Evaluation of the Effect of an Orange Oil Based Soil Ameliorant on Selected Soil Physical Properties

by
Daniël Willem Viljoen

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Supervisor: Dr Josias Eduard Hoffman
Co-supervisor: Dr Dirk Cornelius Uys
Faculty of Agrisciences
Department of Soil Science

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Abstract

A new orange oil based soil ameliorant is available on the market. Apart from the orange oil, the other main constituents of the product are a nonionic surfactant and an anionic surfactant. Surfactants are used in the agricultural sector, amongst others, as a countermeasure for soil with poor infiltrability or with hydrophobic characteristics. Farmers who applied the orange oil based soil ameliorant to the soil observed a positive growth response by the crop. However, the main concern about surfactants is that it can cause the soil to disperse and thereby decrease the infiltration and saturated hydraulic conductivity thereof. The aim of this study was therefore to determine the effect which this product might have on the following selected soil physical properties: bulk density, aggregate stability, soil strength and unsaturated hydraulic conductivity. The product was applied on four farms on soils with different textures: Dublin Farm (22% clay), Wansbek (20% clay), Toitskraal (7% clay) and Two Rivers (3% clay). Field studies were repeated at Dublin Farm and Toitskraal to study the longevity effect of the product. Differences in bulk density were not attributed to the effect of the product, but to spatial variation. The aggregate stability at the 50 mm depth tended to decrease after application of the product at Dublin Farm trial 1, Toitskraal trial 1 and at Wansbek. At Dublin Farm trial 2 and Toitskraal trial 2 the application of the product tended to increase the aggregate stability. For Dublin Farm trial 2 and Wansbek the shear strength at the 50 mm depth tended to increase with increased application rates. The opposite was observed at Toitskraal and Two Rivers. The unsaturated hydraulic conductivity tended to be higher at the 0 mm depth for the treated soils at all of the trials except Toitskraal trial 2. From the aggregate stability results it is clear that the initial effect of the product was detrimental which can be attributed to the anionic surfactant. The long term effect can be attributed to the effect of the nonionic surfactant. The differences in shear strength can be attributed to aggregate stability (for Dublin Farm trial 2) and bulk density (for Two Rivers). There is however no explanation for the results found at Toitskraal and Wansbek. From the linear regression of bulk density against unsaturated hydraulic conductivity for Wansbek and Two Rivers it is clear that the application of the product definitely had an influence on the unsaturated hydraulic conductivity. For both farms, the correlation between bulk density and unsaturated hydraulic conductivity was better for the control than for the treated soils. To conclude with, the application of the product according to the recommended application rate, resulted in a slightly detrimental effect to the soil on the short term, but on the long term it tended to have a slightly positive effect on the soils.

Opsomming

‘n Nuwe grondverbeteringsproduk met lemoenolie as ‘n basis en ‘n nie-ioniese en ‘n anioniese benattingsmiddel as hoof bestandele, is op die mark. In die landbou sektor word benattingsmiddels onder andere gebruik as ‘n teenvoeter vir gronde met swak infiltrasie of hidrofobiese eienskappe. Die grootste voorbehoud omtrent die gebruik van benattingsmiddels is die moontlike afname in infiltrasie en versadigde hidroulieses geleivermoë as gevolg van klei dispergering. Positiewe reaksies van die gewasse is waargeneem deur boere wat van die produk gebruik maak. Die doel van die studie was dus om die moontlike effek van die bogenoemde grondverbeterings produk op die volgende geselekteerde grondfisiese eienskappe te bepaal: bulkdigtheid, aggregaatstabiliteit, grondsterkte en onversadigde hidrouliese geleivermoë. Die produk is toegedien op vier plase met verskillende grondteksture: Dublin Farm (22% klei), Toitskraal (7% klei), Wansbek (20% klei) and Two Rivers (3% klei). ‘n Ondersoek na die lewensduur van die produk is gedoen deur ‘n opvolg studie te doen by Dublin Farm en Toitskraal. Vir die bulkdigtheid resultate kon geen van die verskille toegeskryf word aan die effek van die produk nie. Die aggregaate stabiliteit by die 50 mm diepte van Dublin Farm proef 1, Toitskraal proef 1 en Wansbek, het geneig om laer te wees vir die behandelde gronde. Die aggregaatstabiliteit by die 50 mm diepte van Dublin Farm proef 2 en Toitskraal proef 2 het geneig om hoër te wees vir die behandelde gronde. Die skuifsterkte by die 50 mm diepte by Dublin Farm proef 2 en Wansbek, het geneig om toe te neem met ‘n toename in toedienings hoeveelheid, terwyl die teenoorgestelde tendens by Toitskraal en Two Rivers waargeneem is waar minder klei teenwoordig is in die grond. Die onversadigde hidroliese geleivermoë het geneig om hoër te wees by die 0 mm diepte van al die plase met die uitsondering van Toitskraal proef 2. Dit is duidelik vanaf die aggregaatstabiliteit resultate dat die aanvanklike effek van die produk nadelig is en dit kan toegeskryf word aan die effek van die anioniese benattingsmiddel. Die langtermyn effek kan toegeskryf word aan die nie-ioniese benatingsmiddel wat aggregaatstabiliteit kan verbeter. Die verskille in skuifsterkte kan toegeskryf word aan die verskille in aggregaatstabiliteit (vir Dublin Farm proef 2) en bulkdigtheid (vir Two Rivers). Daar is egter geen verklaring vir die verskille in skuifsterkte by Toitskraal en Wansbek nie. Die liniêre regressie van bulkdigtheid teenoor onversadigde hidroliese geleivermoë van Wansbek en Two Rivers dui aan dat die produk ‘n invloed het op die onversadigde hidroliese geleivermoë. Vir albei plase het die kontrole die beste liniêre verband tussen die twee grondeienskappe gehad, met ‘n swakker korrelasie vir gronde waar die lemoenolieproduk toegedien is. Dus kan die afleiding gemaak word dat op die korttermyn het die produk ‘n geringe negatiewe effek op die grond, maar op die langtermyn neig dit om ‘n positiewe effek te hê.

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Table of Contents

List of figures

List of tables

1. Introduction

Nowadays, surfactants are not that popular anymore in the agricultural sector compared to approximately 40-50 years ago. It was applied to soils exhibiting hydrophobic character, which were not uncommon at that time (DeBano, 1981). These hydrophobic soils did not wet evenly and usually resulted in overland flow or preferential flow paths (DeBano, 1981; Letey *et al.*, 1962b), which resulted in poor crop yields. The main concern about surfactants is the impact it has on aggregate stability. Previous research indicated that surfactants can cause a decrease in aggregate stability which can cause a decrease in saturated hydraulic conductivity and infiltration (Law *et al.*, 1966; Mbagwu *et al.*, 1993; Piccolo & Mbagwu, 1989; Piccolo & Mbagwu, 1994). This might cause poor soil aeration and subsequently an unfavourable environment for soil microbes.

Due to increased pressure on the agricultural sector to produce more with less and due to restricting soil conditions such as hydrophobicity and compaction, it might be necessary to use such products again to try to reach optimum production. Different types of surfactants result in different reactions in the soil, e.g. anionic surfactants result in aggregate breakdown, while nonionic surfactants result in an increased aggregate stability (Law *et al.*, 1966; Mbagwu *et al.*, 1993; Piccolo & Mbagwu, 1989; Piccolo & Mbagwu, 1994).

A relatively new soil ameliorant is available on the market. This product is a blend of anionic and nonionic surfactants and orange oil.

The aim of this study was to determine the effect of the new soil ameliorant on bulk density, aggregate stability, soil strength (specifically shear strength) and unsaturated hydraulic conductivity. Based on the components of the ameliorants, it was expected that the bulk density would remain the same, the aggregate stability and shear strength would decrease and the unsaturated hydraulic conductivity would increase due to the effect of the soil ameliorant.

2. Literature review

2.1 Introduction

To get a better understanding of surfactants and the mechanism of working, a clear understanding of the relative properties of water is needed. The most important is the concept of surface tension and the effect it has on the wetting of soil. A brief discussion of some of the properties under investigation and of surfactants and its effect on these soil physical properties is given.

2.2 Important properties of water

2.2.1 Introduction

A water molecule consists of an oxygen atom and two hydrogen atoms. The two hydrogen atoms are bound to the oxygen and form an angle of 104.5^{0} (Hillel, 1980). Oxygen, being the more electronegative of these atoms, has a partial negative charge, while the two hydrogen atoms have a partial positive charge. These positive and negative ends of water molecules cause the molecules to cluster together in aggregates which are held together by hydrogen bonds (Doerr *et al.*, 2000).

2.2.2 Surface tension

The net force on an individual molecule within a liquid (Molecule A, Figure 2.1) is zero, because it is surrounded by other molecules and their forces. However, at the surface of the liquid, the net force is inward (Molecule B, Figure 2.1), for beyond the surface no similar forces exist to oppose the attraction. These attracting forces will cause the liquid to minimize the surface area. The liquid will assume a spherical form if the opposing forces outside the liquid are minimal (Doerr *et al.*, 2000).

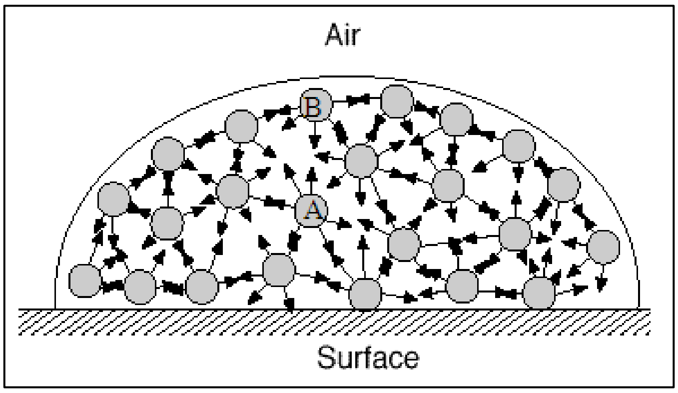

Figure 2.1: Representation of forces by individual molecules on each other within a droplet of water.

Work must be done to enlarge the surface of the liquid. The work that must be done is related to the surface tension of the liquid which is expressed in Newton per meter (N/m). The surface tension of water is at 72.75×10^{-3} N/m a lot higher than that of other liquids which range between 20 and 40×10^{-3} N/m (Doerr *et al.*, 2000).

2.2.3 Liquid-Solid contact angle

Letey *et al.* (1962a) stated that the liquid-solid contact angle (Figure 2.2) is a good reference for the determination of the wettability of a solid if a drop of water is placed on it. Hillel (1980) stated that if the angle (θ) is obtuse (> 90^0), the surface is water repellent.

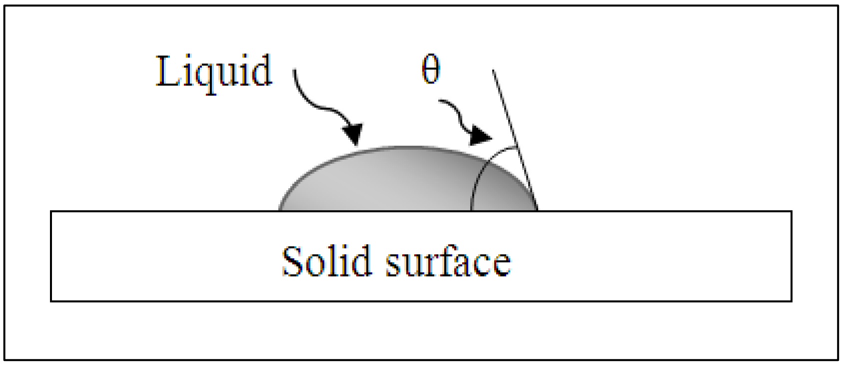

Figure 2.2: Illustration of the liquid-solid contact angle (θ). In this example the liquid-solid angle is smaller than 90°, thus it is a wettable surface.

There are two methods available for measuring the contact angle of a liquid with a solid surface: tensiometry and goniometry. However, to determine the contact angle of water in soil can be quite tricky, since it is difficult to determine the contact angle by direct measuring in porous media. Letey *et al.* (1962a) conducted research on how to determine the contact angle of a liquid in soil. They used Poiseuille's approximation:

$$Q = \frac{\pi r^4 P}{8L\eta}$$

Q is the rate of flow in volume per unit time (Volule/time), P is the pressure driving the water, r the capillary's radius, η is the viscosity of the solution and L is the capillary length. They described pressure (P) with two components, namely gravitational and capillary pressure.

$$P_g = \rho g h \qquad \& \qquad P_c = \frac{2\gamma \cos\theta}{r}$$

In this equation ρ is the density of the solution, g is the gravitational constant, h is the capillary length plus the depth of the solution above the capillary, γ is the surface tension of the solution and θ is the liquid-solid contact angle.

Substituting the equations for P_c and P_g into Poiseuille's approximation produces the following equation:

$$Q = \frac{\pi r^3(\rho rgh + 2\gamma\ cos\theta)}{8L\eta}$$

This equation express the rate of water entry into the soil as a volume, it is however more convenient to express it in terms of depth. Dividing Q by πr^2, the cross sectional area of the capillary, converts the rate of water entry in terms of volume to depth of water (Q'). This equation represents only one capillary and the soil consists of several capillaries. Thus, multiply the rate of water entry with the porosity (C) and the following equation is obtained:

$$Q'' = \frac{Cr(\rho rgh + 2\gamma\ cos\theta)}{8L\eta}$$

For sand columns the above equation cannot be used. Since $P_c = P_g$ at equilibrium, the height of capillary rise can be derived from:

$$h = \frac{2\gamma\ cos\theta}{\rho gr}$$

In the last two equations only *r* and *θ* is unknown or cannot be measured. Ethanol wets all surfaces with an apparent angle of zero, and by using ethanol for infiltration or capillary rise, *r* can be solved, which is a characteristic of the soil column and not the liquid. With *r* known, the contact angle for different solutions can be determined.

2.3 Soil physical properties

2.3.1 Aggregate stability

2.3.1.1 Introduction

Aggregate stability is a relative concept and is defined as "the resistance of aggregates to breakdown when subjected to potentially disruptive forces" (Hillel, 1980). A well aggregated soil is well aerated and water can infiltrate faster compared to a soil of similar mineral and organic matter composition, but which is not aggregated. A well aggregated soil is also less susceptible to erosion and less susceptible to compaction under traffic and the impact of rain drops. Furthermore, conditions in well aggregated soils are more beneficial for plant roots to penetrate the soil and anchor itself. Crust formation, which is a state of a soil with poor aggregate stability, may also decrease seedling emergence and thereby production.

2.3.1.2 Factors affecting the formation and breakdown of aggregates

Factors that influence the formation, degradation and stability of aggregates in the soil can be physical, chemical or biological, but usually is a combination of the three. Five factors according to Harris *et al*. (1966) that affect aggregate dynamics are cropping systems, microorganisms, earthworms, cultivation and climate.

For cropping systems, the most important is the influence of the roots, which can either cause breakdown or aggregate formation. Roots can penetrate aggregates and thereby break it into smaller units (Harris *et al*., 1966). In soils with smaller aggregates, or which are single grained, the roots can enmesh the soil particles and compress it into larger aggregates.

Soil microbes convert root secretions and residues to organic binding agents. The type of plants that are established in the soil therefore plays an important role in the activity of the microbes in the soil. According to Hillel (1980) the microorganisms in the soil can bind aggregates. Some of the microbial products that bind aggregates are polysaccharides, hemicelluloses and levans (a type of polysaccharide). These products are attached to the surfaces of the clay particles by cation bridging, hydrogen bonding, Van der Waals forces and anion adsorption. Harris *et al*. (1966) reported differences in effectiveness of different soil organisms regarding aggregation. Fungi and streptomycetes were the most effective in aggregation, more so than bacteria and yeasts.

Earthworms also play an important role in aggregate dynamics. The casts from earthworms are more water stable than aggregates from soil with no worms. The burrowing activity of earthworms enhances soil aeration and infiltration, creating a more favourable environment for soil microbes and root growth. Factors that affect the amount of earthworm casts produced are time of the year, worm species, soil type, soil water content, soil temperature, pH, calcium availability, organic matter availability, vegetative cover and soil management practices. Ploughed soil had the smallest amount of worm casts (Harris *et al*., 1966).

Cultivation in this context refers to tillage practices (Van der Watt & Van Rooyen, 1995). Tillage in soil which is too wet or too dry can have an adverse effect on aggregate stability (Harris *et al*., 1966). Álvaro-Fuentes *et al*. (2008) demonstrated that no-tillage and reducing the time a field lies fallow resulted in increased soil aggregation. They proposed that reduced tillage and less fallowing increased soil organic carbon content and microbial biomass.

Climate is one of the non-biotic aspects of aggregation. Seasonal effects of climate like freezing and thawing and wetting and drying have an influence on the aggregate dynamics of the soil. There is no definite rule on the influence of freezing and thawing on aggregate dynamics. Harris *et al.* (1966) mentioned different results obtained from various researchers. Some researchers reported that freezing and thawing have no effect on aggregate stability. Others indicated that rapid freezing results in the formation of many small aggregates while slow freezing promotes the formation of large aggregates. Others indicated that slow freezing causes great pressure in the soil as a result of the expansion of water when it freezes and that aggregates form due to this pressure. There are studies that indicated that larger aggregates are more prone to breakdown by freezing than smaller ones.

Research on the effect of the amount of wetting and drying cycles of soil and to what extent the soil is dried out, on aggregate dynamics, showed that soil particles, rearrange to a position of minimum free energy when it is kept at constant water content for long periods (Semmel *et al.,* 1990). Soils that is dried out more intensively, has higher bulk densities due to the water menisci forces which pull the particles together. The tensile strength of aggregates is influenced by the extent to which the soil is dried out. If the soil is dried out to a high degree, the salts, humic acids and soil colloids concentrate at the contact points of the soil particles via the transport of it through the water films around the soil particles. This causes the particles to be cemented even stronger. The swelling and shrinkage of a homogenized soil will lead to the heterogenisation of the pore system and the soil will reach a region of stability after a period of time. Harris *et al*. (1966) reported that uneven swelling of aggregates and entrapped air in a wetted soil can be detrimental to aggregate stability (discussed in section 2.3.1.3).

2.3.1.3 Breakdown mechanisms of aggregates

According to Le Bissonnais (1996) there are four mechanisms of aggregate breakdown namely slaking, breakdown through differential swelling, breakdown caused by the impact of raindrops and physico-chemical dispersion.

Slaking is when soil aggregates is wetted rapidly and the air inside the aggregates is compressed. This results in a clod that shatters as the compressed air inside the aggregate escapes. As the clay content of the aggregate increases, the risk of aggregate breakdown due to slaking decreases. Hillel (1980) refers to this process as air slaking. Differential swelling increases as the clay content of the aggregate increases. The same factors which controls slaking controls differential swelling. It is the volume of air inside the aggregate, the rate at which the aggregate wets and the shear strength of the aggregate. Breakdown by the impact of raindrops is much more severe when a soil is wet and uncovered. When the soil is wet the aggregates are weaker and when vegetation is present it breaks the impact of the raindrops (Le Bissonnais, 1996).

Physico-chemical dispersion occurs when there is a decrease in the attractive forces between colloids while wetting. The type of cation present plays an important role in dispersion and stability. Monovalent cations cause dispersion and polyvalent cations cause flocculation. The exchangeable sodium percentage (ESP) of the soil is the main soil property affecting dispersion. When an aggregate is broken down due to dispersion, it breaks down into its individual particles and not into smaller aggregates. Thus it is the most destructive force involved in aggregate breakdown (Le Bissonnais, 1996).

2.3.2 Soil strength and penetration resistance

2.3.2.1 Introduction

Soil strength is defined as "the resistance that has to be overcome to obtain a known soil deformation" (Lal & Shukla, 2004). Horn & Baumgartl (2002) explain it as the stress that needs to be applied for deformation to occur at the weakest point in the soil matrix. High soil strength prevents soil deformation and compaction under traffic and it prevents the destructive effect of erosion. The negative effects of high soil strength are poor root growth, low seedling emergence and high energy requirements for soil preparation (Lal & Shukla, 2004).

Penetration resistance is usually a measure of soil compaction, but is also a measure of the soil strength. Van der Watt & Van Rooyen (1995) defines it as the "resistance offered by a soil against the penetration of a standard probe." It is expected that if the shear strength increases, the penetration resistance will also increase (Bachmann *et al.*, 2006; Manuwa & Olaiya, 2012).

2.3.2.2 Forces responsible for shear strength

Shear strength is due to interaction of three forces, namely the structural resistance to displacement of soil particles, frictional resistance to translocation between the individual soil particles due to interparticle contacts and forces of cohesion and adhesion (Lal & Shukla, 2004). Shear strength increases when the resistance at the contact points increases or if the amount of interparticle contact points increases (Horn & Baumgartl, 2002).

Soil properties associated with shear soil strength are soil structure, bulk density, properties of soil solids and soil moisture content (Lal & Shukla, 2004). Soil structure includes aggregate dynamics like aggregate size, stability and distribution. Shear strength increases with greater aggregate diameter and increasing aggregate stability (Baumgartl & Horn, 1991). An aggregate has high stability if the forces which keep the soil particles together are high (Baumgartl & Horn, 1991).

Since clay is more cohesive than sand, soil strength increases with increasing clay content (Lal & Shukla, 2004). Precipitated calcium carbonate causes an increase in shear strength (Horn & Baumgartl, 2002). Soil organic matter can also increase in aggregate stability and possibly shear strength. Organic matter is broken down by microbes into organic cementing agents. On the contrary, an increase in organic matter can decrease bulk density and result in lower shear strength (Lal & Shukla, 2004).

It was already mentioned that more cycles of wetting and drying results in cementing agents which concentrate at the contact points in the soil. This causes an increase in aggregate stability. Low soil water contents pull the soil particles together which results in a higher bulk density, so the shear strength will increase (Koolen & Kuipers, 1983; Lal & Shukla, 2004). The result is that at lower water contents, the shear strength will increase due to an increase in bulk density and an increase in cementation of the different particles.

2.3.3 Infiltration and hydraulic conductivity

2.3.3.1 Infiltration

According to Brady & Weil (2008) infiltration is the process by which water enters the soil pores and infiltrability refers to the rate at which the water enters the soil. Infiltrability is important since it determines the amount of rain or irrigation water that will enter the soil and what will be lost due to overland flow (Radcliffe & Rasmussen, 2002). Hydraulic conductivity, soil water content before infiltration and soil aggregation plays an important part in how much water is going to enter the soil and how much is going to be lost via overland flow (Lal & Shukla, 2004). Poor infiltration may be the result of various interacting factors texture, crust formation, salinity, sodicity, compaction and hydrophobicity.

Agassi *et al.* (1981) found that two mechanisms can be at work during crust formation of a rain exposed soil. The first mechanism, the physical dispersion of the soil particles, is caused by the detachment of the particles by the physical impact of the raindrops. These particles then block the soil pores to prevent rapid infiltration of water. Secondly there is chemical dispersion which is influenced by the exchangeable sodium percentage (ESP) and electrical conductivity (EC) of the applied water. They found that at low to no electrolyte concentration the soil was very sensitive to the ESP. Even low ESP values caused dispersion. On the other hand, when water with high electrolyte concentrations were used, the ESP did not have such a large influence on dispersion as is the case with low electrolyte concentrations. Similar results were obtained by Shainberg & Singer (1985) for the effect of the electrolyte concentration. However, crusts formed via the physical mechanism (Agassi *et al.*, 1985), and crusts formed due to deposition of flocculated particles (Shainberg & Singer, 1985), are more permeable than crusts formed by chemical dispersion.

Infiltrability decrease with an increase in clay content (Medinski *et al.*, 2009). Ben-Hur *et al.* (1985) however, found that with an increase in clay content, infiltrability does not necessarily decrease. They reasoned that a soil with a higher clay content has a more stable structure. Thus it is less susceptible to crust formation. Aggregate stability plays a significant role in structure.

2.3.3.2 Hydraulic conductivity

Hydraulic conductivity can be divided into saturated hydraulic conductivity (K_s) and unsaturated hydraulic conductivity (K_u). K_s are the ability of the soil to conduct water when all the pores are saturated with water (Lal & Shukla, 2004). K_u is the ability of the soil to conduct water when some of the pores are filled with air. K_u is a much more complex process than K_s.

Hillel (1980) mentioned some of the important factors influencing the K_s of the soil including the total porosity of the soil as well as the size of the conducting pores. Thus a soil with large pores, such as a sandy soil, may have a lower total porosity than a clayey soil. However, the clay will have a smaller K_s, because of smaller pores. McNeal *et al.* (1968) did research on the K_s of soils with different clay contents, but with more or less the same clay mineralogy. The soils had an average clay content of 5.7, 16.2 and 48.5% respectively. The mineralogical composition of the clay fraction consisted of 42% montmorillonite, 29% mica and 16% quarts and feldspars. The overall result was a decrease in K_s with an increase in clay content.

McNeal *et al.* (1968) also found that free iron oxides have an influence on hydraulic conductivity. They found that soil with free iron oxides is more stable when solutions with high sodium and low salt solutions are applied than soils without the iron oxides. They also found that it is the more easily extractable iron oxides that stabilize the soil against dispersion.

Another factor mentioned by Hillel (1980) is the presence of preferential flow paths, e.g. cracks, channels of decayed roots and worm holes. When any of these are present in the soil a higher K_s is expected, especially when the channels are connected. Preferential flow paths can also occur in soils or rather part of the soil which has macro pores from top to bottom of the profile (Brady & Weil, 2008).

Entrapped air can also be a cause of a lower K_s. When a soil is completely saturated with water, no air bubbles are present. This however is difficult to achieve due to the entrapment of air bubbles in flow passages where the passage narrows (Hillel, 1980).

The effect of salt concentration on hydraulic conductivity should also be considered. Usually this will be associated with the dispersion and flocculation of clay particles. These processes are discussed in more detail in section 2.3.3.1 since the effect it has on hydraulic conductivity and infiltration is more or less of one accord.

K_u is different in certain aspects. While K_s are dependent on the structure of a soil, more specifically the macro pores of the soil, K_u is dependent on the texture. When some of the pores empty, the water cannot flow through it anymore. The water then needs to flow along the sides of the pores or through the smaller pores (Hillel, 1980). When the soil desaturates (matric potential becomes higher), K_u decreases. Since the coarser textured soils have more macro pores than meso and micro pores, the decrease in K_u is more rapid than for the same matric potential in a finer textured soil. Therefore a sandy soil will have a higher K_s than a more clayey soil, but as the matric potential becomes higher the K_u drops beneath that for a clayey soil at the same matric potential (Lal & Shukla, 2004; Radcliffe & Rasmussen, 2002).

2.4 Surfactants

2.4.1 Introduction

Surfactant is an abbreviation for “surface active agent.” Surfactants are also known as wetting agents. When it comes to agriculture, specifically focussing on soil, surfactants are used to improve soils with hydrophobic character which may have slow infiltration rates or to improve soil structure and thereby control erosion (Abu-Zreig *et al.*, 2003; Mustafa & Letey, 1969; Pelishek *et al.*, 1962).

2.4.2 Mechanism of adsorption

An interface indicates the boundary between any two immiscible phases e.g. the boundary between a solid and a liquid (Rosen, 2004). Surface indicates that at least one of the phases is a gas (Rosen, 2004). Surfactants have the ability to adsorb to an interface and thereby cause a change in physical properties of the latter. According to Eastoe (1993), this adsorption can be attributed to both the solvent nature and the properties of the surfactant. Usually the solvent is water, which has a dipole nature. Eastoe (1993) described the surfactant as being amphiphilic. Such molecules have a polar and a non-polar group. This is however not the only type of surfactant that exists. In a solution where water is the solvent, the non-polar end of the amphiphilic molecules will tend to be orientated away from the polar water molecules. In a hydrophobic soil these non-polar ends will bind to the hydrophobic coating on the soil mineral particle. Through this binding, the polar, hydrophilic ends of the surfactant molecules are facing outward allowing water molecules to bind to it. These amphiphilic molecules decrease the surface tension (or interfacial tension). Long-chain alcohols also have the ability to bind to a hydrophobic surface with its hydrophilic group facing outward resulting in the hydrophobic surface becoming hydrophilic. These alcohols are not true surfactants. A surfactant forms oriented mono-layers at the surface of the interface and it has the ability to form micelles and vesicles when in bulk.

Law *et al.* (1966b) explained the adsorption mechanism in the same way as above, but used specific surfactants on clays. They found that anionic surfactants were not adsorbed in large quantities on clay. Law *et al.* (1966a) found that since anionic surfactants do not form strong bonds with soil particles, it moves with the soil solution. Nonionic surfactants adsorb on clay particles with the hydrophobic tail facing towards the outside, making the soil more hydrophobic (Law *et al.*, 1966a).

2.4.3 General overview of different surfactants

Anionic surfactants are negatively charged. According to Poulter (2003), it has a negative impact on soil structure, is often phytotoxic to plants and thus are not used to manage soil water repellency. A disadvantage of anionic surfactants such as carboxylic acid salts is that it can form insoluble soap with divalent and trivalent cations. Other major groups of anionic surfactants are sulfonic acid salts, sulphuric acid ester salts, phosphoric and polyphosphoric acid esters and fluorinated anionics (Rosen, 2004; Parr & Norman, 1965). Anionic surfactants do not bind as strong as cationic and nonionic surfactants to soil (Liu & Roy, 1995).

Cationic surfactants are positively charged. They have the ability to change hydrophilic soil to a hydrophobic soil by adsorption of the surfactant on the soil particles. Thus, they also are not used to manage soil water repellency (Poulter, 2003; Parr & Norman, 1965). The cationic surfactants are attracted to the negative sites on bacteria cell surfaces. This usually leads to the injury of the cell and eventually death.

Nonionic surfactants have no net charge, but the molecules are polar. A nonionic surfactant consists of ethylene oxide and propylene oxide units, which in short are known as EO/PO block copolymers. They are long chain polymers which is hydrophobic at the one end and hydrophilic at the other. The hydrophobic end of the molecule binds to the coating on the soil particle while the hydrophilic end is facing outward (Parr & Norman, 1965; Poulter, 2003). This is in contrast to Law *et al.* (1966a) who reported that it is the hydrophilic end of the molecule binding to the soil particle, resulting in the soil becoming more hydrophobic. Law *et al.* (1966a) referred to a nonionic surfactant which binds to soil that is not hydrophobic while Poulter (2003) and Parr & Norman (1965) to a nonionic surfactant that is applied to a hydrophobic soil.

There are also other types of surfactants available. Amphoteric surfactants have a positive and negative end on one molecule. Lubricants containing various types of poly-oxyalkylene glycols are good agents to wet the soil with. Granular soil wetting agents is a combination of surfactants, inert clay and organic material while synergistic compounds are a combination of nonionic surfactants and lubricants. Soil humectants are large complex molecules, which are used in skin moisturisers. These compounds are not popular to use as a wetting agents since it accumulates near the surface due to its size. Organic acids apparently remove the hydrophobic compounds that cover the soil particles, but there is no evidence to prove it. Gemini surfactants consist of two to three hydrophobic groups and two hydrophilic groups (Poulter, 2003).

2.4.4 Effect of surfactants on hydraulic conductivity and infiltration

Pelishek *et al.* (1962) conducted research on the effect of wetting agents, which were available at that time, on infiltration. All had one factor in common: the wetting agent solutions had a lower surface tension than the water itself. The recommended dilutions of the wetting agents did not have an appreciable effect on the viscosity or density of the water. No chemical or structural information was given for the wetting agents under investigation.

Pelishek *et al.* (1962) also tested the infiltration rates of wetting agent solutions on thatch which is generally a hydrophobic material. Six cores were used, three for the treatment and the control each. The treatment was a wetting agent solution while the control was only water. The time it took for the first droplet to appear at the bottom of the core was taken (penetration time) and also the time it took for 100 ml to pass through the core. The residual effect was tested afterwards by running only pure water through all the cores. In the hydrophobic soils the infiltration rate increased after application of the wetting agent, but no major differences were observed in the infiltration rate after application to a hydrophilic soil (Pelishek *et al.*, 1962).

Abu-Zreig *et al.* (2003) found that the application of anionic surfactants can cause a decrease in hydraulic conductivity by the breakdown of the aggregates and soil dispersion. The nonionic surfactants did not have a significant effect on the hydraulic conductivity.

According to Liu & Roy (1995), the introduction of a solution of sodium dodecylsulfate (SDS) to a column which consists of only sand did effect on the hydraulic conductivity. Hydraulic conductivity studies on soil columns with different clay contents indicated decreased hydraulic conductivity when the SDS was applied and the hydraulic conductivity decreased as the concentration of SDS increased in the solution. The decrease in hydraulic conductivity could have been due to one or more of the following: swelling of the clays, deflocculation due to sodium and smaller particles blocking the pores.

2.4.5 Aggregate stability and surfactants

Various researchers evaluated the effect of surfactants on the aggregate stability of soils. The focus was mainly on anionic and nonionic surfactants.

In all instances anionic surfactants decreased aggregate stability at the macro and micro level (Law *et al.,* 1966; Mbagwu *et al.,* 1993; Piccolo & Mbagwu, 1989; Piccolo & Mbagwu, 1994). The anionic surfactants can only adsorb on soil particles through weak Van der Waals interactions and hydrophobic bindings between the apolar end of the surfactant molecule and the apolar parts of the soil particles (Mbagwu *et al.,* 1993; Piccolo & Mbagwu, 1989). The hydrophilic end is thus facing away from the soil particle, which will enable water to wet the aggregates easier. This poor adsorption of anionic surfactants causes it to move more easily with the soil water in the same way as the soluble salts.

Most literature on the nonionic surfactants was not always the same. Mostly the results showed that aggregate stability increased at the macro level after application (Law *et al.,* 1966; Piccolo & Mbagwu, 1989; Piccolo & Mbagwu, 1994). However, Mustafa & Letey (1969) found that after the application of a nonionic surfactant to a hydrophobic soil the aggregate stability decreased, but that application to a hydrophilic soil might increase the stability. Piccolo & Mbagwu (1989) found that at the micro level, aggregates are better stabilized when more clay is present. They proposed that the polar end of the surfactant binds with the hydroxyls and oxygens of the clay particles. This causes the hydrophobic ends of the surfactant molecule to face away from the clay which results in the aggregate being more hydrophobic.

2.4.6 Bulk density and surfactants

Literature on the effect of surfactants on bulk density was limited. Brandsma *et al.* (1999) researched the effect of different soil conditioners, which is fundamentally the same as surfactants, on the bulk density of a loamy sand (5.4 % clay) soil which contains 1.9% organic matter. The soil conditioners under investigation were a blend of organic wetting agents, enzymes and surfactants, an anionic polyacrylamide conditioner, a humic acid conditioner and an anionic conditioner. They found that all the soil conditioners caused a significant decrease in the soil bulk density at the 0-50 mm depth.

2.4.7 Adsorption and degradation of surfactants in the soil

Different types of surfactants react differently in soil and with different minerals (refer to section 2.4.5). Sánchez-Martin *et al.* (2008) studied the adsorption of anionic, cationic and nonionic surfactants on clay minerals. The clay minerals (with CEC in brackets) used in this study was montmorillonite (82 $cmol_c/kg$), illite (15 $cmol_c/kg$), kaolinite (6.1 $cmol_c/kg$), muscovite (21 $cmol_c/kg$), sepiolite (5.0 $cmol_c/kg$) and palygorskite (27 $cmol_c/kg$).

The cationic surfactant showed the highest adsorption to all the minerals except for kaolinite and sepiolite. Law & Kunze (1966) found that for cationic surfactants, small organic cations adsorb in quantities of up to the CEC of the soil, while larger molecules adsorbed in excess of the CEC.

The anionic surfactant showed the greatest adsorption to kaolinite and sepiolite in the study by Sánchez-Martin *et al.* (2008), while Law & Kunze (1966) found that the anionic surfactants adsorbed on kaolinite up to 50% of the CEC. For the montmorillonite no adsorption was detectable, as the montmorillonite has a net negative charge. The latter explains why cationic surfactants are adsorbed in large quantities by clay minerals with large CECs.

The nonionic surfactant adsorbed the best on montmorillonite and illite. The polar end of the nonionic surfactant molecules forms hydrogen bonds with the oxygen at the clay surface (Law & Kunze, 1966; Sánchez-Martin *et al.*, 2008). Since kaolinite is a non-swelling clay (the kaolinite layers are bound by hydrogen bonds between the OH^- groups of the octahedral sheet of one layer to the O^{2-} of the tetrahedral sheet of another layer), adsorption only happen on the surfaces of the lattice exposed to the surfactant solution and at the edges of the layers. There can be no interlayer adsorption as with montmorillonite, which is a 2:1 clay mineral. The montmorillonite consists of an octahedral sheet between two tetrahedral sheets. Thus both surfaces of a montmorillonite layer have oxygen ions. The montmorillonite layers are bound by monovalent cations which are hydrated. Since these cations can easily be displaced by other cations in solution, the surface available for the nonionic surfactant to adsorb on is high for montmorillonite. According to Law & Kunze (1966) a mono layer of nonionic surfactant molecules tended to form on each side of a montmorillonite clay layer resulting in two layers of surfactant molecules between two clay layers. Law & Kunze (1966) and Sánchez-Martin *et al.* (2008) found that the degree of nonionic surfactant adsorption depends on the concentration of it in the solution in the soil.

Valoras *et al.* (1976) studied the degradation of different nonionic surfactants in the soil. They found that 50% of the surfactants, applied according to the recommended application rate, were degraded after 60 days. The percentage decomposition was at higher application rates not as rapid as with the lower concentrations. As mentioned, nonionic surfactants are usually adsorbed in the soil by montmorillonite and illite. The greatest adsorption is at the soil surface where it is applied which is also where the highest microbial activity occurs. However, if the surfactant is adsorbed, the degradation process was not as rapid as in soil where it was not adsorbed (Valoras *et al.*, 1976).

The d-spacing of dehydrated montmorillonite are 10 Å and it can be as high as 21 Å (21×10^{-10} m) while bacteria in soil can be as small as 1 µm (1×10^{-6}m) (Coleman *et al.*, 2004). It can therefore be assumed that the nonionic surfactants are preserved when it is adsorbed between the montmorillonite layers.

2.5 Orange oil

The main constituent of cold pressed orange oil is D-limonene (see Figure 2.3) making up approximately 95% of its composition (Dugo *et al.*, 2011). D-limonene is a cyclic monoterpene and it has a characteristic lemon-like odour (Gerhartz *et al.*, 1988). It has a melting point of -99.4°C and a boiling point of 178°C. D-limonene is insoluble in water, but still a reactive compound which is often oxidized resulting in the formation of an epoxide. Limonene is toxic to insects and is used to control cat fleas (Hink & Feel, 1986), mealy bugs and scale insects (Hollingsworth, 2005). Limonene is also used in manufacturing of fragrances for perfumes, food and detergents.

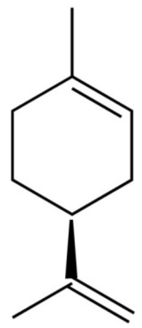

Figure 2.3: Structure of D-limonene, the compound making up more than 90% of the composition of orange oil.

Research on the effect of various monoterpenes on the germination, root growth and mitochondrial respiration of maize indicated that limonene, which is lipophilic (soluble in fat), did not have an effect on seed germination and root growth (Abrahim *et al.*, 2000). However, application of limonene in concentrations of 0.1-5.0 mM to mitochondria resulted in uncontrolled respiration. The limonene was probably acting as an uncoupler in the oxidative phosphorylation process. A 10.0 mM limonene solution did not affect the mitochondria. The limonene probably formed micelles, which prevented the substance from interfering with mitochondrial processes.

3. Materials and Methods

3.1 Description of study areas

3.1.1 Introduction

Trials were done on four farms namely, Dublin Farm, Toitskraal, Two Rivers and Wansbek. The soils differed in texture and was free of hydrophobicity or other problems, except at Wansbek, where the soil had a low infiltration rate.

3.1.2 Dublin Farm

Dublin Farm (Figure 3.1) is situated approximately 30 km west of Hoedspruit in the Limpopo Province (S24^{o}21.750' E30^{o}39.345'). The elevation is approximately 464 m above sea level. Hoedspruit has a mean annual rainfall of 520 mm, most of it precipitating during the hot and humid summer months. The citrus trees of the trial orchard, Bahianina navels, are established on highly weathered, red, Shortland 2120 soils (Soil Classification Working Group, 1991). The red structured B horizon was classified as eutrophic and non-calcareous in the lower B horizon which had a medium to coarse blocky B horizon. Both the topsoil and subsoil have a Munsell soil colour of 5YR 3/3. These sandy clay loam soils (~22% clay) are homogeneous to a depth of 400 mm where there is a slight, but definite change in colour from red to more yellow. The slope was less than 5%, straight and was facing towards the east.

3.1.3 Toitskraal

The farm Toitskraal (Figure 3.1) is situated about 20 km southwest of Marble Hall, Limpopo Province (S25^{o}03'19.64" E29^{o}08'24.8"). At 927.5 m elevation, it has a mean annual rainfall of 572 mm which precipitates mostly during the summer months. As at Dublin Farm, the trials were conducted in a citrus orchard. This soil is on the border between a loamy sand (~7% clay) and sandy loam and has approximately 8% coarse fragments. In the dry state it becomes extremely hard possibly due to silica cementation (Figure 3.2). It is classified as an Oakleaf 2110 (Soil Classification Working Group, 1991), which has a bleached A-horizon, a non-red B-horizon and a non-luvic B1-horizon. The slope was between zero and two percent.

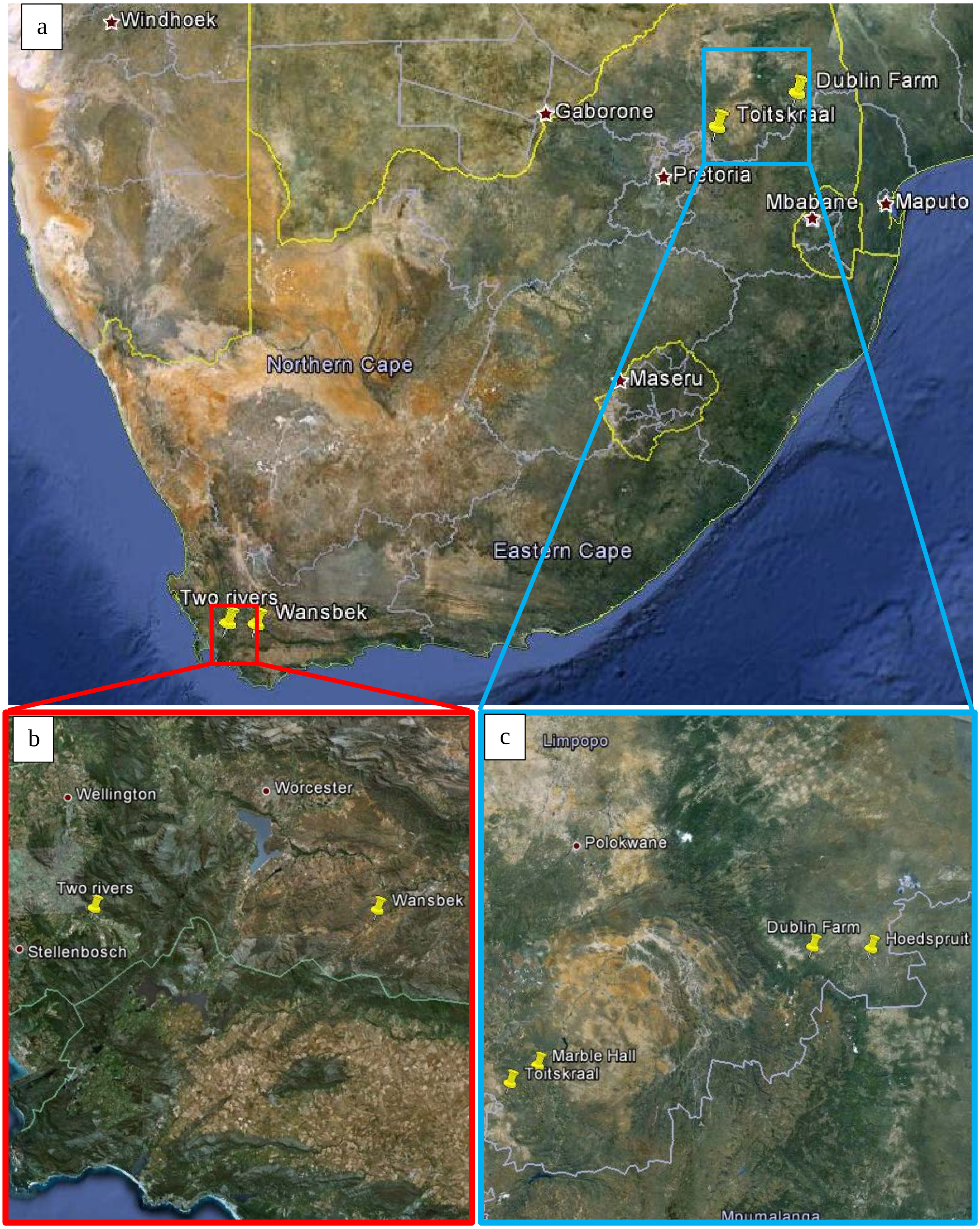

Figure 3.1: Google Maps images of the locations of the different farms where the trials were conducted in a) South Africa and at larger scale within the b) Western Cape and c) Limpopo Province.

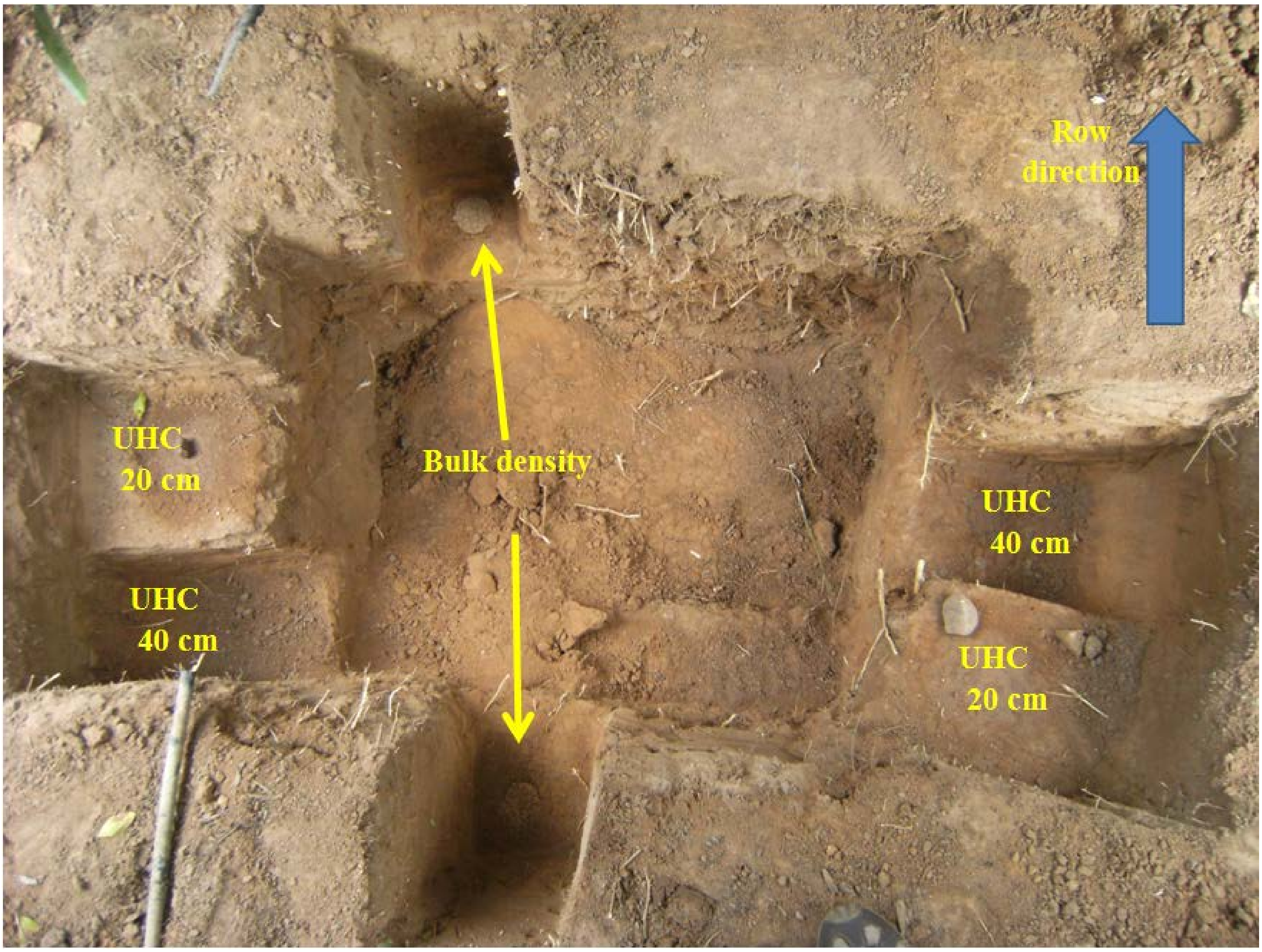

Figure 3.2: A view of a profile pit at Toitskraal trial 1 from above. Locations where K_u and bulk density samples were taken are indicated on the figure. Note that this soil only has approximately 8% clay, but due to silica cementation, is extremely hard in the dry state.

3.1.4 Wansbek

Wansbek (Figure 3.1) is situated about 27 km southwest of Robertson in the Western Cape. Production on this farm (S33°54'2.96" E19°40'31.61" and 203 m above sea level) is dependent on irrigation water since the mean annual rainfall, which occurs mostly during the winter months, is about 270 mm. Various grape cultivars are present on the farm. Field studies were done in a block of Shiraz on Richter 110 rootstock. The slope of less than 5% faced in a south eastern direction. The Valsrivier 1212 soil form (Soil Classification Working Group, 1991) is dominant and it has approximately 20% clay (sandy loam). The orthic A horizon were not bleached which were on top of a red pedocutanic B horizon with a sub angular to fine angular structure which is calcareous.

3.1.5 Two Rivers

Two Rivers (S33 ° 52’23.59” E19 ° 1'56.91", Figure 3.1) is situated approximately 7 km west northwest from Franschhoek. Like Wansbek, this farm is in a winter rainfall region with a mean annual rainfall of 840 mm. The plum orchard where the field studies were conducted is situated less than 400 m from the confluence of the Berg River and the Wemmers River.

It is a deep sandy soil containing 3-4% clay, which is dark when moist and a light grey-brown colour when dry. The side of the orchard closest to the river has a lot of stones which were transported and deposited by water (Figure 3.5).

Although this is a deep sandy soil with no clay subsoil, the plum trees are planted on ridges due to wet subsoils. The slope is 0-5% and faces in a south-eastern direction.

3.2 Product characteristics

The product is a proprietary product of Oro Agri®. It contains orange oil and a blend of anionic and nonionic surfactants as main constituents.

The recommended application rate at the start of this study was as follows: 30 ℓ/ha for full surface irrigation, 20 ℓ/ha for micro irrigation (assuming 2/3 of surface is wetted) and 10 ℓ/ha for drip irrigation (assuming 1/3 of soil surface is wetted). It must preferably be applied through the irrigation system. Otherwise it must be diluted in water, applied on the soil surface, and subsequently washed in by applying more water.

The present recommended application rate is based on the area in m^2 effectively wetted by the irrigation system and is 3 $mℓ/m^2$. Field studies conducted in 2011 were all based on trials with different application rates of the product according to the first (ℓ/ha) recommendation of Oro Agri. Those done in 2012 were done on trials according to the new (3 $mℓ/m^2$) recommendation made by Oro Agri.

3.3 Application and site selection within study area

3.3.1 Dublin Farm

At Dublin Farm the application of the product could not be done via the irrigation system, since flood irrigation is used in the trial orchard. The product was diluted and applied to the surface of the water in the irrigation basins beneath each tree just after it was filled during irrigation. Application of the product was made on 17 August 2010 at a rate of 20 ℓ/ha. The first two rows of the trial orchard, highest up on the slope, served as an untreated control and did not receive any application of the product. These two rows were selected to eliminate the lateral movement of the product with the soil water along the slope. The profile pits of the control and the treatment were in rows next to each other and not too far apart within the row to eliminate soil variation as far as possible between the pits. Three pits for each of the treatments and the control were dug between two trees of the same row the pit being approximately 800 mm by 800 mm and 500 mm deep. Field studies were conducted from the 22nd to 24th of March, 2011, seven months after application of the product.

A second application of 20 mℓ/tree (more or less 10 ℓ/ha) was made on 5 September 2011 so from the 20th to 22nd of June 2012, field studies were again conducted at Dublin Farm. The same procedure in terms of site selection was followed this time as compared to trial 1. A trial layout with an approximate indication of the profile pit selection is presented in Figure 3.3a. The results are referred to as Dublin Farm trial 1, the 2011 field studies, and Dublin Farm trial 2, the 2012 field studies.

3.3.2 Toitskraal

At Toitskraal micro irrigation lines are installed underneath the trees and emitters partially wet the soil surface (about 67 %). The product was applied through the irrigation system at a total application rate of 20 ℓ/ha (a 10ℓ/ha application was made on 11 November 2010, and again on 4 April 2011) in the treated blocks. There are three irrigation blocks in the orchard (Figure 3.3b). Two were treated with the product and one was an untreated control. Three profile pits for each of the control and the treatment were dug, a pit between two trees of the same row with approximate dimensions of 800 mm by 800 mm and 500 mm deep. Similarly, in order to eliminate soil variations as far as possible, the profile pits were not too far apart from each other. Field studies were conducted on the 6th, 7th and 9th of May, 2011, one month after the second application.

Another application of the product was done on 25 June 2011, also through the irrigation system. However, this application was done only in one irrigation block (Treatment 3 in Figure 3.3b) at a rate of 3 mℓ/m². Field studies were subsequently conducted on the 18th and 19th of June 2012. Two profile pits were dug in the untreated control irrigation block, two were dug in the irrigation block that did not receive another application after the April 2011 application and two pits were dug in the irrigation block that received an application after the April 2011 application. The pit dimensions were the same as for trial 1, except where a coarse fragment layer at 300 mm prevented excavation to further depths.

The trial layout and relative profile pit locations are presented in Figure 3.3b. The results are referred to as Toitskraal trial 1, the 2011 field studies, and Toitskraal trial 2, the 2012 field studies.

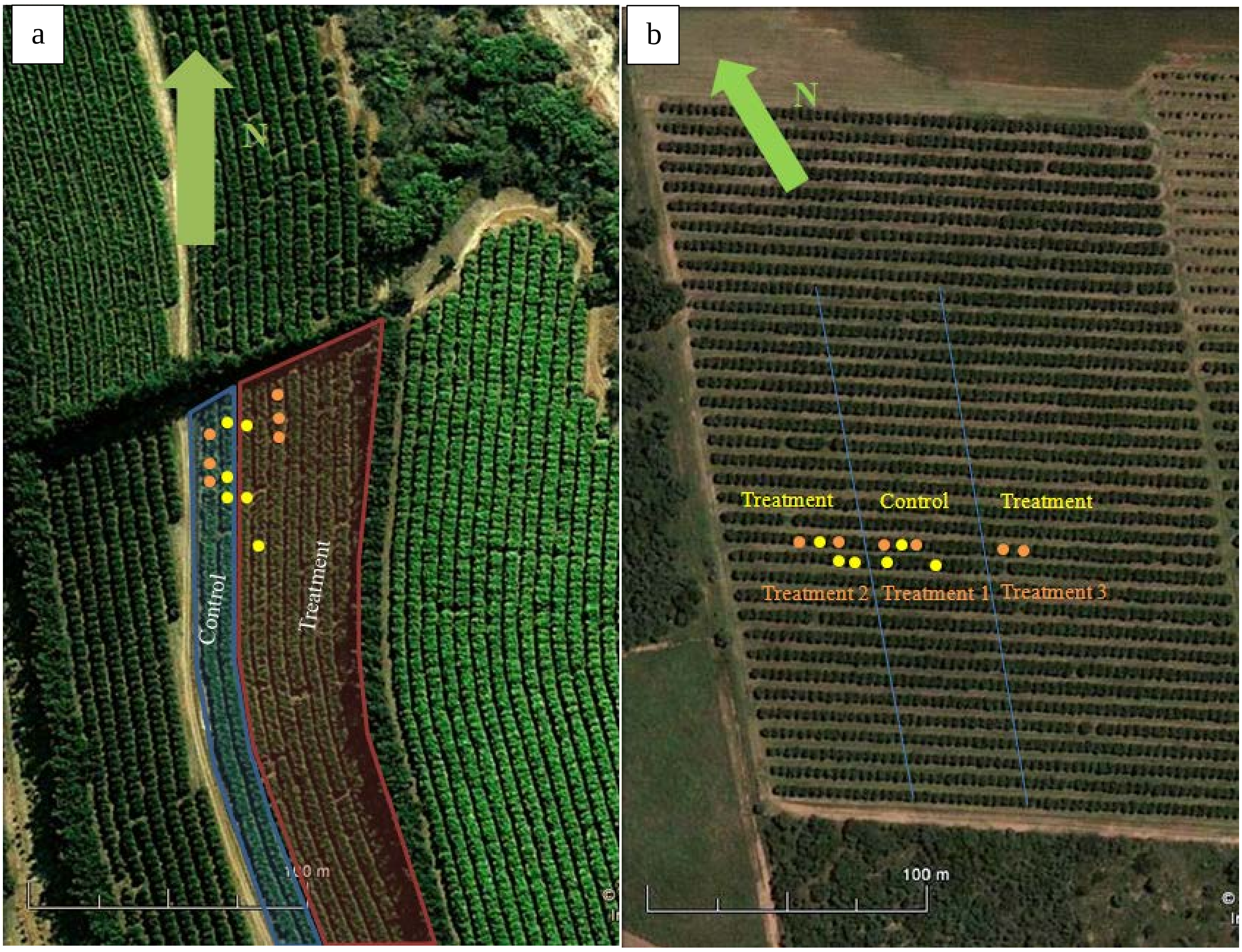

Figure 3.3: Approximate locations of the profile pits at a) Dublin Farm and b) Toitskraal. The yellow dots indicate the profile pits for the first trials and the orange dots indicate the profile pits for the second trials. At Dublin Farm the control and treatment block in the trial orchard was the same for both trial 1 and 2. At Toitskraal trial 1 and trial 2 is indicated by approximate yellow and orange colours respectively. The blue lines in b) indicate irrigation block boundaries are approximately. Treatment 2 in b) refers to the 1-year treatment and treatment 3 refers to the 2-year treatment.

Hereafter, for trial 2, the control block is referred to as the control, treatment 2 referred to as the 1-year treatment and treatment 3 referred to as the 2-year treatment.

3.3.3 Wansbek

At Wansbek, sites had to be selected based on the layout of an existing irrigation trial. The first two sections (of five vines per section) were selected of each of six rows for the research (Figure 3.4). One section represented an experimental plot. The 12 sections were divided into three groups. Each section of one of the four sections in a group received a different treatment. Thus there were four different treatments. First was the untreated control where no application of the product was made. Secondly an application of half (5 ℓ/ha) the recommended application was made. Thirdly a recommended (10 ℓ/ha) application was made and lastly a double (20 ℓ/ha) the recommended application was made. Hereafter, they are referred to as the control, 5 ℓ/ha, 10 ℓ/ha and 20 ℓ/ha treatments respectively. Sixty-two and a half millilitres of the product was diluted in a 5 ℓ volumetric flask and transferred to 100 mℓ plastic bottles. To achieve the desired application rates, one 100 mℓ bottle was applied per dripper for the 5 ℓ/ha treatment, two bottles for the 10 ℓ/ha treatment and four bottles for the 20 ℓ/ha. The bottles were emptied out underneath the dripper in little basins made by hand at the beginning of the irrigation period.

Solutions of the product were made up for each experimental plot and applied directly under the dripper. The soil water level was maintained between 70-80% of field capacity. The product was applied on 21 October, 2011 for the 5 ℓ/ha and 10 ℓ/ha applications. About three quarters (three bottles, equals 15 ℓ/ha) of the 20 ℓ/ha application was applied on the same date at each dripper and the second application (one bottle, equals 5 ℓ/ha) was made on 26 October 2011. The field studies were conducted from 28 November 2011 up to 13 December 2011. At each experimental plot three profile pits were dug for the field studies.

3.3.4 Two Rivers

At Two Rivers different concentrations and number of applications of the orange oil product was tested, as well as three other products. A summary of the different treatments are presented in Table 3.1. For the purpose of this study, the untreated control (no.1), the 2 mℓ/m^2 (no.3) and the 2 × 2 mℓ/m^2 (no.6) were investigated. Each experimental plot consisted of ten trees. Each treatment was replicated on four plots, thus a total of 40 plots. The layout of the trial and plots selected for this study are presented in Figure 3.5.

At Two Rivers micro irrigation is installed in the trial block. The product was applied diluting the solution and spraying it onto the soil. Thereafter the irrigation was switched on for approximately 60 minutes to wash the product into the soil.

Eight profile pits, distributed over different experimental plots, were dug per treatment (Figure 3.5). For treatment 3, two profile pits were dug in rows 1 (R1) and 5 (R5) each. Four profile pits were dug for all the other selected plots. Field studies were conducted from 7 to 11th of May 2012.

Hereafter, treatment 1 is referred to as the control, treatment 3 referred to as the 1×2 mℓ/m^2 treatment and treatment 6 is referred to as 2×2 mℓ/m^2 treatment.

Table 3.1: Summary of different treatments at Two Rivers farm. The product refers to the orange oil based soil ameliorant.

Treatment	Description	Rate (mℓ/m^2)	Application 1	Application 2	Application 3
1	Untreated control				
2	The product	1	14 Feb 2012		
3	The product	2	14 Feb 2012		
4	The product	3	14 Feb 2012		
5	The product	1	14 Feb 2012	2 Mar 2012	
6	The product	2	14 Feb 2012	2 Mar 2012	
7	The product	1	14 Feb 2012	2 Mar 2012	16 Mar 2012
8-10	Other non-applicable treatments				

3.4 Soil sampling

At Dublin Farm soil samples of 1-2.5 kg were taken at depths of 0-200 mm and 200-400 mm. These samples were taken at each profile pit by collecting soil from all four walls of the profile pit with a spade and a geological hammer. The same procedure was followed at Toitskraal, however different horizons were identified at different depths, and thus samples were taken representative of these horizons.

At Wansbek, approximately 8-12 kg soil was taken at each experimental plot. The soil was mixed in a 20 ℓ bucket and a 2 kg sub sample was taken out of it. Samples were taken at 0-200 mm and 200-400 mm depths.

At Two Rivers combined samples were taken. For each grey block indicated on the layout (a plot in the larger trial) a sample was taken at both 0-200 mm and 200-400 mm depth. Approximately 8-12 kg soil was taken from the four profile pits (in two of the cases it is two profile pits only). The soil was mixed in a 20 ℓ bucket and a 2 kg sub sample was taken out of the larger sample.

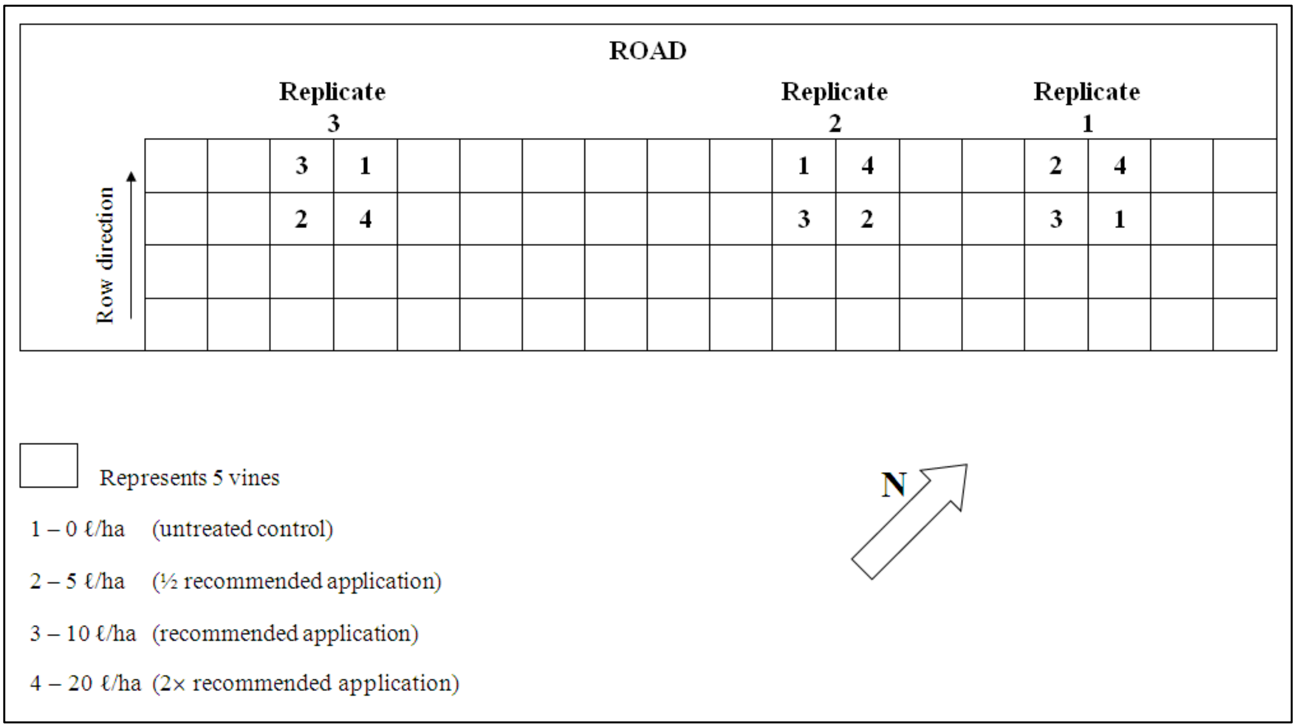

Figure 3.4: Trial layout at Wansbek.

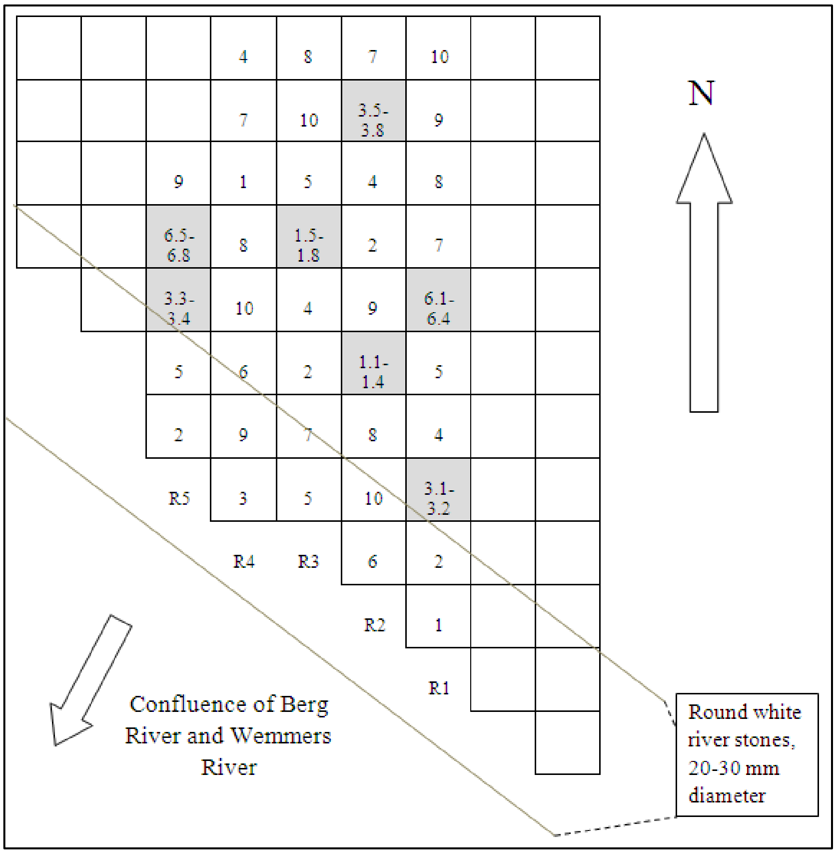

Figure 3.5: Trial layout at Two Rivers. Only the shaded plots from treatment 1, 3 and 6 were under investigation. Treatment 1 refers to the control, treatment 3 refers to the 1×2 mℓ/m² treatment and treatment 6 refers to the 2×2 mℓ/m² treatment.

3.5 Physical properties

3.5.1 General

3.5.1.1 Texture analysis

All texture analyses were done according to the pipette method described by Gee & Bauder (1986).

A texture analysis was performed for each sample of Dublin Farm (total of 12 analysis) and Toitskraal (total of 14 analysis). For Wansbek it was assumed that the variation between the experimental plots that were in a group (Figure 3.4) were negligible so only samples from the untreated control plots were analysed. For the Two Rivers farm, texture analysis was done on samples from the control in R3 (block 1.5-1.8 in Figure 3.5), the 1×2 mℓ/m² treatment in R1 (block 3.1-3.2 in Figure 3.5) and the 2×2 mℓ/m² treatment in R5 (block 6.5-6.8 in Figure 3.5)

Gee & Bauder (1986) describes different cementing agents, which soil particles, that should be removed prior to the texture analysis, namely, organic matter, silica cementing agents, carbonates and iron oxides and hydroxides. Not every cementing agent are always present in a soil. Thus, the organic matter was removed for each of the samples analysed. The iron oxides and hydroxides of the Dublin Farm samples and Wansbek samples were removed and the silica cementing agents of the Toitskraal samples.

3.5.2 Bulk density

At Dublin Farm bulk density was determined using the core method. For trial 1, four undisturbed cores were taken at each 100 mm depth increment up to 400 mm at each profile pit. The cores were dried for 48 hours at 50 - 60^{o}C. After that the cores were weighed and the bulk density calculated. Since bulk density was determined for Dublin Farm during the trial 1, fewer samples were taken during trial 2. The purpose of the samples taken during trial 2 was mainly to obtain samples for aggregate stability. Thus, only two samples were taken per profile pit for each 100 mm depth increment up to 300 mm.

At Toitskraal the bulk density was determined by using the sand fill method. A metal cylinder was used to remove approximately 260 g of soil, which was weighed immediately after withdrawal from the soil (Figure 3.6 a-c). Swimming pool filter sand (1.70 – 2.10 mm particle size) was poured into a beaker, placed on a small scale and the scale was zeroed (the scale then gives a zero reading with the beaker and sand on it). The hole was filled with the sand up to surface level through a cone to ensure the sand packing was more or less the same at each application. The beaker was placed back on the scale and the negative reading obtained was the mass of sand in the hole (Figure 3.6 d-f). The soil sample taken with the cylinder was dried for 48 hours at 50 - 60^{o}C and weighed. The bulk density of the filter sand was determined and each weight of sand poured into a hole converted to volume. Bulk density was determined at each 100 mm depth increment up to 500 mm. Two samples were taken at each profile pit. During trial 2 bulk density was determined in the same manner, but only up to 300 mm depth.

At Wansbek, the core method was also used. Two samples were taken at each of the three profile pits in an experimental plot. Usually the samples were taken directly beneath the locations where the minidisk infiltrometer measurements were taken. In this way six samples per depth per experimental plot were obtained. Samples were also taken for each 100 mm depth increment up to 500 mm.

The bulk density for Two Rivers was determined up to 500 mm depth for each 100 mm depth increment using the core method. At each profile pit two samples were taken per depth. The samples were also dried, weighed and the bulk density calculated as explained previously.

3.5.3 Aggregate stability percentage (ASP)

The bulk density samples were used to collect the aggregates. Aggregate stability was determined for each 100 mm depth interval up to 300 mm depth for both trials of Dublin Farm and Toitskraal.

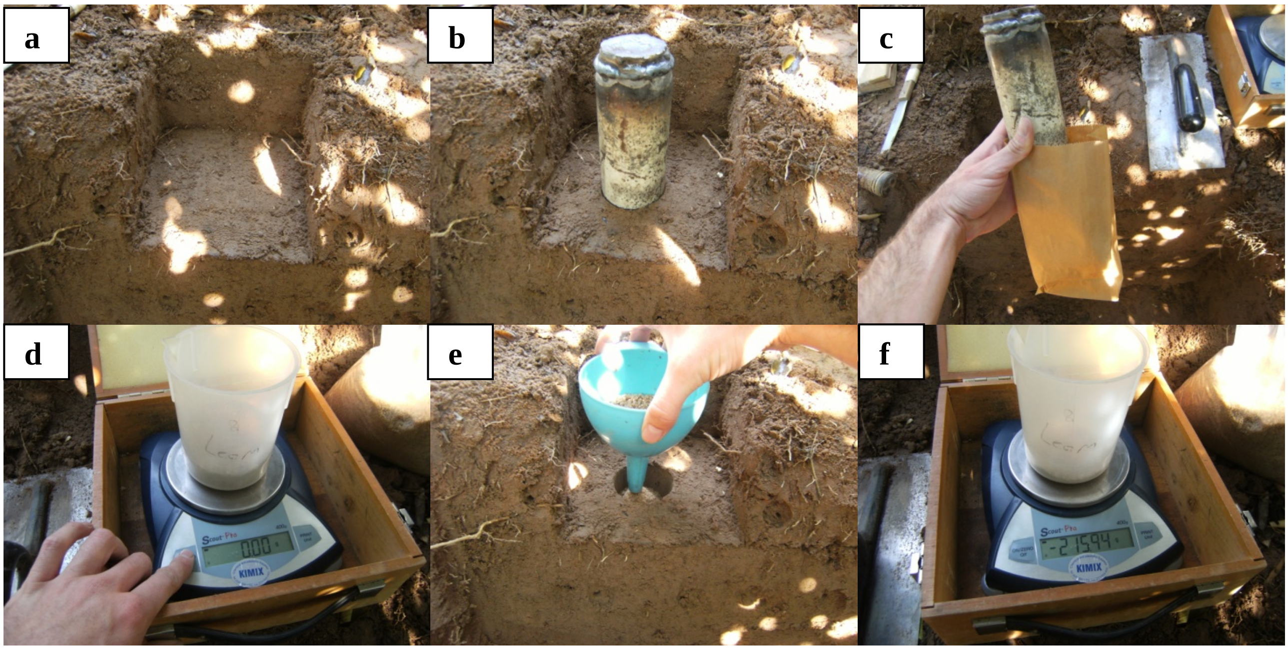

Figure 3.6: Bulk density determination according to the sand fill method: a) First the soil surface is made even, b) a steel cylinder is driven into the soil, c) the steel cylinder is removed, the soil is transferred to a paper bag and weighed, d) a beaker with filter sand is placed on a scale and zeroed, e) the filter sand is poured into the hole with a cone up to surface level, f) the remaining filter sand

is poured back into the beaker and placed on the scale. The negative reading is the mass of filter sand in the hole.

Nine replicates for each of the treatments and control per depth were done for both trials at Dublin Farm and for trial 1 at Toitskraal. For Toitskraal trial 2, eight replicates were done for the 0-100 mm depth of each treatment, but for the next two depth increments the aggregate stability of only the control and 1-year treatment was determined. The wet sieve method according to Kemper & Rosenau (1986) was followed.

Aggregate stability was also determined up to 300 mm depth for Wansbek, but only for the control and 10 ℓ/ha treatment (recommended application). Nine replicates were done for each treatment for each depth.

No aggregate stability was done for Two Rivers since it is a single grained soil with few to none aggregates.

The aggregates selected for Dublin Farm trial 1, Toitskraal trial 1 and Wansbek were 2-4 mm in diameter. Those selected for Dublin Farm trial 1 and Toitskraal trial 1 was 1.0-2.8 mm in diameter.

3.5.4 Shear strength

Shear strength was determined using the pocket vane tester (Figure 3.7). The data for Dublin Farm trial 1 was not reliable due to the fact that the readings were taken in a dry soil. During trial 2 however, the readings were taken on the same locations where the minidisk infiltrometer measurements were taken. The readings were taken approximately 30 minutes after the minidisk measurements were done. Thus it was done only at 0, 200 and 400 mm depths. Twelve readings was taken per depth per profile pit.

The Toitskraal soil was dry and hard during trial 1. Thus the profile wall was first wetted and left for 30 minutes to an hour before readings were taken. Measurements were taken for each 100 mm depth increment up to 400 mm depth. Approximately eight readings were taken per profile pit per depth. During trial 2 the control soil and the 1-year application soil was moist enough to determine the shear strength without wetting the soil first. For the 2-year application however, the soil was very dry and was treated in the same way as explained for Toitskraal trial 1. At trial 2, ten readings were taken at each profile pit for each depth for the control and 1-year treatment. Readings were only taken up to 200 mm depth for the 2-year application due to too many coarse fragments present in the soil, while only 15 readings were taken at the 300-400 mm depth of the control. The bulk density samples were used to determine the water content of the soil.

Shear strength was determined at Wansbek at the same depths as for Toitskraal. Since the soil water content was always kept above 70% of field capacity, the soil was always wet enough to take measurements. Four readings was taken per profile pit per depth, resulting in 12 readings per experimental plot per depth.

For shear strength readings at Two Rivers, a different head (CL 102 in Figure 3.7) was used on the pocket vane tester than the one fixed on the apparatus (CL 100 in Figure 3.7). Readings were determined at the same depths as at Wansbek and Toitskraal. Five readings per depth were taken per profile pit, resulting in 40 readings per treatment per depth.

The shear strength readings collected during field trials were processed in Microsoft Excel. One complete revolution with the CL100 head represents 1.0936 kg/cm² and one complete revolution with the CL102 head represents 2.734 kg/cm².

$$\frac{Value\ for\ complete\ revolution}{10} \times Reading\ value\ \div 100 = kPa$$

The "Reading value" is the value on the dial of the apparatus after a measurement is taken. If not divided by 100, then the answer is in kg/cm².

Figure 3.7: The pocket vane tester (top left) and the two additional heads (top right and bottom) for different soil texture classes (Eijelkamp Agrisearch Equipement, 2011).

3.5.5 Penetration resistance

Penetration resistance was determined using the pocket penetrometer (Figure 3.8). It was only determined during Dublin Farm trial 2 of and Toitskraal trial 2. Direct values are taken from the apparatus in kg/cm².

Figure 3.8: The SOILTEST Inc., Chicago-USA Pocket Penetrometer model nr. CL-700 that was used for determining the penetration resistance.

At Dublin Farm, penetration resistance was determined at 0 mm and 200 mm depths at the same location where the minidisk infiltrometer readings were taken. Twelve readings were taken per profile pit per depth.

At Toitskraal the readings were taken up to 300 mm depth. Ten readings per depth per profile pit were taken. At the 150 mm depth of one of the profile pits in the 2-year application of Toitskraal, only five readings were taken due to coarse fragments and at both profile pits in the 2-year treatment readings were only done for the 50 mm and 150 mm depths.

3.5.6 Unsaturated hydraulic conductivity

The minidisk infiltrometer was used to determine the K_u of the soil at 0, 200 and 400 mm depths. During trial 1 at Dublin Farm conductivity at -1 tension was determined at each depth in duplicate, where readings with the minidisk were done for 20 minutes. The soil surface was evened and sifted soil was applied on top of the undisturbed, even soil surface. This spot was wetted beforehand and the minidisk was placed on the surface.

During trial 2, four replicate readings were taken at each depth at each profile pit. The soil surface was evened with a trowel and only if needed, sifted soil was applied. The soil was wetted before the minidisks were placed on the surface. Each minidisk was left for up to 35 minutes if it did not run empty before the time. Readings were taken each minute and the tension was set on -2.

The same procedure was followed at Toitskraal trial 1 as for Dublin Farm trial 1 except for the tension which was set at -2. For Toitskraal trial 2 the minidisk measurements was approached more or less in the same way as to Dublin Farm trial 2. A typical setup for trial 2 is presented in Figure 3.9. On each profile pit four replicates were done per depth, resulting in eight replicates per treatment per depth (only two profile pits per treatment). For the 2-year application only the 0 mm and 200 mm depths were done, since the coarse fragments occupied a large volume of the soil deeper down.

At Wansbek, three replicates were done per experimental plot per depth. The tension was set on -1. At Two Rivers eight replicates were done per treatment per depth and the tension was set on -2.

Figure 3.9: Making use of multiple minidisk infiltrometers at Toitskraal trial 2. The minidisk infiltrometer was used to determine K_u.

3.6 Chemical properties

3.6.1 pH

The pH was measured for each horizon or layer identified using an *827* and a *744 pH lab Metrohm Swiss mode* pH meter. Measurements were in both de-ionized water and a 1 M KCℓ solution. Ten gram of air dried soil was weighed and 25 ml of either de-ionized water or KCℓ solution was added and shook for 20 minutes on a shaker.

3.6.2 Electrical conductivity

Electrical conductivity (EC) was measured in a 1:5 soil to water ratio. It was determined for each horizon or layer identified within the soil. A 10 gram air dried soil sample was weighed into a plastic bottle and 50 ml de-ionized water added. It was placed on a shaker for 20 minutes and the electrical conductivity was measured using a *Jenway* 4510 Electric Conductivity meter.

3.6.3 Exchangeable cations

The exchangeable cations were determined according to the ammonium acetate method described by Thomas (1982). The büchner funnel procedure was followed. The exchangeable cations for one topsoil and subsoil of a control plot were determined for each farm.

3.6.4 Exchangeable acidity

The exchangeable acidity was determined for Dublin Farm, Toitskraal and Two Rivers for one topsoil and subsoil of a control plot. The exchangeable acidity was not determined for Wansbek since the pH was above seven. The Eksteen method was followed. A potassium acetate buffer solution needed to be prepared. It was done by dissolving 435 g of potassium sulphate and 25 g of potassium acetate in 5 ℓ of distilled water. Four to five drops of phenolphthalein were added to the solution and titrated with a 0.1 M potassium hydroxide solution until a slight pink colour was visible. Fifty millilitres of the potassium acetate buffer was added to 20 g of soil and left for one hour. The contents were then brought onto a funnel which had a filter paper and leached with potassium acetate buffer solution until the final volume was 200 mℓ. A few drops of phenolphthalein were added to the filtrate which was then titrated with 0.1 M sodium hydroxide until a slight pink colour was observed. The exchangeable acidity was then calculated by using the following equation:

$$cmol\ H^{+}.kg^{-1}\ soil = V\ (\ell)\ \times 0.1\ M\ \div 0.02\ kg\ \times 100$$

V is the volume of sodium hydroxide solution that was titrated in litre, 0.1 M is the concentration of the sodium hydroxide solution used to titrate, 0.02 kg is the mass of the soil used and 100 is the conversion from mol to cmol.

3.6.5 Organic matter content

The organic matter content was determined for only one sample of Two Rivers. One gram of air dried soil was left for eight hours at 800°C. The organic matter content was determined with the following equation:

$$OM = \frac{M_{before} - M_{after}}{M_{before}} \times 100$$

OM is the organic matter percentage; M_{before} is the mass before the sample went into the oven and M_{after} the mass of the sample that came out of the oven.

3.7 Statistical analysis

Statistical analysis was done by making use of SAS Enterprise Guide (2012). One-way analysis of variance (ANOVA) was used to determine if there were any significant differences between the control and treatments in a specific depth class. A confidence interval of 95% was used throughout the statistical analysis, thus a P value of less than 0.05 indicated a significant difference between two or more of the treatments. The *post hoc* test used to calculate the differences between the treatments, were Tukey's studentized range test (HSD). This *post hoc* test uses the minimum significant difference (MSD) to determine whether the difference between two averages is significant.

The assumption of normality was tested by calculating the Shapiro-Wilk and Kolmogorov-Smirnov statistics. If the test for normality for a data set failed, a log transformation was performed on the whole data set and a test for normality repeated. After the test for normality was completed, the test for the assumption of homoscedasticity was also performed using Bartlett and Levene's tests. If this assumption failed, Welch's variance-weighted ANOVA was done in addition to the one-way ANOVA.

The data are presented mostly as averages on a bar graph. On each bar graph the error bars indicate the standard deviation of that specific data set (e.g. the bulk density of the control for 50 mm depth of Wansbek). Unless otherwise stated, the error bars are presented on each figure. If there were significant differences, the p-value obtained from the ANOVA and the MSD are reported in the relavant paragraph.

4. Results and Discussion

4.1 Texture analysis

The main purpose of the texture analysis data was to partially explain the behaviour of the soil properties under investigation. The particle size distribution of the soil may especially have a significant influence on K_s and K_u. No change in texture caused by the product was expected and the differences observed in the particle size distribution are therefore assumed to be due to soil variation. Results for texture analysis and coarse fragment content are presented in Table 4.1.

Dublin Farm and Wansbek soils had higher clay contents than the other two farms and were on the borderline between sandy clay loam and sandy loam soils. Both Dublin Farm and Wansbek also had iron oxides and hydroxides present the clay fraction of the soil. Dublin Farm’s clay content in the topsoil was higher than in the subsoil. For Wansbek the clay content increased from topsoil to subsoil. The sand grade of Wansbek was fine while Dublin Farm tended to be medium and coarse. Clay content for Dublin Farm could have been underestimated. It is possible that the method used did not remove all the iron oxides and hydroxides before analysis, since the soil contained exceptionally high levels of iron oxides and hydroxides. Iron oxides and hydroxides could have acted as cementing agent between clay particles, thereby artificially increasing silt-sized particles.

Toitskraal soils had low clay contents (6-8%), but it was still classified as a sandy loam (like Dublin Farm and Wansbek) and loamy sand. The subsoil tended to have slightly more clay than the topsoil. This farm also had the highest coarse fragment content of the four farms. These soils however were characterized by hardness in the dry state, which could possibly be due to silica cementation.

The Two Rivers soil was of alluvial origin and the differences between topsoil and subsoil were marginal. The soil had low clay contents (3-4%) and high sand contents. It was classified as a sand according to most of the texture analysis results, but in some instances also as a loamy sand. The sand grade alternated between coarse and medium.

Table 4.1: Soil texture and coarse fragment content for each of the four study areas. The coarse fragments are expressed as a percentage of the total mass of the sample. The sand, silt and clay fractions are expressed as a percentage of the < 2 mm fraction.

Farm	**Sample**	**Depth**	***n***	**Coarse fragments**	**SAND**				**SILT**		**CLAY**	**Texture class**	**Sand grade**
					Coarse	**Medium**	**Fine**	**Very fine**	**Coarse**	**Fine**			
				> 2 mm	**0.5 – 2.0 mm**	**0.25 - 0.5 mm**	**0.106 - 0.25 mm**	**0.053 - 0.106 mm**	**0.05 - 0.02 mm**	**0.02 - 0.002 mm**	**< 0.002 mm**		
Dublin Farm	Control	0-200 mm	3	1.21	9.50	23.12	22.87	9.65	8.92	0.92	25.03	Sandy clay loam	Medium
		200-400 mm	3	1.78	10.15	25.51	25.28	10.38	7.34	1.59	19.73	Sandy loam	Medium
	Treatment	0-200 mm	3	1.23	14.58	20.61	20.40	9.07	10.98	1.75	22.61	Sandy clay loam	Coarse
		200-400 mm	3	1.30	12.00	21.66	22.92	9.78	11.09	1.19	21.36	Sandy clay loam	Medium
Toitskraal	Control	0-200 mm	3	10.42	21.76	18.71	26.34	12.64	12.77	1.54	6.24	Loamy sand	Coarse
		200-400 mm	3	6.42	17.82	17.97	25.98	13.56	16.05	0.81	7.80	Sandy loam	Coarse
	Treatment	0-200 mm	3	7.22	18.74	18.90	28.52	12.93	12.90	1.15	6.86	Sandy loam	Coarse
		200-400 mm	3	5.09	20.15	18.58	26.30	11.66	14.84	0.94	7.53	Sandy loam	Coarse
Wansbek	1.1	0-200 mm	1	0.78	3.78	8.20	31.83	21.52	13.61	4.31	16.74	Sandy loam	Fine
		200-400 mm	1	0.48	3.57	8.78	31.16	24.62	12.76	2.91	16.21	Sandy loam	Fine
	1.2	0-200 mm	1	1.64	5.92	12.31	30.47	17.29	10.32	3.46	20.23	Sandy loam	Fine
		200-400 mm	1	2.13	5.11	12.60	28.27	19.14	8.50	2.97	23.42	Sandy clay loam	Fine
	1.3	0-200 mm	1	1.70	4.87	9.41	29.66	17.36	14.71	3.29	20.71	Sandy loam	Fine
		200-400 mm	1	2.23	4.13	7.41	26.25	19.47	13.50	1.38	27.86	Sandy clay loam	Fine
Two Rivers	1.5-1.8	0-200 mm	1	0.36	20.84	30.56	25.64	8.69	6.57	4.22	3.48	Sand	Coarse
		200-400 mm	1	0.40	22.67	30.72	26.25	6.99	8.46	1.74	3.16	Sand	Coarse
	3.1-3.2	0-200 mm	1	0.31	17.20	32.73	28.57	7.63	8.32	1.91	3.65	Sand	Medium
		200-400 mm	1	0.34	16.62	33.03	27.52	7.53	6.67	4.75	3.88	Sand	Medium
	6.5-6.8	0-200 mm	1	0.43	16.99	29.01	27.47	9.98	8.80	3.81	3.93	Loamy sand	Coarse
		200-400 mm	1	0.45	16.74	27.66	28.67	9.60	10.29	3.22	3.83	Loamy sand	Coarse

The sum of different fractions of the texture analysis is presented in Table 4.2. The first data column consists of the medium and fine sand fraction. The second data column consists of the sum of all the fractions smaller than 0.25 mm. Note that Dublin Farm and Wansbek had more or less the same clay percentage. However, when comparing the < 0.25 mm fraction, which consists of the fine sand, very fine sand, silt and clay fractions, Wansbek had an average of 86% compared to Dublin Farm which had an average of 66%. This higher < 0.25 mm fraction at Wansbek could have significantly decreased the K_u of this soils compared to the soils of Dublin Farm.

Table 4.2: Totals of different particle size fractions. Each fraction is expressed as a percentage of the total < 2 mm fraction. The 2.0 – 0.25 mm fraction consists of the coarse and medium sand and the < 0.25 mm fraction consists of the fine and very fine sand, the coarse and fine silt, and the clay fraction. This should add up to 100%. The sand, silt and clay fraction should add up to 100%.

Farm	Sample	Depth	2.0 mm-0.25 mm	< 0.25 mm	SAND	SILT	CLAY
Dublin Farm	Control	0-200 mm	32.62	67.38	65.13	9.84	25.03
		200-400 mm	35.66	64.34	71.33	8.94	19.73
	Treatment	0-200 mm	35.19	64.81	64.66	12.73	22.61
		200-400 mm	33.66	66.34	66.35	12.29	21.36
Toitskraal	Control	0-200 mm	40.47	59.53	79.45	14.31	6.24
		200-400 mm	35.79	64.21	75.34	16.86	7.80
	Treatment	0-200 mm	37.64	62.36	79.09	14.05	6.86
		200-400 mm	38.74	61.26	76.69	15.78	7.53
Wansbek	1.1	0-200 mm	11.98	88.02	65.33	17.93	16.74
		200-400 mm	12.35	87.65	68.12	15.67	16.21
	1.2	0-200 mm	18.23	81.77	65.99	13.78	20.23
		200-400 mm	17.70	82.30	65.11	11.47	23.42
	1.3	0-200 mm	14.28	85.72	61.29	18.01	20.71
		200-400 mm	11.55	88.45	57.27	14.88	27.86
Two Rivers	1.5-1.8	0-200 mm	51.41	48.59	85.73	10.79	3.48
		200-400 mm	53.39	46.61	86.63	10.20	3.16
	3.1-3.1	0-200 mm	49.92	50.08	86.12	10.23	3.65
		200-400 mm	49.65	50.35	84.70	11.42	3.88
	6.5-6.8	0-200 mm	46.01	53.99	83.46	12.61	3.93
		200-400 mm	44.39	55.61	82.66	13.51	3.83

4.2 Bulk density

4.2.1 Dublin Farm

The 50, 150, 250, 350 and 450 mm depths in graphs represent the 0-100, 100-200, 200-300, 300-400 and 400-500 mm depth increments. For Dublin Farm trial.1 there were no significant differences between the bulk density for the control and treatment at any of the depths (Figure 4.1a). The bulk density was more or less the same (± 1.4 g/cm³) for the 50 mm, 150 mm and 250 mm depths. However, from the 250 mm to the 350 mm depth the bulk density tended to increase up to 1.6 g/cm³.

For Dublin Farm trial 2 the bulk density at the 50 mm depth for the treatment tended to be lower (±1.45 g/cm³) than that of the control, while it was comparable at the 150 mm depth (Figure 4.1b). Bulk density at the 250 mm depth was significantly higher for the treatment than for the control ($p = 0.024$, MSD = 0.0825). The bulk density for the control tended to increase from the 50 mm depth to the 150 mm depth and to decrease to the 250 mm depth, while that of the treatment tended to increase from the 50 mm depth to the 250 mm depth.

In both trial 1 and 2, the control tended to have a slightly higher bulk density at the 50 mm and 150 mm depths compared to the treatment and a lower bulk density at the 250 mm depth. These differences may be attributed to natural variation in soil bulk density and not necessarily due to the effect which the product might have had on the soil.

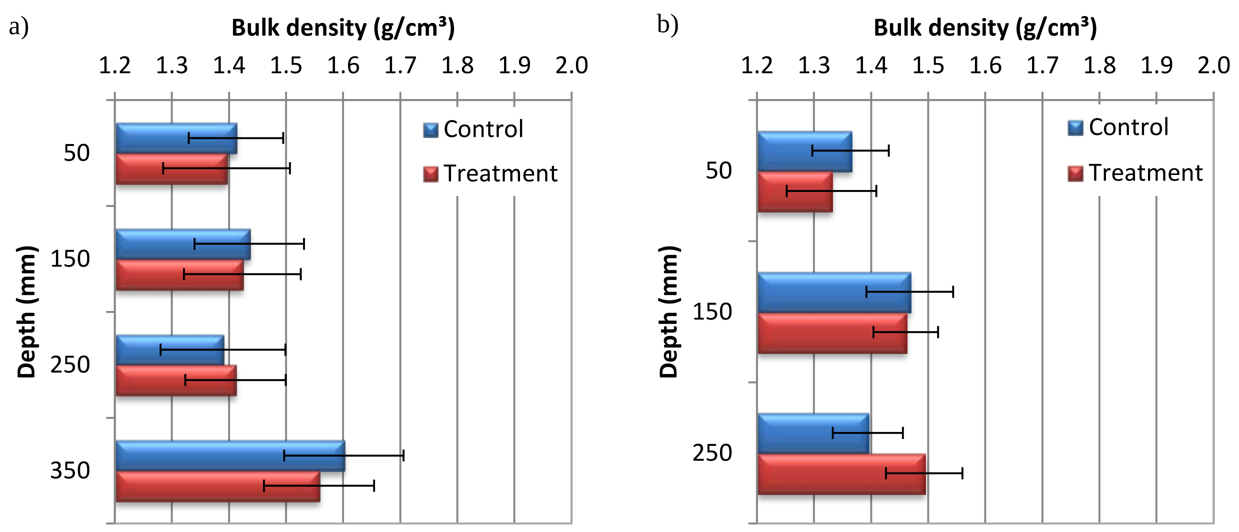

Figure 4.1: Bulk density at Dublin Farm a) trial 1 and b) trial 2.

4.2.2 Toitskraal

For Toitskraal trial 1 there were no significant differences in the bulk density between the treatments at any of the depths (Figure 4.2a). At the 50 mm depth the bulk density for the control and treatment were almost the same. At the 150 mm depth the bulk density for the control tended to be higher than for the treatment while the opposite was observed for the 250 mm, 350 mm and 450 mm depths. The bulk density for both the control and treatment tended to be higher for the 150 mm to 350 mm depths compared to near the soil surface (50 mm) or deep in the soil profile (450 mm).

For Toitskraal trial 2 there were also no significant differences between the bulk densities of the treatments at any depth (Figure 4.2b). At the 50 mm and 150 mm depth the 1-year application tended to have a higher bulk density than the control. The 2-year application tended to have the highest bulk density at the 50 mm depth. This might be due to the dry state in which the samples of the 2-year treatment were taken. The average volumetric water contents of the bulk density samples of the 2-year treatment was less than half of that of the control and the 1-year treatment (Table 4.3). It is due to the irrigation that was applied before and during the field studies at the control and 1-year treatment. At the 250 mm depth the bulk density of the control tended to be higher than the treatment. The bulk density tended to increase from the 50 mm to the 250 mm depth.

No general trend can be obtained from the data of trial 1 and trial 2. It confirms the statement for the Dublin Farm trials that the differences in soil bulk density were not due to the effect of the product, but possibly due to natural variations.

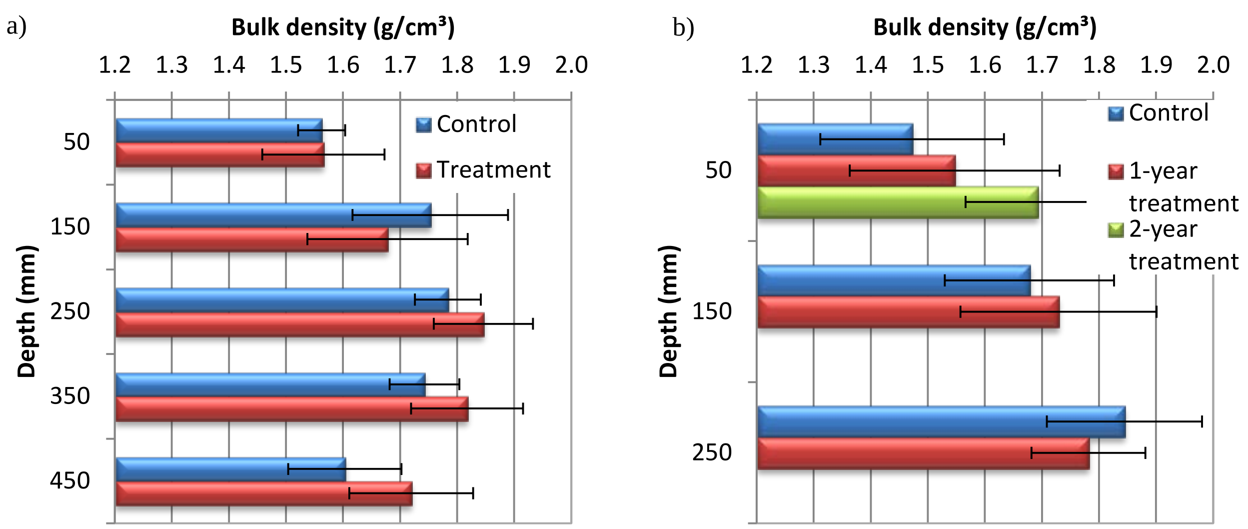

Figure 4.2: Bulk density at Toitskraal a) trial 1 and b) trial 2.

Table 4.3: Average volumetric water contents of the bulk density samples of Toitskraal trial 2.

Depth increment	Volumetric water content (m/m)		
	Control	**1-year treatment**	**2-year treatment**
0-100 mm	0.141	0.139	0.067
100-200 mm	0.142	0.124	
200-300 mm	0.211	0.115	

Toitskraal, where the bulk density was determined using the sand fill method, had a greater MSD than the farms where the bulk density was determined using the core method. This can be due to fewer replicates taken when using the sand fill method compared with when the core method was used. The samples taken with the steel cylinder could also have caused more disturbances to the soil sample and surrounding soil than the one used to draw soil cores. Filling up the hole with the filter sand to exactly the same level each time was difficult which could have resulted in obtaining inaccurate volumes (calculated from the mass of the sand) of the hole. The sample size of the sand fill method might have been too small, causing great variation between samples. With the above mentioned factors in mind, larger samples tend to minimize the variations and errors caused by it and more replicates tend to reduce the effect of an outlier.

4.2.3 Wansbek

At Wansbek at the 50 mm depth the bulk density of the control was significantly lower than the 5 ℓ/ha treatment ($p = 0.012$, MSD = 0.0783) and tended to be lower compared to the other two treatments (Figure 4.3). At the 150 mm and 250 mm depths the control tended to have a lower bulk density than all the other treatments. At the 350 mm depth the 20 ℓ/ha treatment tended to have the lowest bulk density of the four treatments. At the 350 mm depth the 20 ℓ/ha treatment was significantly smaller than the 10 ℓ/ha treatment ($p = 0.057$, MSD = 0.1072). Even though the p-value for the 350 mm depth was above 0.05, Tukey's studentized range test still indicated a significant difference. However, at the 450 mm depth both the control and 20 ℓ/ha treatment tended to be the lowest.

The bulk density tended to increase from the 50 mm to the 250 mm depth where after it tended to fluctuate with no definite trend. Deeper in the soil profile, the highest bulk density occurred at the 450 mm depth (±1.6 g/cm³).

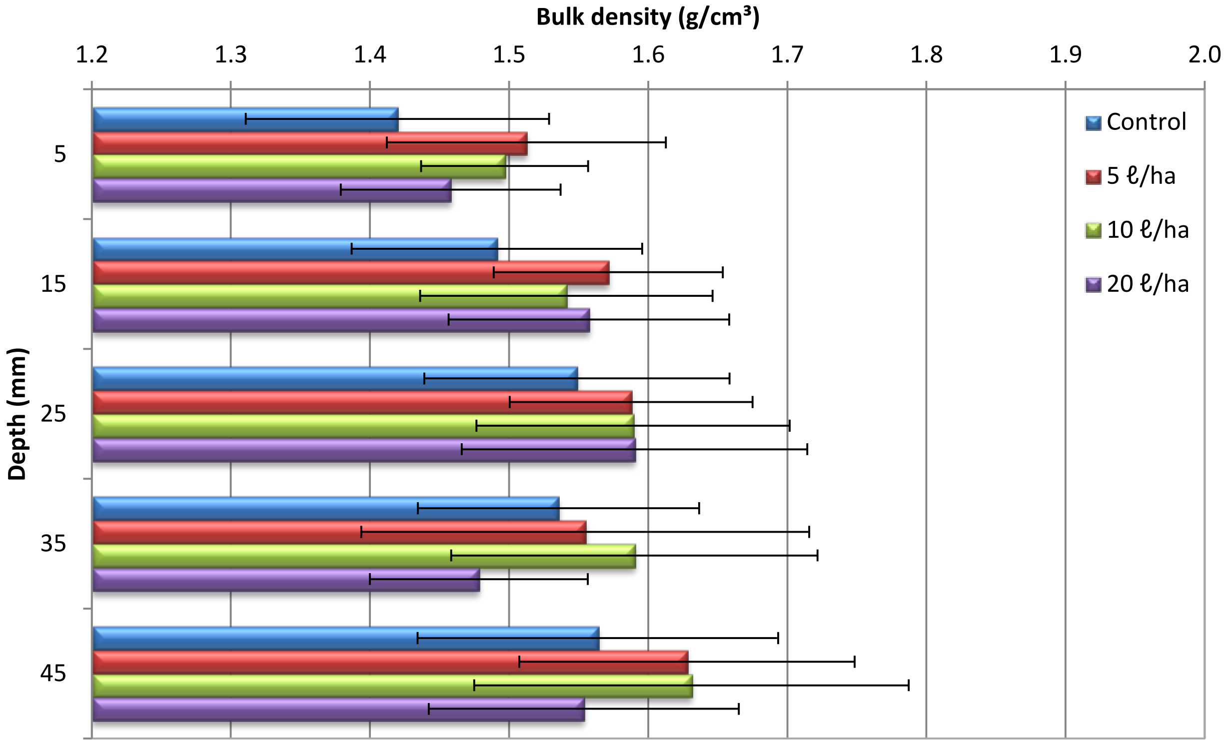

Figure 4.3: Bulk density at Wansbek.

4.2.4 Two Rivers

The bulk density results for Two Rivers are presented in Figure 4.4. The 1×2 mℓ/m² treatment tended to have the highest bulk density at each depth except at the 250 mm depth where bulk density of the treatments tended to be similar. At the 50 mm depth the 1×2 mℓ/m² treatment had a significantly higher bulk density than the 2×2 mℓ/m² treatment ($p = 0.0086$, MSD = 0.0634). Except for the 50 mm depth where the control tended to have a higher bulk density than the 2×2 mℓ/m² treatment, these two treatments had comparable bulk density at each depth. In general the bulk density tended to increase from the 50 mm to the 250 mm depth after which it remained relatively constant.

The bulk density values obtained for Two Rivers were exceptionally low, i.e. below 1.4 g/cm³ for the 50 mm and 150 mm depths. According to Skopp (2002) sandy soils have bulk density values ranging from 1.4 to 1.9 g/cm³.

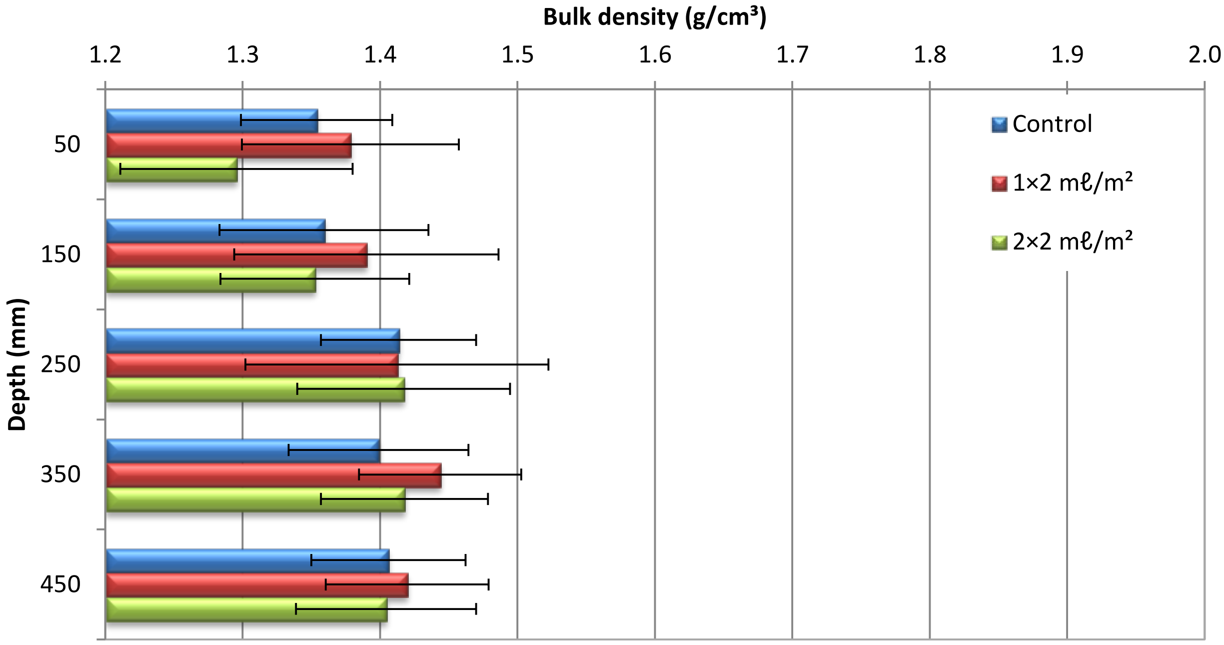

Figure 4.4: Bulk density at Two Rivers.

4.2.5 Discussion

The results for the 2×2 mℓ/m² treatment of Two Rivers at the 50 mm depth showed similar results as found by Brandsma *et al.* (1999). The bulk density samples taken by them were at the 0-50 mm depth. Two Rivers had an organic matter content of 2.7% at the 50 mm depth (see section 4.8). The low bulk density for the 2×2 mℓ/m² treatment of Two Rivers at the 50 mm depth compared to the control could possibly have been due to a reaction between the product and the organic matter, but there is no evidence to confirm this.

4.3 Aggregate stability percentage

4.3.1 Dublin Farm

For Dublin Farm trial 1 there were no significant differences between the ASP of the control and the treatment at any of the depths (Figure 4.5a). The ASP at the 50 mm depth tended to be higher for the control than for the treatment. At both the 150 mm and 250 mm depths the ASP for the control and treatments were almost exactly the same within the depth. The control ASP decreased from the 50 mm to the 150 mm depth and then remained constant from the 150 mm to the 250 mm depth. The ASP of the treatment tended to remain more or less the same throughout the soil profile.

For Dublin Farm trial 2 there was no significant difference between the ASP of the control and treatment at the 50 mm depth although the treatment tended to have a higher ASP than the control (Figure 4.5b). The opposite was observed at the 50 mm depth of Dublin Farm trial 1. At the 150 mm depth, the ASP of the control and treatment were similar. At the 250 mm depth the ASP for the treatment was significantly higher than the control ($p = 0.0198$, MSD = 13.7). The ASP of the control tended to decrease from the 50 mm to the 250 mm depth while the ASP for the treatment tended to decrease from the 50 mm to the 150 mm, but then remained the same to the 250 mm depth.

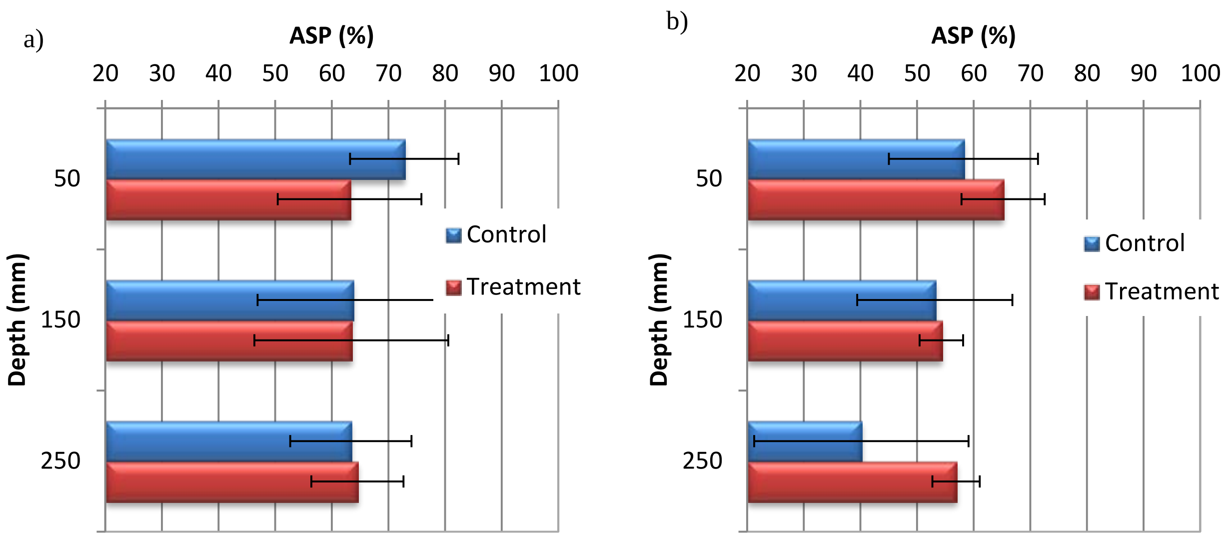

Figure 4.5: ASP at Dublin Farm a) trial 1 and b) trial 2.

Note that the standard deviation for the treatment in trial 2 (error bars in Figure 4.5b) is much smaller than those of the control.

4.3.2 Toitskraal

For Toitskraal trial 1 there were no significant differences between the ASP of the control and the treatment at any of the depths (Figure 4.6a). At the 50 mm depth the control tended to have a slightly higher ASP than the treatment and at the 150 mm and 250 mm depths the opposite were observed. The ASP tended to decrease from the 50 mm to the 250 mm depth.

For Toitskraal trial 2 there were no significant differences between the ASP of the control and the treatment at any of the depths (Figure 4.6b). At the 50 mm and 250 mm depth the control tended to have the lowest ASP. The 2-year application tended to have the highest ASP at the 50 mm depth.

From the 50 mm to the 150 mm the ASP tended to decrease and at the 250 mm it tended to be the same than the 150 mm depth.

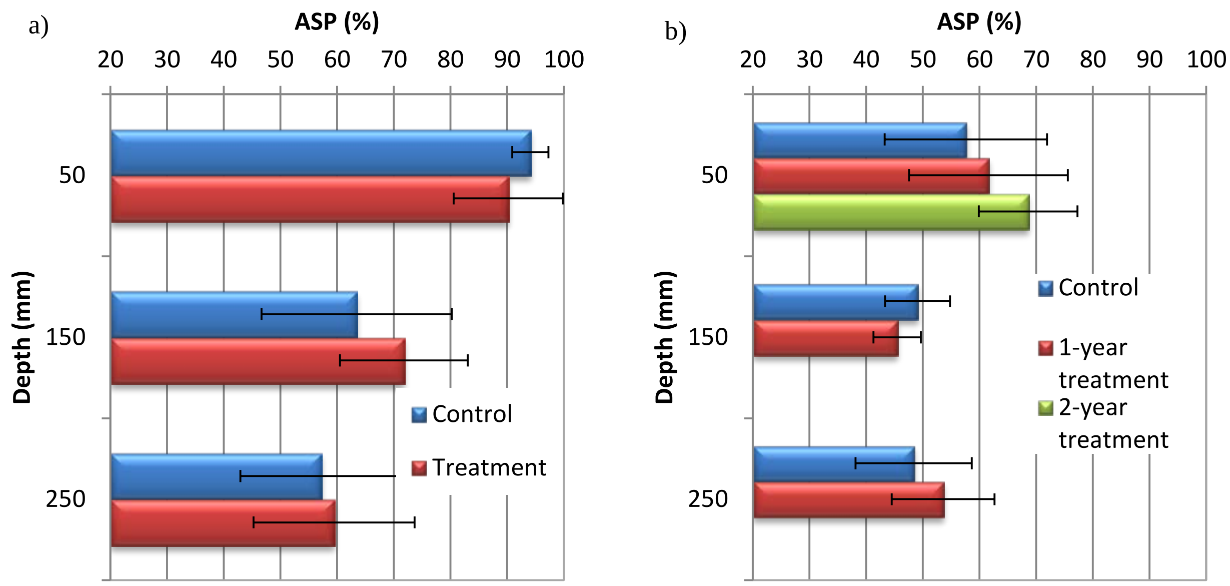

Figure 4.6: ASP at Toitskraal a) trial 1 and b) trial 2.

4.3.3 Wansbek

For Wansbek there were no significant differences between the ASP of the control and the 10 ℓ/ha treatment at any of the depths (Figure 4.7). At the 50 mm and 150 mm depth the control tended to have a higher aggregate stability than the 10 ℓ/ha treatment. At the 250 mm depth it was the opposite of the two preceding depths. The aggregate stability for the 10 ℓ/ha treatment tended to increase from the 50 mm to the 250 mm depth. For the control the 150 mm depth tended to have a higher aggregate stability than the 50 mm and 250 mm depths.

4.3.4 Discussion

Aggregate stability was not determined for Two Rivers since it was a single grained soil. According to Horn & Baumgartl (2002) aggregates form when more than 15% clay is contained in the soil. Toitskraal had 6-8% clay (Table 4.1) which means that the clay was not necessarily as much a part of the aggregation process as at Dublin Farm and Wansbek.

With reference to the ASP of the 50 mm depth: Dublin Farm trial 1, Toitskraal trial 1 and Wansbek all showed a tendency for the control to have a higher ASP than the treatment. The opposite was observed for Dublin Farm trial 2 and Toitskraal trial 2. For the first three farms mentioned, the application was done at seven months, one month and one month respectively before the field studies were conducted. For the last two, the last application before field studies was made nine and a half months and twelve months respectively before field studies. For the first three farms, aggregates used in the analysis were 2-4 mm in diameter while the aggregates used for the second two were 1-2.8 mm in diameter. So the phenomenon that occurred here could either have been due to time or due to aggregate size.

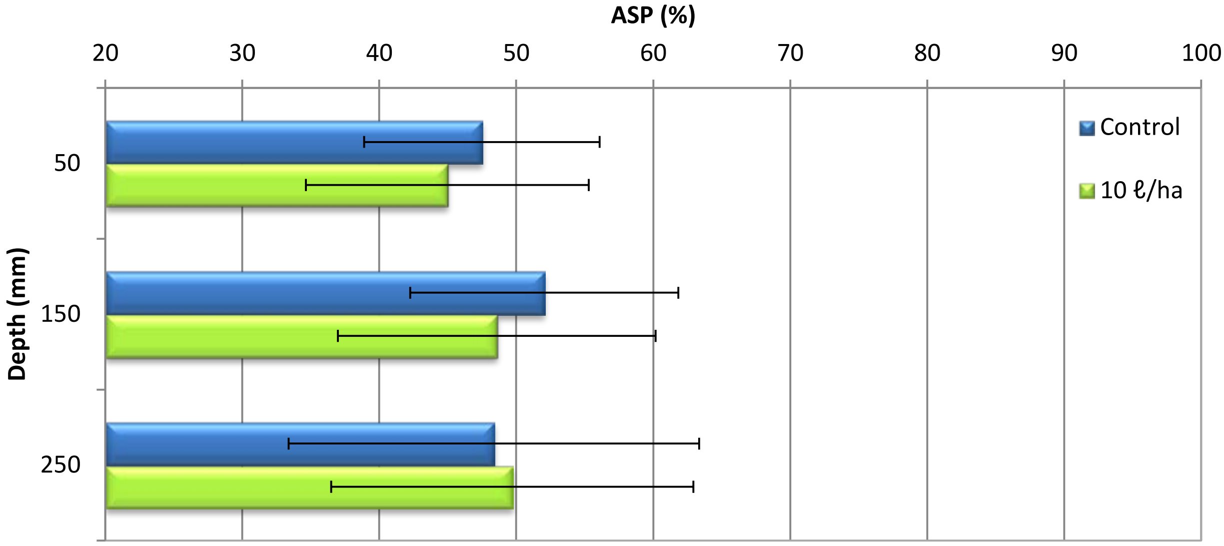

Figure 4.7: ASP at Wansbek. Note that only the ASP for the control and the 10 ℓ/ha treatment (recommended application rate) was determined.

The decrease in aggregate stability at the 50 mm depth of Dublin Farm trial 1, Toitskraal trial 1 and Wansbek was also found by Mbagwu *et al.* (1993), Piccolo & Mbagwu (1989) and Piccolo & Mbagwu (1994) after the application of an anionic surfactant. Humic acids could enhance aggregate stability by acting as a binding agent (Piccolo & Mbagwu, 1989) and by increasing hydrophobicity through orientation of the hydrophobic components of the humic acids towards the outside of the aggregate. Due to this, the aggregate does not wet that easy. As a result, the organic substances prevents the aggregate from wetting rapidly and being subjected to the destructive forces of air slaking (Hillel, 1980; Le Bissonnais, 1996). However, when an anionic surfactant and even a nonionic surfactant are applied, the soil wets the hydrophobic aggregates easier, which might enhance the breakdown of the aggregates due to slaking.

According to Law *et al.* (1966) anionic surfactants do not adsorb strongly to soil and it tends to move with the soil water while nonionic surfactants tend to adsorb immediately to the soil after application. As explained, the aggregate stability at the 50 mm depth for the four trials where the field studies were done shortly after application, Dublin Farm trial 1 (7 months), Toitskraal trial 1 (1 month) and Wansbek (1 to 1 ½ months) confirmed the results found in literature for the effect of an anionic surfactant on aggregate stability.

Mbagwu *et al.* (1993), Piccolo & Mbagwu (1989) and Piccolo & Mbagwu (1994) found that the nonionic surfactant increased the aggregate stability at the macro level and that more clay in the soil enhanced the effect of the nonionic surfactant. This agrees with the results found at the 50 mm depth for Toitskraal trial 2 and all of the depths of Dublin Farm trial 2. The effect of a nonionic surfactant on aggregate stability was confirmed by the results obtained for Dublin Farm trail 2 and Toitskraal trial 2. It can therefore be reasoned that the anionic surfactant in the product tended to have a detrimental effect on the aggregate stability, but that it leached out since it moves with the soil solution. The damage however, was done. On the other hand the nonionic surfactant could have adsorbed onto the soil particles with a beneficial effect on aggregate stability over the longer term.

4.4 Shear strength

4.4.1 Dublin Farm

The shear strength for Dublin Farm trial 2 shear strength did not differ between the control and treatment at the 0 mm depth, although that of the treatment tended to be higher (Figure 4.8). The shear strength for the treatment was significantly higher than for the control at the 200 mm ($p = 0.0471$, MSD = 1.889) and 400 mm ($p = 0.0437$, MSD = 1.991) depths. The shear strength tended to increase from the 0 mm to the 400 mm depth. This agrees with the research of Baumgartland & Horn (1991) which indicated that soil strength increases with increasing soil load.

4.4.2 Toitskraal

For Toitskraal trial 1 there were no significant differences between the shear strength of the control and the treatment at any of the depths (Figure 4.9a). At the 50 mm and 150 mm depths the control and treatment had almost the exact same shear strength values. At the 250 mm and 350 mm depths the control tended to have a higher shear strength value than the treatment. From the 50 mm to the 350 mm depth the shear strength tended to increase.

The shear strength results for Toitskraal trial 2 are presented in Figure 4.9b. At the 50 mm depth, the shear strength for the control was significantly higher ($p = 0.0019$, MSD = 2.2783) than for the

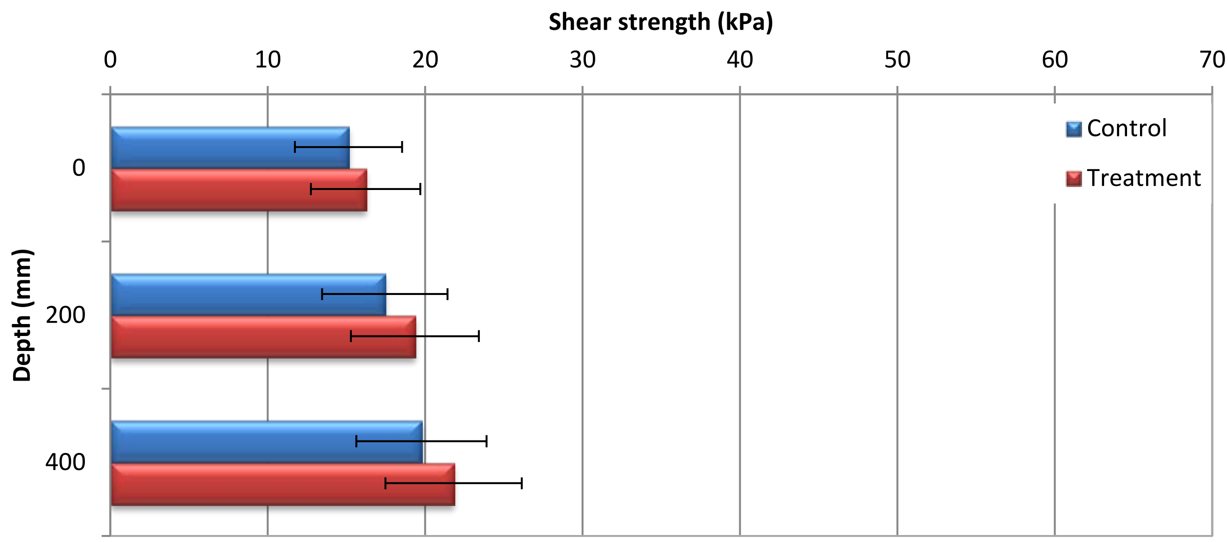

Figure 4.8: Shear strength at Dublin Farm trial 2.

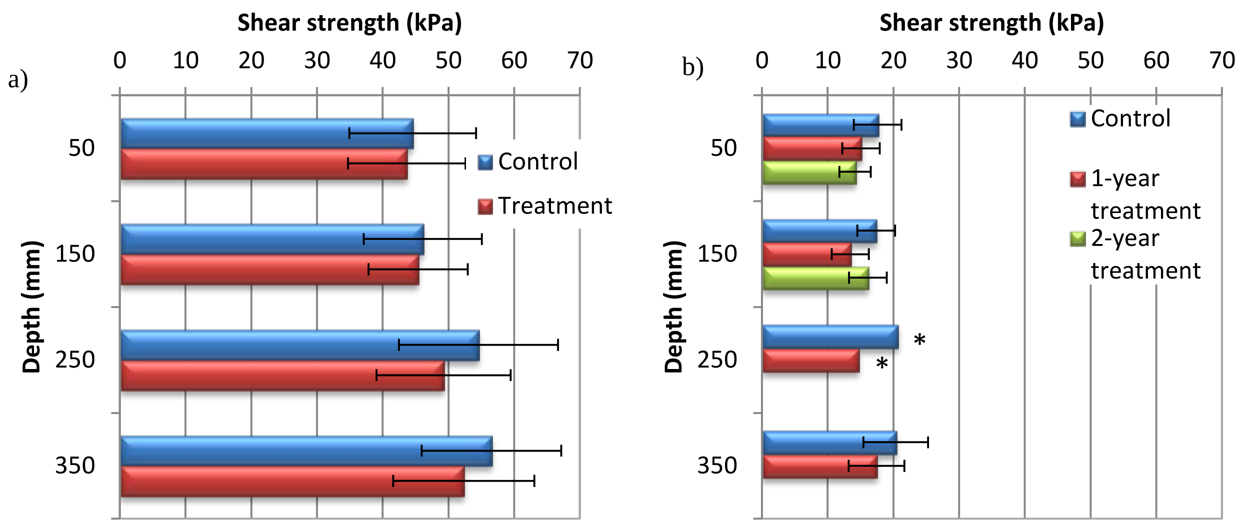

Figure 4.9: Shear strength at Toitskraal a) trial 1 and b) trial 2. (* a non-parametric test was performed)

two treatments. The shear strength for the 1-year treatment and 2-year treatment at the 50 mm depth did not differ significantly, however, the 2-year treatment tended to be lower. At the 150 mm depth, the 1-year treatment was significantly smaller than the control and the 2-year treatment (p = 0.0002, MSD = 2.1635). At the 250 mm depth a non-parametric Wilcoxon rank-sum test was performed since the data was not normally distributed. According to this test, the control was significantly higher than the 1-year treatment. At the 350 mm depth there was no significant difference between the control and the 1-year treatment, but the control still tended to have a higher shear strength. Note that at every depth for trial 1 and 2, the control tended to have the highest average shear strength of that depth class. The shear strength tended to increase slightly from the 50 mm to the 350 mm depth.

4.4.3 Wansbek

Note that the statistical analysis was done on the log transformed data to satisfy the assumptions of normality and homoscedasticity. The averages and standard deviations were back transformed to present it in the figures. The data for the 150 mm depth was not normally distributed in the normal state or in the log transformed state, thus no statistical analysis was performed on the data as for the other depths. Consequently, only the averages of the log transformed data was calculated. These averages were then transformed from the log state to the normal state to present it with the other data.

The shear strength results for Wansbek are presented in Figure 4.10. There was no significant difference between the treatments at the 50 mm depth. The shear strength tended to increase as the application rate increased. The same tendency was observed at the 50 mm depth of Dublin Farm trial 2 and it is the opposite of the results for the 50 mm depth of Toitskraal trial 1 and 2. At the 150 mm, 250 mm and 350 mm depths the shear strength for the control tended to be the lowest. At the 250 mm and 350 mm depths the tendency was the same: the shear strength tended to increase with increasing application rate up to the 10 ℓ/ha treatment, but the 20 ℓ/ha treatment tended to be higher than the control, but lower than the other two treatments. At the 250 mm and 350 mm depths the shear strength for the control was significantly smaller ($p = 0.038$ and MSD = 1.192 for the 250 mm depth; $p = 0.040$, MSD = 1.211 for the 350 mm depth) than the 10 ℓ/ha treatment. The general trend was that the shear strength increased from the 50 mm depth to the 350 mm depth.

4.4.4 Two Rivers

The shear strength results for Two Rivers are presented in Figure 4.11. There were no significant differences in any of the depths between any of the treatments. The high shear strength values that were obtained relative to the other farms in a soil which had 3-4% clay and was single grained was due to the use of the CL102 head of the pocket vane tester (Figure 3.7).

At the 50 mm, 150 mm and 350 mm depths the control and 1×2 mℓ/m² treatment tended to have the same shear strength values and the 2×2 mℓ/m² treatment tended to have the lowest shear strength. At the 250 mm depth the 1×2 mℓ/m² treatment tended to have the lowest shear strength while the control and 2×2 mℓ/m² treatment tended to be the same. The general trend was that the shear strength tended to increase from the 50 mm to the 350 mm depth.

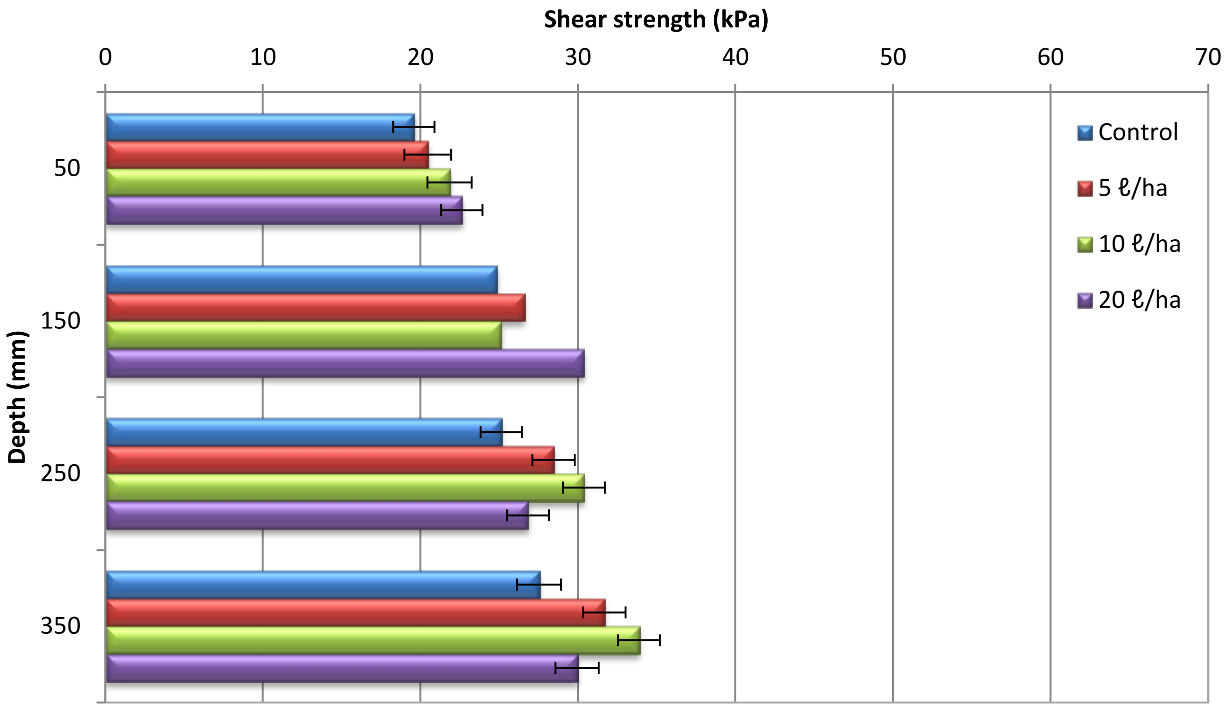

Figure 4.10: Shear strength at Wansbek. No statistical analysis was done on the 150 mm depth since the data was not normally distributed. Note that the 50, 250 and 350 mm depths were log transformed and the results transformed back for the purposes of the graph.

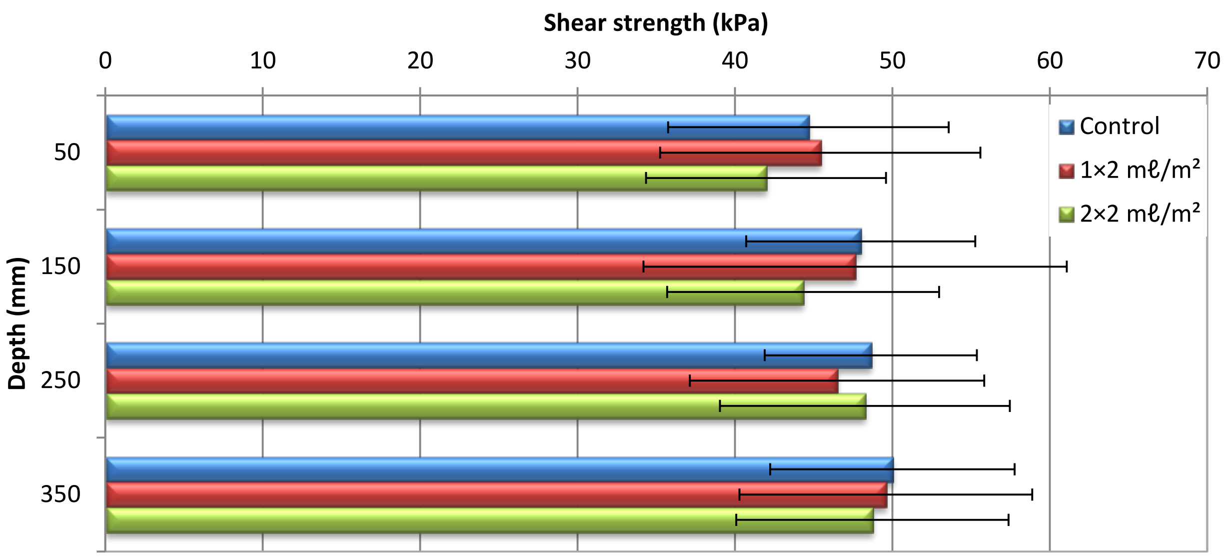

Figure 4.11: Shear strength at Two Rivers. Note that the CL 102 head was used for the analysis on this farm and not the CL 100.

4.4.5 Discussion

With reference to the 50 mm depth: For Wansbek and Dublin Farm trial 2 (approximately 20% clay), a phenomenon occurred where the shear strength of the control was higher than those of the treatments. The opposite happened at Toitskraal trial 1 and 2 and Two Rivers (approximately 7% and 3% clay respectively). No literature was found on the effect that surfactants have on shear strength, but certain deductions can be made from other literature found on shear strength. As explained in section 2.3.2, Lal & Shukla (2004) described three forces responsible for shear strength. These three forces will be referred to in the next three paragraphs to help explain the shear strength results.

At Dublin Farm trial 2 the shear strength as well as aggregate stability tended to be higher for the treatment than for the control. This confirms the results found by Baumgartland & Horn (1991) that an increase in aggregate stability leads to an increase in shear strength. Lal & Shukla (2004) explained that one of the forces responsible for shear strength is the resistance of the structure to the displacement of soil particles.

Both trials at Toitskraal showed the opposite trend to that of Dublin Farm trial 2. There was no clear relationship between shear strength, aggregate stability or even the bulk density of Toitskraal. In this case the differences in shear strength are therefore not attributed to structural or frictional resistance, but could have been due to the forces of cohesion and adhesion. The volumetric water content for the bulk density samples of trial 2 are presented in Table 4.3. It was expected that the control, which had the higher volumetric water content in all the depths would have had higher strength values than the treated soils. However the data showed the opposite. Note that the bulk density samples were not taken at the exact location where the shear strength readings were taken. Thus variation in the soil by means of bulk density and water content could have been the reason for the poor correlation.

At Wansbek, the trend observed at the 50 mm depth for the shear strength was the same as at Dublin Farm trial 2, i.e. increased with higher application rates. For Wansbek the observed trend did not correspond with the bulk density or the aggregate stability. It could have been due to the soil water content of each treatment. According to Lal & Shukla (2004) the soil strength increases as the soil water decreases. As explained in section 2.3.2, low water content pulls the soil particles together. There is however no evidence of what the cause of the differences could have been.

At Two Rivers the shear strength tended to increase with an increase in bulk density. The force due to structural resistance can be assumed as negligibly small since the soil is single grained and there were no aggregates present in the soil. The force due to frictional resistance increases with an increase in bulk density. At the 50 mm depth the shear strength and bulk density tended to obey this rule. The reason for the poor relationship below the 50 mm depth between bulk density and shear strength might be due to soil variations. The shear strength readings were taken from the profile pit wall while the bulk density samples were taken in the profile pit. The bulk density and shear strength were never the exact same soil. The bulk density could have been different at the locations where the shear strength was taken compared to the actual samples that were obtained.

4.5 Penetration resistance

The penetration resistance data for Dublin Farm trial 2 and Toitskraal trial 2 were not normally distributed in the untransformed state. The data was therefore log transformed and the statistical analyses done on the transformed data. The results were back transformed to present it in an understandable way.

4.5.1 Dublin Farm

The results for Dublin Farm trial 2 are presented in Figure 4.12. The penetration resistance for the control was significantly higher than for the treatment at both the 0 mm and 200 mm depths ($p = 0.0002$, MSD = 1.188 for 0 mm; $p = 0.026$, MSD = 1.219 for 200 mm). These results were the opposite of the results for the shear strength of Dublin Farm trial 2. It was expected that the penetration resistance would show the same trend as shear strength. The penetration resistance tended to increase from the 0 mm to the 200 mm depth for the control and the treatment.

4.5.2 Toitskraal

The results for Toitskraal trial 2 are presented in Figure 4.13. At the 50 mm depth the penetration resistance for the 2-year treatment was significantly higher than for the control and 1-year treatment ($p = 0.015$, MSD = 1.288). The difference between the control and the 2-year treatment was the opposite from that of Dublin Farm trial 2.

At the 150 mm depth the 2-year treatment was significantly higher than the control ($p = 0.048$, MSD = 1.244). At the 150 mm and 250 mm depth the control and 1-year treatment did not differ significantly, but the 1-year treatment tended to have a higher penetration resistance than the control.

The penetration resistance tended to increase from the 50 mm to the 250 mm depth.

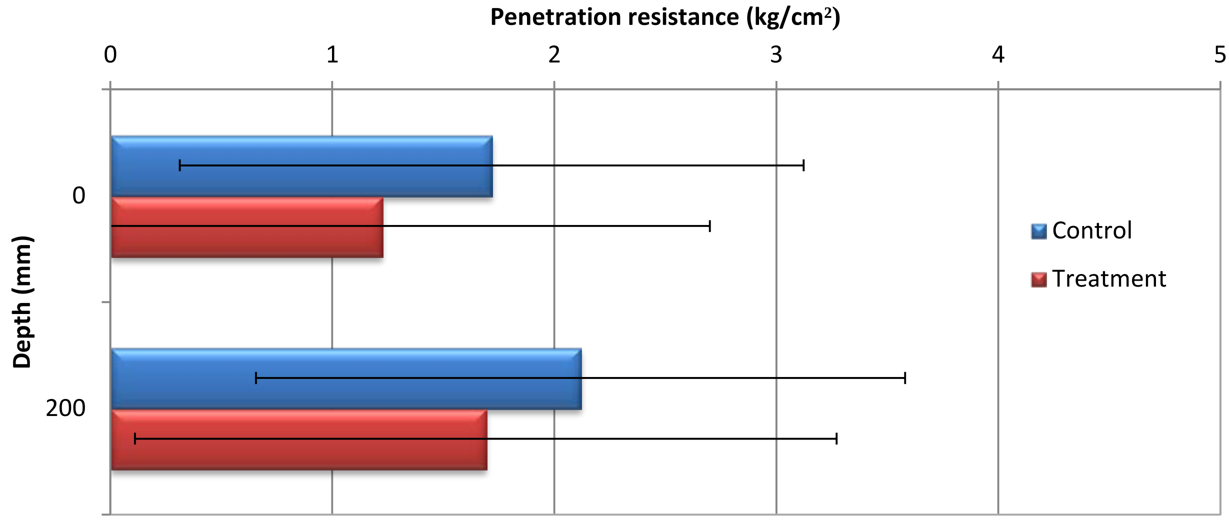

Figure 4.12: Penetration resistance at Dublin Farm trial 2. The data were log transformed and the results transformed back for the graphing purposes.

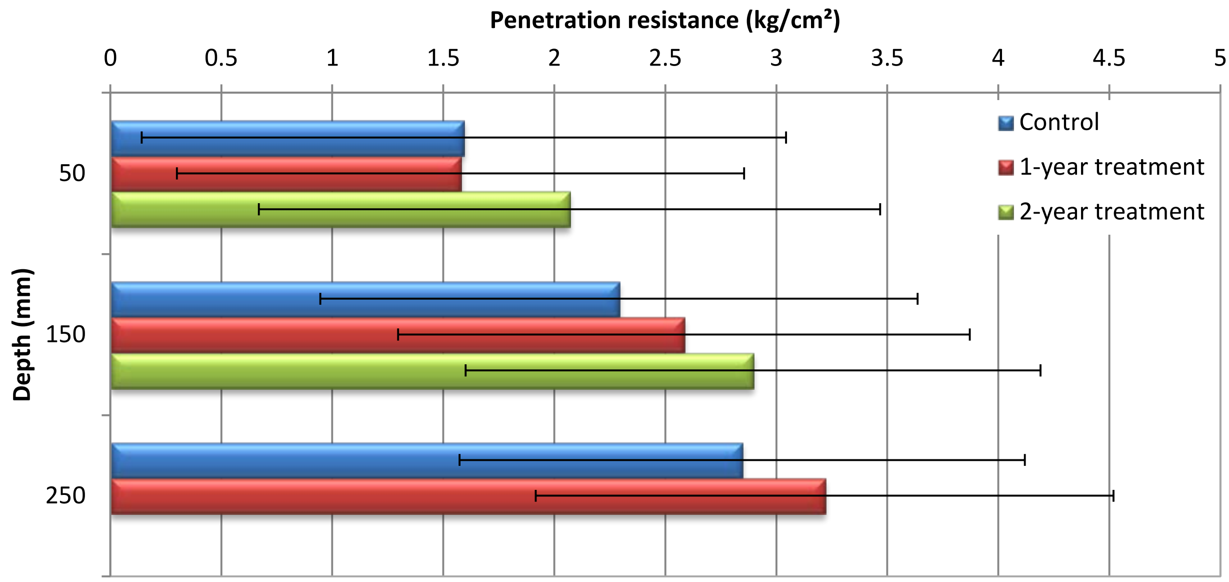

Figure 4.13: Penetration resistance at Toitskraal trial 2. The data were log transformed and the results transformed back for the graphing purposes.

4.5.3 Discussion

As mentioned, the penetration resistance results for Dublin Farm were the opposite of the results obtained for the shear strength. Penetration resistance is a good indication for compaction (Lal & Shukla, 2004), but the effect of structure, texture, organic matter and moisture content has a big influence on it. For Dublin Farm trial 2 at the 0 mm depth, the penetration resistance could have been higher for the control due to a higher bulk density at the 50 mm depth. The bulk density samples were taken approximately at the locations where the penetration resistance measurements were taken. So comparing the 200 mm penetration resistance with the 250 mm depth bulk density it is clear from these results that bulk density does not explain the penetration resistance results.

Toitskraal trial 2 showed a better correlation between bulk density and penetration. From the bulk density results it is clear that the soil is more compact from the 150 mm to the 350 mm depth. This is in accordance with the literature that a higher bulk density results in a higher penetration resistance (Lal & Shukla, 2004).

4.6 Unsaturated hydraulic conductivity

4.6.1 Dublin Farm

The results for Dublin Farm trial 1 are presented in Figure 4.14a. Too few replicates (six per depth for each of the control and treatment) were done to perform a statistical analysis, thus only the averages are given. The average for the control was lower than the treatment at each depth. The magnitude of the difference tended to increase with an increase in depth. The K_u for the control tended to decrease with an increase in depth while it tended to increase for the treatment. The extremely large differences might be due to experimental errors and due to a too short run time for the mini disk infiltrometer (20 minutes compared to at least 30 minutes or more for the other trials).

The results for trial 2 are presented in Figure 4.14b. No significant differences were observed between the K_u for the control and for the treatment at any depth. At the 0 mm depth the control tended to have a lower K_u than the treatment. The opposite results were obtained for the 200 mm depth and the difference between the control and treatment at the 400 mm depth was marginal. The K_u tended to increase with an increase in depth.

It was expected that the K_u would be lower at least at the 400 mm depth since there was a sharp increase in bulk density from the 250 mm to the 350 mm depth (Figure 4.1), but the opposite was observed in the results.

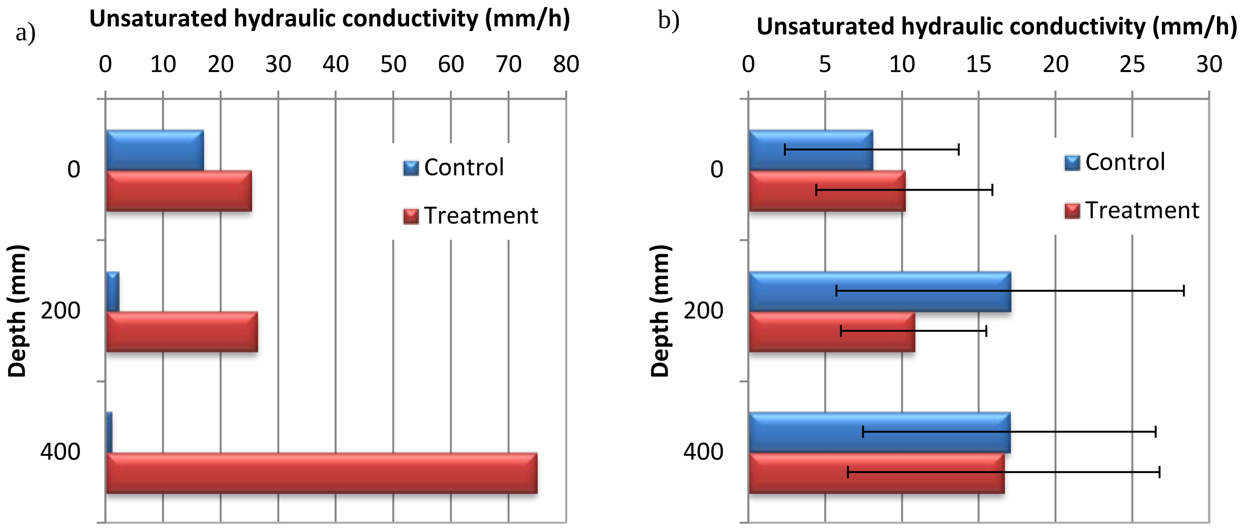

Figure 4.14: K_u at Dublin Farm a) trial 1 and b) trial 2. The suction for trial 1 was set on -1 and for trial 2 on -2. No statistical analysis was done for trial 1.

4.6.2 Toitskraal

The results for Toitskraal trial 1 are presented in Figure 4.15a. No statistical analysis was done on the data from trial 1, only the averages are given. At each depth the control tended to have a lower K_u. The large differences between the control and treatment, especially at the 200 mm and 400 mm depth, might also be due to the same experimental errors as explained for the K_u of Dublin Farm trial 1.

The results for Toitskraal trial 2 are presented in Figure 4.15b. At the 0 mm depth the control had a significantly higher K_u than the 1-year treatment ($p = 0.00192$, MSD = 13.064). This was contrary to the results of trial 1 where the control was lower than the treatment. At the 200 mm and 400 mm depths the control tended to have a higher K_u than the 1-year treatment. At the 200 mm depth the K_u for the 2-year treatment was significantly greater than for the 1-year treatment ($p = 0.0081$, MSD = 17.082). The higher K_u for the 2-year treatment, especially at the 200 mm depth, could have been due to the higher coarse fragment content of the soil in this treatment block. The coarse fragments could have caused the mini disk infiltrometer to not make full contact with the soil surface. The higher standard deviation for the 2-year treatment compared to the other treatments also confirms that there was much more variation in the soil.

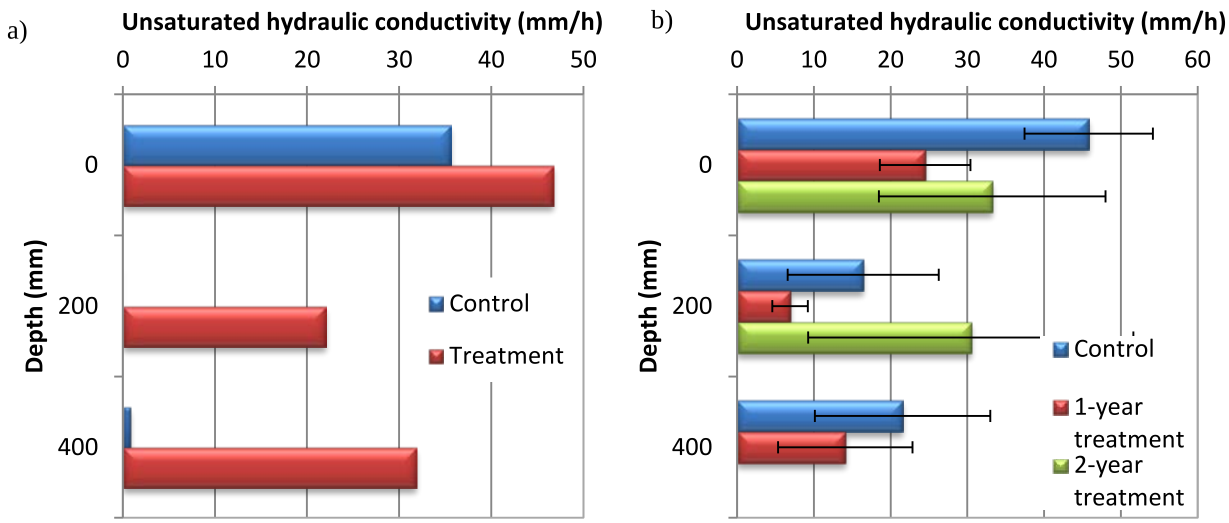

Figure 4.15: K_u at Toitskraal a) trial 1 and b) trial 2. Suction was set on -2 for trial 1 and -1 for trial 2. No statistical analyses were done on data from trial 1.

The K_u tended to decrease from the 0 mm depth to the 200 mm depth for all the treatments and then it tended to increase again to the 400 mm depth. The effects of the higher bulk density values at the 200 mm depth (Figure 4.2) were clearly noticeable.

4.6.3 Wansbek

The results for Wansbek are presented in Figure 4.16. No significant differences were observed in K_u at the 0 mm and 200 mm depths. It was clear that at the 0 mm depth, the K_u tended to increase with increasing application rates. The same trend is not discernible at the 200 mm depth as at the 0 mm depth. However, at both the 200 mm and the 400 mm depths, the control tended to have a higher K_u than the 5 ℓ/ha treatment while the 20 ℓ/ha treatment tended to have a higher K_u than the control and the 5 ℓ/ha treatment. The 10 ℓ/ha treatment tended to have the lowest K_u at the 200 mm depth, but tended to have the highest at the 400 mm depth where it was significantly higher than the 5 ℓ/ha treatment ($p = 0.0112$, MSD = 3.8134). The K_u for the control, 5 ℓ/ha treatment and 20 ℓ/ha treatment all tended to decrease from the 0 mm to the 200 mm depth and then tended to remain the same from the 200 mm to the 400 mm depth. The K_u for the 10 ℓ/ha treatment tended to decrease from the 0 mm to the 200 mm depth and then tended to increase to the 400 mm depth again.

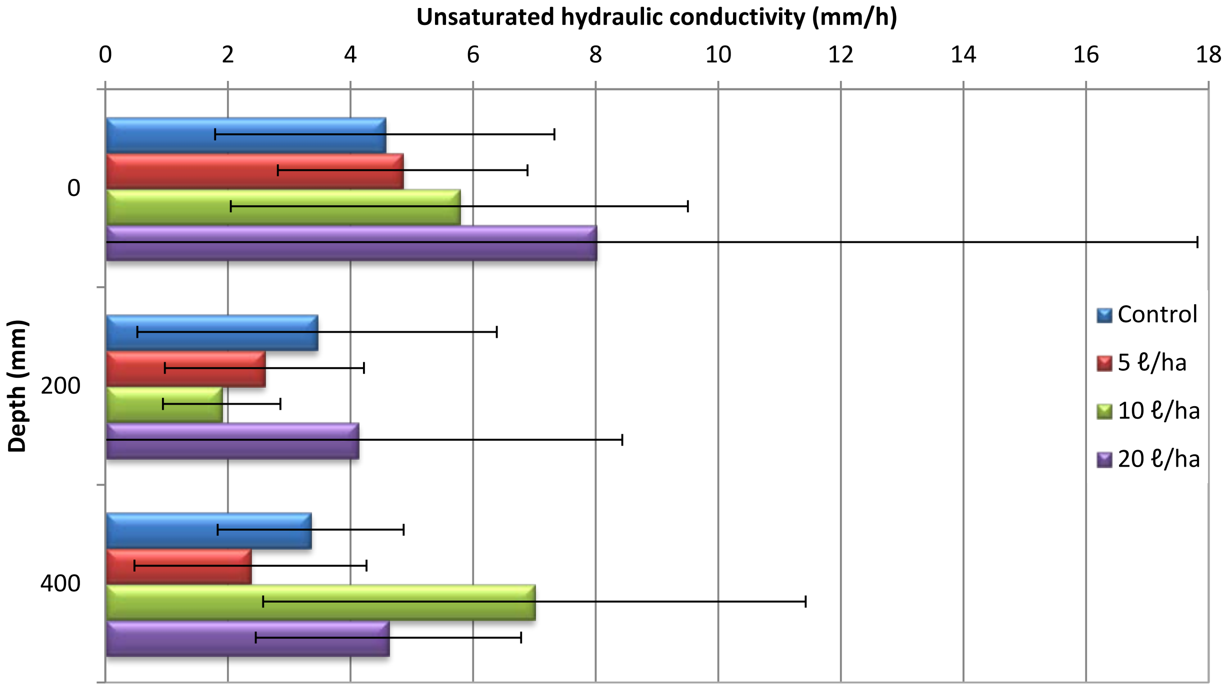

Figure 4.16: K_u at Wansbek.

4.6.4 Two Rivers

The results for Two Rivers are presented in Figure 4.17. No significant differences were observed between the K_u for the treatments at any of the depths. At the 0 mm and 400 mm depths the control tended to have the lowest K_u and the 1×2 mℓ/m² treatment the highest. At the 200 mm depth the only difference in the trend observed for the other two depths, was that the 1×2 mℓ/m² treatment tended to have the lowest K_u instead of the highest. The K_u for the control and 2×2 mℓ/m² treatment tended to decrease with an increase in depth. The K_u for the 1×2 mℓ/m² treatment tended to decrease from the 0 mm to the 200 mm depth and then tended to increase again to the 400 mm depth.

4.6.5 Discussion

It was expected that the product will result in an increase in K_u, at least where it was applied to the soil surface. For five of the six trials the control tended to have the lowest K_u at the 0 mm depth. Only at Toitskraal trial 2 the control tended to have a higher K_u at the 0 mm depth than the 1-year treatments.

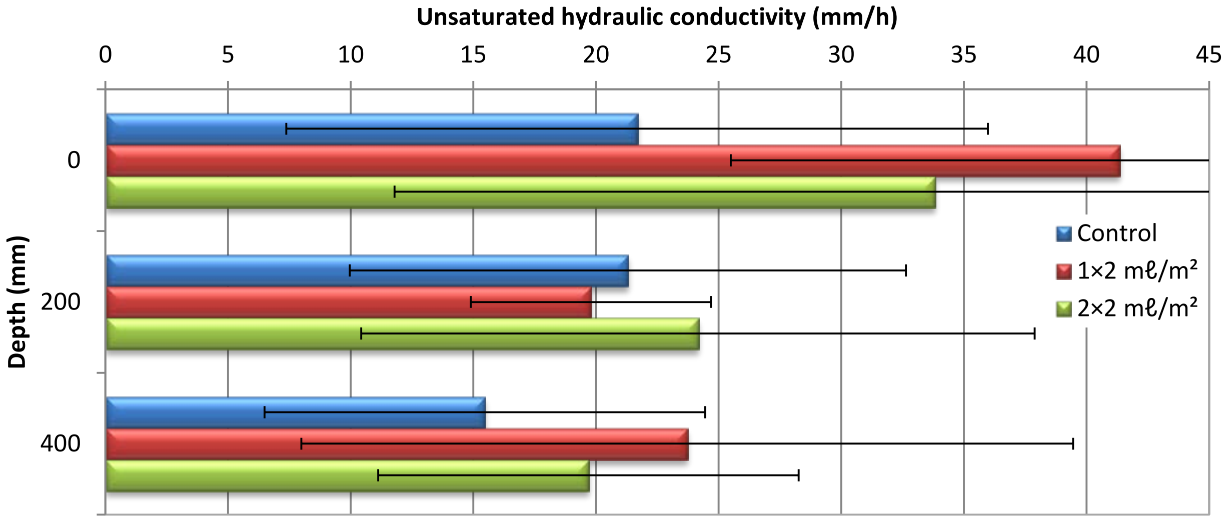

Figure 4.17: K_u at Two Rivers.

No literature could be found of the effect of surfactants on K_u. Most literature focuses on infiltration and saturated flow in the soil. Some of the literature indicated that anionic surfactants causes a decrease in K_s since it causes the aggregates to degrade and the clay to disperse which leads to blocked flow paths (Abu-Zreig *et al.*, 2003; Liu & Roy, 1995). It is important to understand the difference between saturated flow and unsaturated flow. According to Hillel (1980) saturated flow is when all the pores are filled with water and are conducting water. Unsaturated flow is when some of the pores are air filled. When soil desaturates it is the largest pores which drain first. The more the soil desaturates, the longer the path becomes along which the water are conducted. This means that the hydraulic conductivity for unsaturated flow is much lower than for saturated flow.

K_u increased in contrast with the literature for infiltration and K_s which showed a decrease after surfactant application (Abu-Zreig *et al.*, 2003; Liu & Roy 1995). Surfactants decrease the surface tension of the water resulting in the soil wetting faster. The surfactants can either adsorb (usually nonionic surfactants) to soil or move with the soil solution (usually anionic surfactants). From the aggregate stability data in section 4.3 it is clear that at the 50 mm depth for the treated soils of Dublin Farm trial 1, Toitskraal trial 1 and Wansbek the decrease in aggregate stability in the treated soils was not significant. So in the topsoil (in this case referring to the 0-100 mm depth) the effect which the residual surfactants in the soil could have had on the infiltrating water might have overshadowed the little effect it had on the aggregate stability.

At Dublin Farm trial 2 the last application of the product was 9½ months prior to field studies. The aggregate stability tended to be lower for the control soils compared to the treated soil. The increase in aggregate stability could have been the reason for the increase in K_u in the treated soils even though the aggregate stability mainly influences K_s.

4.7 Bulk density versus unsaturated hydraulic conductivity

A simple linear regression was performed on the 0 mm K_u and 50 mm bulk density data of Two Rivers and Wansbek. The bulk density value are plotted against the corresponding K_u value.

4.7.1 Wansbek

The results for Wansbek are presented in Table 4.4 and Figure 4.18. There were no straight-line relationship ($p > 0.05$) between the bulk density and the K_u for any of the treatments. The control had the highest R^2 value and the lowest p-value (Table 4.4). A trend can be observed from the control that as the bulk density increases, the K_u decreases. Based on the high p-values and low R^2 values (Table 4.4), no trends can be derived from Figure 4.18 for the treatments.

4.7.2 Two Rivers

At Two Rivers the control had a significant linear relationship between the bulk density and K_u (Figure 4.19 and Table 4.5). Approximately 70% of the variation in the K_u can therefore be explained by the variation in bulk density. In the case of the 1×2 mℓ/m² treatment only 56% of the variation of the K_u was explained by the variation in bulk density. Differences in K_u of the 2×2 mℓ/m² treatment were not related to bulk density.

4.7.3 Discussion

Unlike the results found for Wansbek in Figure 4.18, Two Rivers showed a positive relationship between the bulk density and K_u. To explain this, the particle size distribution and porosity must be taken into consideration. From Table 4.2 it is clear that approximately 50% of the soil particles smaller than 2 mm are medium (0.25-0.5 mm) and coarse (0.5-2.0 mm) sand. As mentioned earlier, the bulk densities for this soil are quite low for a sandy soil. The average porosity for the 50 mm depth is 0.49 for the control and 1×2 mℓ/m² treatment and 0.51 for the 2×2 mℓ/m² treatment (assuming particle density of 2.65 g/cm³). It must also be kept in mind that K_u refers to the flow of the water along the pore walls. So with the high porosity and the relatively large particles making up the composition, there can be too few contact points for the water to be conducted from one particle to the next. It might be that when the soil is denser that there is more contact between the different soil particles so that the water can be conducted along more "paths" in the soil. This result confirms the results of the studies conducted by Morin (2006). He found that it is possible to have a negative correlation between porosity and hydraulic conductivity of unconsolidated coarse textured soils.

Table 4.4: The R^2 values and p-values for each of the four linear regression models fitted on the K_u vs. bulk density scatter plots of each treatment of the surface data of Wansbek.

Treatment	R^2	p - value
Control	0.3702	0.082
5 ℓ/ha	0.0006	0.949
10 ℓ/ha	0.0151	0.753
20 ℓ/ha	0.0436	0.590

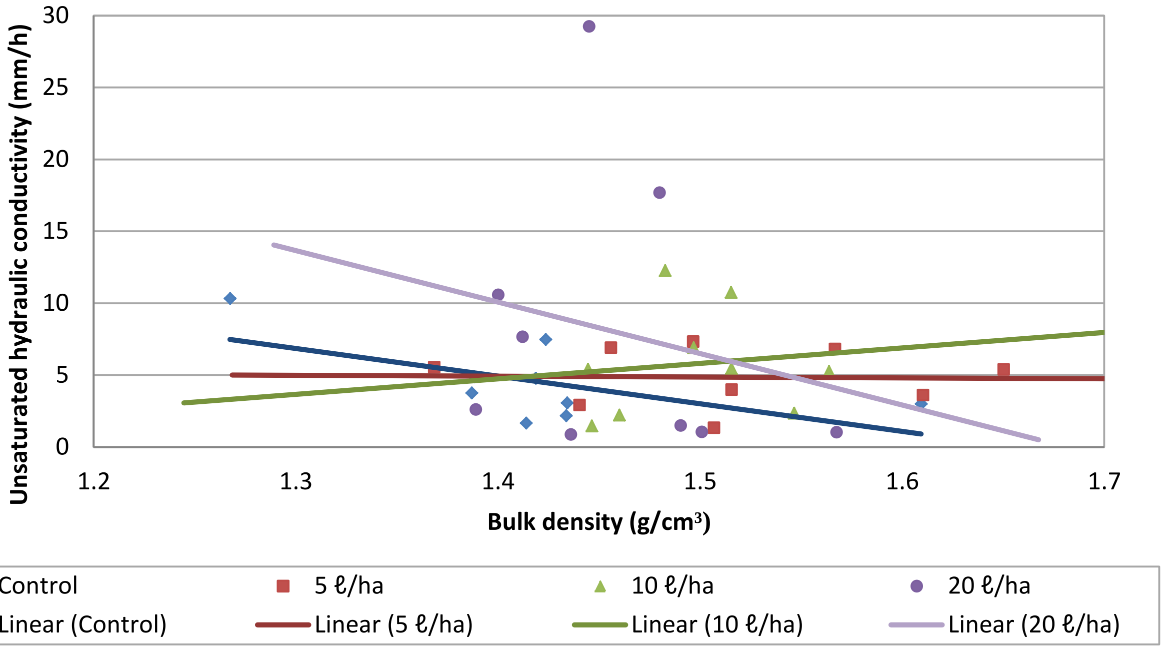

Figure 4.18: K_u at the surface (0 mm) plotted against the corresponding bulk density (50 mm) for Wansbek.

Table 4.5: The R^2 values and p-values for each of the four linear regression models fitted on the K_u vs. bulk density scatter plots of each treatment of the surface data of Two Rivers.

Treatment	R^2	p-value
Control	0.7043	0.0182
1×2 mℓ/m²	0.5625	0.0321
2×2 mℓ/m²	0.0587	0.6006

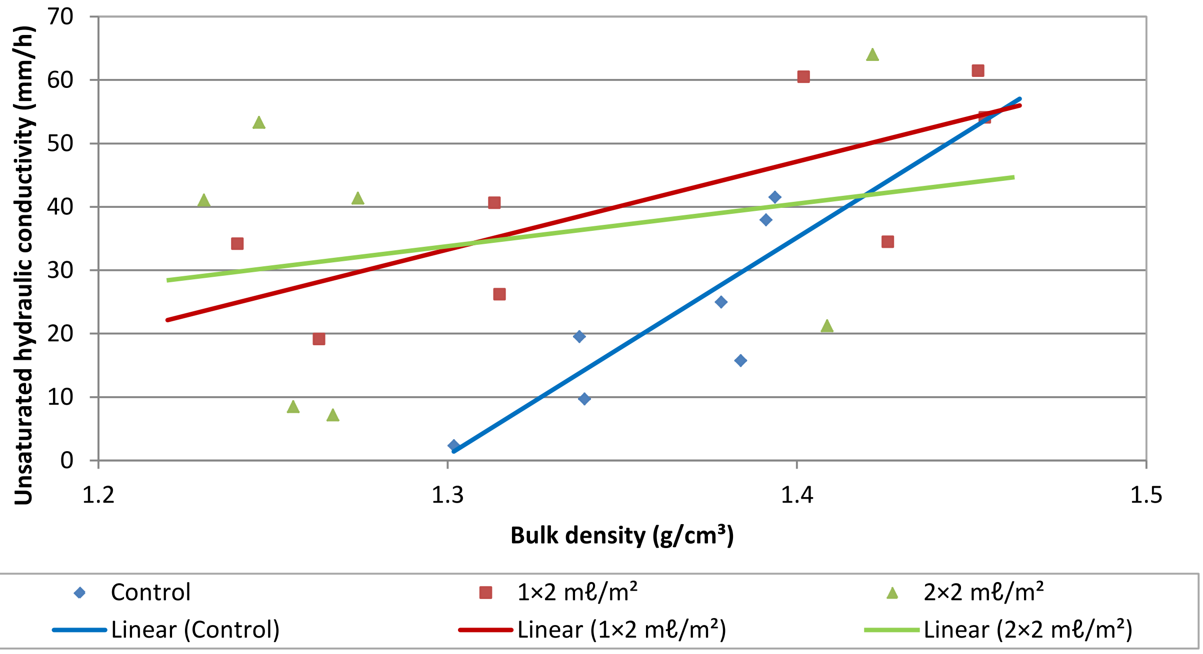

Figure 4.19: K_u at the surface (0 mm) plotted against the corresponding bulk density (50 mm) for Two Rivers.

What is obvious for both farms is that the R^2 value is the highest for the control. Although there is no linear relationship between the bulk density and K_u for Wansbek, the R^2 value is still much higher for the control than for the treated soils. These results may indicate that the product affected the K_u.

The poor relationships between hydraulic conductivity and bulk density at Wansbek compared to those obtained for Two Rivers might be due to some of the following factors: Firstly, the cylinder used to obtain the bulk density core samples was driven in horizontally underneath the locations where the minidisk infiltrometer was used. So an average of the two cores obtained was calculated and plotted against the K_u. At Two Rivers the cylinder used to obtain bulk density was driven into the soil vertically at the exact spot where the minidisk infiltrometer was used and the core closest to the surface was used. So the bulk densities at Two Rivers were much more precise for the small area the minidisk infiltrometer covered. Secondly, the soil at Wansbek varied a lot due to clods that might have formed during ploughing when the vineyard block was established. The soil at Two Rivers was much more uniform from one point to another. Thirdly, the way in which the minidisk infiltrometer was used at Wansbek might have caused variation in data. A thin layer of soil was sieved on the location where the minidisk infiltrometer was placed to create an even and level surface for the minidisk infiltrometer to stand on. The sandy soils at Two Rivers were easily made level. Based on the second and third points, the probability for the disc of the minidisk infiltrometer to not make full contact with the soil surface was much higher at Wansbek than at Two Rivers.

4.8 Chemical characteristics

No statistical analyses were done on the pH and electrical conductivity (EC). The averages are presented in Table 4.6 for each farm. Dublin Farm, Toitskraal and Two Rivers had pH(H_2O) values below seven while Wansbek had pH values above seven.

At Dublin Farm the pH and EC increased from the topsoil to the subsoil. At Toitskraal the pH decreased from topsoil to subsoil and the EC increased. At Wansbek there was at each treatment a slight increase in pH from topsoil to subsoil. The EC decreased from topsoil to subsoil. At Two Rivers the pH increased from topsoil to subsoil. In the control and 1×2 mℓ/m² treatment the EC increased from topsoil to subsoil while the opposite result was obtained for the 2×2 mℓ/m² treatment.

The chemical results of specific samples are presented in Table 4.7. The T-value which is the sum of the basic cations and the exchangeable acidity was used as an indication for the type of clay that might be present in the soil. The nonionic surfactants tend to adsorb on 2:1 clays like montmorillonite and illite (Law & Kunze, 1966; Sánchez-Martin *et al.*, 2008). It was only done for the results obtained for the subsoil (200-400 mm) of Dublin Farm, Toitskraal and Wansbek with the following equation:

$$CEC\ (clay) = T - value\ \times 100/clay\%$$

In the subsoil the organic matter does not contribute as much to the CEC as in the topsoil. At Two Rivers organic matter was the main source of CEC since it contained 2.7% organic matter on a weight basis. This contributed abundantly to the CEC of the soil.

The clay for Dublin Farm had a CEC of 72.8 $cmol_c$/kg. This is almost in the region of the CEC for montmorillonite which have a CEC of between 80 and 150 $cmol_c$/kg (Sparks, 2003). The clay present is more likely vermiculite which has a CEC of 10-200 $cmol_c$/kg. Vermiculite is also a 2:1 clay like montmorillonite and it also have many oxygen ions on both sides of the clay layer to which the nonionic surfactant molecules can bind. It was mentioned in Section 4.1 that the dispersion of clay during the texture analysis could have been incomplete due to iron oxides and hydroxides that could have been present that could have bound the clay particles which then acted as silt. If the silt is added to the clay fraction the CEC for the clay + silt fraction is 51.1 $cmol_c$/kg.

Toitskraal had a low CEC, however, when the CEC for the clay was calculated it ended up being 54.7 $cmol_c/kg$ for the subsoil. This could indicate that a 2:1 clay mineral was present in the soil. The subsoil CEC for Wansbek was 15.7 $cmol_c/kg$ and for the clay it was 67.0 $cmol_c/kg$.

So for Dublin Farm and Wansbek it is clear that some sort of 2:1 clay was present in the soil since the CEC confirmed it and the soil had moderate structure. The aggregate stability for Dublin Farm trial 2 also indicated that the nonionic surfactant had a long lasting effect on the soil which could only have happened if it were adsorbed in the soil. At Toitskraal the CEC also indicated that the little amount of clay present in the soil were of 2:1 nature. And like Dublin Farm trial 2, Toitskraal trial 2 also showed some tendency in the aggregate stability results that the nonionic surfactant were present in soil longer than the anionic surfactant. This could only have happened if there were a 2:1 clay on which it could have adsorbed and which protected the surfactant molecule against degradation.

Table 4.6: Average pH and EC results for each farm.

Farm	**Treatment**	**Depth**	***n***	**pH (H_2O)**	**pH (KCl)**	**EC (µS/cm)**
Dublin Farm	Control	0-200 mm	3	4.82	3.89	220.40
		200-400 mm	3	5.71	5.22	297.97
	Treatment	0-200 mm	3	4.84	3.79	146.17
		200-400 mm	3	5.11	4.44	370.33
Toitskraal	Control	0-200 mm	3	6.22	5.48	108.90
		200-400 mm	3	5.56	4.53	125.23
	Treatment	0-200 mm	3	5.34	4.46	118.00
		200-400 mm	3	4.71	3.95	138.43
Wansbek	Treatment 1	0-200 mm	1	8.31	7.64	118.53
	(control)	200-400 mm	1	8.38	7.55	86.40
	Treatment 2	0-200 mm	1	7.84	7.04	107.97
		200-400 mm	1	8.37	7.41	77.63
	Treatment 3	0-200 mm	1	8.26	7.60	116.60
		200-400 mm	1	8.65	7.84	102.00
	Treatment 4	0-200 mm	1	8.13	7.38	118.27
		200-400 mm	1	8.19	7.53	94.47
Two Rivers	Treatment 1	0-200 mm	2	5.88	4.89	40.90
	(control)	200-400 mm	2	6.10	5.06	49.25
	Treatment 3	0-200 mm	3	5.61	4.61	41.53
		200-400 mm	3	5.83	4.78	46.17
	Treatment 6	0-200 mm	2	5.53	4.77	88.20
		200-400 mm	2	5.79	4.93	57.80

Table 4.7: Exchangeable cations and acidity (pH = 7), pH and Ec, and silt, Fe and clay fractions of selected samples of each farm. The Fe fraction was determined during the texture analysis. Subsoil and topsoil samples of the control sites of each farm were analysed. The T-value is synonym to the CEC of the soil. Take note that the organic matter content for the soil of Two Rivers was 2.7%.

Farm	Depth (mm)	$cmol_c/kg$						pH (H_2O)	pH (KCl)	EC (µS/cm)	Total silt (%)	Fe oxides/ hydroxides (%)	Clay (%) + Fe oxides/ hydrox-ides (%)
		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	H^{+}	T-value						
Dublin Farm	0-200	7.78	3.79	0.30	1.15	1.37	14.39	5.28	4.16	178.5	9.46	5.89	25.41
	200-400	6.79	6.75	0.57	0.23	0.21	14.54	6.46	6.15	431.0	8.45	2.97	19.98
Toitskraal	0-200	1.95	1.56	0.26	0.18	0.35	4.30	5.98	5.33	77.4	16.47	-	7.21
	200-400	1.80	1.73	0.30	0.15	0.65	4.63	5.54	4.51	79.7	18.58	-	8.47
Wansbek	0-200	10.38	2.63	0.30	0.54	-	13.85	8.57	7.91	116.1	13.78	2.99	20.23
	200-400	12.03	2.96	0.26	0.43	-	15.68	8.79	8.04	89.4	11.47	4.57	23.42
Two Rivers	0-200	2.55	0.49	0.26	0.28	1.00	4.58	5.76	4.91	56.0	10.79	-	3.48
	200-400	2.30	0.41	0.17	0.20	0.70	3.79	5.98	5.02	70.0	10.20	-	3.16

5. Conclusions

A new orange oil based soil ameliorant is available on the market. As main constituents, apart from the orange oil, it also contains a nonionic surfactant and an anionic surfactant. The aim of this study was to evaluate the effect it might have on soil bulk density, aggregate stability, soil strength and K_u.

The product had the greatest impact in the topsoil i.e. 50 mm. The bulk density was not affected by the product at any depth, except at Two Rivers where the highest concentration treatment (2×2 mℓ/m² treatment) tended to have lower bulk density than the other treatments at the 50 mm depth.

The product tended to have a negative impact on aggregate stability at the 50 mm depth for the trials where the product was applied not too long before the field studies were conducted (Dublin Farm trial 1, Toitskraal trial 1 and Wansbek). Reduced stability may be attributed to the anionic surfactant, which lowers the surface tension of the applied water causing easier wetting of the hydrophobic aggregates by water with a net result of aggregates breaking down due to slaking. From Dublin Farm trial 2 and Toitskraal trial 2 it is clear that the nonionic surfactant of the product were active much longer in the soil than the anionic surfactant since it increased aggregate stability. From the chemical analysis of the soils, it can be derived that Dublin Farm, Toitskraal and Wansbek might have had 2:1 clay minerals. Nonionic surfactants adsorb the best onto these types of clay minerals thus preventing rapid decomposition of the surfactants. As a result, the effect of the nonionic surfactant was lasting longer in these soils.

At Dublin Farm and Wansbek, the shear strength at the 50 mm depth tended to be higher for the treatment than for the control. At Toitskraal and Two Rivers the trend was the opposite: the control tending to have a higher shear strength than the treated soils. It was not always clear what was causing the differences in the shear strength between the treatments. The shear strength for Dublin Farm trial 2 corresponded with the aggregate stability while the shear strength for Two Rivers tended to correspond with the bulk density.

The penetration resistance at Dublin Farm trial 2 tended to be lower for the treated soils compared to the control soils. The opposite results were obtained at Toitskraal trial 2. The results obtained for penetration resistance corresponded mostly with the bulk density. So the differences in penetration resistance can be assumed to be purely due to natural variation in the soil and not due to the product.

As expected, the K_u at the surface tended to be higher for the treated compared to the untreated soils. Only at Toitskraal trial 2 the K_u at the surface gave the opposite of the expected result. The control had the best linear regression relationship between K_u (at 0 mm depth) and bulk density (at 50 mm depth) at Wansbek and Two Rivers. Compared to the control, poorer linear regression relationships between the K_u and bulk density – at least of the surface soils treated by the product – indicate that the product affected hydraulic conductivity.

According to the data found in this research, it can be concluded that the changes in bulk density, aggregate stability, shear strength and K_u, if any, due to the application of the product, were not of such magnitude that it might have caused a positive crop response. In more problematic soils, e.g. hydrophobic soils, the effect might be more prominent.

Future research would include more trials with the experimental design similar to that of Two Rivers. This could, for example at Toitskraal, discern better between product effects and give a more accurate indication of soil variations like bulk density and soil texture differences that could have caused differences which were interpreted otherwise as the effect of the product.

The effect of the product on soils with high organic matter such as at Two Rivers should also be studied. The bulk density tended to be lower at the 50 mm depth for the highest application rate at Two Rivers. A previous study showed a similar result.

The reaction of the product with different types of clay minerals should be investigated. In this study, the focus was not so much the reaction of the product with different types of clays (micro scale), but more on the macro scale. Future research should thus focus more on the chemistry of the product in the soil to obtain a better understanding of the results obtained for the physical characteristics of the soil.

The effects of the individual constituents of the product, the orange oil, the anionic surfactant and the nonionic surfactant, should also be studied. The effect of different combinations of the constituents should be investigated to determine the exact role and mechanism of each main constituent in the soil. The effect which limonene might have on crops should also be investigated since it was found in previous research that limonene has an influence on the respiration process in the mitochondria.

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Appendices

Appendix 1.1: Terrain and morphological soil characteristics of the soil of Dublin Farm.

Latitude + Longitude: S24º21.750' E30º39.345'
Climate zone: Lowfield
Altitude: 464 m
Terrain unit: Midslope
Slope: < 5%
Slope shape: Straight
Aspect: East
Microrelief: None

Soil form and family: Shortland Roedtan
Surface rockiness: None
Surface stoniness: None
Occurrence of flooding: None
Wind erosion: None
Water erosion: None
Vegetation / Land use: Citrus orchard
Water table: None
Date described: 22/03/2011

Master horizon	Depth (mm)	Description	Diagnostic horizon
A	0-100	dry colour: dark reddish brown 5YR 3/3 ; texture: sandy clay loam; structure: moderate, medium blocky; consistence: sticky; diffuse transition	Orthic A
B	100-400	dry colour: dark reddish brown 5YR 3/3; texture: sandy clay loam to sandy loam; structure: moderate, medium to coarse blocky; consistence: sticky	Red structured B

Appendix 1.2: Terrain and morphological soil characteristics of the soil of Toitskraal.

Latitude + Longitude: S25^{o}03'19.64" E29^{o}08'24.8"
Climate zone: Highfield
Altitude: 927.5 m
Terrain unit: Crest
Slope: < 2%
Slope shape: Straight
Aspect: -
Microrelief: None

Soil form and family: Oakleaf Cooper
Surface rockiness: None
Surface stoniness: None
Occurrence of flooding: None
Wind erosion: None
Water erosion: None
Vegetation / Land use: Citrus orchard
Water table: None
Date described: 06/05/2011

Master horizon	Depth (mm)	Description	Diagnostic horizon
A	0-100	dry colour: brown 7.5YR 5/2; moist colour: brown 7.5YR 4/4; texture: loamy sand to sandy loam; cementation: silica; structure: moderate, fine blocky; diffuse transition	Orthic A
B	100-400	dry colour: brown 7.5YR 5/2; moist colour: brown 7.5YR 4/4; texture: sandy loam; cementation: silica; structure: massive	Neocutanic B

Appendix 1.3: Terrain and morphological soil characteristics of the soil of Wansbek.

Latitude + Longitude: S33°54'2.96" E19°40'31.61"
Climate zone: Mediterranean
Altitude: 203 m
Terrain unit: Lower midslope
Slope: < 5%
Slope shape: Straight
Aspect: South east
Microrelief: None

Soil form and family: Valsrivier Dewetsdorp
Surface rockiness: None
Surface stoniness: None
Occurrence of flooding: None
Wind erosion: None
Water erosion: None
Vegetation / Land use:
Water table: None
Date described: 28/11/2011

Master horizon	Depth (mm)	Description	Diagnostic horizon
A	0-100	dry colour: yellowish red 5YR 5/6; moist colour: yellowish red 5YR 4/6; texture: sandy loam; structure: moderate blocky structure; consistence: slightly sticky; diffuse transition	Orthic A
B	100-400	dry colour: yellowish red 5YR 5/6; moist colour: yellowish red 5YR 4/6; texture: sandy loam to sandy clay loam; structure: moderate blocky structure; consistence: slightly sticky	Pedocutanic B

Appendix 1.4: Terrain and morphological soil characteristics of the soil of Two Rivers.

Latitude + Longitude: S33 ° 52’23.59” E19 ° 1'56.91"
Climate zone: Mediterranean
Altitude: 250 m
Terrain unit: Valley bottom
Slope: < 5%
Slope shape: Straight
Aspect: South east
Microrelief: None

Soil form and family: Oakleaf Ritchie
Surface rockiness: None
Surface stoniness: None
Occurrence of flooding: None
Wind erosion: None
Water erosion: None
Vegetation / Land use: Plum orchard
Water table: None
Date described: 07/05/2012

Master horizon	Depth (mm)	Description	Diagnostic horizon
A	0-100	dry colour: dark brown 10YR 3/3; moist colour: black 10YR 2.5/1; texture: sand to loamy sand; structure: apedal single grained; consistence: friable; diffuse transition	Orthic A
B	100-400	dry colour: dark brown 10YR 3/3; moist colour: black 10YR 2.5/1; texture: sand to loamy sand; structure: apedal single grained; consistence: friable	Neocutanic B

Appendix 2.1: Average bulk density for each farm. A different alphabetical letter next to a value indicates a significant difference between the averages of depth class of a farm according to Tukey's studentized range test.

Farm	**Treatment**	***n***	**Depth (mm)**				
			50	**150**	**250**	**350**	**450**
Dublin Farm trial 1	Control	12	1.412 a	1.436 a	1.389 a	1.601 a	-
	Treatment	12	1.396 a	1.423 a	1.411 a	1.558 a	-
	Tukey MSD(0.05)		*0.0829*	*0.0839*	*0.084*	*0.0852*	-
Dublin Farm trial 2	Control	6	1.364 a	1.468 a	1.394 b	-	-
	Treatment	6	1.331 a	1.461 a	1.493 a	-	-
	Tukey MSD(0.05)		*0.0937*	*0.0863*	*0.0825*	-	-
Toitskraal trial 1	Control	6	1.562 a	1.753 a	1.784 a	1.743 a	1.603 a
	Treatment	6	1.565 a	1.678 a	1.846 a	1.817 a	1.719 a
	Tukey MSD(0.05)		*0.1044*	*0.178*	*0.0949*	*0.1049*	*0.1337*
Toitskraal trial 2	Control	4	1.472 a	1.678 a	1.845 a	-	-
	1-year treatment	4	1.547 a	1.729 a	1.781 a	-	-
	2-year treatment	4	1.692 a	-	-	-	-
	Tukey MSD(0.05)		*0.3133*	*0.2777*	*0.2065*	-	-
Wansbek	Control	18	1.420 b	1.491 a	1.549a	1.536 ab	1.564 a
	5 ℓ/ha treatment	18	1.512 a	1.571 a	1.588 a	1.555 ab	1.628 a
	10 ℓ/ha treatment	18	1.497 ab	1.541 a	1.589 a	1.590 a	1.631 a
	20 ℓ/ha treatment	18	1.458 ab	1.557 a	1.590 a	1.478 b	1.554 a
	Tukey MSD(0.05)		*0.0783*	*0.0866*	*0.0959*	*0.1072*	*0.1146*
Two Rivers	Control	16	1.354 ab	1.359 a	*1.413 a	1.399 a	1.406 a
	1×2 mℓ/m^2	16	1.378 a	1.390 a	1.412 a	**1.444 a	$^{+}$1.420 a
	2×2 mℓ/m^2	16	1.296 b	1.353 a	1.417 a	1.418 a	$^{++}$1.404 a
	Tukey MSD(0.05)		*0.0634*	*0.0695*	*0.0736*	*0.0553*	*0.0555*

* $n = 15$ ** $n = 13$ $^{+}$ $n = 14$ $^{++}$ $n = 12$

Appendix 2.2: Average aggregate stability percentages for each farm. A different alphabetical letter next to a value indicates a significant difference between the averages of depth class of a farm according to Tukey's studentized range test.

			Depth (mm)		
Farm	**Treatment**	***n***	**50**	**150**	**250**
Dublin Farm trial 1	Control	9	72.78 a	63.69 a	63.34 a
	Treatment	9	63.15 a	63.45 a	64.53 a
	Tukey MSD(0.05		*11.223*	*16.944*	*9.4943*
Dublin Farm trial 2	Control	9	58.18 a	53.13 a	40.18 b
	Treatment	9	65.18 a	54.30 a	56.89 a
	Tukey MSD(0.05		*10.645*	*10.044*	*13.688*
Toitskraal trial 1	Control	9	94.07 a	63.42 a	57.15 a
	Treatment	9	90.19 a	71.78 a	59.45 a
	Tukey MSD(0.05		*7.1745*	*14.273*	*14.196*
Toitskraal trial 2	Control	8	57.61 a	49.04 a	48.39 a
	1-year treatment	8	61.58 a	45.48 a	53.59 a
	2-year treatment	8	68.58 a	-	-
	Tukey MSD(0.05		*15.891*	*5.3713*	*10.372*
Wansbek	Control	9	47.49 a	52.04 a	48.37 a
	10 ℓ/ha	9	44.97 a	48.57 a	49.72 a
	Tukey MSD(0.05		*9.493*	*10.72*	*14.111*

Appendix 2.3: Average shear strength for each farm. A different alphabetical letter next to a value indicates a significant difference between the averages of depth class of a farm according to Tukey's studentized range test.

Farm	Treatment	*n*	Depth (mm)			
			50	**150**	**250**	**350**
Dublin Farm trial 2	Control	36	15.13 a	17.44 b	19.76 b	-
	Treatment	36	16.22 a	19.35 a	21.81 a	-
	Tukey MSD(0.05)		*1.616*	*1.889*	*1.991*	-
Toitskraal trial 1	Control	24	*44.55 a	46.11 a	54.59 a	*56.53 a
	Treatment	24	**43.64 a	45.38 a	49.26 a	52.31 a
	Tukey MSD(0.05)		*5.6709*	*4.8206*	*6.5011*	*6.2783*
Toitskraal trial 2	Control	20	+17.61 a	17.39 a	20.64*	20.34 a
	1-year treatment	20	15.09 b	13.45 b	14.65*	17.44 a
	2-year treatment	20	14.19 b	16.13 a	-	-
	Tukey MSD(0.05)		*2.2783*	*2.1635*	-	*3.1599*
Wansbek	Control	36	19.59 a	26.03	25.13 b	27.53 b
	5 ℓ/ha treatment	36	20.48 a	29.04	28.45 ab	31.69 ab
	10 ℓ/ha treatment	36	21.85 a	26.19	30.37 a	33.88 a
	20 ℓ/ha treatment	36	22.63 a	31.17	26.84 ab	29.96 ab
	Tukey MSD(0.05)		*1.219*	-	*1.192*	*1.211*
Two Rivers	Control	40	44.67 a	47.98 a	48.63 a	50.00 a
	1×2 mℓ/m²	40	45.42 a	47.64 a	46.48 a	49.59 a
	2×2 mℓ/m²	40	41.97 a	44.32 a	48.26 a	48.73 a
	Tukey MSD(0.05)		*4.7598*	*5.3821*	*4.5192*	*4.5622*

* *n* = 23 and ** *n* = 21 + *n* = 15

* *Nonparametric Wilcoxon rank-sum test ~ significant difference was observed*

Appendix 2.4: Average penetration resistance for Dublin Farm trial 2. A different alphabetical letter next to a value indicates a significant difference between the averages of depth class of a farm according to Tukey's studentized range test.

Treatment	*n*	Depth (mm)	
		0	**200**
Control	36	1.72 a	2.12 a
Treatment	36	1.22 b	1.69 b
Tukey MSD(0.05)		*1.188*	*1.219*

Appendix 2.5: Average penetration resistance for Toitskraal trial 2. A different alphabetical letter next to a value indicates a significant difference between the averages of depth class of a farm according to Tukey's studentized range test.

Treatment	*n*	Depth (mm) 50	150	250
Control	20	1.59 b	2.29 b	2.85 a
1-year treatment	20	1.58 b	2.58 ab	3.22 a
2-year treatment	20	2.07 a	*2.90 a	
Tukey MSD(0.05)		*1.288*	*1.244*	*1.176*

* *n* = 15

Appendix 2.6: Average K_u for each farm. A different alphabetical letter next to a value indicates a significant difference between the averages of depth class of a farm according to Tukey's studentized range test.

Farm	Treatment	*n*	Depth (cm) 0	20	40
Dublin Farm trial 1	Control	6	16.875	2.216	0.925
	Treatment	6	25.227	26.250	74.752
Dublin Farm trial 2	Control	12	8.037 a	17.044 a	*16.990 a
	Treatment	12	10.161 a	10.759 a	**16.626 a
	Tukey MSD(0.05)		*4.8259*	*7.3432*	*9.0167*
Toitskraal trial 1	Control	6	35.556	0.000	0.767
	Treatment	6	46.667	21.988	31.817
Toitskraal trial 2	Control	8	45.814 a	16.426 ab	21.550 a
	1-year treatment	8	24.495 b	6.907 b	14.094 a
	2-year treatment	8	33.235 ab	30.457 a	
	Tukey MSD(0.05)		*13.064*	*17.082*	*10.915*
Wansbek	Control	9	4.559 a	3.455 a	++3.349 ab
	5 ℓ/ha treatment	9	4.853 a	2.595 a	2.368 b
	10 ℓ/ha treatment	9	5.777 a	+1.899 a	7.001 a
	20 ℓ/ha treatment	9	8.007 a	4.125 a	+4.621 ab
	Tukey MSD(0.05)		*7.0528*	*3.6526*	*3.8143*
Two Rivers	Control	8	++21.684 a	21.299 a	15.471 a
	1×2 mℓ/m²	8	41.334 a	19.792 a	23.720 a
	2×2 mℓ/m²	8	++33.822 a	24.163 a	19.694 a
	Tukey MSD(0.05)		*23.417*	*13.578*	*14.583*

* *n* = 10 ** *n* = 11 + *n* = 8 ++ *n* = 7