil from Rama, on which the farmer irrigated by means of a centre pivot, was less than 10 $mm.h^{-1}$. During the same period unpublished studies were conducted on a soil from a potato field in the Gamtoos Valley where the farmer could not apply more than 7 mm water at a time by centre pivot before ponding and runoff started;
- Even where the sprinklers are lowered as far as possible to lower drop energy, the inevitable high application rate in the outer diameter of the pivot causes a high-energy flux, which is the key factor in causing soil crusting. In the field, the author has observed soil crusting and its negative effects under centre pivot irrigation more than once on widely different soils, as mentioned earlier.

Liengme (1994) did field studies by means of mini runoff plots at three selected positions along the laterals of two centre pivots. The study was done in KwaZulu-Natal. The soil under both centre pivots was of the Avalon form. The slope gradients of the plots were adjusted to between 4 and 5 %. Runoff increased from 4.7% to 36.0% (Pivot 1) and 9.5% to 45.6% (Pivot 2) on moving out along the laterals. Runoff from non-irrigated control plots was insignificant (<1%).

Liengme (1994) attributed the increased runoff along the lateral to the greater "energy flux density" (intensity x kinetic energy) towards the outer end of the lateral resulting in a less permeable crust. He concludes: *"the study clearly demonstrates the importance of reducing the energy flux density of the applied water for sprinkler systems by changing the application rate, median drop diameter and fall height of the drops"*.

By means of scanning electron microscope studies, Liengme (1995) showed that crusts were well established (at 0.8-1.2 mm depth) after four high-energy irrigation applications. Further irrigation applications had little effect on crust development but increased the strength of the existing crust.

In the comprehensive study reported by Bloem (1992), Bloem et al. (1992) and Bloem and Laker (1994a), criteria were developed for the adaptation of the design and management of overhead irrigation systems to the infiltration rate of soils. An implicit key element was to minimize crusting and its negative effects. Equations/models describing the relationship between design application and soil properties are provided for the following scenarios:

a. If the energy flux delivered by the system is fixed and cannot be changed: calculation of the maximum amount of water that can be applied per irrigation without causing ponding/runoff;
b. If the energy flux delivered by the system is not fixed and can be changed and the aim is to apply a certain pre-determined amount of water per irrigation: calculation of the maximum permissible energy flux that the system may deliver.

The second scenario is most important concerning new irrigation system design for any specific case. In the development of the equations it was found that soils had to be divided into three different groups, based on their susceptibility to crusting, and those different equations had to be derived for the different groups. The first distinction is between chemically dispersive and chemically stable soils. Chemically dispersive soils have (i) ESP values higher than 2.0%, (ii) exchangeable Ca:Mg ratios lower than 1:1, (iii) soil organic matter less than 0.2% and clay mineralogy dominated by smectite and less than approximately 20%. The chemically stable soils, mainly with clay mineralogy dominated by kaolinite, are then subdivided into those with significant amounts of smectitic clay and those without.

Unfortunately, the most useful and freely available of the publications (Bloem and Laker, 1994a) has a misleading title, which is probably why it is not widely used. The misleading title was enforced because, one of the reviewers of the article insisted that the title must state that it provided criteria for the design and management of centre pivot irrigation systems. This is not the case. It provides criteria for the design and management of all types of overhead irrigation systems, as is also clear from the title of the dissertation by Bloem (1992). When it comes to calculation of energy fluxes these irrigation systems are all subject to the same principles.

On crusting soils where overhead irrigation systems are not suitable, especially those that are chemically dispersive, flood irrigation, particularly furrow irrigation, are potentially viable options. During a NIRESA (Network on Irrigation Research and Extension in Smallholder Agriculture) workshop in 2005, this was clearly seen in a tomato field, on a farm along the Mzimvubu River near Port St. Johns in the Eastern Cape. The part under drip irrigation had serious drought stress, while the part under furrow irrigation had no problem. In a comparison elsewhere, the senior author has repeatedly observed that in areas with crusting soils in central California almost all fields under annual crops are under furrow irrigation and other field crops, like Lucerne, under flood bed irrigation. No crusting problems were evident in these. In contrast, serious crusting problems were seen in the same area in vineyards under drip irrigation, as mentioned earlier.

7 Prevention and/or amelioration of crusting by means of gypsum/phosphogypsum or soil conditioners

Where soil crusting poses serious problems and limitations, especially in high-income irrigated agriculture, measures have to be taken to prevent crusting or ameliorate crusts that have already been formed. The basic objective is to enhance aggregate stability at the soil surface. In many cases, removal of excess Na is required to achieve this.

The key strategy in such cases has traditionally been to replace the Na on the exchange complex with Ca and then leach out the Na. This requires two things, viz. (i) the Na must be replaced by Ca and (ii) the soil must be in a flocculated condition, so as to maintain high enough permeability to ensure leaching out of the Na. Because of cost considerations, gypsum has traditionally been used as source of Ca. Because of its availability, PG has become the most general source of gypsum used in soil reclamation. Van der Merwe (1965) showed that gypsum achieves the first objective, but often fails to achieve the second objective. The latter is because the solubility of gypsum is too low to give the threshold electrolyte concentration required to achieve flocculation of the soil. This is especially the case for sodic soils in which magnesium is the dominant divalent cation (Van der Merwe, 1965). Weber and Van Rooyen (1971) overcame this problem by using a combination of gypsum and molasses meal. Gypsum alone provided Ca (but could not give the required flocculation). Molasses meal alone could not replace the Na. However, an energy-rich material stimulates microbial growth that produces microbial mycelia that give very high aggregate stability. Thus, in the combination the molasses meal ensures adequate permeability for effective leaching of the Na that is replaced by the Ca supplied by the gypsum. Van der Merwe shortly after the above study in an unpublished field experiment with wheat on a non-sodic crusted soil at the Sandvet irrigation scheme in the Free State achieved very successful alleviation of crusting with molasses meal alone (A.J. van der Merwe, personal communication). The increase in yield was such that the treatment was economically feasible.

Many more studies have been done in South Africa on the efficiency of gypsum, often in the form of PG, to prevent crusting or ameliorate existing crusts. In the majority of cases it was found that PG reduces crusting and runoff (e.g. Harmse, 1989). In the field runoff studies of Stern et al. (1991b), PG brought about substantial reductions in runoff compared with control plots. It was much less effective than mulching, however (Table 2).

Table 2 Runoff from control, PG treated and mulched plots (extracted from Stern et al., 1991b)

Site	Seasonal rainfall (mm)	Runoff as % of rain		
		Control	**PG**	**Mulch**
Irene	340	32.9	18.3	3.5
Potchefstroom	316	63.6	35.9	4.6
Aliwal North	501	66.9	45.3	8.8

In a comparative experiment at the Potchefstroom site during a subsequent season, PG was also found to be less effective than a small (20 kg.ha^{-1}) application of PAM, an organic soil conditioner. The runoff figures, as percentage of rain for the control, PG and PAM being 72.5, 37.7 and 27.9% respectively (Stern et al., 1991b). Important aspects found by Stern et al. (1991b) regarding PG include:

- PG was effective in reducing runoff under low intensity rain, but not during high intensity storms. The latter may also be the case under high intensity overhead irrigation;
- The effectiveness of PG was maintained during the first season, but decreased rapidly during the second season until it later did not differ from the control. This was due to a decline in EC on the PG plots and eventually failure to remain above the required threshold concentration;
- The long-term effectiveness of PG depends on the rainfall pattern and the characteristics of the seal, which determine infiltration rate and runoff volume.

In an irrigation experiment with wheat on a crusting red soil of the Hutton form, classified as a Rhodudalf in Soil Taxonomy of the United States (Soil Survey Staff, 1999), Stern (1990) found that PG reduced the runoff loss of irrigation water over the growing season to 12.8%, compared with 36.1% from the control plots. Where application of PG was combined with PAM, runoff was further reduced to only 1.4%.

Van der Watt and Claassens (1990) found very large increases in FIR, both at planting and at harvest, from PG application made before planting. At a rate of 2 $t.ha^{-1}$ PG alone its effect was similar to that of 4 or 8 $t.ha^{-1}$ mulch alone. At an application of 5 $t.ha^{-1}$ PG it was much more effective than the mulch applications alone. Where PG and mulch applications were combined, the effects were even much bigger. In the study of Materechera et al. (2007) 3 $t.ha^{-1}$PG gave statistically significant better results than the control for seedling emergence, pegging and podding and only in regard to seedling emergence was it inferior to mulch. (Here it is very important to note again that the interpretations are based on the author's recalculated two-year average values and not on the values as they are given in the paper.)

In the field study of Laker and Vanassche (2001) in an irrigated citrus orchard at Addo, PG had absolutely no effect, in contrast to a coal-derived humic product, which had a highly beneficial effect in alleviating the crust in the severely crusted soil. In the same vicinity in the

Sundays River Valley, Harmse and co-workers from the then Potchefstroom University for CHE actually obtained negative results with PG applications.

Harmse (1989) and Harmse and Nel (1990) showed that bare patches in natural veld (rangeland) could be re-vegetated by applying PG at levels of 4 to 6 $t.ha^{-1}$ to alleviate a soil crust. In view of the big differences from different studies reported above, this would, of course depend upon the soil.

During the 1950s and 1960s, much research was done overseas on the potential use of organic soil conditioners, mainly synthetic ones like PVA, to stabilise soil aggregates. They were highly effective, but interest in them declined because the costs were prohibitive. At that stage, the objective was to use it for stabilising structure to significant depth in a profile, e.g. the whole plough layer. In about the 1980s new interest in these products arose as potential ameliorants for soil crusting. Since only a few millimetres thick layers had to be ameliorated only a small amount of conditioner would be required, which could be economically viable. Botha et al. (1979, 1981) found that application of PVA successfully alleviated soil crusting in the red sandy soils of the Vaalharts irrigation scheme. It was found to be effective only if the soil was allowed to dry out in a crumbed state.

In the study of Materechera et al. (2007), an application of 1 $t.ha^{-1}$ (i.e. a very large application) of some unspecified "polymer gel" failed to give statistically significant improvement over the control in regard to seedling emergence, pegging or podding of Bambara groundnut in a crusting soil. Regarding seedling emergence and podding it was statistically significant inferior to mulch. (Here it is again very important to note that the interpretations are based on the author's recalculated two-year average values and not on the values as they are given in the paper.)

PAM is probably the compound that received most attention from the 1980s onwards as soil conditioner for alleviation of soil crusting. Several studies with it as possible ameliorant for crusting were conducted in South Africa also, including those reported by Stern et al. (1991b) and Stern et al. (1992). PAM was found to be effective at low application rates. At the Irene site PAM applied at 20 $kg.ha^{-1}$ (the recommended rate) maintained a FIR of over 35 $mm.hr^{-1}$ during a quite heavy storm when the FIR for the control and PG plots were only 2.4 and 10.8 $mm.hr^{-1}$, respectively (Stern et al., 1991b). Stern et al. (1991b) concluded that the greater effect of PAM, compared with PG, was *"probably due to the coating effect of the polymer, which inhibited both physical and chemical mechanisms affecting slaking and dispersion of aggregates"*.

In field studies, at different sites, Stern et al. (1991b) found that PAM at an application rate of 5 $kg.ha^{-1}$ was virtually as effective as 20 $kg.ha^{-1}$. On the chemically highly dispersive soil from Aliwal North 5 $kg.ha^{-1}$ was even slightly (insignificantly) better than 20 $kg.ha^{-1}$. Runoff, as percentage of seasonal rain, was 11.6 and 15.3% for the 20 and 5$kg.ha^{-1}$PAM applications, respectively.

Smith et al. (1990) found that addition of PAM in the presence of electrolytes, supplied either by PG or using tap water (TW) instead of distilled water, in rainfall simulation studies increased both FIR and cumulative infiltration by 7 to 8-fold compared with the control and was much more effective than PAM, PG or TW alone. This resembles the findings of Weber and Van Rooyen (1971) with the use of gypsum and molasses meal together mentioned earlier.

In 2014, an extreme case of biological crusting was observed in a macadamia orchard in Levubu District in Limpopo (S. Schoeman, personal communication). No weeds any longer grew in the crusted areas. Due to excessive runoff from the crusted areas severe soil erosion occurred during rainstorms. The orchard was heavily infested with phytophthora root rot disease due to poor soil aeration. The latter was mainly ascribed to the effect of the crust. A trial surface application of PAM was made on a crusted area in the orchard, with "100%" quick response — "within weeks" (S. Schoeman, personal communication). The crust broke up and curled up, exposing the uncrusted soil beneath, and dense weed growth appeared immediately. Unfortunately, the orchard was already in a too bad state to try to save it. Recently (2016), an almost identical situation of moss and algal crusting, erosion and heavy phytophthora infestation has been observed in a citrus orchard near Mbombela in the lowveld of Mpumalanga (S. Schoeman, personal communication). The senior author received photographic documentation of the untreated crust and the effect of PAM in the first case and of the crusting and erosion in the second case.

In field trials during 2015 in avocado and macadamia orchards, in the Lowveld of Mpumalanga Province, Nortjé and Schoeman (2016) tested the effects of application of PAM alone, and in combination with other products on soil crusts, on water infiltration and crust strength. Results of these trials indicated the positive reaction of PAM with alleviating soil crusts compared to other more general soil conditioning products and methods. The 2 g/m^2 PAM treatment performed the best, while the 2 l/m^2 compost outperformed PAM treatments, although, non-significantly. PAM treatment costs are very low while compost treatments were the highest.

It is very important to keep in mind that there are various types of PAM and that the correct type of PAM must be used to achieve success in alleviating soil crusting. It must have a large anionic saturation (close to 30%) and very large molecules (Stern et al., 1991b).

The senior author and co-worker Ingrid Bredell conducted numerous experiments on the potential use of coal-derived humic substances as possible ameliorants for crusting soils, with products developed at CSIR. The vast majority of products were unsuccessful, but through a system of systematic product development and testing, it was possible to develop coal-derived HP that succeeded in bringing about large increases in soil aggregate stability (Laker and Bredell, 1990). Stringent rainfall simulation tests with high-energy rain with distilled water (very low EC), as well as wet sieving were used as first step screening tests. The products that passed these tests successfully were as second step tested in greenhouse plant growth studies. Those that succeeded in passing this test were then approved for larger scale production. These products were then subjected to further greenhouse studies. In order to be approved for the production of enough material for field scale testing, a product had to pass this greenhouse test.

The final step, in the testing of coal-derived HP, was a field study in a citrus orchard on the chemically highly dispersive soil on which water ponded under micro-sprinkler irrigation near Addo (Laker and Vanassche, 2001). The soil was of the Oakleaf form. The topsoil had 49% fine sand, 29% silt, giving 78% (fine sand + silt) and 17% clay, with an ESP of 13.5%, which is about the worst possible combination in terms of crusting. Eight different treatments were applied at the end of February 1991 (Table 3). Application rates may appear to be very high, but keep in mind that actual quantities were not high, because only a very thin soil layer was amended, because the objective was to only alleviate the crust and applications were made only under the tree canopies.

Table 3 Treatments applied in field study with HP (from Laker and Vanassche, 2001)

Treatment number	Treatment
1	Control A: Soil surface scratched loose under tree canopy
2	HP 0.25% surface application under canopy, surface scratched loose
3	HP 0.375% surface application under canopy, surface scratched loose
4	Gypsum 5 $t.ha^{-1}$ equivalent under canopy, surface scratched loose
5	Combination of Treatments 2 and 4
6	Control B: Surface scratched loose under canopy + trench 1 m deep along row under drip line
7	HP 0.25% surface application under canopy and mixed into 1 m deep trench under drip line
8	HP 0.375% surface application under canopy and mixed into 1 m deep trench under drip line

The orange yield results are presented in Table 4. Yields were determined in July 1991 (as control), 1992 and 1993. Because of big differences in yields between trees statistical analyses were not done on actual yields, but on yield increases between 1991 and 1993. It should, however be kept in mind that it is very difficult to obtain statistically significant differences under conditions of such high variation as in this struggling orchard.

Table 4 Orange yield results from field experiment with coal-derived HP (from Laker and Vanassche, 2001)

Treatment		**Fresh orange yield** (kg/tree)			Yield increase (kg/tree) 1991 to 1993
Number	**Type**	**1991**	**1992**	**1993**	
1	Control A	34.3	31.0	49.9	15.6b*
2	HP low surface	23.9	30.2	61.9	38.0a
3	HP high surface	38.8	38.6	67.7	28.9ab
4	Gypsum surface	26.5	19.5	38.2	11.7b
5	Gypsum + HP	33.6	33.6	50.6	17.0b
6	Control B	24.2	17.6	37.5	13.3b
7	HP low surface /trench	24.6	23.2	49.6	26.4ab
8	HP high surface /trench	16.3	19.6	44.7	28.4ab

*Figures with the same symbol do not differ statistically significantly.

The most outstanding conclusions/observations from the results in the last column of the table are:

- The most positive results were obtained with HP scratched in only at the soil surface under the canopy of the trees (the problem zone). In terms of actual yields in 1993 it was head and shoulders above the rest;
- Gypsum had no effect. It was actually slightly negative. This fits in with the results of Harmse and co-workers in this area;
- Deep trenching without HP at the surface (treatment 6, Table 3) had no effect. It was actually slightly negative. This was not surprising, because this soil does not have a high bulk density — as mentioned earlier. Yet farmers were going into high costs to do deep cultivation, without addressing the actual problem, viz. crusting in the strip under the canopy.

It is important to note that in the case of orchard or vineyard crops, results are almost never obtained in the first year and sometimes not even in the second year for soil physical amendment treatments.

The senior author and co-worker Ingrid Bredell also achieved great success in several unpublished laboratory and green house studies with different commercially available soil conditioners on a number of problem soils.

These soil conditioners were also tested with great success on materials from gold mine slimes dams in several laboratory and greenhouse studies. The physical condition of gold mine slimes dam material, including severe crusting, is extremely poor. One Belgian product was specifically very effective in creating stable aggregation of slimes dam material. This could be important in the reclamation and stabilisation of slimes dams. Paterson et al. (2011) obtained positive results with palm mat "mulches" on mine slimes dams.

8 Special effects of 'Biological Surface Crusts' (BSCs)

The ability of BSCs to protect soil against erosion has been mentioned. Protection of sandy soils against wind erosion in semi-arid and arid areas is particularly important. Physical disturbance, such as trampling, of BSCs damages them and will limit their effectiveness in this regard. According to Elliott et al. (2014) and others cyanobacterial crusts have a strong potential to recover quickly after physical disturbance, however. On the other hand, recovery of lichen crusts after physical disturbance is very slow and can take between 5 and 530 years (Lalley and Viles, 2008). Large areas in Namibia are covered by lichen-dominated crusts and damage to these crusts by indiscriminate off-road driving is a matter of great concern.

Some BSC organisms, such as cyanobacteria, have the ability to fix nitrogen from the air and thus improve soil fertility (Thomas et al., 2008; Elliott et al., 2014).

Several papers on the role of BSCsin CO_2 fluxes in drylands have been published by members of the Dougill & Thomas Group, e.g. Thomas et al. (2008, 2011), Thomas and Hoon (2010) and Lane et al. (2013). Accelerated respiration, by heterotrophic soil organisms, due to elevated temperatures lead to lower C levels in soils and higher CO_2 efflux into the atmosphere (Thomas et al., 2008, 2011). Large pulses in respiration due to heavy rain after dry periods aggravate this. BSC organisms photosynthesise and thus remove CO_2 from the atmosphere. Consequently, they mitigate CO_2 efflux from the soil and can even reverse it into net CO_2 sequestration. Photosynthesis by lichens and mosses is larger than by cyanobacteria. Loss of BSC cover in drylands can thus lead to greater soil C loss and higher CO_2 efflux from soil due to respiration. Therefore, also in this regard damage to lichen dominated crusts, like those in Namibia, by indiscriminate off-road driving should be a matter of great concern.

9 Soil crusting and "fairy rings" in South Africa (Northern Cape) and Namibia

Densely distributed, mysterious "fairy rings" or "fairy circles" are found in a strip stretching from southern Angola in the north through Namibia to just across the border of South Africa in the south (Van Rooyen et al., 2004; Cramer and Barger, 2013). These are on sandy plains in the "pro-Namib", i.e. along the eastern boundary of the Namib Desert (Van Rooyen et al., 2004). A "fairy ring" consists of a circle with bare soil devoid of vegetation, usually surrounded by a thin line of grass that is taller than the grasses in the grassland in which the circles are found.

Numerous studies have been conducted on the fairy rings and a large number of hypotheses for the causes of their origin and development have been put forward. Van Rooyen et al. (2004) reviewed these. None of the studies and hypotheses have provided conclusive explanations for the origin and development of the rings (Van Rooyen et al., 2004), however. The authors consider none of the post-2004 publications that they have seen to be more convincing than the pre-2004 publications reviewed by Van Rooyen et al. (2004). Identical fairly circles with identical spatial distribution patterns have recently also been discovered in an arid region of Western Australia. The authors could not find any scientific publications on these, probably because they have been discovered so recently. Several 2016 news reports, with photographic evidence and comments by scientists, are available on the internet. Some theories have been put forward, but according to a prominent Australian scientist the mystery of the fairy rings have not yet been solved.

Almost all studies on the fairy rings have been concentrated in certain areas in the northern parts of Namibia. Only a small number included studies in the south. It is noticeable that Van Rooyen et al. (2004) collected soil samples from north to south but give analytical data only for samples collected in Hartman's Valley, Gibires Plain and Marienfluss, the three traditionally most studied areas in the far north of Namibia. For their study, Cramer and Barger (2013) collected a significant number of soil samples for their model development from the latter three areas, but the vast majority in the south, but in a geographically limited area near the NamibRand private nature reserve, as indicted in their Figure 6.

During the late 1990s, the senior author conducted comprehensive cursory studies on fairy rings on the NamibRand private nature reserve and a nearby farm and in the Naukluft National Park along the road from the entrance gate near Sesriem to Sossusvlei. The senior author also studied fairy rings in an outlier area east of Keetmanshoop, which is also indicated in Figure 6 of Cramer and Barger (2013). The senior author observed a spatially well "organised" distribution of the rings on the flat areas where they mainly occur east of the Namib Desert and near Keetmanshoop. The author also observed them on the slopes of dunes bordering on the flat area at NamibRand and the nearby farm and in valleys between the dunes. Here they were not as densely distributed and not spatially so well organised. A few isolated fairy rings were also observed on the slope of a dune in Naukluft National Park, where they could be clearly identified as the typical circular slight depressions with a thin ring of grass right around them. It was a dry period and there was no grass on the rest of the dune.

The senior author started his studies in the dune areas on the farm. The first observation was that the bare areas were very slight depressions, as also described by Van Rooyen et al. (2004), almost like a saucer. The edges of the saucers were loose sand, but the "bottoms", i.e. the actual bare circles, had a smooth surface and looked dense. Digging of pits in the middle of circles revealed that they had a thin crust at the surface or very close to the surface, and sometimes a succession of thin crusts. Qualitative water infiltration studies revealed that water infiltration in the circles was very slow, as is typical of a crusted soil. Because the crust form the bottom of a slight depression the author hypothesized that what was now the crusted layer was not originally at the soil surface, but was originally covered by a thin sand layer, which was possibly removed by wind erosion when the area became devoid of vegetation.

On the plain with dense orderly distribution of fairy rings the circles generally had even harder crusts. A local labourer informed the author that after rains water infiltration in the circles was very slow. Thus, additional water in the soil around the fringes after rain due to runoff from the circle would be the logical explanation for the more luxurious grass growth usually found around the fringes. Cramer and Barger (2013) quote photographic evidence of runoff from fairy circles (photo 1D in their paper). Runoff from the circles is also one of the main characteristics of the recently discovered circles in Australia.

In the outlier area east of Keetmanshoop the crust generally appeared to be harder and thicker. Here the soil is less sandy than in the traditional fairy ring zone and the rainfall higher (about 140 mm per annum opposed to between 50 and 100 mm per annum). According to the available news reports the soil in which the Australian fairy rings are found are also less sandy.

The senior author at a stage as a teenager lived at Vredendal in an area known for its dorbanks (duripans) in the arid north-western part of the Western Cape. In their garden, he found a thin dorbank that he could break with a normal garden fork under a thin sandy topsoil. Somehow the appearance of the crusted circles on the plain created a suspicion that it was actually a thin dorbank and that after the area became bare because the plants died the thin sandy layer covering is was blown away — thus the slight depression. Plants would have died of drought because their roots would not have been able to penetrate through the dorbank and utilise water stored in the soil below it. A dorbank is a layer that is cemented by silica (Soil Classification Working Group, 1991). The test for a dorbank is that it does not slake in water or acid, but only when treated with strong alkali. The senior author got the necessary chemicals from the farmer and his wife on the farm in Namibia where he studied the circles. The hard layer did not slake in water or acid, but when treated with soap soda (NaOH) it becomes so soft that it could be mixed with a small plastic spoon. Therefore, it was indeed a thin dorbank.

So, the crusted layer, at least in some circles, is indeed a thin dorbank. The dorbank (or other crust) is obviously perpetuating a circle, preventing grasses from successfully re-establishing in it. However, for its formation a source of silica is required. Because of the circular form, one would suspect a shrub or tree as possible source. Some plants are hyperactive accumulators of silicon. When they die and decompose, they add increased silicon levels to top soils. Some organisms, for example mosses, are also hyper-accumulators of silicon.

Acknowledgement

The authors wish to express their sincere gratitude towards the University of South Africa for making the publication of this paper possible.

References

Agassi, M., Shainberg, I., Morin, J., 1981. Effect of electrolyte concentration and soil sodicity on infiltration rate and crust formation. Soil Science Society of America Journal 45, 848-851.

Ben-Hur, M., Shainberg, I., Bakker, I., Keren, R., 1985. Effect of soil texture and $CaCO_3$ content on water infiltration in crusted soil as related to water salinity. Irrigation Science 6, 281-294.

Bloem, A.A., 1992. Kriteria vir die aanpassing van die ontwerp en bestuur van oorhoofse besproeiingstelsels by die infiltreerbaarheid van gronde. MSc dissertation, University of Pretoria.

Bloem, A.A., Laker, M.C., 1993. Die invloed van druppelgrootte, valhoogte en toedieningstempo op die generasie van afloopwater onder gesimuleerde oorhoofse besproeiing. Water SA 19, 307-312.

Bloem, A.A., Laker, M.C., 1994a. Criteria for the adaptation of the design and management of centre-pivot irrigation to the infiltrability of soils. Water SA 20, 127-132.

Bloem, A.A., Laker, M.C., 1994b. Infiltrasie onder veld- en laboratoriumtoestande. Water SA 20, 133-138.

Bloem, A.A., Laker, M.C., Lagrange,L.F, Smit,C.J.,1992. Aanpassing van oorhoofse besproeiingstelsels by die infiltreerbaarheid van gronde. WRC Report No. 208/1/92. Pretoria: Water Research Commission.

Botha, F.J.P., Bennie, A.T.P., Burger, R. du T., 1979. Grondverdigting onder besproeiing op die Vaalharts besproeiingskema: Volume IV. Die bekamping van grondverdigting deur struktuurvormende poliviniel verbindings. Departement van GrondkundeVerslagNr. 79/4. Bloemfontein: UOFS.

Botha, F.J.P., Bennie, A.T.P., Burger, R. du T., 1981. The influence of polyvinyl alcohol stabilisation on the strength characteristics of fine sandy soils. Agrochemophysica 13, 43-46.

Bühmann, C., Beukes, D.J., Turner, D.P., 2006. Clay mineral associations in soils of the Lusikisiki area, Eastern Cape and their agricultural significance. South African Journal of Plant and Soil 23, 78-86.

Bühmann, C., Rapp, I., Laker, M.C., 1996. Differences in mineral ratios between disaggregated and original clay fractions in some South African soils as affected by amendments. Australian Journal of Soil Research 34, 909-923.

Cass, A., Johnston, M.A., 1985. Physical and clay mineralogical properties of some Natal and eastern Transvaal soils. South African Journal of Plant and Soil 2, 79-84.

Cramer, M.D., Barger, N.N., 2013. Are Namibian "fairy circles" the consequence of self-organizing spatial vegetation patterning? PLoS One 8(8): e70876 DOI: 10.1371/journal.pone.0070876.

D'Huyvetter, J.H.H., 1985. Determination of threshold slope percentages for the identification and delineation of arable land in Ciskei. MScAgric dissertation, University of Fort Hare.

Dougill, A.J., Thomas, A.D., 2004. Kalahari sand soils: Spatial heterogeneity, biological soil crusts and land degradation. Land Degradation and Development 15, 233-242.

Du Plessis, H.M., Shainberg, I., 1985. Effect of exchangeable sodium and phosphogypsum on the hydraulic properties of several South African soils. South African Journal of Plant and Soil 2, 179-186.

Elliott, D.R., Thomas, A.D., Hoon, S.R., Sen, R., 2014. Niche partitioning of bacterial communities in biological crusts and soils under grasses, shrubs and trees in the Kalahari. Biodiversity and Conservation 23, 1709-1733.

Ellis, F., 1988. Die gronde van die Karoo. PhD thesis, University of Stellenbosch.

FAO/ISRIC/ISSS. 1998. World Reference Base for Soil Resources. World Soil Resources Report No. 84. Rome: FAO

Frenkel, H., Fey, M.V., Goodall, G.H., Russell,W.B.,1989. Effect of soil surface amendments on runoff and erosion from simulated rain applied to a sesquioxic soil. S. Afr. J. Plant Soil 6, 197-202.

Frenkel, H., Levy, G.J., Fey, M.V.,1992. Clay dispersion and hydraulic conductivity of clay-sand mixtures as affected by the addition of various anions. Clays and Clay Minerals 40, 515-521.

Gerber, F.A., Harmse, H.J. von M., 1987. Proposed procedure for the identification of dispersive soils by chemical testing. The Civil Engineer in South Africa 29, 397-399.

Harmse, H.J. von M., 1989. The chemical amelioration of soils with prominent crusting. Abstracts of Combined Congress, Wild Coast Sun, January 1989 (no page numbers).

Harmse, H.J. von M., Nel, D.J. 1990. Chemical amelioration of a Swartland soil with prominent crusting. Applied Plant Science 4, 62-66.

Hutson, J.L., 1971. Crust formation on some Natal soils. MScAgric dissertation, University of Natal.

ISSS Working Group RB. 1998. World Reference Base for Soil Resources: Introduction. Deckers J.A., Nachtergaele F.O., Spaargaren O.C. (Eds.). First Edition. ISSS, ISRIC, FAO. Leuven: Acco.

Jones, A., Breuning-Madsen, H., Brossard, M., Dampha, A., Deckers, J., Dewitte, O., Gallali, T., Hallett, S., Jones, R., Kilasara, M., Le Roux, P., Micheli, E., Montanarella, L., Spaargaren, O., Thiombiano, L., Van Ranst, E., Yemefack, M., Zougmoré, R. (Eds.), 2013. Soil Atlas of Africa. Luxembourg: European Commission, Publications Office of the European Union.

Laker, M,C., 2001. Soil compaction: Effects and amelioration. Proceedings of the South African Sugar Technologists Association 75, 125-128.

Laker, M.C., 2004. Advances in soil erosion, soil conservation, land suitability evaluation and land use planning research in South Africa, 1978-2003. South African Journal of Plant and Soil 21: 345-368.

Laker, M.C., Bredell, I.H., 1990. Amelioration of crusting soils by means of coal-derived humic products. Papers 16th Soil Science Society of South Africa Congress, Pretoria, July 1990, 637-650.

Laker, M.C., D'Huyvetter, J.H.H. 1988. Slope-erodibility relationships for different soils in a semi-arid region of Ciskei. Proceedings of the 5th International Soil Conservation Conference: Land Conservation for Future Generations, Bangkok, January 1988, 641-653.

Laker, M.C., Vanassche, F.M.G., 2001. Alleviation of soil crusting in a citrus orchard by means of a coal-derived humic product. Programme and Extended Abstracts, Joint Congress 2001, Pretoria, January 2001, 265-266.

Lalley, J.S., Viles, H.A., 2008. Recovery of lichen-dominated soil crusts in a hyper-arid desert. Biodiversity and Conservation 17, 1-20.

Lane, R.W., Menon, M., McQuaid, J.B., Adams, D.G., Thomas, A.D., Hoon, S.R., Dougill, A.J., 2013. Laboratory analysis of the effects of elevated carbon dioxide on respiration in biological crusts. Journal of Arid Environments 98, 52-59.

Levy, G.J., 1988. The effects of clay mineralogy and exchangeable cations on some hydraulic properties of soils. DScAgric thesis, University of Pretoria.

Levy, G.J., Berliner, P.R., du Plessis, H.M., Van der Watt, H. vH., 1988. Micro-topographical characteristics of artificially formed crusts. Soil Science Society of America Journal 52, 784-791.

Levy, G.J.,Van der Watt H. v H., 1988. Effects of clay mineralogy and soil sodicity on soil infiltration rate. South African Journal of Plant and Soil 5, 92-96.

Liengme, D.P., 1994. Crust formation under centre pivot irrigation systems. Extended abstracts 18th Soil Science Society of South Africa Congress, Potchefstroom, January 1994, 35-37.

Liengme, D.P., 1995. A scanning electron microscope (SEM) study of crusts formed under centre pivot irrigation systems. Paper presented at Joint Congress, Stellenbosch, January 1995.

Loxton, Venn and Associates, 1987. Lower Fish River irrigation project – Ciskei development project. Vol. 2: Resource base study and agricultural potential. Bisho: Ciskei Agricultural Corporation, Unpublished report.

Louw, P.J.E., 1991. Die beskerming van onstabiele bogrondstruktuur vir 'n volgehoue hoë infiltrasietempo in wingerdgronde. MScAgric dissertation, University of the Orange Free State.

Louw, P.J.E., Bennie, A.T.P., 1991. Soil surface condition effects on runoff and erosion from selected vineyard soils. Proceedings of the Conference on Cover Crops for Clean Water, Jackson, Tennessee, 25-26.

Louw, P.J.E., Bennie, A.T.P., 1992. Water runoff and erosion in vineyard soils. Australian Grape Grower and Wine Maker, 20th Annual Technical Issue, 110-113.

Mager, D.M., Thomas, A.D., 2011. Extracellular polysaccharides from cyanobacterial crusts: A review of their role in dryland soil processes. Journal of Arid Environments 75, 91-97.

MacVicar, C.N., De Villiers, J.M., Loxton, R.F., Verster, E., Lambrechts, J.J.N., Merryweather, F.R., Le Roux, J., Van Rooyen, T.H., Harmse, H.J. von M., 1977. Soil Classification: A Binomial System for South Africa. Pretoria: Department of Agricultural Technical Services.

Manyevere, A., Bangira, C., Gotosa, J., Munjonji, L., Chikwari, E., 2015. Characteristics and management options of crusting soils in a smallholder farming area of the Zambezi metamorphic belt in northern Zimbabwe. South African Journal of Plant and Soil, DOI: 10.1080/02571862.2015.1018355.

Manyevere, A., Muchaonyerwa, P., Mnkeni, P.N.S., Laker, M.C., 2016. Examination of soil and slope factors as erosion controlling variables under varying climatic conditions. Catena 147, 245-257.

Maribeng, L., 2007. The influence of parent material (granite and schist) on physical and chemical properties of soils of the Syferkuil experimental farm. MScAgric dissertation, University of Limpopo.

Massingue, F.I., 2002. The effect of crop residue cover and soil texture on soil crusting. MScAgric dissertation, University of the Free State.

Maswana, N.N., 2001. Community based soil conservation as basis for land reclamation in the Eastern Cape. MInstAgrar dissertation, University Pretoria.

Materechera, S.A., 2009. Aggregation in a surface layer of a hard-setting and crusting soil as influenced by the application of amendments and grass mulch in a South African semi-arid environment. Soil & Tillage Research 105, 251-259.

Materechera, S.A., Motsuenyane, B., Modise,J.R., 2007. The effects of soil amendments and mulch on emergence, pod development and yield of Bambara groundnut (Vigna subterranean L.) in hard-setting soil. South African Journal of Plant and Soil 24 (2), 100-105 DOI: 10.1080/02571862.2007.10634789.

Menon, M., Yuan, Q., Dougill, A.J., Hoon, S.R., Thomas, A.D., Williams, R.A., 2011. Assessment of physical and hydrological profiles of biological soil crusts using microtomography and modelling. Journal of Hydrology 397, 47-54.

Meyer, J.H., Van Antwerpen, R., Meyer, E.,1996. A review of soil degradation and management research under intensive sugarcane cropping. South African Sugar Technologists Association 70, 22-28.

Mills, A.J., Fey, M.V., 2004a. Declining soil quality in South Africa: effects of land use on soil organic matter and crusting. South African Journal of Plant and Soil 21: 388-398.

Mills, A.J., Fey, M.V., 2004b. Frequent fires intensify soil crusting: physicochemical feedback in the pedoderm of long-term burn experiments in South Africa. Geoderma 121, 45-64.

Molope, M.B., 1992. Soil degradation in Bophuthatswana. Proceedings of the 17th Congress of the Soil Science Society of South Africa: 4-21 to 4-26.

Moolman, J.H., Weber,H.W., 1978. 'n Ondersoek na die bydrae van die fynsandfraksie tot die verdigbaarheid van fynsandgronde in Suid-Kaapland. Agrochemophysica 10, 39-46.

Nel, D.J., 1986. Evaluering van die chemiese en fisiese toestand van die gronde van die voorgestelde Tyefu besproeiingskema. Potchefstroom Universityfor CHE: Institutefor Soil Science Research, Unpublished report.

Nel, D.J., 1989. Die relatiewe invloed van Ca en Mg op fisiese eienskappe van grond. DSc thesis, Potchefstroom University for CHE.

Nel, D.J., Harmse, H.J. von M., Laker, M.C., 1989. The influence of varying Ca:Mg ratios on the dispersion and hydraulic conductivity of a vertisol. Abstracts Combined Congress, Wild Coast Sun, January 1989 (no page numbers).

Nortjé, G.P., 2014. Studies on the impacts of off-road driving and the influence of tourists' consciousness and attitudes on soil compaction and associated vegetation in the Makuleke Contractual Park, Kruger National Park. PhD thesis, University of Pretoria.

Nortjé, G.P., Schoeman, S.F., 2016. Subtropical orchard soil surface crusting and PAM. Journal of the Southern African Macadamia Growers' Association, Vol. 23.

Nortjé, G.P., van Hoven, W. and Laker, M.C. 2012. Factors affecting the impact of off-road driving on soils in an area in the Kruger National Park, South Africa. Environmental Management. Vol 50(6), December 2012: 1164-1176.

Nortjé, G.P., van Hoven, W., Laker, M.C., Jordaan, J.C. and Louw, M.A. 2016. Quantifying the impact of off-road driving on root-area distribution in soils using photographic image analysis. African Journal of Wildlife Research April 2016, 46(1) 33-48.

Nyamapfene, K., 1991. The soils of Zimbabwe. Harare: Nehanda Publishers.

Nyamapfene, K.W., Hungwe, A.P., 1986. Nature, distribution and management of crusting soils in Zimbabwe. In: Callebaut F., Gabriels D., De Boodt M. (Eds), Assessment of Soil Surface Sealing and Crusting: Proceedings of Symposium held in Ghent, Belgium, 1985. Ghent: Flanders Research Centre for Soil Erosion and Conservation: 320-329.

Page, E.R., Hole, B.J., 1976. Soil crust strength measurement. Communications in Soil Science and Plant Analysis 8(2), 139-148.

Paterson,D.G., Barnard, R.O., 2011. Beneficial effect of palm geotextiles on inter-rill erosion in South African soils. South African Journal of Plant and Soil 28, 193-200.

Paterson, D.G., Bühmann, C., Pienaar, G.M.E., Barnard, R.O., 2011. Beneficial effect of palm geotextiles on inter-rill erosion in South African soils and mine dam tailings: A rainfall simulator study. South African Journal of Plant and Soil 28, 184-192.

Rapp, I., 1998. Effects of soil properties and experimental conditions on the rill erodibility of selected soils. PhD thesis, University of Pretoria.

Richards, L.A., (Ed) 1954. Diagnosis and improvement of saline and alkali soils. Washington: Agriculture Handbook No. 60, USDA.

Schofield, R.O., Samson, H.R., 1954. Flocculation of kaolinite due to the attraction of opposite charge crystal faces. Discussions of the Faraday Society 18, 138-145.

Smith, H.J.C., 1990. The crusting of red soils as affected by parent material, rainfall, cultivation and sodicity. MScAgric dissertation, University of Pretoria.

Smith, H.J.C., Levy, G.J., Shainberg, I., 1990. The effect of water drops' energy and soil amendments on infiltration and erosion. Papers 16th Soil Science Society of South Africa Congress, Pretoria, July 1990, 651-670.

Snyman, K., Fey, M.V., Cass, A., 1985. Physical properties of some Highveld Vertisols. South African Journal of Plant and Soil 2, 18-26.

Soil Classification Working Group, 1991. Soil Classification: A Taxonomic System for South Africa. Pretoria: Department of Agricultural Development.

Soil Survey Staff, 1999. Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. Second Edition. USDA-NRCS Agricultural Handbook 436. Washington, DC: US Government Printing Office.

Sombroek, W.G., 1986. Introduction to the symposium. In: Assessment of soil surface sealing and crusting. Eds F. Callebaut, D. Gabriels, M. de Boodt. State University of Ghent, Belgium pp 1–7.

Stern, R., 1990. Effects of soil properties and chemical ameliorants on seal formation, runoff and erosion. DScAgric thesis, University of Pretoria.

Stern, R., Eisenberg, B., Laker, M.C., 1991a. Correlation between micro-aggregate stability and soil surface susceptibility to runoff and erosion. South African Journal of Plant and Soil 8, 136-140.

Stern, R., Laker, M.C., Van der Merwe, A.J.,1991b. Field studies on effect of soil conditioners and mulch on runoff from kaolinitic and illitic soils. Australian Journal of Soil Research 29, 249-261.

Stern, R., Van der Merwe, A.J., Laker, M.C., Shainberg, I.,1991c. Surface sealing effect on runoff and erosion from stable and dispersive kaolinitic soils. Soil Science Society of America Journal 55, 935-939.

Stern, R., Van der Merwe, A.J., Laker, M.C., Shainberg, I.,1992. Effect of surface treatments on runoff and wheat yields under irrigation. Agronomy Journal 84, 114-119.

Sumner, M.E., 1957. The chemical and physical properties of tall grass veld soils of Natal in relation to their erodibility. MScAgric dissertation, University of Natal.

Tengberg, A., Stocking, M., 1997. Erosion-induced loss in productivity and its impacts on agricultural production and food security. Lead paper to FAO/Agritex consultation on integrated soil management for sustainable agriculture and food security in Southern and Eastern Africa, Harare. Rome: FAO.

Thomas, A.D., Dougill, A.J., 2006. Distribution and characteristics of cyanobacterial soil crusts in the Molopo basin, South Africa. Journal of Arid Environments 64, 270-283.

Thomas, A.D., Hoon, S.R., 2010. Carbon dioxide fluxes from biologically crusted Kalahari sands after simulated wetting. Journal of Arid Environments 74, 131-139.

Thomas, A.D., Hoon, S.R., Dougill, A.J., 2011. Soil respiration at five sites along the Kalahari transect: Effects of temperature, precipitation pulses and biological soil crust cover. Geoderma 167-168, 284-294.

Thomas, A.D., Hoon, S.R., Linton, P.E., 2008. Carbon dioxide fluxes from cyanobacteria crusted soils in the Kalahari. Applied Soil Ecology 39, 254-263.

Thompson, J.G., 1986. Sodicity phenomena in red sesquioxic clay subsoils. South African Journal of Plant and Soil 3, 189-192.

Valentin, C., 1995. Sealing, crusting and hard-setting soils in Sahelian agriculture. In: So HB, Smith G.D., Raine S.R., Schafer B.M., Loch R.J. (Eds) Sealing, Crusting and Hard-setting Soils: Productivity and Conservation. Proc. 2nd International Symposium on Sealing, Crusting and Hard-setting Soils: Productivity and Conservation, Brisbane, February 1994, 53-76.

Van der Merwe,A.J., 1965. Certain fundamental characteristics of selected alkali soils. MScAgric dissertation, University of the Orange Free State.

Van der Merwe,A.J., 1973. Physico-chemical relationships of selected O.F.S. soils – A statistical approach based on taxonomic criteria. DScAgric thesis, University of the Orange Free State.

Van der Watt, H. v H., Claassens, A.S.,1990. Effect of surface treatments on soil crusting and infiltration. Soil Technology 3,241-251.

Van der Watt, H. v H., Valentin, C., 1992. Soil crusting – The African view. In: Sumner ME, Stewart BA (eds.) Soil crusting, chemical and physical processes. Boca Raton: CRC Press. pp301-338.

Van Deventer, P.W., 2000. Die invloed van uitruilbare natriumpersentasie en kleimineralogie op die infiltreerbaarheid van gronde wat reeds as gevolg van sikliese besproeiing verseël is. WRC Report No. 499/1/00. Pretoria: Water Research Commission.

Van Rooyen, M.W., Theron, G.K., Van Rooyen, N., Jankowitz, W.J., Matthews, W.S., 2004. Mysterious circles in the Namib Desert: Review of hypotheses on their origin. Journal of Arid Environments 57, 467-485.

Weber, H.W., Van Rooyen, P.C., 1971. Polysaccharides in molasses meal as an ameliorant for saline-sodic soils compared to other reclamation agents. Geoderma 6, 233-253.

WRB (World Reference Base for Soil Resources) 1998. Rome: Food and Agriculture Organization of the United Nations (FAO).